RISK AND DECISION ANALYSIS OF SPECTRUM USAGE

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The past decades have witnessed wireless communications traffic exploding. The static spectrum allocation approach can hardly meet the soaring service requirement. Therefore, different spectrum sharing methodologies emerged, such as Authorized Spectrum Access, TV White Space, unlicensed usage, etc. The vast amounts of research work demonstrates that spectrum sharing provides flexibility in spectrum access, increases spectrum usage efficiency, and improves spectrum users utilities.

Despite of these advantages, spectrum sharing has been adopted slowly due in part to the embedded risks. Specifically, each spectrum sharing method leads to different costs, revenue, and Quality of Services (QoS) levels. Based on spectrum users requirement on QoS and profits, they encounter distinct risks. Meanwhile, risks may not necessarily lead to failure. Spectrum users can actively cope with risks through mitigation strategies. Moreover, like any engineering investment, spectrum usage is a decision making process for spectrum users. Different choices are made based on distinct incentives and limitations.

In order to transform spectrum sharing from a radical strategy to commercial reality, it is essential to quantify risks that associate with each spectrum usage method and understand spectrum users decision process. Consequently, this dissertation focuses on determining expected profits, QoS level, risks, and mitigation strategies for each spectrum sharing method, and applying a decision model to analyze spectrum users' choices.

In detail, two types of risks are modeled in this dissertation: (1) QoS risks with respect to throughput, and (2) monetary risks in terms of profits. Specifically, QoS risks are quantified by M/G/C queue. Monetary risks consider costs, revenues, and mitigation strategies. The

value of mitigation strategies is determined by the real options approach to reflect the worth of management flexibility. The best spectrum usage method is identified according to decision criteria such as profits maximization and risk minimization.

The merit of this dissertation is two-fold. First, it helps spectrum entrants select the most appropriate spectrum sharing method based on existing spectrum usage environment, potentials of each method, as well as their goals and limitations. Second, it helps regulators, policy makers, and spectrum market understand spectrum entrants' behavior and create interventions in order to obtain favorable outcomes.

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PREFACE

I would like to thank my parents, my husband, and my son, for their continuous love, support, encouragement and sacrifice during my Ph.D. study and I dedicate this work to them. I would also like to thank my dissertation advisor Dr. Martin B.H. Weiss for being such a great mentor. I will carry on his advice, support, and friendship into the future. My sincere thanks to the members of committee, Dr. David Tipper, Dr. Benoit Morel, Dr. Jon Peha, and Dr. Marek Druzdzel for their guidance and comments.

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1.0 INTRODUCTION

Spectrum, which supports the transmission of sound, data, and video, is one of the most valuable wireless communication networks resources. Two authorities are responsible for managing spectrum in the U.S.: the National Telecommunications and Information Administration (NTIA) and the Federal Communication Commission (FCC). NTIA manages spectrum used by federal government while FCC is responsible for spectrum used by individuals, private organizations, public safety, and health officials [1].

In the non-federal spectrum domain, the FCC has two primary spectrum management approaches: command-and-control for licensed bands and commons or open access for unlicensed bands. In the command-and-control approach, a fixed amount of spectrum is assigned to wireless service providers for a certain technology, application and specific period of time. According to [2], the command-and-control approach involves four steps: allocation, adoption of service rules, assignment, and enforcement. In the allocation process, the FCC determines the type of use for each spectrum bands. Then, it establishes rules that specify the transmission parameters and rules for the service allocated in this band. Four types of assignment mechanisms have been adopted throughout the year: fist-come-first served licensing, lotteries, comparative hearings, and auctions. Finally, the FCC enforces its allocations, rules, assignments against spectrum users. In the commons approach, unlimited number of unlicensed users are allowed to access the spectrum that are governed by technical standards or etiquette on a non-protection basis [3].

1.1 WHY SPECTRUM SHARING

The dominant challenge for licensed bands is that the rapid proliferation of various forms of mobile devices, coupled with the expansion of wireless Internet services, made it impossible to allocate enough spectrum to new entrants and incumbents [4]. Two problems lead to this spectrum scarcity situation, namely the spectrum access problem and the full usage problem. The spectrum access problem means the spectrum is still available, but it cannot be accessed. The full usage problem, on the other hand, means the spectrum has already been fully occupied, but it does not yield reasonable efficiency because of the lag in technology. The first problem can be solved by allowing more users to access that spectrum band; while the second one can be improved by adopting advanced technologies or devices [5].

In fact, observations showed that spectrum scarcity is mostly a spectrum access problem [4, 5, 6]. According to the FCC, license holders did not fully use their spectrum. The consumption of spectrum only accounts for 15% to 85% in spatial and temporal variations [7]. Specifically, the average spectrum utilization in Chicago for the frequency bands below 3 GHz was 17.4% during two days measurement [8]. The average spectrum occupancy was 13% in New York City between August 31 and September 1, 2004 [8].

The spectrum access problem stems from the concept of exclusive usage inherent in the command-and-control approach and spectrum auction assignment mechanism. Under this strategy, spectrum users other than licensees are not allowed to access the spectrum. This exclusive usage largely prevents man-made interference from nearby geographic areas and frequencies, and then avoids costly enforcement actions [3]. It also guarantees a level of predictable usage and therefore service reliability. Notably, predictable usage is achieved at the expense of spectrum utilization efficiency, which is not a problem when the spectrum demand is relatively easily met through technology innovation that expanded the range of economically feasible frequencies [9]. However, as the spectrum access requests grow exponentially, exclusive usage that is achieved by a static spectrum allocation strategy can hardly meet the soaring demand.

Unlicensed usage, on the other hand, eliminates the barrier of spectrum access. In the unlicensed bands, all spectrum users have equal rights to utilize frequencies. The Industrial, Scientific and Medical (ISM) band is well known for unlicensed usage. It has been extraordinarily successful in stimulating innovation and short-range communications. The main advantage of unlicensed usage is flexibility and the absence of licensing costs. The challenge of unlicensed usage derives from this merit as well. Without incentives to reserve spectrum and coordination, catastrophic interference among spectrum users may occur.

To address the apparent spectrum scarcity and service reliability, spectrum sharing in licensed bands, as a compromised approach, has moved from being a radical notion to a principal policy focus in the past decade. In contrast to exclusive usage, spectrum sharing provides the flexibility needed to respond to temporal and spatial variations of traffic statistics and bandwidth requirements of different services. It is an *ex post* strategy to assign spectrum on demand and improve usage efficiency of the initial spectrum allocation. Also, unlike unlicensed usage, where reliable services are difficult to maintain, users in spectrum sharing have the opportunity to negotiate spectrum sharing etiquette and achieve expected QoS.

Spectrum sharing in licensed frequency bands is organized under a hierarchical spectrum rights regime. Accordingly, two categories of users are formed: Primary Users (PUs) and Secondary Users (SUs). PUs are license owners of the frequency bands, and SUs are parties that obtain subordinate rights to access the spectrum. SUs are wireless service providers that do not have the FCC authorized licenses but provide service on certain frequency bands. In this dissertation, the term spectrum entrant is used to describe users that seek frequency bands to provide wireless services. Depends on their spectrum usage choices, they will become a PU or SU when they enter the wireless market. The term spectrum users includes both PUs and SUs.

While conceptually simple, the realization of spectrum sharing gives rise to several technical, regulatory, and economic challenges. Technical challenges emanate from the inherent difficulty of accurately sensing radio environments and efficiently coordinating transmission activities. The regulatory issues deal with the need to motivate spectrum sharing by liberalizing spectrum license and adjusting policies. Economic problems concern about secondary spectrum market and trading frameworks. The following section provides an overview of technical and regulatory evolution that make spectrum sharing possible.

1.2 EVOLUTION THAT MAKES SPECTRUM SHARING POSSIBLE

Spectrum sharing only happens when both technology and policies are ready. In reality, technology innovations and policy adjustment intertwine with each other. This section outlines the evolution of technology and policies that make spectrum sharing come true.

1.2.1 EVOLUTION OF REGULATIONS

Since the spectrum has become a scarce resource, regulators have been seeking policies that offer more spectrum access opportunities. This section briefly summarizes the major regulation milestones in this regard.

First, in the year 2000, the FCC issued several policy statements [10] indicating its guidelines for promoting efficient use of the radio spectrum through the development of secondary markets. In 2003, the FCC issued regulation on spectrum leasing that specified some of the methods to enter into leasing arrangements for wireless radio licensees [10]. Spectrum leasing and secondary spectrum market partially change the command-and-control strategy to a right based regulation, which permits organizations to transfer, purchase, and sell the rights to use spectrum in private market transactions [11].

Second, the FCC created the Spectrum Policy Task Force (SPTF) in June 2002 to study alternatives to command-and-control approach. They were charged with making specific recommendations on a more integrated, market-oriented approach that would lead to greater regulatory certainty while minimizing regulatory intervention. In particular, they assisted the FCC in addressing spectrum issues such as interference protection, spectral efficiency, effective public safety communications, and implications of international spectrum policies [12].

One of the suggestions that SPTF made is the Interference Temperature metric. The goal of Interference Temperature is to provide more spectrum access opportunities for SUs and maintain the existing QoS for PUs. Specifically, an Interference Temperature threshold was to be determined for each frequency band, and SUs would be permitted to transmit in any band as long as they did not cause the threshold to be exceeded [12]. The majority of comments suggested the FCC to terminate the broad proceeding, especially in the 6 GHz bands that support critical infrastructure industries [13, 14, 15, 16, 17]. Incumbents are understandably uncomfortable about Interference Temperature due to the extra uncertainty and potential competition [18]. Parties that would be directly benefit from the Interference Temperature metric, such as unlicensed device industry, the Wi-Fi Alliance and the IEEE 802 group, also doubted the performance of implementing the Interference Temperature concept due to the technical difficulties and economic uncertainties. In May 2007, the FCC published the ORDER to terminate the Interference Temperature proceeding without prejudice to its substantive merits [19].

Third, in 2008, the FCC released the Second Report and Order [20] to allow unlicensed devices to transmit in the broadcast television frequency bands at locations where licensed services are absent, referred to as TV white space (TVWS). All devices except personal/portable devices operating in client mode must have three capabilities in order to operate in the TVWS: (1) geolocation capability; (2) capability to access the database and obtain a list of the permitted channels before transmission; (3) capability to sense TV broadcasting and wireless microphone signals. In 2010, the Second Memorandum Opinion and Order [21] eliminates the sensing requirement for TV bands devices with geo-location capability and ability to access the database. In 2012, the FCC further defined channel emission limit and maximum permissible power spectral density in the Third Memorandum Opinion and Order [22].

Fourth, the 2010 Presidential Memorandum "Unleashing the Wireless Broadband Revolution" requires 500 MHz of spectrum to be made available for commercial use within 10 years [23]. In 2012, President's Council of Advisors on Science and Technology (PCAST) further advised the president to require the Secretary of Commerce to identify 1000 MHz of federal spectrum in which to implement shared-use spectrum pilot projects [24]. In December 2012, the FCC proposed a three-tiered prioritization spectrum scheme, which allows two new categories of commercial use into the federal frequency bands [25]. NTIA issued reports to evaluate different federal and non-federal spectrum bands for accommodating wireless broadband systems. Those bands include Meteorological-Satellite (space-to-earth) and Meteorological aids services on 1675-1710 MHz, federal government for fixed and mobile services in 1755-1780 MHz, Department of Defense Radar service in 3500-3650 MHz, and internationally reserved for radio altimeters in 4200-4220 MHz, 4380-4400 MHz bands [26].

Last but not least, a new licensed model, called Authorized Shared Access (ASA), authorizes spectrum entrants (ASA licensees) to have the exclusive rights where and when spectrum is not used by PUs. It aims at authorizing spectrum sharing in licensed frequency band in real-time. Moreover, the ASA platform is fully configurable so PUs can alter the sharing etiquette and constraints. Three items compose the ASA model: spectrum allocation engine, spectrum supply manager, and coexistence manager. Spectrum allocation engine optimizes spectrum allocations considering constraints such as geographic area, bandwidth, time, QoS, and regulation. Spectrum supply manager is the communication interface to external band managers. Coexistence manager ensures co-located users can achieve expected levels of QoS through coordination [27].

1.2.2 EVOLUTION OF TECHNOLOGY

Besides the evolution of spectrum regulation policies, the industry also witnessed technology innovations. Several technologies that emerged during the past decades facilitate spectrum sharing. In this section, a brief overview of ultra-wide band, software defined radio, cognitive radio, spectrum sensing, and channel aggregation will be provided.

Ultra-wide band (UWB) is a radio technology that transmits a signal over a very large portion of radio spectrum at low power [28]. According to the FCC, the bandwidth for UWB should exceed the lesser of 500 MHz or 20% of the arithmetic center frequency. In February 2004, the FCC authorized the unlicensed use of UWB in frequency bands range from 3.1 GHz to 10.6 GHz. The required power spectrum density limit is -41.3 dBm/MHz [29].

Software Defined Radio (SDR) is another advanced technology. It is a radio communication system where components such as mixers, filters, amplifiers, modulators/demodulators, and detectors are implemented by means of software on a computer or embedded system [30]. The dominant advantage of software defined radio is that the radio system can be configured on-the-fly. That is, the transmission parameters can be reconfigured depending on services requirements and existing spectrum usage situation. Three well-known software radio systems are listed here as examples. They are: GNU Radio project at the Massachusetts Institute of Technology (MIT) [31], Iris that developed in the University of Dublin and Trinity College [32], and Sora that was developed by the Microsoft Research group [33].

Cognitive radio was proposed by Mitola in 1999 [34]. As defined by the FCC "A cognitive radio (CR) is a radio that can change its transmitter parameters based on interaction with the environment in which it operates. The majority of cognitive radios use SDR, but neither having software nor being field programmable are requirements of a cognitive radio." In particular, CR makes an autonomous decision on how to configure itself to maximize the satisfaction of the communication requirements with four inputs, namely (1) the environment in which it operates; (2) the communication requirements of the users; (3) the regulatory policies which apply to it; and (4) its own capabilities [28].

The last key technology that enhances the spectrum sharing is spectrum aggregation, also called carrier aggregation. Spectrum aggregation is proposed in Long-Term Evolution (LTE) Advance, which allows multiple contiguous and non-contiguous spectrum bands to be treated as one virtual wideband pipe. Carrier aggregation can go beyond LTE frequencies to further enlarge the potential benefits [35]. The major advantage of spectrum aggregation is that spectrum users can provide a high data rate over multiple small fragments of spectrum that they bought from different PUs or left by PUs' inactive services. It improves wireless services' performance and increase the value of fragmented spectrum blocks [36].

1.3 MOTIVATION

While spectrum sharing provides flexibility, certain level of QoS guarantees, and an increase spectrum utilization efficiency, it has been adopted slowly. Several factors impede spectrum entrants from sharing spectrum: (1) the quantity of shareable spectrum; (2) cost of accessing spectrum, including both monetary cost and processing time; (3) uncertainties and risks in spectrum sharing. The FCC and NTIA have made a great effort to enlarge the amount of shareable spectrum. For example, the TVWS is free for unlicensed access, and federal frequency bands, such as 1670 MHz and 3.5 GMz, are under consideration for federal-commercial sharing. Moreover, with the database assisted approach, the processing time of authorization is significantly shortened. Additionally, spectrum is allowed to be traded in the secondary spectrum market. When requirements are met, the trading can be approved within 24 hours.

Although more spectrum has been made available for sharing and the cost has been reduced, uncertainties and risks that are embedded in each spectrum sharing method still exist. Moreover, these uncertainties and risks are the very barrier that hinders spectrum sharing from proliferating, in part because spectrum entrants and incumbents will not share spectrum when future conditions are difficult to foreseen.

Therefore, minimizing risks is essential to fulfill the great potentials of spectrum sharing. Several solutions reduce the spectrum sharing risks. Enforcement that make spectrum sharing etiquette more effective can reduce risks for both PUs and SUs. From PUs' perspectives, understanding the risks that may bring from spectrum sharing and techniques that allow them to modify SUs' transmissions reduce risks. [37] investigates the impact from secondary spectrum market to a GSM based cellular license holder, and analyzes PUs' incentives in sharing the spectrum. Risks and incentives for spectrum entrants are equally important, since they are the demand side of spectrum sharing. In addition, spectrum sharing risks vary with spectrum sharing methods, such as cooperative sharing through trading, ASA, TVWS, Cognitive Radio (CR) based DSA, and unlicensed usage in the ISM bands. They also change with locations, coverage, and frequency bands.

Consequently, this dissertation aims at minimizing risks for spectrum entrants and investigate their incentives in selecting a particular spectrum sharing method. In brief, quantifying the spectrum risks for each spectrum usage method is the first step. It will assist spectrum entrants in making informed decision based on their decision criteria, incentives, and limitations. Moreover, risks do not necessarily lead to monetary loss or services degradation, because spectrum entrants have mitigation strategies to cope with risks. They have the capability to adjust their decisions in unexpected situations. Therefore, identifying mitigation strategies that embedded in each spectrum usage method and quantifying the value of these mitigation strategies also reduce spectrum entrants' [1] risks. In general, the focus of this

[1] A spectrum entrant is a potential wireless service provider who has not enter the wireless market.

research is driven by two questions:

- Why should a spectrum entrant choose a specific spectrum usage model? Under what conditions?
- What are risks and mitigation strategies in each spectrum usage model?

The outcome of this dissertation will assist spectrum entrants in selecting the most appropriate spectrum usage method given their situations. It will also help understanding the potential problems for each spectrum sharing method. Therefore, policy makers, operators, and the spectrum market could create interventions in order to obtain the favorable outcomes.

1.4 DISSERTATION OUTLINE

This dissertation is structured as follows: Chapter 2 provides a literature review of the spectrum sharing domain. Chapter 3 proposes research questions and methodologies include decision models, real options, and queueing system. Chapter 4 describes spectrum usage methods that will be analyzed in this dissertation. Chapter 5 qualitatively identify risks and mitigation strategies in each spectrum usage method. Chapter 6 illustrates the decision and risks analysis model for spectrum usage. Chapter 7 provides numerical results and discussion. Chapter 8 concludes the dissertation and proposes future research directions.

Typically, they fact the problem of selecting one spectrum usage method before becoming a wireless service provider.

2.0 LITERATURE REVIEW

As mentioned above, an explicitly understanding of spectrum entrants' spectrum usage choices based on incentives, risks, and mitigation approaches is essential for both spectrum users and regulators. However, research efforts are light on this issue. The incentives and risks that PUs have for sharing spectrum have been studied in [37, 38, 39, 40]. [37] quantifies the impact of secondary spectrum market on a GSM-based cellular license-holder. [38] points out the importance of risk management in spectrum sharing, and analyzes risks in terms of interference. [39] provides a high level risk analysis in spectrum usage from business and management perspective. [40] indicates that without a clear understanding of potential risks, spectrum sharing in 3.5 GHz is too good to be true.

Although research in decision and risk analysis of spectrum usage can be hardly found, research efforts in related areas are crucial for this dissertation. Therefore, this chapter provides literature review in pertinent fields: technologies in spectrum sharing, spectrum rights and spectrum trading.

2.1 TECHNOLOGIES IN SPECTRUM SHARING

From a technology perspective, there are two major activities of spectrum sharing. The first one is identifying spectrum holes by sensing or modeling. The second one is sharing the available spectrum efficiently.

2.1.1 SPECTRUM SENSING

Spectrum sensing is the key component for sensing based opportunistic sharing. It provides SUs with the current spectrum utilization situation and identifies spectrum holes. Sensing accuracy and security are the two challenges for spectrum sensing.

Sensing techniques start from energy sensing, in which sensors compare the observed energy value with a predetermined threshold and decide the spectrum availability. The major problem for energy sensing is that it cannot differentiate signals from interference. In order to overcome this shortcoming, advanced sensing technologies emerged, such as matched filter detection, cyclostationary feature detection, and eigenvalue-based detection. While these alternatives provide higher accuracy, they require a priori knowledge of the signal shape and intensify the computational complexity. Furthermore, no matter how advanced the technology is, individual sensing faces hidden node, fading, and multipath problems.

Collaborative sensing, which requires cooperation among sensors, is known to be a more reliable approach. [41] compares the cooperative detection with individual spectrum sensing in TVWS. [42] shows that the detection performance can be significantly improved by collaborative sensing in fading channels. [43] suggests that SUs can be divided into different clusters, then the final decision is based on the output from the most favorable user in each cluster. [44] further complicates the model to reflect the real situation by assuming different average Signal to Noise Ratio (SNR) for SUs instead of constant one.

While collaborative sensing shows its superiority in improving accuracy, it raises security challenges to the system. There are two ways for malicious users to attack collaborative sensing. On one hand, by always reporting that PUs are present, malicious users can decrease SUs' utilization, or they can selfishly transmit in these time slots. On the other hand, malicious users can harm PUs system by always reporting that PUs are absent. Reputation-based schemes are a common methodology to handle falsification attacks [45]. [46] proposes a trust value calculation algorithm based on historical local sensing results for each node. [47] suggests a Weighted Sequential Probability Ratio Test for collaborative sensing and proves this scheme is robust against Byzantine failure problem. [45] further decouples sensors' trustworthy from capability in order to filter out real malicious users and protect the benign nodes who suffer from multipath and fading problems.

2.1.2 MODELING SPECTRUM USAGE

Although spectrum sensing provides spectrum utilization information for SUs, it leads to extra expense. For example, SUs need to install sensing capabilities which requires expenditures on devices. Moreover, when SUs sense the spectrum, they cannot transmit data, which decreases the spectrum utilization. Therefore, the spectrum usage model emerged as an alternative approach to identify spectrum holes.

The majority of spectrum usage model utilizes Markov processes. Gosh, et. al., validate the Markov process for spectrum utilization by real-time measurements collected in 928-948 MHz [48]. Zahmati, et. al., analyze spectrum holes with one PU and n SUs [49]. They study the probability of spectrum occupancy for the PU and each SU. Patil, et. al., investigate a system with two PUs and $2n$ SUs [50]. They evaluate four performance metrics: blocking rate, mean number of SUs, utilization ratio, and deprivation rate which is the rate that a SU is forced to vacate the channel due to PUs' arrival. Both [48] and [51] use a Hidden Markov process to predict PUs' presence. Similarly, in [52] and [53], the authors adopt a Hidden Markov process based spectrum sensing mechanisms to detect spectrum hole availability.

The significant body of research work in modeling spectrum usage helps spectrum entrants understand the spectrum usage situations. However, two questionable assumptions limit their applicability in a real setting. First, the assumption of steady-state behavior is far from reality for most frequency bands. For example, as shown in [54, 55, 56], voice and data traffic in cellular network has distinct temporal and spatial variations. Particularly, the traffic has a pronounced diurnal behavior which changes with day of the week. Moreover, the busy and idle periods occurred at different time in different cells. Second, the majority of the research work only considers PUs' behavior when modeling spectrum holes. It is true that PUs have the highest priority in licensed bands and may dominate the spectrum usage. Nonetheless, competitions among SUs in spectrum access are not negligible. For example, mobile off-loading comes from mobile operators may occupy unlicensed usage due to the large quantity of data. Therefore, spectrum usage should be modeled as time-varying behavior and considering both PUs' and SUs' traffic.

2.1.3 EFFICIENT SHARING

After identifying spectrum holes, SUs start transmitting signals. In order to achieve high QoS and spectrum utilization efficiency, efficient sharing is preferred when there is more than one SU. Two approaches exist for efficient sharing. The first one is admission control and is fulfilled by MAC schemes. The second one is resource allocations in terms of power level and channel.

A significant number of the research papers focus on MAC strategies among SUs in unlicensed and opportunistic sharing, only a few of which are summarized here. [57] proposes a common spectrum coordination channel (CSCC), by which SUs coordinate with each other for spectrum access. [58] further divides SUs into groups and group members share the same common control channel for signaling. [59] provides a MAC scheme for SUs on TDMA/FDMA based GSM network. They use a similar concept as a three-way handshake. SUs exchange a request to send, a clear to send, and a reservation message before operation. [60] continues the three-way handshake with a concern about the SUs' hardware capability constraints. Two types of constrains are considered: sensing limitation and transmission limitation. The Berkeley group suggests that geolocation database is another candidate for SUs to coordinate with spectrum access. In [61], they argue that instead of providing information on idle channel, the database should also hold the information about aggregated emissions to level. In [62], they further claim that SUs can use database to achieve both frequency- and spatially awareness.

Two types of resources allocation exist in unlicensed bands and opportunistic usage, power allocation and channel allocation. Under a power allocation regime, [63] uses incentives to achieve fairness and efficiency by deriving the Nash equilibrium in a repeated game. [64] investigates power allocation in two distributed schemes with a goal of maximizing system performance while limiting the interference to primary receivers. [65] models the multi-channel power allocation as a non-cooperative game with concerns of co-channel interference among SUs and interference temperature that determined by regulator. Channel allocation is often modeled as a graph coloring problem. [66] uses list-coloring scheme to allocate channel according to three algorithms: distributed greedy algorithm, distributed fair algorithm, and randomized distributed algorithm. [67] provides a general approximation method through vertex labeling for channel allocation. It examines the utilization and fairness in both centralized strategy and distributed approach. The above resource allocation only concerns one spectrum dimension, in [68] authors introduces the concept of a time-spectrum block and allocate resources in this two dimensional space.

2.2 SPECTRUM RIGHTS

Technologies makes spectrum sharing possible. Policy adaptations such as spectrum rights help realize spectrum sharing. Therefore, the development of spectrum rights plays an important role in the evolution of spectrum sharing. In the traditional form, two types of spectrum rights regimes were identified: the property right and commons. In spectrum commons, no user has exclusive rights in utilizing spectrum. Instead, any authorized device can operate in these so called unlicensed bands, such as ISM bands in 2.4GHz. The low entrance barrier stimulates the innovation in technology and services. Due to the success of spectrum commons model, the FCC opened the TVWS for unlicensed usage. The spectrum common regime is quite simple and straightforward, thus the focus of this section is on property rights.

Traditionally, spectrum users have exclusive usage rights in licensed bands. This means PUs operate on the spectrum under license terms exclusively. These terms determine location of transmitters, peak power levels, technologies, service types, operation duration, frequency bands, etc. PUs cannot change the technology and service type even if they provide higher profits. For example, TV broadcasters cannot use their spare spectrum for wireless broadband. Since PUs do not own the spectrum, they have no rights to trade and exchange license with other spectrum users. Thus, although the spectrum sharing technology is available, it is not allowed from policy side.

The ban on bargaining between spectrum licensees was regarded as a barrier by Ronald

Coase. He pointed out that the most efficient way to assign spectrum is to give it to those users who value it the most through property-like rights in secondary markets [69]. As defined in [70] "The term [property rights] implies the ability to buy; hold; use; sell; dispose of, in whole or in part; or otherwise determine the status of an identifiable, separable and discrete object, right or privilege." Defining spectrum rights as property rights is a leap in regulation, since the property rights provide license holders the rights to trade and exchange the license in any dimension of the spectrum in a private market.

However, property right is not designed for spectrum sharing and coexistence due to the inherent concept of exclusive usage rights. PUs only sell spectrum that they do not operate on under property right regime. It is a "all-or-nothing" type of sharing. The challenge here is that it is difficult for PUs to estimate the quantity of idle bands a priori. Therefore, in order to avoid interference, they tend to behave conservatively by using guard bands and transmission power caps to prevent potential coexistence. The spectrum cannot be fully utilized while the exclusive usage right is enforced, since spectrum should not be constraint by number of users, but the amount of interference that wireless systems can sustain.

The newest spectrum right, spectrum usage right (SUR) [71], defined by Office of communications (Ofcom), targets spectrum sharing. SUR regulates the emissions that PUs may radiate in neighboring locations and frequency bands. It provides two major advantages for spectrum sharing. First, PUs would have greater flexibility in selecting technologies and applications. Second, neighboring spectrum users have a clearer view of potential interference.

2.3 SECONDARY SPECTRUM MARKETS AND TRADING FRAMEWORKS

After the liberalization of spectrum licenses, PUs have the rights to trade their spectrum license in the secondary spectrum market. The target of spectrum trading is to allocate spectrum to users who value it the most. The structure of the market and trading frameworks significantly impact the spectrum allocation results.

A significant body of research has been focussed on spectrum trading, by taking game theory and auction based approaches. Game theoretic approaches aim at finding the best strategies that optimize the utilities in different scenarios. [72] investigates the best strategy for PUs to maximize their profits under QoS constraints in an oligopoly market. [73] improves the previous work by considering collusion among spectrum users. [74] uses a multi-stage game to provide a collusion-resistant dynamic pricing approach, in which spectrum users' utilities are maximized while combating their collusive behaviors. [75] studies the multi-seller and multi-buyer trading market. Authors use evolution game to investigate the dynamic behaviors of SUs, and apply non-cooperative game to model PUs' competition. In [76], authors argue that spectrum is interference-limited not quantity-limited, which means more than one user can occupy the same channel as long as QoS is acceptable. Therefore, they develop a multi-winner game with a collusion-resistant mechanism. [77] investigates the competition among PUs in the situation where two PUs exist and only one SU is in the market.

The auction based approach treats the spectrum resource as divisible goods and applies different auction mechanisms to maximize revenue or achieve fairness. [78] designs a general framework to maximize seller's profits with interference constraints in a monopoly market. [79] provides a winner determining sealed-bid knapsack auction mechanism to allocate spectrum to wireless service providers. It further analyzes the interactions between end users and wireless service providers. In addition to maximize PUs' revenue, [80] aims at enforcing truthfulness and reducing computational complexity. [81] analyzes the competition and fairness among SUs and discusses the uncertainty about the wireless environments.

In spectrum trading, pricing is the key issue of interest to PUs and SUs. [82] studies the price war from two perspectives. In the short-term price war, providers lower the price to gain profits; while in the long-term price war, providers aim at monopolizing the market by predatory pricing strategy. It also provides responding strategy for small providers and regulators to avoid illicit competition. [83] explores the price dynamics in multi-seller and multi-user environment. Instead of assuming that all channels are similar for SUs, they assume different buyers set different spectrum values for each channel depending on their application, operating technologies and locations. They also consider two types of users, the quality-sensitive and price-sensitive, to make the research more realistic. [84] studies PUs' behaviors in three pricing models: market equilibrium pricing, competitive and cooperative pricing. The objectives and the relationship among PUs are altered in each model. Therefore PUs adopt different strategies to maximize their own profits. [85] proposes two charging mechanisms in charging SUs in spectrum auction. The first one is based on received Signal-to-Interference plus Noise Ratio (SINR) and the second one is based on transmission power.

Other research work in the spectrum trading area mainly focuses on three research questions. The first question is how to make the market work. [86] analyzes potential benefits and costs of spectrum trading, as well as regulatory and policy issues relating to it. [87] suggests that in order to make market to work, rules should endow operators with the highest flexibility. [88] further makes four regulatory and statutory recommendations, including "(1) the elimination of use restrictions for new wireless allocations; (2) the replacement of existing use restrictions with power limits sufficient to minimize the potential for harmful interference; (3) the enactment of rules expressly allowing private parties to contract around established interference limits; and (4) the identification of 'safe harbor' spectrum leasing arrangements that are deemed permissible under the FCC's license transfer of control requirements." The second research question is how to improve market liquidity. [38] suggests that market liquidity can be improved by boosting spectrum availability, increasing achievable QoS and reducing transaction costs and risks. [89] further proposes a time-limited lease to reduce the risk and increase spectrum supply. [90] focuses on determining the conditions of viability of spectrum markets. By using agent-based model, it considers scenarios with different market structure, number of trading participants and amount of trading spectrum. Finally, a set of research papers examine the question of what are potential causes for market failure. [91, 87] identifies causes for potential market failure including interference, standards, transaction costs, asymmetric and imperfect information, and market power. In addition, [38] analyzes the interlinked technical and economic issues associated with spectrum market.

3.0 RESEARCH QUESTIONS AND METHODOLOGIES

Before entering the wireless market, spectrum entrants have many spectrum usage methods to choose from, such as cooperative sharing through trading, CR based DSA, unlicensed usage, etc. Moreover, each method leads to unique risk portfolio and mitigation strategies. Therefore, understanding the potentials of each method is very important for spectrum entrants to make informed decisions and regulators to make interventions for the desired outcome. Consequently, the objective of this dissertation is to investigate spectrum entrants' decisions under different spectrum usage situations, goals and limitations. 3.1 provides a comprehensive list of research questions and hypothesis that will be examined. 3.2 delineates the scope of this dissertation. 3.3 introduces the research methodologies that will be applied in quantifying risks and determining the most appropriate decisions.

3.1 RESEARCH QUESTIONS AND HYPOTHESIS

In this section, a comprehensive list of research questions is provided. Due to the large scope of the research questions, not all of them will be addressed in this dissertation. Q1 is qualitatively investigated in chapter 5. Q2 is qualitatively studied in section 6.1. Q3.1-Q3.8 will be tested by three hypothesis in 3.1.2 quantitatively. Other research questions will considered in future research.

3.1.1 RESEARCH QUESTIONS

(Q1). What are risks and mitigation strategies in each spectrum sharing method?

(Q1.1) Identify risks for each sharing method.

(Q1.2) Map risk and mitigation strategies to each sharing method.

(Q2). What are spectrum entrants' decision criteria? What are attributes that impact spectrum entrants' decision?

(Q2.1) Identify spectrum entrants' criteria.

(Q2.2) Identify attributes that impact spectrum entrants' choices.

(Q3). Quantify risks and mitigation strategies with different spectrum entrants' decision criteria.

(Q3.1) What is the expected cost that each spectrum usage method requires under different scenarios?

(Q3.2) What is the projected revenue that each spectrum usage method brings under different scenarios?

(Q3.3) What is the capacity that each spectrum usage method can get under different scenarios?

(Q3.4) How does application type impact spectrum entrants' choices?

(Q3.5) How does geographic area impact spectrum entrants' decisions?

(Q3.6) How does spectrum entrants' awareness of spectrum utilization situation impact their choices?

(Q3.7) How does operation duration impact spectrum entrants' decision?

(Q3.8) What is the value of mitigation strategies?

(Q3.9) How does enforcement impact on spectrum entrants' decisions?

(Q3.10) How does spectrum entrants' risk attitude impact their decisions?

(Q3.11) What is the impact on spectrum utilization from spectrum entrants' choices?

3.1.2 HYPOTHESIS

In order to answer research questions Q3.1-Q3.8, a decision and risk model is build and described in chapter 6. Following three hypothesis will be quantitatively tested by the decision and risk model in chapter 7.

(H1). QoS levels and risks change in diverse situations:

(1) Different spectrum usage methods

(2) Location: urban/rural

(3) Capacity requirement: time varying/constant

(H2). Spectrum entrants have different expected profits and monetary risks under diverse situations:

(1) Different spectrum usage models

(2) Location: urban/rural

(3) Operation duration:short/long

(4) Profit requirement: urban/rural large/small coverage

(H3). Spectrum entrants have different choices in diverse situations:

(1) Location: urban/rural

(2) Operation duration:short/long

(3) Capacity requirement: time varying/constant

(4) Risk awareness

(4-1) Risk awareness

(4-2) Risk unawareness

(5) Distinct decision criteria:

(5-1) Profit maximization

(5-2) QoS Risk minimization

(5-3) Mixed decision criteria

Following table summarizes the correspondence of hypothesis with the comprehensive research question list.

Table 1: Correspondence between hypothesis and research questions

Proposed research for this dissertation	Research questions
H1	Q3.1, Q3.2, Q 3.8
H2	Q3.3
H3	Q3.4, Q3.5, Q3.6, Q3.7

3.2 SCOPE OF THE DISSERTATION

Factors such as application types, location, frequency bands, decision criteria, etc, impact spectrum entrants' choices of spectrum usage method. In this dissertation, only several cases will be tested under the proposed decision and risk framework. Specifically, spectrum usage methods that considered in this dissertation include:

- Primary usage (6 MHz in 700 MHz band Block A: 698-704 MHz)
- Cooperative through spectrum trading (6 MHz in 700 MHz band Block A: 698-704 MHz)
- CR based DSA (6 MHz in 700 MHz band Block A: 698-704 MHz)
- TVWS (692-698 MHz)
- ISM (2400-2500MHz)
- ASA (3.5 GHz)
- Mixed strategies

They will be introduced in detail in chapter 4.

Additionally, only two types of risks will be quantified: QoS risks and monetary risks. It is assumed that the QoS risks in primary usage and quasi-static sharing comes from license/contracts availability. On the contrary, the QoS risks in dynamic sharing comes from the competition in access spectrum among PUs and SUs. Specifically, in CR based DSA and TVWS, both PUs and target SUs' traffic will be considered; while in the unlicensed bands, only SUs' traffic will be considered. Competition among SUs are not considered in the decision analysis, but are addressed in the sensitivity analysis.

Monetary risks consider costs, revenue, and value of mitigation strategies. Costs model is based on each spectrum sharing method, operating frequency, and target coverage. Two types of revenue functions are considered. For primary usage and quasi-static sharing, the revenue is based on the service demand. For dynamic sharing, the revenue is based on both the expected throughput (QoS level) and service demand. Two types of demand are applied in analysis. The first one assumes that spectrum entrants will have constant demand for the entire operation. The second one assumes that the demand linearly decreases with the increase of price. In addition, the cost and demand are assumed to be uniformly distributed across the geographic coverage. When quantifying mitigation strategies, two types of mitigation strategies are considered: lease spectrum/infrastructure, and improve.

When estimating throughput for dynamic sharing, it is assumed that spectrum users with higher priority (PUs) have the right to preempt spectrum users with lower priority (SUs). Spectrum users within the same priority are served as First In First Out (FIFO). Moreover, the unit of arrival for TV broadcaster is program, and unit for other services' arrivals are packets. Two types of arrival process are considered: time-varying and constant arrival, in other to capture both human-centered applications and machine-to-machine communications. In order to simplify the calculation, it is assumed that the base station coverage is circular. Furthermore, spectrum holes are assumed to be exogenous, although we argued that spectrum holes should be endogenous. Exogenous spectrum holes means the spectrum hole is solely created by PUs' usage. SUs do not have controls or impact the quantity of spectrum holes. This is not realistic, since PUs' may transmitting meaningless signal to deter SUs' usage or SUs' can provide enough incentives to PUs in order to have more spectrum access opportunity. Therefore, we argue that spectrum holes should be endogenous. That means spectrum hole are created by bilateral negotiation between PUs and SUs. However, the creating of endogenous holes that involves business strategies, negotiations, and competition, complicates the model. Therefore, in this dissertation, the spectrum hole is simplified by assuming they are created by PUs' wireless traffic only. All the parameters that are applied in the numerical results analysis are summarized in section 7.2.2.

Two locations will be investigated: a urban area and a rural area. It is assumed that the population is higher in the urban area than in the rural area. Therefore, the wireless service traffic is more intense in the urban than in the rural place.

The best spectrum usage choice is determined for the spectrum entrant that aims at providing broadband services who has a time-varying wireless traffic. Therefore, the revenue is based on data services instead of voice. In the sensitivity analysis, other types of spectrum entrants' (such as spectrum entrants with constant wireless traffic and event support services) choices are briefly addressed. Moreover, the best option is determined for two types of risk attitudes: risk awareness and risk unawareness. In the fist case, spectrum entrants ignore the risk and consider the best case scenario. For example, the expected QoS level is the desired one in all cases, and the demand is high and constant all the time. In the second case, spectrum entrants consider potential risks in demand, throughput, and the value of mitigation strategies. Within each risk attitude, three decision criteria are applied: profit maximization, QoS risk minimization, and mixed strategies. Furthermore, spectrum entrants are assumed to be risk-neutral. Although most people are not risk-neutral in the reality, it is reasonable to assume the decision maker is risk-neutral especially for large corporations where the amount of money involved in a decision is relatively small compared to their total assets [92].

Limitations of this dissertation: (1) According to Okumura Hata propagation model, the path loss is less in the rural than in the urban. Therefore, the coverage of the base station with the same transmission power is larger in the rural than in the urban area. However, this dissertation assumes the coverage is the same for both urban and rural area when they have the same device and transmission power level. (2) In the queueing model, it is assumed that spectrum users can detect others' service and coordinate with each other perfectly. The greedy behavior and interference due to imperfect detection and wireless channels are ignored. This can be improved by replacing the existing static service rate to a function of service rate that depends on distance. (3) Service demand that changes with price is ignored. However, the sensitivity analysis provides the results with different price and same amount of demand. (4) The spectrum license is auctioned in the real world, so bidding strategies and other spectrum entrants' behaviors impact the spectrum price. It is ignored in this dissertation. The spectrum price is considered as a fixed number. However, the availability of license/contract reflect the difficulties in obtaining the license/contract. (5) When calculating cost and revenues, only spectrum related factors are considered. Other factors are outside the scope of the paper. For example, cost of marketing and development are not considered. Impact for spectrum usage from policy change are also ignored. (6) It is assumed that spectrum entrants select a specific spectrum usage method to maximize their utility. Behavior such as deter others' usage, collusion in the auction, etc are ignored. (7) The queueing model that applied in this dissertation is preemptive resume, that means SUs resume from the point where is was preempted. However, there are also other services that will repeat the entire transmission. In this case, preemptive repeat queue should be applied.

3.3 RESEARCH METHODOLOGIES

When quantifying risks and investigating spectrum entrants' decisions, three research methodologies are adopted, namely decision models introduced in section 3.3.1, real options illustrated in section 3.3.2, and queueing models described in section 3.3.3.

3.3.1 DECISION MODEL

This section provides an overview of decision model by answering three questions: (1) What are basic elements of decision models? (2) How to create a decision model? (3) What are key issues in decision models?

3.3.1.1 ELEMENTS OF DECISION MODEL Four basic elements make up a decision model: (1) values and objectives; (2) decisions to make; (3) uncertain events; and (4) consequences [92].

Value is that which matters to decision makers. Different decision makers value each item differently. For example, solving a specific scientific question brings high value to a scientist, while earning profits and acquiring a control of a company provide great value to an investor. An objective is a specific thing that an individual or an entity wants to achieve. A decision makers' value is formed by all of his or her objectives. An important concept that accompany value and objectives is decision context. It is the setting in which decision occurs. For example, a decision context may be deciding what stock to buy, in which case the appropriate objective could be earning profits. It is important because the decision context determines what objectives need to be considered. In the meanwhile, thinking about objectives in advance helps individuals to be prepared when decision context appears [92].

When there are multiple alternatives, a decision must be made. In many cases, in stead of one single decision, there are several sequential decisions. When a decision situation requires sequential decisions, it is better for the decision maker to consider them when making immediate decisions, since a future decision may largely depend on the initial decision [92].

What makes a decision problem even more complicated is many important decisions have to be made with uncertainty about the future. In other words, the decision maker does not know what will happen in the future or what the final outcome will be. The larger the number of uncertain events, the more difficult the decision making process is. Like sequential decisions, more than one uncertainty may be involved in a decision situation, and they are interdependent. Therefore, a decision maker must consider uncertain events and their inter-dependency when making decisions [92].

The consequence occurs after the last decision has been made and the last uncertainty has been resolved. There may be more than one consequence if the decision context requires multiple objectives. In a recruit process, the final consequence is hiring the best available person; while in a business project, the final consequence may be the "net value" that accounts for cash inflows and outflows happen during the time of decision making process [92].

3.3.1.2 CREATING A DECISION MODEL Three fundamental steps are involved in creating a decision model. The first step is to identify and structure the values and objectives. This step requires decision makers to list issues that matter to the individual or the organization. Examples for single objectives include profit maximization, loss minimization, etc. An individual or an organization may also have multiple conflicting objectives. For instance, the company may want to maximize the financial return of an investment while minimize the chance of losing money [92].

The second step is using a logical framework to construct all the elements of the decision context. Two tools can be applied to fulfill this purpose: influence diagrams and decision trees. Influence diagrams provide graphical view of the decision context. Different shapes represent different decision elements: rectangles represent decisions, ovals represent chance events (uncertainties), rectangles with rounded corners represent a mathematical calculation or a constant value. These three shapes are referred to as nodes. Nodes are connected by arrows or arcs. Arcs represent either relevance or sequence, while the meaning of an arrow is determined by the context. The node at the beginning of an arc or an arrow is called predecessor and the node at the end of an arc or an arrow is called successor. The influence diagrams use a simple way to display a decision's basic structure, which ease the communication and conceptualization. However, they hide many of the details that are needed in order to make a decision [92].

Decision trees, on the other hand, display more of the details. As in influence diagrams, different shapes are adopted in the decision trees: squares represent decisions to be made, and circles represent chance events (uncertainties). Branches that originate from a square denotes available choices; and branches emanating from a circle represent the possible outcomes. Consequence locates at the ends of branches. There are three requirements when constructing a decision tree. First, successors of a decision node must be so that the decision maker can choose only one option. Second, chance nodes must be mutually exclusive and collectively exhaustive. Third, a decision tree must contain all possible paths that the decision maker may follow. At the end of each branch, all relevant consequences are listed. While providing more information, the decision trees grows exponentially with possible choices and uncertainties that intense the level of complexity [92].

After constructing objectives and a logical framework, the last step is to refine and specify the definition of all the elements of the decision model. First, all the available alternatives have to be precisely defined. Second, the decision maker must list all uncertainties and come up with plans on how to quantify them. Last but not least, consequences in terms of objectives must be measurable. How to measure objectives with different dimensions, objectives of conflict interests, and the impact from uncertain events are essential to a decision model, and will be discussed in the next section [92].

3.3.1.3 KEY ISSUES IN DECISION MODELS Three key issues are presented in this section: utility functions, decision makers' risk attitudes, and sensitivity analysis. The main reason for using a utility function instead of monetary return is to capture decision makers' attitudes about risk, return, and objectives with different dimensions. As discussed above, decision makers may have objectives such as achieving high returns and minimizing risks. In this case, they can apply an Additive Preference Model to deal with the conflicting objectives. In the Additive Preference Model, a utility score, $(U_1(x_1), \cdots, U_m(x_m))$, will be calculated for each individual objective, $(x_1, \cdots, x_m)$. Then they will be summed up with different weights, $(k_1, \cdots, k_m, \sum_{i=1}^{m} k_i = 1)$, according to the importance of each objective as [92]:

$$
\begin{aligned}
U(x_1, \cdots, x_m) &= k_1 \times U_1(x_1) + \cdots + k_m \times U_m(x_m) \\
&= \sum_{i=1}^{m} k_i U_i(x_i)
\end{aligned}
\tag{3.1}
$$

There are three types of risk attitudes: risk-seeking, risk-averse, and risk-neutral. Generally speaking, an individual who would trade a gamble for a sure amount that is less than the expected value of the gamble indicates a risk-seeking behavior. His utility is captured by a convex function. On the other hand, an individual who purchase insurance indicates a risk-averse behavior. His utility is captured by a concave function. Finally, the utility function for risk-neutral is a simple straight line. For this type of person, maximizing monetary return is the same as maximize utility. Although most people are not risk-neutral in the reality, it is reasonable to assume the decision maker is risk-neutral especially for large corporations where the amount of money involved in a decision is relatively small compared to their total assets. In this dissertation, it is assumed that all decision makers are risk-neutral [92].

The purpose of conducting sensitivity analysis is to find out which factors matter to the outcomes and how much difference they can make. It is central to the constructing and solving decisions models by decision-analysis techniques, since it can lead the decision maker to reconsider the nature of the problem. For example, when we assume decision makers are risk-neutral, the expected monetary values (EMVs) can be a first-cut analysis. However, there may be situations that decision makers' risk attitude largely impacts the consequence. In this case, the assumption of risk-neutral is not a good choice. The decision maker have to reconsider how to capture the risk attitude in the model [92].

3.3.2 REAL OPTIONS

Uncertainties in the investment life cycle complicate the decision making process. Instead of passively taking the uncertainties, corporations have the right to delay, expand, contract, or abandon a project with a given cost or salvage value at some future date. Real options is the collection of these strategies to cope with the unexpected market changes and competitions [93]. In the spectrum usage domain, spectrum entrants face changing situations such as spectrum utilization environment, regulatory rules, and service demands. As a decision maker, they have the right to switch among spectrum usage methods, lease spectrum and infrastructure to others when profits decrease, acquire more spectrum by contract and CR base DSA when the current bandwidth can hardly meet the soaring demand, etc. Consequently, it is important to consider the value of real options when making spectrum usage decisions. This section provides an introduction on real options, categories of options, and how to quantify the value of real options.

3.3.2.1 WHAT ARE REAL OPTIONS? As described in section 3.3.1, monetary gain can be an objective in the decision model. It is traditionally evaluated by discounted-cash-flow (DCF) approach, such as net-present value (NPV) rule. The DCF approach assumes that the decision maker passively commits to a static operating strategy throughout the entire life cycle of the investment. In other words, the individual or the organization does not change their strategies when risks occur and when uncertainties are resolved. It does not capture the management's flexibility which aims at adapting to different situations and revise decisions in response to unexpected situations [94].

Real options, in contrast, target quantifying the value of management's flexibility. This management's flexibility is linked to financial options, which is a derivative instrument for a future transaction on an asset. There are two types of options: call options and put options. Entities that estimate the asset that may decrease in value will write a call option (short call). The buyer of the call option (long call) has the right, but not obligation, to acquire the underlying asset by paying a predetermined price, called strike price. Entities that anticipate the asset may increase in value will write a put option (short put). The buyer of the put option (long put) has the right, but not obligation, to sell the underlying asset and receive the strike price.

Many of the real options occur naturally, while others may be planned and built in at extra cost. Like financial options, an individual or an organization has the right but not obligations to exercise real options. They are only exercised when it is profitable to do so [95].

This asymmetry provides entities instrument to mitigate risks and cope with uncertainties, which is the value of real options [96].

3.3.2.2 CATEGORIES OF REAL OPTIONS Real options may be divided into three categories: investment/growth options; deferral/learning options; and disinvestment/shrinkage options. Investment/growth options include (1) scale up option: the option to scale up through sequential investments when demand and profits increase; (2) switch-up option: the option to upgrade to the next generation of the product or technology or switch to technology and product that lead to higher profits; (3) scope-up option: happen when a company's initial investment provides it a leeway to enter another industry cost-effectively [93].

The most important deferral/learning options, also called study/start options, is delay. It means an individual and an organization has the option to wait until more information or skill is acquired. For example, a company may make an investment after they have a clear view of service demands. Another example is that a pharmaceutical firm may conduct several phases of experimentation with the drug compound before seeking regulatory approval and going to market [93].

A company also has disinvestment/shrinkage options when profits reduce. Three types of options exist inside this category: (1) scale-down option: the option to shrink or shut down a project before completion due to the changes in the expected payoffs; (2) switch-down option: the option to switch to more cost-effective technology and products; (3) scope-down option: the option to decrease or even abandon the project [93].

3.3.2.3 QUANTIFYING REAL OPTIONS As mentioned above, real options stem from options in financial markets. In order to reveal how to quantify real options, it is necessary to trace back to the early origin of evaluating options in the financial markets. Louis Bachelier is considered as the first person that uses advanced mathematics in the study of finance. In [97], he mentions "l'esprance mathmatique du spculateur est nulle". In English it means that in average a speculator's average gain or loss should be zero, mathematical zero. So, the value of the option is the speculator's expected gain or loss.

This sentence can be translated in math as follows. If we denote the value of an option by $H(X,Y,T)$ as the value that a speculator can gain by exchanging asset X for asset Y at time T in the future, the statement that the mathematical expectation of a speculator is zeros means:

$$H(X,Y,T) - e^{-\rho T}\int_{Y}^{\infty}(u-Y)\Psi(u,X,Y,T)du = 0 \tag{3.2}$$

In 3.2, $e^{-\rho T}\int_{Y}^{\infty}(u-Y)\Psi(u,X,Y,T)du$ is the discounted expected value of the gain made by exchanging asset X for asset Y at time T in the future. In the context of a call option on a share, X is the value of a share, Y is the exercise price and T is the exercise time. $\Psi(u,X,Y,T)$ is a time dependent Probability Density Function (PDF) which controls how the values of X and Y compare at time T. The integration provides the expected value of the difference of $(u-Y)$ when $u \geq Y$. It is the expected benefit of making the exchange. $e^{-\rho T}$ is the discount factor. Clearly, the value of option $H(X,Y,T)$ can be written as:

$$H(X,Y,T) = e^{-\rho T}\int_{Y}^{\infty}(u-Y)\Psi(u,X,Y,T)du \tag{3.3}$$

In [97], the PDF for the value of the asset subject to the speculation at the relevant time in the future was Gaussian. This means Bachelier assumed that the value of the underlying assets followed a Brownian motion. Economists since have evolved on this subject. The most commonly used PDF in the financial market is a time dependent lognormal distribution. In this dissertation, the PDF of the demand will be applied when calculating the value of the options.

3.3.3 QUEUEING SYSTEMS

A queueing system is a system in which items arrive for service, wait for service if it is not immediately served, and leave the system after being served [98]. The word “item” is a generic term. It could refer to customers in a bank, parts in a manufacturing factory, packets in the wireless communication networks, etc. The word “service” generally means being processed. The service in the bank could mean depositing and withdrawing money, the process in a manufacturing factory could be smelting and forging, and the process in wireless communications domain could mean transmitting and receiving [99].

3.3.3.1 FUNDAMENTALS OF QUEUEING SYSTEMS

In most cases, five basic characteristics are needed in order to precisely define a queueing system: (1) Arrival pattern of customers measured by the average number of arrivals per unit of time or the inter arrival time; (2) Service pattern of servers measured by the average number of customers served per unit of time or required service time; (3) Number of servers describes the number of parallel service stations; (4) System capacity is the physical limitation of the waiting room for a queue; (5) Queueing discipline is the manner by which customers are selected for service in a queue [100].

Accordingly, Kendall's notation uses a serie of symbols and slashes such as A/B/X/Y/Z to describe a queueing system based on above five characteristics. Table 2 summarizes the meaning of each parameter with examples. In most of the time, only first three symbols, A/B/X is mentioned. Then it is assumed that the system capacity is infinite and the queueing discipline is FIFO [100].

Table 2: Kendall's Notation

Characteristics	Explanation	Examples
A	Interarrival-time distribution	M-Exponential, E_k-Erlang type k (K=1,2)
B	Service-time distribution	D-Deterministic, G-General
X	Number of parallel servers	$1,2,\cdots,\infty$
Y	Restriction on system capacity	$1,2, \cdots, \infty$
Z	Queue discipline	FIFO, LIFO-Last In First Out

3.3.3.2 PERFORMANCE PARAMETERS

There are six essential parameters when analyzing queueing system [101].

1. Probability of the number of jobs in the system (π_k): important probabilities include the probability that the server is idle (π_0), the probability that a job is forced to join a queue (π_c) where c is the number of servers, and the probability that a job is dropped (π_k) where k is the system capacity.

2. Utilization (ρ): $\rho < 1$ is the condition required for a stationary behavior. In other words, the system is stable when the average number of jobs that arrives in a unit of time is less than the average number of jobs that can be serviced by the system. In a single server system, the utilization, ρ, is the fraction of the time in which the server is occupied. When there is no limit on the number of jobs in the single server system, the utilization is calculated as

$$\rho = \frac{mean\ service\ time}{mean\ interarrival\ time} = \frac{arrival\ rate}{service\ rate} = \frac{\lambda}{\mu} \tag{3.4}$$

   The utilization of a multiple servers system is given by

$$\rho = \frac{\lambda}{c\mu} \tag{3.5}$$

3. Response Time (T): also known as the sojourn time, is the total time that a job spends in the queueing system. It includes both service time and waiting time.
4. Waiting Time (W): The waiting time is the time that a job spends in a queue waiting to be serviced.
5. Queue Length (Q): is the number of jobs in the queue. It can be calculated by *Little's theorem* as

$$\overline{Q} = \lambda \times W. \tag{3.6}$$

6. Number of Jobs in the Systems (K): calculates the average number of jobs in the system as

$$K = \sum_{k=1}^{\infty} k \times \pi_k = \lambda \times T. \tag{3.7}$$

3.3.3.3 M/G/C QUEUE M/G/C is a type of queueing system where customers arrive according to a Poisson process with rate λ, the service time follows general distribution with mean μ, and the total number of parallel servers is C. Therefore, one customer can be served immediately after arriving when there are less than C other customers present in the system. Otherwise, the customer has to wait in a queue with infinite capacity and it will be served based on FIFO discipline. Although M/G/C queueing system only relaxes one condition from M/M/C queue, which is the service time distribution, the calculation complexity changes dramatically. There is no analytically results for steady state M/G/C queue. Therefore, the probability that k ($k = 1, 2, \cdots, C$) servers are busy can be approximated by simulation.

3.3.3.4 PRIORITY QUEUE In priority queue, users are assigned with different priority classes $(1, 2, \cdots, k)$. In contrast to FIFO, users with higher class have higher priority when access the server. The two well-known priority disciplines are non-preemptive and preemptive. Under the non-preemptive rule, if a higher priority unit arrives when a lower priority unit is being served, the higher priority unit waits until the lower priority unit completes its service. In preemptive priority discipline, if a higher priority unit arrives when a lower priority unit is being served, the higher priority unit has the right of replacing the lower priority unit from service [102]. Customers in the same priority class is being served as FIFO.

After interrupted by higher priority unit, the lower priority unit on its re-entry may either (1) resume service from the point where it was preempted, called "preemptive resume" or (2) repeat the service, called "preemptive repeat" [103]. This dissertation adopts preemptive resume as priority queueing discipline. It is because PUs have the rights to occupy the licensed spectrum whenever needed. Further, we assume that SUs have enough buffer to save incomplete services and capability to track their transmissions.

4.0 SPECTRUM SHARING METHODS

There are many ways to categorize spectrum usage methods. Depending on explicit coordination between PUs and SUs, spectrum sharing can be divided into cooperative and non-cooperative sharing [104]. Examples of cooperative sharing include spectrum trading and Mobile Virtual Network Operators (MVNOs). Examples of non-cooperative sharing include unlicensed usage and opportunistic sharing. Depending on the rights holders' hierarchy, spectrum sharing can be divided into non-subordinate sharing and subordinate sharing. Sharing among same type of right holders is non-subordinate sharing, such as wireless Local Area Network (WLAN) in ISM bands and Commercial Mobile Radio Services (CMRS) in licensed bands. Sharing between PUs and SUs is subordinate sharing. Examples include spectrum sharing in TV broadcast bands and federal-commercial sharing in 1755-1850 MHz [105].

In this dissertation, the spectrum usage methods are divided into three categories according to the dynamics of spectrum sharing: primary usage, quasi-static sharing, and dynamic sharing. The reason for this categorization approach is that different spectrum usage methods in the same group use identical quantification methodology for calculating risks and revenues. This section introduces spectrum sharing methods that are considered in this dissertation in detail.

4.1 PRIMARY USAGE

Once the spectrum entrant obtains an FCC issued license, he has the exclusive usage right for operating on the licensed bands during the permitted time periods at assigned geographic areas. Accordingly, bandwidth, operation duration, location and coverage determine the price for the spectrum bands. Selected auctions for Pittsburgh (PA), Washington D.C. and New York (NY) are summarized in Appendix A. From the table, several observations can be draw:

- Spectrum license price increases with population.
- Broadband worth much more than narrow band.
- The average license period is 10 years and the majority of them are renewable.
- There is construction requirements for licensees in terms of geographic and population coverage and services.

All radio licenses are assigned based on area. Different area segmentation methods are applied in different types of licenses. Five of them are listed here since they are closely related to the auction summarized in Appendix A: the Basic Trading Areas (BTA)[1], the Major Economic Areas (MEA)[2], the Regional Economic Areas (REA)[3], Cellular Market Areas (CMA)[4], the Economic Area (EA)[5].

4.2 QUASI-STATIC SHARING

In quasi-static sharing, spectrum entrants do not have the exclusive usage right in accessing the spectrum. However, their opportunities in spectrum access is reserved. This is achieved by PUs' and SUs' cooperation in both spatial and temporal domain. Two examples will

[1] Basic Trading Areas delineated by the Rand McNally 1992 Commercial Atlas & Marketing Guide, 123rd Edition, at pages 38-39; extended and revised by the Federal Communications Commission, 59 FR 46195 (September 7, 1994)

[2] Major Economic Areas delineated by the Federal Communications Commission, 62 FR 9636 (March 3, 1997)

[3] Regional Economic Areas delineated by the Federal Communications Commission, 62 FR 9636 (March 3, 1997)

[4] Cellular Market Areas listed by the Federal Communications Commission, DA 92-109 (January 24, 1992), 7 FCC Rcd 742 (1992)

[5] Economic Areas delineated by the Regional Economic Analysis Division, Bureau of Economic Analysis, U.S. Department of Commerce February 1995 and extended by the Federal Communications Commission, 62 FR 9636 (March 3, 1997)

be investigated in this dissertation for quasi-static spectrum sharing: cooperative spectrum sharing through trading and ASA.

4.2.1 COOPERATIVE SPECTRUM SHARING THROUGH TRADING

The FCC released the first Report and Order and Further Notice of Proposed Rulemaking to facilitate spectrum access through the use of spectrum leasing agreement in 2003 [106]. It allows PUs to lease some or all of the spectrum usage rights associated with their licenses to third parties. These leasing agreements need to be submitted to the FCC at least 10 or 21 days (depending on leasing duration) before effective. The second Report and Order provides immediate processing, such as overnight approval, for certain qualified spectrum leasing arrangement [107].

According to the FCC's definition, there are two types of spectrum leasing agreements: spectrum manager lease and *de facto* transfer lease. Under the the spectrum manager lease, both *de jure* and *de facto* control over the leased spectrum are retained by SUs during leasing period. That means SUs have the rights to define their own spectrum usage parameters. On the contrary, under *de facto* transfer, SUs only obtain the *de facto* control of the leased spectrum while PUs keep the *de jure* control over it. In this case, SUs have to follow spectrum sharing etiquette that determined by PUs. Both spectrum leasing agreements have two options: short-term lease and long-term lease. A short-term lease is limited to one year, and a long-term lease last more than one year.

Ideally, we could track the difference between spectrum leasing and auction value if we know how much SUs pay for spectrum leasing. Unfortunately, spectrum leases are considered as private transactions and the information is generally not available. The accessible information captures the number of spectrum leasing arrangement in each year, which provide a sense on spectrum leasing availability. Appendix C summarized number of spectrum leasing under selected spectrum blocks.

4.2.2 ASA

The second type of quasi-static sharing is ASA. The key feature of ASA is to ensure a predictable QoS for spectrum users. When setting up the ASA arrangement, the following steps need to be followed: (1) PUs report the conditions under which ASA will be facilitated; (2) the regulator assesses the relevant conditions of the PUs' usage as reported in step (1); (3) the regulator establishes an ASA licensing process; (4) ASA licensees (SUs) operate according to ASA terms; (5) when PUs need to access the spectrum used by SUs, they must inform SUs by agreed means. Then SUs need to modify their transmission parameters according to the conditions defined in ASA licenses [108, 109, 110].

One application of ASA could be spectrum sharing between federal and non-federal users in federal bands. In July 2012, PCAST recommended the president to identify 1,000 MHz of federal spectrum to share with non-federal users. It further suggested a three-tier hierarchical sharing, in which federal primary systems have the highest priority and are protected from harmful interference. Second tier users, referred to as Priority Access, must register their deployments and receive some QoS protections. The FCC suggested eligible Priority Access users could include hospitals, utilities, state and local governments, etc. In order to provide a QoS guarantee, Priority Access users would only be permitted in areas and time slots that experience little interference from PUs. The third tier users, called General Authorized Access (GAA), opportunistically operate on the spectrum when above two types of users are absent. Unlike the Priority Access, GAA do not have guarantee in spectrum access [24, 111]. Candidate bands for federal and non-federal sharing include Meteorological-Satellite (space-to-earth) and Meteorological aids services on 1675-1710 MHz, federal government for fixed and mobile services in 1755-1780 MHz, Department of Defense Radar service in 3500-3650 MHz, and internationally reserved for radio altimeters in 4200-4220 MHz, 4380-4400 MHz bands [26].

4.3 DYNAMIC SHARING

The feature of dynamic sharing is that spectrum access opportunities are not reserved. Moreover, there is no explicit cooperation requirements among SUs and between PUs and SUs. Three types of dynamic sharing are considered in this dissertation: CR based DSA, unlicensed usage in TVWS, and unlicensed usage in ISM bands.

4.3.1 CR BASED DSA

The goal of CR based DSA is to provide SUs with high bandwidth via heterogeneous architectures and DSA techniques. The full realization of CR based DSA will lead to opportunistic spectrum sharing in any frequency, where SUs find idle bands, use it optimally, and then vacate the bands for others [111]. When it happens in the licensed bands, SUs should transmit on non-interfering basis. In other words, SUs operate when PUs are absent and terminate their operation upon PUs' arrival. There are four major functions for sensing based DSA [7]:

- Spectrum sensing: detecting unused frequency bands.
- Spectrum management: identifying the best available frequency bands for specific communication requirements.
- Spectrum mobility: maintaining seamless communication during the transition to different frequency bands.
- Spectrum sharing: supporting fairness in spectrum sharing with other opportunistic users.

IEEE P1900.5, published in January 2012, is the standard for DSA networks. It defines policy-based control architectures for the regulator, the operator, the user, and the network equipment manufacturer. It also defines policy language requirements on functionality and behaviors of DSA networks. The current standards on CR based DSA include P1900.5.1, P1900.5.a, and P1900.5.2. P1900.5.1 provides the policy language requirements of IEEE 1900.5, including applications, signaling plan, and technical analysis that developed by Modeling Language for Mobility Work Group (MLM-WG). P1900.5.a is an amendment to the existing P1900.5. It defines the interface between policy architecture and components. P1900.5.2 designs methodologies for modeling spectrum consumption of any type of radio frequency spectrum usage [112].

From 2001, the FCC has adopted changes to the equipment authorization rules in order to accommodate the development of SDR and CR. As stated by the FCC, CR based DSA systems are allowed and have already been applied in cellular radio system, real time network control, and WLAN. However, these usages limit CR to PUs' own licensed bands and unlicensed bands. SUs are not allowed to opportunistically access the licensed bands due to potential interference and system failure [111]. Because of its merits, this dissertation includes CR based DSA as a spectrum usage model and analyzes situations that are suitable for it.

4.3.2 TVWS

In 2008, the FCC released the Second Report and Order [20] to allow unlicensed devices to transmit in the broadcast television spectrum at locations where licensed services are absent. These unused TV channels are referred to as white spaces. In this document, the FCC requires:

- All devices (except personal/portable devices operating in client mode), must have geolocation capability and access the database to obtain a list of the permitted channels before transmission. They also must have a capability to sense TV broadcasting and wireless microphone signals, at levels as low as -114 dBm.
- Fixed devices can operate on any channel between 2 and 51, except channels 3,4, and 37, up to 4 Watts effective isotropic radiated power (EIRP). That is frequency bands 54-60 MHz, 76-88 MHz, 174-216 MHz, 470-608 MHz, 614-698 MHz. Similarly, personal portable devices can operate on channels between 21 and 51, except channel 37, which is frequency bands between 512-608 MHz, 614-698 MHz. The transmission power cap in adjacent channels is 40 milliwatts, and for other channels is 100 milliwatts. Devices that only rely on sensing and do not have geolocation and database access capabilities are allowable, but they are subject to a much more rigorous set of tests and the maximum

transmission power is 50 milliwatts instead of 100 milliwatts. All devices must limit out-of-band emissions in the first adjacent channel to a level 55 dB below the power level in the channel they occupy.

- All devices must provide identifying information to the database for the sake of enforcement. All devices must have adaptable power control in order to use the minimum power to complete communications. All devices are subject to equipment certification by the FCC Laboratory before implementation.

In 2010, the FCC released the final rules for unlicensed usage in TV white space in the Second Memorandum Opinion and Order [21]. The most significant change is that the FCC eliminated the sensing requirement for SUs with geo-location capability and the ability to access the database. Moreover, the required in-band emission will be measured within 6 MHz instead of 100 kHz. It also revised the attenuation level from 55 dB to 72.8 dB. They require devices to re-check the database at least once a day after operation. Further, fixed devices are permitted to transmit up to 1 watt in power and may use an antenna that provides up to 6 dBi of gain.

In 2012, the FCC further adjusted rules in the Third Memorandum Opinion and Order [22]. They defined fixed adjacent channel emission limit as the maximum power permitted in a 6 MHz bandwidth minus 72.8 dB. It also slightly increases the maximum permissible power spectral density (PSD) as described in table 3.

Table 3: Regulations in TVWS

Type of TV Bands Devices	Power Limit (6 MHz)	PSD Limit (100 kHz)	Adjacent Channel Limit (100 kHz)
Fixed	30 dBm (1W)	12.6 dBm	-42.8 dBm
Personal/Portable (adj. Channel)	16 dBm (40 mW)	-1.4 dBm	-56.8 dBm
Sensing Only	17 dBm (50 mW)	-0.4 dBm	-55.8 dBm
All other Personal/Portable	20 dBm (100 mW)	2.6 dBm	-52.8 dBm

4.3.3 ISM

The ISM bands are originally reserved for industrial, scientific, and medical purpose other than communications [6]. It includes frequency bands 902-928 MHz, 2400-2483.5 MHz, and 5725-5850 MHz. SUs with frequency hopping and Direct Sequence Spread Spectrum (DSSS) intentional radiators are permitted to operate under many requirements, including minimum separate of hopping channels, average time of occupancy on any frequency band, and minimum hopping frequencies. Regulations that related to transmission power are summarized here [7]: Maximum transmitter output power fed into the antenna is 30 dBm (1 Watt). Maximum EIRP is 36 dBm (4 watt). There are two exceptions for fixed point-to-point link: (1) no requirement on antenna gain in the 5.8 GHz; (2) in 2.4 GHz, system can increase antenna gain above 36 dBm but for every 3 dBi increase of antenna gain, the system have to reduce the transmit power by 1 dBm.

WiFi is the dominant technology for communications in ISM bands. As defined by Wi-Fi Alliance [113], Wi-Fi is "wireless local area network (WLAN) products that are based on the Institue of Electrical and Electronics Engineers(IEEE) 802.11 standards." The newest standard 802.11n, introduced in 2009, increases the maximum single-channel data rate from 54 Mbps to over 100 Mbps. It also accommodates Multiple Input Multiple Output (MIMO) mechanisms which allows up to 4 transmitter and receivers [114].

IEEE 802.11 is a set of physical and link layer specifications created and maintained by IEEE 802 group for implementing WLAN in 2.4, 3.6, 5 and 60 GHz bands. The medium access control (MAC) technique in IEEE 802.11 is Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). Two major functions of CSMA/CA are carrier sense ("Listen before talk") and collision avoidance. Carrier sense means before transmitting, a transmitter must listen to the shared medium, such as wireless channels, to determine resource availability. It can only transmit when the channel is idle. Two techniques fulfill the function of collision avoidance. First, before transmitting, the transmitter could send a Request to Send

[6] ARTICLE 1 - Terms and Definitions (HTML). life.itu.ch. International Telecommunication Union. 19 October, 2009. 1.15. "industrial, scientific and medical (ISM) applications (of radio frequency energy): Operation of equipment or appliances designed to generate and use locally radio frequency energy for industrial, scientific, medical, domestic or similar purposes, excluding applications in the field of telecommunications."

[7] Part 15, Subpart C, Sec. 15.247 Operation within the bands 902-928 MHz, 2400-2483.5 MHz, and 5725-5850 MHz.

(RTS) message to the Access Point (AP). They can only transmit after receiving the Clear to Send (CTS) message from the AP. Second, if the transmitter receives a acknowledgement packet (ACK) from AP, it means there is no collision during transmission. Therefore, although unlicensed bands do not require coordination among users, there are standards that required "Listen before talk" in order to achieve mutual good performance [114].

4.4 MIXED STRATEGY

Spectrum choices are not limited to a single one of the options described above. Mixed strategies that combine more than one spectrum choices are other options for SUs. For example, SUs in cooperative sharing through trading may acquire one or more spectrum usage model in the dynamic spectrum sharing in order to provide continuous services. Another example is that PUs offload traffic from the core network to unlicensed spectrum. It is considered as a cost-effective solution since licensing processes and spectrum expense are avoided. Mixed strategy can be evaluated by real options approach, which is a future research direction.

5.0 RISKS AND MITIGATION STRATEGIES

Each spectrum usage method that described above leads to unique risks portfolio, which brings uncertainties to SUs. With proper mitigation strategies, these risks may not result in system and business failure. Hence, the explicit understanding of risks and mitigation strategies are essential for SUs. This section provides the lists of risks and mitigation strategies, and then map them to each spectrum usage method.

5.1 RISKS

Risks can be divided into two broad categories: internal and external risks. Internal risks are those that arise within the enterprise, while external risks are those that arise outside the enterprise. Within each category, there are many factors that give rise to risks. Factors that bring on internal risks include: human factors, technological factors, and physical factors. Human factors considers issues such as key staff being ill and unable to work and strike actions. Technological factors are the unforeseen changes in technology that result in products and services with better quality, lower price, and higher efficiency in utilizing resources. Physical factors are directly related to loss or damage to the physical property of the enterprise. Factors that cause external risks include economic factors, natural and environment factors, as well as political factors. Economic factors include customer demands and competition for the product, service, and resource. Natural and environment factors are unforeseen changes in climate and environments. Political factors means changes in regulation, policy, and market viability [115]. In this dissertation, only factors that directly related to spectrum usage and its impact will be considered, therefore human factors are outside the scope.

Common risk factors that are faced by every spectrum usage method are: (1) customer demand: when spectrum entrants build out infrastructures and start providing services, there are no guarantees on the service demand. Service demand may change with price, application, location, and even marketing strategies. (2) technological risk: the development of technology in telecommunication field happens often, for instance, the cellular technology evolved from GSM to OFDM. End users' enthusiasm in adopting new technology diminish the value of legacy technology. (3) physical risk: as long as spectrum entrants have physical properties, they have physical risks. In this specific case, physical properties include base stations, transmitters, backhaul equipment, etc

Risk of competition stems from spectrum entrants' competition with their counterparts in getting spectrum. Spectrum entrants cannot avoid competition risks, but they have strategies to increase the chance of winning in the competition. The competition for primary usage and quasi-static sharing comes from getting license and contracts. Competition in auctions increases the license and contracts price. Spectrum entrants in dynamic sharing compete for spectrum access opportunities. Sensors' performance and transmitters' capabilities determine how well they can compete with their counterparts.

Natural and environment risks such as climate change and natural disasters are not considered here. The environment risks in this dissertation is the spectrum usage environment. Specifically, it is the interference level at regions where spectrum entrants operate. Spectrum entrants that target for primary usage have less environment risks since the resource, spectrum, is reserved for their usage. The environment risk increase in the quasi-static sharing. Since SUs have lower priority in access the spectrum than PUs, they may receive interference from PUs. This risk increase even more in the dynamic sharing, since reservation and cooperation are not required. Moreover, the interference level rise when heterogeneous devices and applications operate in the same band.

Political risks come from regulatory actions and spectrum markets. License availability is a decisive factor for primary usage and ASA licensees. This availability depends on regulators' spectrum assignment and allocation, other wireless services and technologies performance, and the licensing process. Market liquidity affects the operation of cooperative spectrum sharing through trading. Factors that affect liquidity include transaction costs, quantity of supply and demand, number of market participants, spectrum market structure, information flow, etc. Dynamic sharing are strongly affected by regulation, since the operable channel, bandwidth, maximum transmission power, etc. are all determined by regulators.

Table 4 summarizes risks for each spectrum usage method. P represents primary usage, C represents cooperative spectrum sharing through trading, A represents ASA, S represents CR based DSA since it requires sensing, T represents TVWS, and I represents unlicensed usage in ISM.

Table 4: Risks for each spectrum usage method

Risk Categories	Risks	P	C	A	S	T	I
Economic	Demand	+	+	+	+	+	+
	Competition for spectrum license	+		+			
	Competition for spectrum leasing agreement		+				
	Competition for spectrum access				+	+	+
Technology	Technology evolution	+	+	+	+	+	+
Physical	Property loss and damage	+	+	+	+	+	+
Political	Spectrum license availability	+		+			
	Spectrum market liquidity		+				
	Action of regulatory body				+	+	+
Environment	Interference level				+	+	+

5.2 MITIGATION STRATEGIES

Risks do not necessarily lead to system failure, since each sharing method has different mitigation strategies to hedge risks. When we recognize spectrum usage as an engineering investment, there are many types of mitigation strategies in the entire investment life cycle.

For example, the project can be postponed to have better recognition of service demand; firms can increase advertisement and improve customer relationships in order to enhance the service penetration. Four mitigation strategies that are closely related to spectrum usage are listed here.

- Switch: ideally, spectrum entrants can switch their spectrum usage methods with associated costs. However, PUs have to obey the construction requirements that stated in the license terms, thus switching is not possible for them.
- Expand: whenever current frequency bands cannot support service demand, spectrum users have the capability to establish more base stations to increase the spectrum reuse factor and then support more customers or provide higher service performance.
- Acquire spectrum: spectrum entrants also have the rights to acquire more spectrum when their service demand cannot be met by current frequency bands. When acquiring more spectrum, spectrum entrants may have extra expenditures on equipment and spectrum access opportunities.
- Lease infrastructure: all spectrum choices can lease infrastructure when it is profitable. When spectrum users lease infrastructure, it is possible that they terminate their own service permanently or they may restart providing wireless services when situation changes.
- Lease spectrum: in this dissertation, only PUs have the option to lease spectrum, since they are the license owners. SUs in cooperative sharing through trading may be able to sublease spectrum depending on the terms of spectrum leasing agreement, which is outside the scope of this dissertation.

Table 5: Mitigation Strategies for Each Spectrum Usage Method

Mitigation Strategies	Primary usage	Cooperative	ASA	CR based DSA	TVWS	Unlicensed
Switch		+	+	+	+	+
Expand	+	+	+	+	+	+
Acquire spectrum	+	+	+	+	+	+
Lease infrastructure	+	+	+	+	+	+
Lease spectrum	+					

6.0 DECISION AND RISK ANALYSIS FRAMEWORK

The basic tenet for this dissertation is to quantify spectrum access risks and analyze spectrum entrants' decisions based on different incentives, limitations, risks, and mitigation strategies embedded in each spectrum usage method. Section 6.1 identifies factors that impact spectrum entrants' choices and decision criteria that will be tested in this dissertation. Section 6.2 describes the models to quantify QoS risks in terms of throughput and monetary risks in terms of profits. In order to quantify risks, section 6.3 adopts queueing systems to determine expected throughput, and section 6.4 provides cost and revenue models for calculating expected profits, as well as real options method to quantify the value of mitigation strategies.

6.1 DECISION CRITERIA

Factors that impact spectrum entrants' decisions are divided into two groups: incentives and limitations. Incentives include target coverage, frequency bands, location, operation duration, and capacity requirements. For example, machine to machine communication may support elastic services, therefore it has lower capacity requirements and does not have to operate in the peak hour. While spectrum entrants that plan to provide broadcast service may prefer locations with high population density, and they are supposed to provide high QoS levels all day long especially in peak hour. The limitation that considered in this dissertation is budget limitation.

Besides incentives and limitations, spectrum entrants also have different criteria. For example, profits maximization and risk minimization are two common decision criteria. There are other decision criteria as well. For example, a spectrum entrant may choose a specific spectrum usage method for a service, and the goal is not to earn profits but keep up with competitors' application development. In other cases, although providing a new service may bring high risk in demand and even lose capital, by doing so spectrum users can occupy the market and then leverage other services.

There are no established criteria for wireless service providers to choose a spectrum access method, however [116] surveys customers' choices on cellphone service. As a cellphone service provider, they generate revenues by services demand. Therefore, we adopt end users' decision criteria and generalize them for spectrum entrants in a broader sense. In this dissertation, only the following decision criteria will be tested:

- Profit maximization: means spectrum entrants prefer the spectrum usage method that provides the highest profits.
- QoS risk minimization: means spectrum entrants prefer the spectrum usage method that has the least risks in throughput.
- Mixed decision criteria with different weights: (1) weight for monetary risks is 0.70 ($W_p = 0.70$) and weight for QoS risk minimization is 0.30 ($W_q = 0.30$); (2) weight for monetary risks is 0.30 ($W_p = 0.30$) and weight for QoS risk is 0.70 ($W_q = 0.70$). (3) weight for monetary risks is 0.5 ($W_p = 0.5$) and weight for QoS risk is 0.50 ($W_q = 0.5$).

6.2 RISK ASSESSMENT

As stated in section 5, two types of risks will be quantified in this dissertation: QoS risks in terms of throughput for dynamic sharing, as well as monetary risks for all spectrum entrants. The risks are calculated as the fraction of the difference between requirement and expected value over the requirement. The following sections will describe the model for quantifying these two types of risks in detail.

6.2.1 RISKS IN THROUGHPUT

The risks in throughput, RT_i^m, for spectrum entrant, i, in this dissertation, is calculated as the fraction of the difference between spectrum entrants' throughput requirement, TR_i^j, $(j = 1, 2, 3)$, and estimated throughput value, T_i^m, over the throughput requirement, as illustrated in equation 6.1. When the expected throughput is larger than the requirement, the risk is 0. m represents the spectrum sharing method. The calculation of the expected throughput in each spectrum usage method will be introduced in section 6.3.

$$\mathrm{RT}_i^m = \begin{cases} 0, & \text{if} \quad \mathrm{TR}_j \leq T_i^m \\ \dfrac{\mathrm{TR}_i^j - T_i^m}{\mathrm{TR}_j}, & \text{if} \quad \mathrm{TR}_j > T_i^m \end{cases} \tag{6.1}$$

From equation 6.1, it can seen that both expected throughput value and the requirement impact the risk value. Therefore, two types of throughput requirements will be applied to test the difference. In the first scenario, spectrum entrants' throughput requirement is constant. Applications such as surveillance monitoring fall in this category. In this case, the throughput requirement function, TR_i^1, can be expressed as:

$$\mathrm{TR}_i^1 = a \tag{6.2}$$

In the second scenario, spectrum entrants' throughput requirement is a step function that changes with time. It represents the scenario where spectrum entrants provide full service during a period of time and limited service for the rest of the day. Cellular and broadband services are candidates for the step function, since their traffic has a pronounced diurnal behavior. In this case, the throughput requirement, TR_i^3, can be modeled as a step function and expressed as:

$$\mathrm{TR}_i^2 = a_1 f_1(x) + \cdots + a_n f_n(x) \tag{6.3}$$

where $a_i \in \mathbb{R}$, $f_i(x) = 1$ if $x \in [a_i, b_i)$ and 0 otherwise, for $i = 1, \cdots, n$.

6.2.2 RISKS IN PROFITS

The risks in profits, RP_i^m, for spectrum entrant i, is calculated as the fraction of the difference between the profits requirement, PR_i, and the expected profits, P_i^m, over the profits requirement. When the expected profits is larger than the requirement, the risk in profits is 0. When the expected profit is negative, the risk in profits is 1. m represents the spectrum sharing method. The model of calculating the expected profits for each spectrum usage method will be introduced in section 6.4.

$$\mathrm{RP}_i^m = \begin{cases} 0, & \text{if } \ \mathrm{PR}_j \leq P_i^m \\ \dfrac{\mathrm{PR}_i - P_i^m}{\mathrm{PR}_i}, & \text{if } \ \mathrm{PR}_i > P_i^m \end{cases} \tag{6.4}$$

Only one type of profits requirement will be applied in this dissertation, where the profit requirement is a constant value p. When p equals to 0, it means the spectrum entrant is satisfied with the spectrum usage method as long as the revenue is no less than than cost.

$$\mathrm{PR}_i = p \tag{6.5}$$

6.3 QUANTIFYING THROUGHPUT

We consider a radio network with M PUs and N SUs. QoS risks will be calculated in terms of throughput for SUs in dynamic sharing. When the packet length is L_i, the length of overhead is L_i^{oh}, and the end-to-end delay is D_i for SU, i, the throughput, T_i is calculated by [117]

$$T_i = \frac{L_i + L_{oh}}{D_i} \tag{6.6}$$

Hence, the main concern is to calculate the end-to-end delay. As introduced in 6.3.1, the end-to-end delay in this case is the sojourn time in the M/G/C queue. It equals the waiting time in the queue plus the transmission time. Two scenarios will be analyzed in the M/G/C queue. The first scenario, described in section 6.3.1.1 considers unlicensed bands, in which SUs are the only type of spectrum users. It is modeled by a single class M/G/C queue. In the second scenario, there are both PUs and SUs in the same frequency band. Thus, PUs are assumed to be able to preempt the transmission of SUs. It is modeled by M/G/C priority queue with preemptive resume, described in section 6.3.1.2.

Instead of steady-state behavior, this dissertation uses time-varying behavior of the arrival rate for both PUs and SUs. It is because the steady-state behavior is far from the reality for most of the frequency bands. Specifically, as [56] shown, spectrum usage has a pronounced diurnal and weekly pattern. Therefore, the end-to-end delay in dynamic sharing is based on the time-varying model, introduced in 6.3.2.

6.3.1 M/G/C queueing model

In the M/G/C queueing model, the arrival process is Poisson and the service time follows a general distribution. The number of available channels for spectrum users is C. The sojourn time of a k-class ($k = 1, 2$) C-server system with queueing discipline d, arrival rate vector $\underline{\lambda}_{(k)}(k = p, s)$, and service rate vector $\underline{\mu}_{(k)}(k = p, s)$ is denoted by $S(d, \underline{\mu}_{(k)}, \underline{\lambda}_{(k)}, C)$. The waiting time of a system with the same parameters is denoted by $W(d, \underline{\mu}_{(k)}, \underline{\lambda}_{(k)}, C)$. In this paper, d is either FIFO or preemptive resume (PR).

In CR based DSA and unlicensed usage in ISM bands, spectrum users' packets arrival and service rates are applied. In TVWS, PUs are TV broadcasters, therefore the arrival and service rate is the rate for a program. SUs' arrival and services rates are based on packets. $S()$ is the end-to-end delay for SUs. The estimated throughput is calculated as packet length divided by $S()$. $W()$ and $S()$ will be calculated in single class and preemptive resume scenarios.

6.3.1.1 Single class The single class M/G/C queueing model assumes that all N SUs are served as FIFO and,

- The arrival of each SU's packets is Poisson distributed with arrival rate $\lambda_i (1 \leq i \leq N)$, and is independent of each other. The total arrival rate $\lambda_s = \sum_{i=1}^{N} \lambda_i$, since the sum of Poisson distribution is still Poisson distribution.
- The service time for SU, i, is exponentially distributed with rate $\mu_i (1 \leq i \leq N)$.
- All channels are statistically identical.

Let S be a random variable denoting service time. The first and second moment of the average service time are $E[S]$ and $E[S^2]$, respectively. The mean waiting time $W(\text{FIFO}, \underline{\mu}_{(k)}, \underline{\lambda}_{(k)}, C)$ is approximated by [118] as

$$W(\text{FIFO}, \underline{\mu}_{(k)}, \underline{\lambda}_{(k)}, C) \approx \frac{\lambda_s^C E[S^2](E[S])^{C-1} p_0(\rho)}{2(C-1)!(C-\lambda_s E[S])^2}, \tag{6.7}$$

where ρ is the utilization of C channels, given by

$$\rho = \frac{\lambda_s E[S]}{C}, \tag{6.8}$$

and $p_0(\rho)$ is the probability that the queue is empty, given by

$$p_0(\rho) = [\sum_{i=0}^{C-1} \frac{(C\rho)^i}{i!} + \frac{(C\rho)^C}{C!(1-\rho)}]^{-1} \tag{6.9}$$

6.3.1.2 Preemptive resume There are two different priority classes: PUs have the highest priority and all SUs belong to the lower one. PUs are able to preempt the transmission of SUs. Spectrum users within the same priority class follow the FIFO discipline. When SUs' transmission is preempted by PUs, they will be taken up into the queue and transmit after PUs finish their services. CR based DSA and spectrum sharing in TVWS fall in this category. The traffic is modeled by M/G/C preemptive resume system that,

- The arrival for each spectrum user is Poisson process, with mean rate λ_i, and independent of each other. The sum of Poisson process is still Poisson. Therefore, $\lambda_p = \sum_{i=0}^{M} \lambda_i$ and $\lambda_s = \sum_{i=0}^{N} \lambda_i$.
- We use $\lambda_{(k)}$ to denote the sum of the first $k(k = p, s)$ priorities of λ_i. $\lambda_{(p)} = \lambda_p$ is the sum of all arrival rates for, the highest priority, PUs. $\lambda_{(s)} = \lambda_p + \lambda_s$ is the sum of all arrival rates for, the first two highest priorities, PUs and SUs.
- The service time for each spectrum user, i, is generally distributed with average service rates per channel μ_i.
- The overall mean service rate of the k highest priority levels, weighted by arrival rates, will be denoted by $\overline{\mu}_{(k)} = \frac{1}{\sum_{j=1}^{k} \frac{\lambda_j}{\mu_j}} \sum_{i=1}^{k} \lambda_i$.

- To ensure the existence of finite waiting times for the k priority classes, it is also assume that the total traffic intensity satisfies $\rho(k) = \sum_{i=1}^{k}(\dfrac{\lambda_i}{C\mu_i}) < 1$.
- All channels are statistically identical.

The primary concern, the sojourn time of SUs, equals the total waiting time in the queue $(W(\text{PR}, \underline{\lambda}_{(s)}, \underline{\mu}_{(s)}, C))$ plus the service time $(\dfrac{1}{\overline{\mu}_{(s)}})$. It follows that the problem of finding approximations to the sojourn times of the individual classes is reduced to the problem of finding approximate values for the waiting time in the queue for the individual class. According to [118], η is the ratio between waiting time in the M/G/C PR queue and waiting time in the M/G/C FIFO qeueue, as

$$\eta = \frac{W(\text{PR}, \underline{\lambda}_{(k)}, \underline{\mu}_{(k)}, C)}{W(\text{FIFO}, \underline{\lambda}_{(k)}, \underline{\mu}_{(k)}, C)} \tag{6.10}$$

In order to approximate the numerator, $W(\text{PR}, \underline{\lambda}_{(s)}, \underline{\mu}_{(s)}, C)$, the next step is to develop an approximation for η since the denominator, $W(\text{FIFO}, \underline{\lambda}_{(k)}, \underline{\mu}_{(k)}, C)$, can be calculated. When C is not very large and the queue of high priority customer is not very long, $\eta' = \dfrac{W(\text{PR}, \underline{\lambda}_{(k)}, C\underline{\mu}_{(k)}, 1)}{W(\text{FIFO}, \underline{\lambda}_{(k)}, C\underline{\mu}_{(k)}, 1)}$ is a good approximation for η.

Consequently, $W(\text{PR}, \underline{\lambda}_{(s)}, \underline{\mu}_{(s)}, C)$ can be approximated by.

$$W(\text{PR}, \underline{\lambda}_{(s)}, \underline{\mu}_{(s)}, C) \approx W(\text{PR}, \underline{\lambda}_{(k)}, C\underline{\mu}_{(k)}, 1)\gamma \tag{6.11}$$

and $\gamma = \dfrac{W(\text{FIFO}, \underline{\lambda}_{(k)}, \underline{\mu}_{(k)}, C)}{W(\text{FIFO}, \underline{\lambda}_{(k)}, C\underline{\mu}_{(k)}, 1)}$.

The first term, $W(\text{PR}, \underline{\lambda}_{(k)}, C\underline{\mu}_{(k)}, 1)$, can be derived from the sojourn time in M/G/1 queue, $S(\text{PR}, m\underline{\mu}_{(p)}, \underline{\lambda}_{(p)}, 1)$, by

$$W(\text{PR}, \underline{\lambda}_{(k)}, C\underline{\mu}_{(k)}, 1) = [\frac{1}{\lambda_{(s)}}\sum_{j=1}^{2}\lambda_j s_k - \frac{1}{C\overline{\mu}_{(s)}}] \tag{6.12}$$

s_k is the sojourn time of individual classes $(k = p, s)$ in an M/G/1 preemptive resume priority system. Let S' be a random variable denoting the service time in the one server system. The first and second moment of the average service time are $E[S']$ and $E[S'^2]$, respectively. s_k is calculated as [119],

$$s_k = \frac{\sum_{j=1}^{k}(\frac{\lambda_j E[S'^2]}{2})}{(1-\sigma_i)(1-\sigma_{i-1})} \tag{6.13}$$

σ_i is the utilization of the server, in an M/G/1 PR system, by jobs of priority 1 to i

$$\sigma_i = \sum_{j=1}^{i} \theta_j \tag{6.14}$$

θ_i is the utilization of the server, in an M/G/1 PR system, by jobs of priority i

$$\theta_i = \lambda_i E[S'] \tag{6.15}$$

The second term, γ, can be approximated by

$$\gamma \approx \frac{P_C(\rho(s))}{\rho(s)} \tag{6.16}$$

$P_C(\rho)$ is the probability of have C or more spectrum users in the queue. It is calculated as

$$P_C(\rho) = \frac{p_0(\rho)(C\rho)^C}{C!(1-\rho)} \tag{6.17}$$

The sojourn time of SUs equals the total waiting time in the queue plus the service time [120]

$$\begin{aligned} S_s = & \frac{1}{\overline{\mu}_{(s)}} + W(\text{PR}, \underline{\lambda}_{(s)}, \underline{\mu}_{(s)}, C) \\ \approx & \frac{1}{\overline{\mu}_{(s)}} + [\frac{1}{\lambda_{(s)}} \sum_{j=1}^{2} \lambda_j s_k - \frac{1}{C\overline{\mu}_{(s)}}]\gamma \end{aligned} \tag{6.18}$$

The total waiting time for PUs can be evaluated as though SUs did not exist, which it is not the focus of this dissertation.

6.3.2 Time-varying behavior

The basis of most spectrum hole models in the literature is a finite state continuous-time Markov process which is studied under steady state conditions. In this dissertation, we consider spectrum users' time varying behaviors. Therefore, the mean arrival rate is $\lambda_i(t)$ and the mean service rate is $\mu_i(t)$. The waiting time in time-varying model can be solved by [121]

1. Specify the time interval of interest $[t_0, t_f]$ and a time step Δt. Set the current time t to $t = t_0$.
2. Approximate the time varying parameters in $W()$ by a constant over Δt.
3. Apply a standard numerical solution in equation 6.18 and 6.7.
4. Increment time, $t = t + \Delta t$, if $t < t_f$, go to step 2, else stop.

In dynamic spectrum sharing, when the packet length is L_i and length of overhead is L_{oh} for SU, i, the throughput, T_i is calculated by [117]

$$T_i(t) = \frac{L_i + L_{oh}}{S(d, \underline{\mu}_{(k)}, \underline{\lambda}_{(k)}, C)(t)} \tag{6.19}$$

6.4 QUANTIFYING PROFITS

Profits equals revenue minus cost: $Profits = Revenue - Cost$. When SUs' target operation time is longer than 1 month, two strategies will be applied in calculating profits. First, spectrum entrants are not risk awareness, so they ignore the changes in demand and value of management flexibility. The profits will be calculated by Net Present Value (NPV) in this case. The assumption for NPV is that the present value of cash worth more than the future cash flow. In order to compare the value of project with different operation duration, the cash flow in the future need to be discounted back to its present value as:

$$NPV = \sum_{t=1}^{n} \frac{P_t}{(1+r)^t} \tag{6.20}$$

where r is the annual discount rate, P_t is the profits in year t and the lifetime of the project is n.

The assumption of constant demand and passively undertaking risks are not realistic. Therefore, in the second strategy, profits will be evaluated based on the anticipation of changes of demand. Only one type of changes in demand will be tested in this dissertation: linear decrease with price increase. Moreover, the value of management flexibility, mitigation strategies, that cope with the changes in the demand will be quantified using the real options method. Profits without and with the value of management flexibility will be compared in the numerical results. The following sections introduce the cost model (section 6.4.1), revenue model (section 6.4.2), and real options method for evaluating management flexibility (section 6.4.3 in detail.

6.4.1 COST MODEL

The cost of providing wireless services varies with each spectrum usage method. For example, the FCC has rules on maximum transmission power, which limit the coverage of each base station and then impact the number of base stations that spectrum users need to deploy in order to meet the coverage requirement. Additionally, spectrum entrants have to pay a significant spectrum licensing fee if they choose primary usage, while there is no charge for spectrum in unlicensed usage. In this dissertation, both capital expenditure (CAPEX) and operational expenditure (OPEX) that related to spectrum usage will be included. The main elements in the cost structure mode are [122, 123]:

- Investment in base stations (C_B)
- Investments in radio equipment (C_R)
- Investments in spectrum (C_S)
- Site leases (C_L)
- Maintenance and running cost (C_M)

The cost of establishing base stations (C_B) equals the number of base stations (N_B) that are needed for the target coverage multiplied by the cost of each base stations (C_b), as described in equation 6.21. The total number of base stations (N_B) equals the area of target coverage (CV_t) divided by the area that can be covered by each base station (CV_{bs}). In this dissertation, we assume the shape of the cell is circular. Therefore, if the radius of the base station is R_{bh}, the area is πR_{bh}^2.

$$\begin{aligned} C_B = \quad & N_B \times C_b \\ & \frac{\mathrm{CV}_t}{\pi R_{bh}^2} \times C_b \end{aligned} \tag{6.21}$$

The investment in radio equipment, C_R, included the investment in transmitters (C_{TR}) and sensors (C_{SE}) if applicable. The cost of transmitter (C_{TR}) equals the number of radio per base station (N_{rb}) multiplied by the number of base stations (N_B) multiplied by the cost per transmitter (C_{tr}). Sensor cost (C_{SE}) equals the number of sensors (N_{se}) multiplied by the cost per sensor (C_{se}). The number of sensors equals the target coverage area divided by the sensor density (D_{SE}). The costs of cognitive capability, data fusion center, and geolocation capability are evaluated per base station.

$$C_{TR} = N_{rb} \times N_B \times C_{tr} \tag{6.22}$$

$$C_{SE} = \frac{CV}{D_{SE}} \times C_{se} \tag{6.23}$$

$$C_{CC} = N_B \times m \tag{6.24}$$

Where, CC represent cognitive capability, data fusion center, and geolocation capability. m is the cost of cognitive capability, data fusion center, and gelocation capability per base station.

The cost for purchasing the right to access the spectrum (C_S) varies with spectrum sharing method. In primary usage, C_S is the bid if the spectrum entrant wins the spectrum auction. In cooperative spectrum sharing through trading, C_S is the spectrum leasing fee. In ASA, C_S is the ASA licensing fee. SUs in TVWS, ISM band, and CR based DSA do not have the cost of purchasing the right to access the spectrum.

The site lease (C_{SL}) is the cost for leasing the space for base stations per year. It is assumed that spectrum users with high transmission power need to lease a site for base

Table 6: Cost models for spectrum usage method

	C_B	C_S	C_R	C_{SL}	C_M
Primary Usage	Eq 6.21	Spectrum bid	Eq 6.22	Yes	Yes
Cooperative	Eq 6.21	Spectrum leasing fee	Eq 6.22	Yes	Yes
ASA	Eq 6.21	ASA licensing fee	Eq 6.22	Yes	Yes
TVWS	Eq 6.21	–	Eq 6.22 6.23	–	Yes
ISM	Eq 6.21	–	Eq 6.22	–	Yes
CR based DSA	Eq 6.21	–	Eq 6.22 6.23 6.24	Depends	Yes

stations, while the site lease for low power transmitters can be ignored. Two types of the transmission power will be investigated for CR base DSA, so the site lease cost for it depends on the transmission power. The maintenance and running cost include the cost of maintaining equipment, base stations, and the cost of electricity. The parameters that applied in this dissertation is summarized in 7.2.2. Table 6 summarizes the cost model for each spectrum usage method.

6.4.2 REVENUE MODEL

Two types of revenue functions are applied in this dissertation. When the spectrum is reserved for SUs, such as in the primary usage and quasi-static sharing, the revenue is based on the number of channels that have been used by the end customers' service demand. That is, the revenue, R_i^r, for spectrum entrant i equals the unit revenue, U_{rc}, per channel per unit of time multiplied by the number of channels during time interval τ, $N_C(\tau)$, multiplied by the total number of unit of time. $N_C(\tau)$ is simulated based on PUs' and SU's traffic. The number of time units equals to the total operation duration (T) divided by time interval (τ). The number of channels that have been used in each time slot is simulated by a M/G/C queue model. Appendix C provides the validation of the simulation.

$$R_i^r = U_{rc} \times N_C(\tau) \times \frac{T}{\tau} \tag{6.25}$$

When spectrum entrant do not have reserved bandwidth, such as in dynamic sharing, their revenue is based on the throughput that they can support and the quantity of transmitted data. Therefore, the revenue, R_i^o, for spectrum entrant i equals to the unit revenue, U_{rt}, per bits multiplied by the quantity of transmitted data size (D_i^m). The unit revenue is determined by the lowest throughput throughout the day.

$$R_i^o = U_{rt} \times D_i^m \tag{6.26}$$

6.4.3 QUANTIFYING MITIGATION STRATEGIES

According to equation 3.3, the value of the option equals to the discounted value of the gain that achieved by the option, $H(X, Y, T) = e^{-rT} \int_Y^{\infty} (u - Y)\Psi(u, X, Y, T)du$. r is the annual discounted rate and is the same as the r in NPV approach. In the option of switch, expand, and acquire spectrum, Y is the cost of deploying new spectrum usage method. It is similar to the cost of each method. X is the revenue that spectrum users can gain by switching, expanding, and acquiring spectrum. The PDF, $\Psi(u, X, Y, T)$ in this case is the changes of demand. In this dissertation, only linear discrete increase and decrease will be tested. On the other hand, the options of lease spectrum and infrastructure only happens when demand decrease and the profits of providing services is less than leasing. In these cases, Y is the revenue that spectrum users can get from leasing spectrum and infrastructure. X is the value that spectrum users can gain by providing wireless services.

7.0 NUMERICAL RESULTS AND DISCUSSION

This chapter starts from executive summary that concludes the observations for all hypothesis. Then, section 7.2 provides the traffic model and all parameters that applied in the numerical analysis. The following two sections, section 7.3 and section 7.4, analyze the QoS and profits in detail. The last section, section 7.5 identifies risks according to spectrum entrants' requirement and the best spectrum usage method for distinctive incentives and limitations.

7.1 EXECUTIVE SUMMARY

This section summaries all observations and results directly related to research hypothesis.

7.1.1 QoS

Hypothesis 1: QoS levels and risks change in diverse situations:

- Different spectrum usage models
- Location: urban/rural
- Capacity requirement: time varying/constant

Section 7.3 supports Hypothesis 1 (H1). Expected QoS levels in terms of throughput are calculated for different spectrum sharing methods for both urban and rural areas. In addition, the best and worst cases of throughput are identified to show the impact of risk awareness.

In brief, spectrum entrants' throughput is largely dependent on PUs and competing SUs' usage. When PUs' usage increase, the expected throughput decreases dramatically. This brings a significant risk for SUs in CR based DSA. That is, PUs may transmit meaningless signals to deter SUs' usage, since PUs cannot benefit from CR based DSA. It further promotes cooperative spectrum sharing that is bilaterally negotiated between PUs and SUs. In this way, PUs have incentives to share their spectrum while SUs can have a higher QoS level. Additionally, the queueing models that use mean arrival rate to analyze the spectrum access opportunities cannot capture the real situations for frequency bands that have diurnal behaviors. The mean value analysis leads SUs to be over optimistic or over pessimistic about expected QoS level. Accurate anticipation is extremely important when SUs make their spectrum usage decision. Moreover, the throughput increase with the augment of number of operable channels. Noted here, the higher throughput does not necessarily lead to higher profits, since the cost for expanding the number of operable channels may outnumber the revenue.

Dynamic sharing is not the only method that has QoS risks. SUs in primary usage and quasi-static sharing also have QoS risks due to the license/leasing agreement availability. When the license/leasing agreement is not available, SUs do not have the permission to operate, the throughput is zero. It is even lower than the expected throughput for dynamic sharing. Several factors determine the availability of license/leasing agreement: (1) The availability of the license/leasing agreement from regulators' and PUs' perspective. For example, if the FCC does not start a spectrum auction, no spectrum license is available. (2) The competition in obtaining the license/leasing agreement. When the competition is high, the price of license/leasing agreement increases. It may decrease the probability for certain SUs to acquire the license/leasing agreement.

The QoS risks depends on the competition of spectrum access, as well as SUs' QoS requirement. Two types of requirement are applied in the numerical analysis: constant throughput requirement and time varying throughput requirement. Surveillance camera can be one application for the constant throughput requirement. In the time varying requirement, it is assume that spectrum entrants have high throughput requirement from 1 to 8 am, and low requirement in the rest of the day. Data backup and server upgrade can be candidate for this types of requirement. The results show that time varying requirement has lower risk, since the throughput requirement is opposite to PUs' arrival rate. In general, investigation of PUs' and competing SUs' behavior are essential. Heterogeneous spectrum usage lead to lower risks.

7.1.2 PROFITS

Hypothesis 2: Spectrum entrants have different expected profits and monetary risks under diverse situations:

- Different spectrum usage methods
- Location: urban/rural
- Operation duration:short/long
- Profit requirement: urban/rural, large/small coverage

Section 7.4 provides results for Hypothesis 2 (H2) in the research questions. Profits are calculated for each spectrum usage method in both urban and rural area. The figures in section 7.4 only provide the profits in the 10th year. The detailed profits for each year can be found in Appendix C. The profits are calculated for best cases (risk unawareness), worst case (risk awareness), and risk with mitigation strategies. In addition both constant traffic and time varying model are considered.

In summary, the rank of cost in both urban and rural area is: primary usage, cooperative sharing through trading, CR based DSA, ASA, TVWS, and unlicensed usage in ISM bands. Spectrum cost in primary usage and cooperative sharing through trading is the factor that leads to the highest cost. There are two advantage of cooperative sharing through trading over primary usage. First, SUs in cooperative sharing through trading only pays the license fee for target coverage and transmission duration, whereas PUs pay the entire geographic area and operation duration that listed under a license even if they do not provide services in certain places and times. Second, cooperative sharing through trading requires less upfront cost which lowers the market entry barrier for SUs. In addition, primary usage and cooperative sharing in rural area requires less cost than urban area due to less spectrum cost. CR based DSA has the third highest cost, due to the expense of sensors, programmable transmitters, and the data fusion center. ASA has higher infrastructure based costs than primary usage and cooperative sharing through trading, since the frequency bands for ASA are assumed to be at 1700 MHz while primary usage and cooperative sharing through trading are at 700 MHz. The higher the frequency, the lower the coverage per base station, and then the more base stations are required to cover the same geographic area. Unlicensed usage and TVWS have similar costs. SUs in ISM bands do not have expense on geolocation capability. However, the radius for SUs in the ISM bands is less than TVWS, therefore, more base stations are required.

When considering revenue and profits, there is no static rank in all cases, since the revenue and profits change in different situations such as locations and risk awareness. Several observations can be made. First, primary usage and quasi-static sharing provides higher revenue than dynamic sharing. However, higher revenue may not lead to higher profits. Primary usage and cooperative sharing through trading lead to negative profits in urban area due to the high spectrum cost, while several types of dynamic sharing provide positive profits in both best and worst cases. Second, ASA provides higher revenue than primary usage and cooperative sharing through trading, since it has larger number of base stations and then more service demand can be met. When considering the option to improve for primary usage and cooperative through trading by implementing more base stations, similar amount of revenue can be generated for these two spectrum usage methods. Third, two reasons lead to the low revenue of dynamic sharing. The first one is the pricing scheme. In dynamic sharing, there is no resource reservation, therefore, the pricing scheme is different from primary usage and quasi-static sharing. The second one is the expected throughput. For example, unlicensed usage in ISM bands provides positive profits in all cases since the spectrum can support all the demand in current setting. Whereas, the profits for TVWS and CR based DSA changes with locations and wireless traffic. Fourth, although rural area has less service demand than urban area, it may lead to higher profits due to less spectrum cost.

Moreover, two types of mitigation strategies are quantified. The first one copes with the situation when demand decreases or the revenue cannot justify the cost. In this case, spectrum users can lease the infrastructure and spectrum. When the same distribution is applied for leasing, the higher the spectrum entrant pays (including both spectrum cost and infrastructure related costs), the higher the value of mitigation strategies. The second type of mitigation strategy targets on situations when the current spectrum cannot meet the demand or extra spectrum can lead to higher profits. In this case, spectrum users have the option to improve, such as deploy more base stations, expand the number of operable channels, and switch to other spectrum usage method. In this dissertation, only improve by the same spectrum usage method is tested. It can be seen that significant amount of profits are generate for spectrum users by deploying more base stations. Noted here, it is essential to consider and quantify the value of mitigation strategy especially when the demand can hardly been foreseen.

Different profit requirements are applied to urban and rural area for large and small coverage. Here are some highlights: (1) ASA has no risks due to the low cost. (2) PUs and cooperative sharing have the highest risks in urban area due to the large spectrum cost. It is because the pricing strategy is based on data service and the wireless traffic is assumed to be data only. It further explains the phenomenon that PUs offload their traffic to unlicensed band. When considering revenue that generated by voice services, different results may be achieved. (3) There are less risks for PUs and cooperative sharing in rural area due to the lower profit requirement and spectrum cost. (4) TVWS has negative profits in the worst case and positive profits in the best case, which demonstrate the importance of considering competition in spectrum access.

7.1.3 SPECTRUM ENTRANTS' DECISIONS

Hypothesis 3: Spectrum entrants have different choices in diverse situations:

- Location: urban/rural
- Operation duration:short/long
- Capacity requirement: time varying/constant
- Profit requirement: urban/rural, large/small coverage
- Risk awareness
- distinct decision criteria: profit maximization; risk minimization; mixed decision criteria.

Section 7.5 addresses the Hypothesis 3 (H3). In which, Spectrum entrants have different decision criteria (profit maximization, QoS risk minimization, and mixed strategies). Moreover, different risk awareness and capacity requirement are applied to both urban and rural areas.

Based on the current assumption, the rank changes dramatically with decision criteria. In particular, ASA provides the best results among primary usage and quasi-static sharing due to the lack of spectrum cost. It followed by trading and primary usage. Trading outperforms primary usage since the spectrum cost is not an upfront cost and the time factor decreases the total cost. However, primary usage has less risk than trading as long as the license is obtained. SUs in trading need to get leasing agreement periodically. In dynamic sharing, unlicensed usage in the ISM band provides the best results, due to the high expected throughput. It further explains the popularity of the ISM band. The drawback for CR based DSA is that the cost is high for sensing, programmable transmitters, and data fusion centers. The drawback for TVWS is that the throughput maybe low. In CR based DSA and unlicensed usage in ISM bands, the same traffic is applied to PUs and competing SUs, however the expected throughput change significantly. It is because PUs have higher priority in CR based DSA.

Best choices under different decision criteria are list as follows: (1) ASA is the best choice in profit maximization; (2) Unlicensed usage in ISM band is the best choice in QoS risk minimization. The rank of primary usage, quasi-static sharing, and dynamic sharing depends on the availability of the license/contract. (3) Unlicensed usage in ISM band outperform in mixed strategy as well. Following three paragraphs analyze results for each decision criteria.

Observations from table 12 for spectrum entrants that seek profit maximization: (1) Under the current assumption, cost determines the rank. The higher the cost, the lower the rank. Therefore, ASA provides the highest profits for all three cases due to the exemption of spectrum cost. (2) In urban area large coverage, the rank stays the same for all three decision criteria. In the best case scenario, the first four strategies (ASA,unlicensed usage in ISM bands,TVWS,CR based DSA) provide positive profits; in the worst case scenario, the first two strategies (ASA,unlicensed usage in ISM bands) provide positive profits; when considering risks and mitigation, the first three strategies (ASA,unlicensed usage in ISM bands,TVWS) provide positive profits. (3) In urban area small coverage, TVWS is slightly better than unlicensed usage in the ISM band in the best case scenario and when considering risks with mitigation strategies, since the total cost for ISM is higher than in the TVWS (the coverage radius is smaller for unlicensed users in the ISM than ones in the TVWS, which leads to more base stations and then higher cost). However, TVWS provides negative profits in the worst case, due to the extremely low throughput. (4) In rural area large coverage, CR based DSA leads to negative profits in all cases and TVWS leads to negative profits in the worst case. Among spectrum sharing methods that bring positive profits, the less the cost, the higher the rank. (5) In rural area small coverage, besides CR based DSA and TVWS, primary usage leads to negative profits in the worst case and when considering risks with mitigation. Unlicensed usage in the ISM bands is less profitable than cooperative sharing through trading due to the different pricing schemes.

Observations from table 12 for SUs that seek QoS risk minimization: (1) ISM has the lowest risks in QoS. (2) In urban area, primary and quasi-static sharing has larger risks than dynamic sharing, since PUs' usage may be high and the competition in getting the license and leasing agreement is intense. (3) In rural area, PUs' usage decreases and the competition in getting license and leasing agreement is not intense, therefore, primary and quasi-static sharing has lower risks than CR based DSA and TVWS.

Observations from table 12 for SUs that apply mixed strategies: (1) In the urban area, the first three choices for SUs are: unlicensed usage in the ISM bands, TVWS, and ASA. Primary usage and cooperative sharing through trading are the least preferred methods due to the low possibility in getting the license/leasing agreement, and the negative profits. They will rank higher than TVWS if the license and the leasing agreement are always available. (2) In rural area, unlicensed usage in the ISM bands are always preferred. It is followed by primary usage and quasi-static sharing. It is because that these four methods does not have monetary risks, while TVWS and CR based DSA have. Moreover, TVWS and CR based DSA also have QoS risks. In other words, in area that the probability of getting a license is high and the license is not very expensive, transmitting in an exclusive way is preferred. The reason that unlicensed usage in ISM bands ranks high is because there is no QoS risks in the current assumption. However, with the intensive usage such as mobile offloading , SUs in the ISM bands has potential QoS risks.

Analysis of factors that affect spectrum entrants' decision: (1) Traffic parameters: the best spectrum usage method is determined for broadband service which is assumed to have time-varying wireless traffic. In the sensitivity analysis, service with constant wireless traffic is determined as well. The QoS risks changes dramatically, however the decision remain the same under the current setting. (2) QoS requirements: when spectrum entrants' wireless traffic requirement is opposite to PUs' and competing SUs' traffic, their QoS risks reduce dramatically. It further promotes spectrum sharing among heterogeneous applications. (3) Operation duration: Appendix C provides cost and revenue for the entire ten years. It is clear that if SUs only want to provide services for less than one year, neither spectrum sharing method can provide positive profits. In other words, infrastructure based spectrum sharing method is not preferred for short-time, also called event based, services. For spectrum entrants that seeks to provide event based services, Mobile Virtual Network Operators (MVNOs) may be the best choice. (4) Budget limitation: companies with stringent budget limitation prefer options such as ASA, TVWS and ISM. Primary usage is the one that requires the highest upfront cost. Cooperative spectrum sharing through trading requires recurrent spectrum cost.

7.2 TRAFFIC MODELS AND PARAMETERS

7.2.1 TRAFFIC MODELS

As mentioned above, different spectrum usage methods pose various levels of risks for spectrum entrants. Therefore, two types of traffic model are investigated: time invariant traffic and the duty cycle model proposed by [56].

7.2.1.1 Time invariant In the time invariant traffic model, the arrival rate is a constant value A. The time invariant traffic for spectrum user, i, λ_i^s is expressed as,

$$\lambda_i^s(t) = A \tag{7.1}$$

7.2.1.2 Duty cycle model In duty cycle model, the arrival rate changes with time. [56] models the duty cycle of spectrum usage and validate with measurement. Duty cycle, $\Psi(t)$, is the utilization in percentage. Therefore, the arrival rate, λ_i^d, is expressed as utilization times the maximum arrival rate (A_{max}),

$$\lambda_i^d(t) = \Psi(t) \times A_{max} \tag{7.2}$$

$\Psi(t)$ is approximated by following equations, where $\Psi_{min} = \min \Psi(t)$ and $\overline{\Psi}$ is the average of $\Psi(t)$.

$$\Psi(t) \approx \Psi_{min} + \frac{2T(\overline{\Psi} - \Psi_{min})}{\Sigma\sqrt{\pi}} \times \frac{f_{exp}^{l/m}(t, \tau_m, \sigma)}{f_{erf}^{l/m}(T, \tau_m, \sigma)} \tag{7.3}$$

where $\overline{\Psi} \geq \Psi_{min}$ and:

$$f_{exp}^{l/m}(t, \tau_m, \sigma) = \sum_{m=0}^{M-1} e^{-(\frac{t-\tau_m}{\sigma})^2} \tag{7.4}$$

$$f_{erf}^{l/m}(T, \tau_m, \sigma) = \sum_{m=0}^{M-1} [erf(\frac{\tau_m}{t}) + erf(\frac{T-\tau_m}{\sigma})] \tag{7.5}$$

Parameters that applied to model weekday and weekend traffic are summarized in table 7, specified in "(minimum; average; maximum)" format. Figure1 shows static traffic and duty cycle model with average parameters. The urban area adopts the weekday traffic, and the rural area adopts the weekends traffic, since it is assumed that rural area has less traffic than urban area.

The duty cycle model only provides the percentage of utilization, therefore when calculating the throughput, the maximum acceptable arrival rate, service rates and capacity needs to be determined. It is assumed that the system capacity (C) is 11 in all cases. The service rate is 10^6 bits per second. Each packet contains 1500 bits, therefore the service rate (μ) is $10^6/1500$ packets per second. The service rate for TV broadcasters is 0.5 per hour. When PUs are TV broadcasters, the maximum arrival rate is 0.1 per hour. When PUs are other service providers, the maximum arrival rate is 300 packets per second. In the unlicensed band, the maximum arrival for competing SUs are 300 packets per second. The maximum arrival rate for the target spectrum entrant is 1 packet per second. Table 8 summaries all the parameters that are needed for QoS analysis.

Table 7: Parameter for duty cycle model

Model	Parameter	Weekday	Weekday
Duty Cycle	$\overline{\Psi}$	0.45	0.2
	$\overline{\Psi}_{min}$	(0.00;0.04;0.31)	(0.00;0.05;0.35)
	τ_0	(-6.20;-5.01;-3.91)	(-4.72;-3.58;-2.46)
	τ_1	(10.74;11.65;12.28)	(12.04;13.03;14.05)
	τ_2	(17.80;18.99;20.09)	(19.28;20.42;21.54)
	σ	(3.00;3.88;4.31)	(2.49;3.59;5.83)
	T	24	

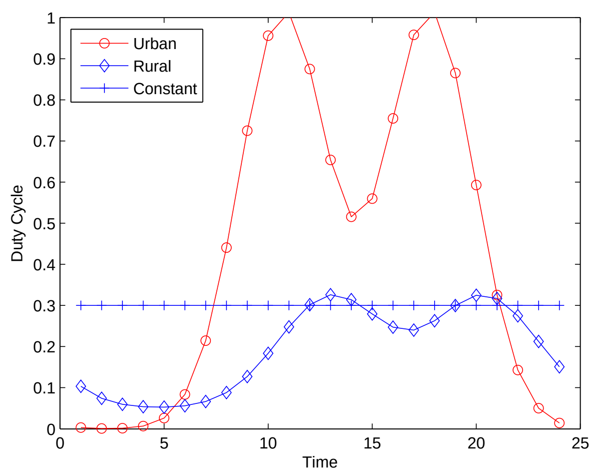


Figure 1: Spectrum users' traffic models

Table 8: Traffic Parameters

Parameter	Value	Units
C	11	
μ	$10^6/1500$	packets per second
μ for TV broadcasters	0.5	program per hour
self A_{max}	1	packet per second
A_{max} for PUs in TVWS	0.1	program per hour
A_{max} for PUs in CR based DSA	300	packets per second
A_{max} for other SUs in ISM band	300	packets per second

7.2.2 PARAMETERS

7.2.2.1 PARAMETERS FOR URBAN AND RURAL AREAS Different parameters are assumed for analyzing urban and rural areas. According to the spectrum auction results from Auction 73 700 MHz Band Block A (698-704 / 728-734 MHz), the winning bid for urban is much higher than the one for rural area. In this dissertation, we choose winning bids for Atlanta GA-AL-NG Economic Area ($103388000) to represent the spectrum price for urban, and the winning bid for Albany GA Economic Area ($647000) to represent the spectrum price for rural area.

According to the census statistics, Atlanta, GA [1] has an area of $342.9Km^2$ and Albany, GA [2] has a area of $144.7Km^2$. For the sake of simplicity, it is consider that the large coverage at urban area is $350Km^2$ and the large coverage at the rural area is $150Km^2$. The small coverage for both cases is $5Km^2$. Table 9 summarize all parameters that applied in this dissertation.

[1] http://www.atlantaga.gov

[2] http://www.albany.ga.us

Table 9: Parameters for urban and rural areas

Parameter	Urban	Rural
Spectrum price	\$1.03388e^8 per year	\$6.47e^5 per year
Coverage	350/5 Km^2	150/5 Km^2
Demand	weekday	weekend

7.2.2.2 PARAMETERS FOR COST AND REVENUE ANALYSIS The coverage of the base station is a factor that is difficult, if not impossible, to estimate. Meanwhile, it is important for estimating the cost. Several factors impact the coverage, including target data rate, path loss, noise, technologies, frequencies, etc. In this dissertation, it is assumed that the coverage per base station for primary usage and cooperative sharing through trading is 8.5 Km. The coverage per base station for ASA is 4 Km since the ASA is in the 3.5 GHz band, which is much higher than 700 MHz. The coverage per base station for TVWS and CR based DSA is 1 Km, while the coverage per base station for unlicensed usage in the ISM band is 0.5 Km [124]. The opportunity of implementing micro cell in primary usage and quasi-static usage will be studied through real options. Moreover, the coverage is calculated as a circle rather than hexagon for the sake of simplicity.

In primary and quasi-static usage, the service revenue is based on the utilization of the spectrum. The high unit revenue is \$0.09 per minute per channel. This number comes from the data usage of \$20 for 300 MB and assume the data rate is 1 mbps. The low unit revenue is \$0.009 per minute per channel in order to show the difference. Moreover, when calculating profits, it is assumed that FCC's spectrum license, spectrum leasing agreements, and ASA license are always available and the impact from bidding price on these availability are neglected. The license and leasing agreement availability is considered in he QoS risks. The revenue in dynamic sharing depends on QoS (throughput level) and the transmitted data size. Specifically, since the spectrum is not reserved for dynamic sharing, the throughput level may change dramatically. It is assumed that the unit price (\$ per bit) that service provider can charge is determined by the lowest throughput level in a day. The total revenue equals the unit price times the total transmitted data size. Table 10 summarize all the cost parameters that have been applying in this dissertation. Table 11 summarizes the unit price for dynamic sharing based on 1 Km^2 coverage. When coverage shrink to 0.5 Km^2, the unit price reduced to 25% or the listed ones.

7.3 QOS ANALYSIS OF DYNAMIC SHARING MODEL

7.3.1 EXPECTED THROUGHPUT

In primary usage and quasi-static sharing, it is assumed that the spectrum entrants can achieve their desired QoS level as long as they obtain the license/leasing agreement due to the resource reservation. However, in the dynamic sharing, there is no resource reservation, so spectrum entrants may experience different levels of QoS. The QoS in this dissertation is measured by throughput, and modeled by time varying preemptive resume M/G/C queue.

Three factors will be tested:(1) wireless traffic shape: constant and time varying; (2) other spectrum usage: PUs' usage and other competing SUs' usage; and (3) number of available channels.

Before digging into the detail, there are conclusions from analysis: (1) The assumption of constant arrival rate cannot depict the real situation when the traffic has a diurnal feature; (2) Spectrum entrants will experience severe service degradation if they cannot accurately predict PUs and other competing SUs' traffic; (3) the larger the number of available channels are, the higher the throughput. However, in order to operate on wide band, SUs may have extra cost. This will be analyzed in the real options model; (4) PUs' traffic determine the shape of throughput in TVWS and CR based DSA since they have the highest priority; (5) when the competition from both PUs and other SUs is low, high throughput can be achieved.

The two letters in the legend throughout this section indicates the wireless traffic shape. The first letter represents the traffic shape for the focused spectrum entrant (C for Constant, V for time Varying). The second letter represents the traffic shape for PUs or competing

Table 10: Cost and revenue parameters

Name	Parameters	Unit and Comments
Fixed Sensors	10	per km^2
Fixed Sensor Price	$300	per sensor
Fixed Sensor Installation Cost	$20	per sensor
Cost of Fusion Center	$160000	per 226.87Km^2
Cost of Cognitive Function in Base Station	$1000	per base station
Cost of Establishing a Base Station	$6000	
Electricity and Maintenance per month	$7	high power transmitter
Electricity and Maintenance per month	$1	sensor and low power transmitter
Maintenance of Cognitive Base Stations	$ 250	per base station per month
Maintenance of Base Station	$ 200	per base station per month
Base Station Rental Fees	$350	per base station site per month
Cost of Transmitter	$6000	high power transmitter
Cost of Transmitter	$300	low power transmitter
Transmitter per Base Station	3	high power transmitter
Transmitter per Base Station	1	low power transmitter
Unit Revenue per channel	$0.09/ $0.009	per minute per channel
Base station radium in 700 MHz high power	8.5	Km
Base station radium low power	1	Km
Base station radium in 2.5 GHz	0.5	Km
Base station radium in 1750 Hz higher power	4	Km

Table 11: Unit price for dynamic sharing

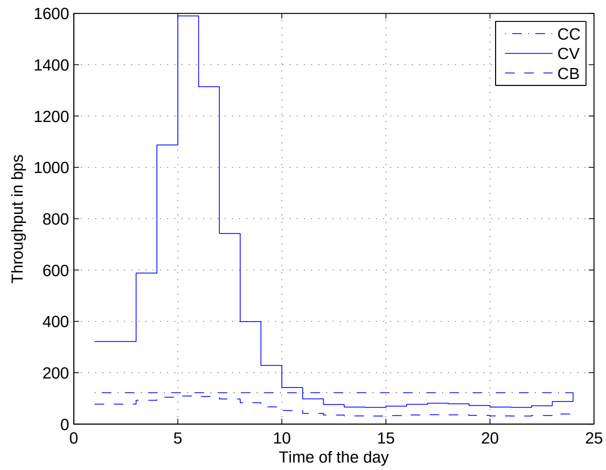
Throughput	Unit Price
< 50 bps	3.25×10^{-10} / bit / day / base station
< 100 bps	7×10^{-10} / bit / day / base station
< 500 bps	1.5×10^{-9} / bit / day / base station
< 1000 bps	5×10^{-9} / bit / day / base station
< 2000 bps	10^{-8} / bit / day / base station
< 5000 bps	5×10^{-8} / bit / day / base station
$< 10^6$ bps	9×10^{-8} / bit / day / base station

SUs (C for Constant, V for time Varying, and B for Both constant and time varying).

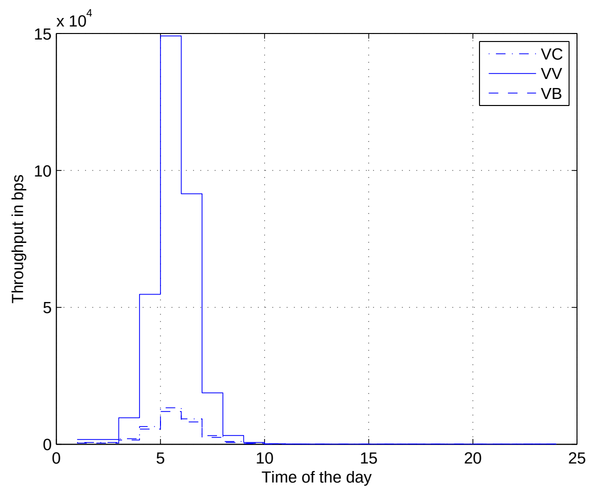
7.3.1.1 TVWS Figure2 provides the throughput for spectrum entrants in TVWS at urban area. Several observations can be made: (1) the throughput is higher in the dawn since PUs' usage is low; (2) VV has higher peak throughput, since both spectrum entrants and PUs ahve low arrival rate in the early morning; (3) it is clear that when PUs' usage is heavy, the throughput for spectrum entrants is low.

Figure3 shows the throughput for spectrum entrants in the TVWS at rural area. The peak throughput in rural case is lower than the urban area, it is due to the traffic shape. According to the duty cycle model, the minimum arrival rate for rural area is higher than urban area, although the peak and average arrival rate for rural area is much lower than urban area. In rural area, when spectrum entrants' traffic shape changes from time-varying to constant, the throughput level does not change significantly since PUs' usage is the dominant factor.

7.3.1.2 CR based DSA Figure4 provides the throughput for spectrum entrants in CR based DSA at urban area. Similar observations as the case for TVWS can be made. PUs'

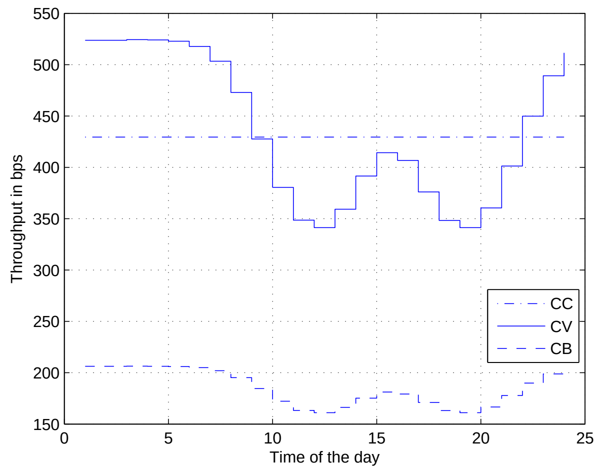


(a) Throughput of TVWS in urban area when spectrum entrants have constant arrival rate

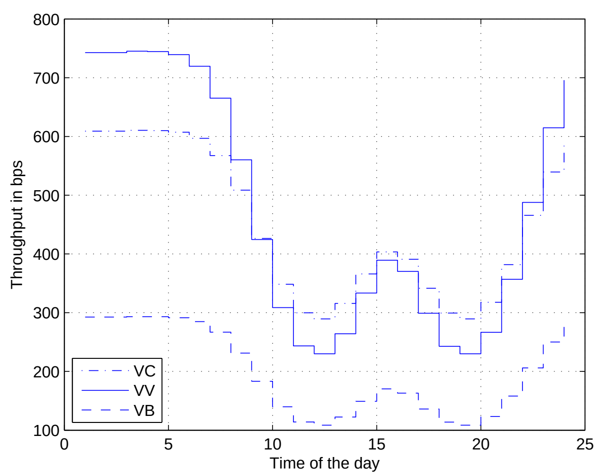


(b) Throughput of TVWS in urban area when spectrum entrants have time varying arrival rate

Figure 2: Throughput for TVWS in urban area



(a) Throughput of TVWS in rural area when spectrum entrants have constant arrival rate



(b) Throughput of TVWS in rural area when spectrum entrants have time varying arrival rate

Figure 3: Throughput for TVWS in rural area

usage dominates the shape of throughput. When PUs' traffic increases from V to B, the throughput decreases dramatically.

Figure5 provides the throughput for spectrum entrants in CR based DSA in rural area. Compare to Figure4, the minimum throughput in rural area is much higher, since the maximum utility in duty cycle for rural area is less the one in urban area.

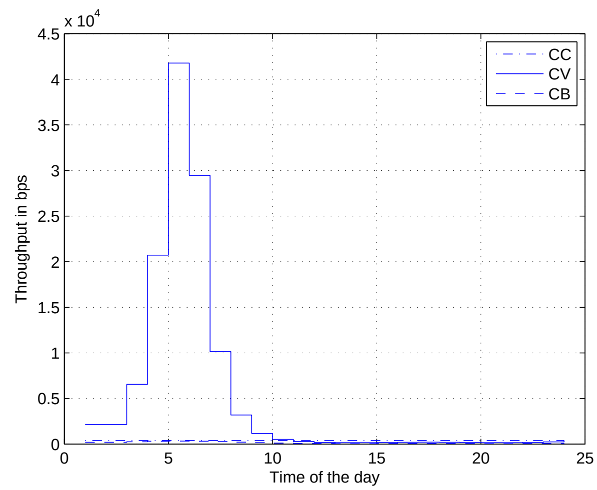
7.3.1.3 UNLICENSED USAGE IN ISM BANDS In this section, the throughput for spectrum entrants in the ISM bands are provided. Figure6 and Figure7 depict throughput for urban and rural area. According to the figure, the throughput is almost $10^6 bps$ throughout the day. It is because the service rate is larger than arrival rate. The throughput mainly depends on service time, which is the transmission time of packets.

The comparison of Figure6 and Figure7 with Figure4 and Figure5 shows that the throughput for target spectrum entrant in the ISM bands is much higher than the one in CR based DSA, although PUs in the CR based DSA and competing SUs in the ISM bands have the same traffic intensity and shape. It is because that spectrum entrants have lower priority in CR based DSA and their services can be preempted by PUs, while all spectrum entrants have the same priority in the ISM bands and served as FIFO.

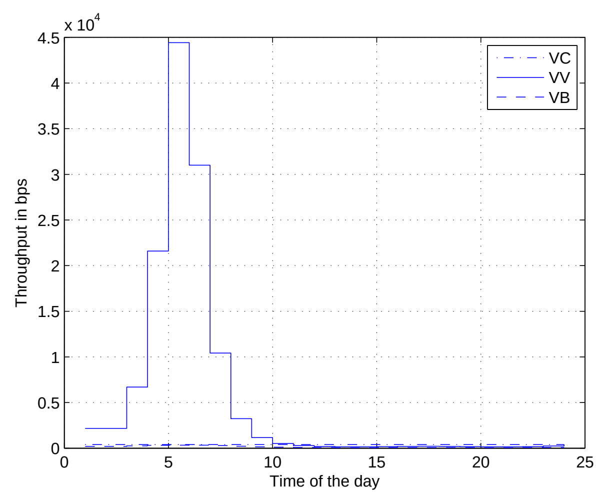
7.3.1.4 SENSITIVITY ANALYSIS Sensitivity analysis is important to show how the output can be affected by uncertainties. In this section, three sensitivity analysis will be conducted. The results will be compared with throughput for CR based DSA. The factors that will be tested include: capacity, competition among spectrum entrants, and PUs' arrival rate.

The first sensitive analysis focuses on capacity. In Figure8, the system capacity increases from 11 to 22 in the CR based DSA, the throughput increases dramatically. For example, the peak throughput increases from 44418.43 bps to 85099.71 bps. Noted here, the increase of throughput does not necessarily lead to increment of profits. The profits depends on cost of increasing capacity, demand, and pricing schemes.

The second sensitivity analysis focuses on the competition among spectrum entrants in CR based DSA. In this case, the arrival rate for spectrum entrants doubled, however the

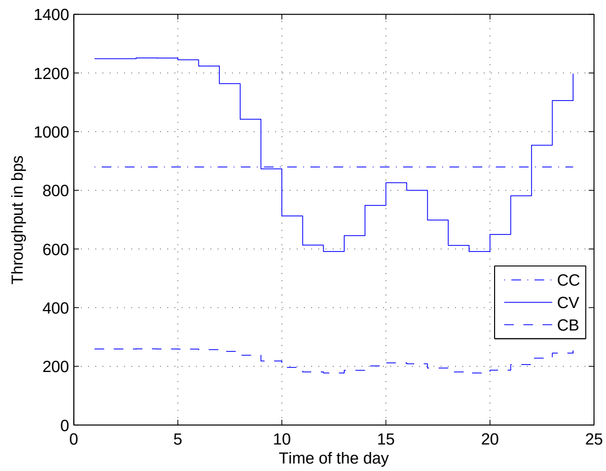


(a) Throughput of CR based DSA in urban area when spectrum entrants have constant arrival rate

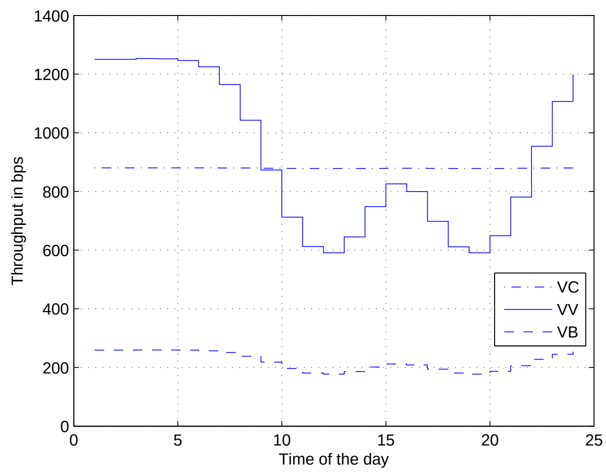


(b) Throughput of CR based DSA in urban area when spectrum entrants have time varying arrival rate

Figure 4: Throughput for CR based DSA in urban area

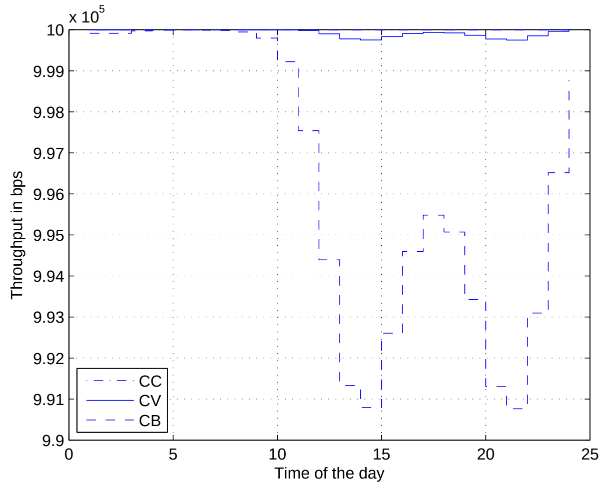


(a) Throughput of CR based DSA in rural area when spectrum entrants have constant arrival rate

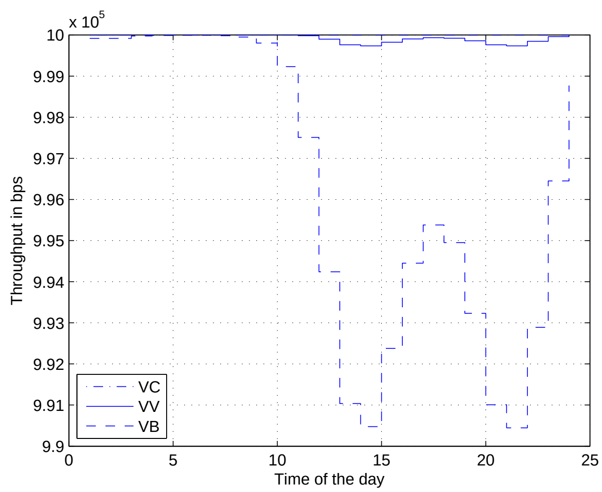


(b) Throughput of CR based DSA in rural area when spectrum entrants have time varying arrival rate

Figure 5: Throughput for CR based DSA in rural area

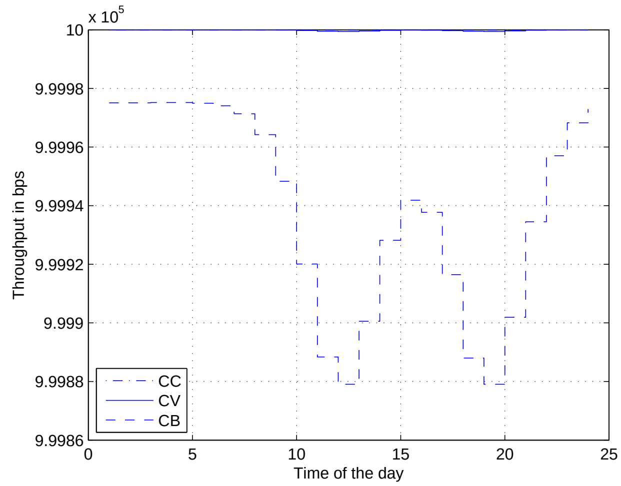


(a) Throughput of ISM in urban area when spectrum entrants have constant arrival rate

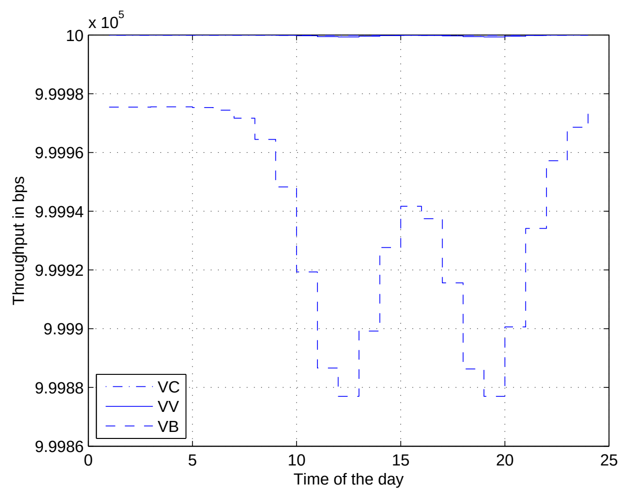


(b) Throughput of ISM in urban area when spectrum entrants have time varying arrival rate

Figure 6: Throughput for ISM in urban area



(a) Throughput of ISM in rural area when spectrum entrants have constant arrival rate



(b) Throughput of ISM in rural area when spectrum entrants have time varying arrival rate

Figure 7: Throughput for ISM in rural area

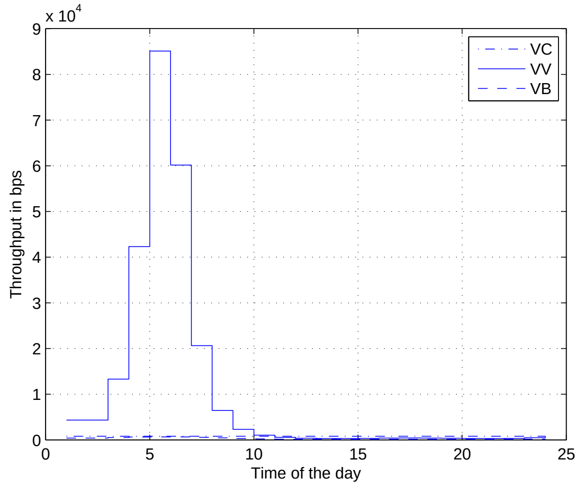


Figure 8: Throughput for CR based DSA in urban with time varying arrival with high number available channels

throughput does not decrease dramatically. The peak throughput decrease from 44418.43 bps to 44137.42 bps. Several reasons lead to this conclusion: (1) this dissertation assumes that all spectrum entrants can coordinate with each other; (2) all spectrum entrants have the same priority, therefore they are served as FIFO. If spectrum entrants cannot coordinate with each other, they may experience extra interference and then service degradation.

The third sensitivity analysis focuses on PUs' arrival rate. In this analysis, the PUs' maximum arrival rate decrease from 300 packets per second to 150 packets per second. The peak throughput increases from 44418.43 bps to 155975 bps. It further shows that PUs' usage dominates the throughput.

7.3.2 QoS RISKs

QoS risks come from different factors in different spectrum sharing methods. In primary usage, spectrum license availability and the competition in the FCC spectrum auction determine the risks in QoS. In quasi-static sharing, spectrum leasing agreement and ASA license availability determines the risks in QoS. Moreover, the competition among spectrum entrants

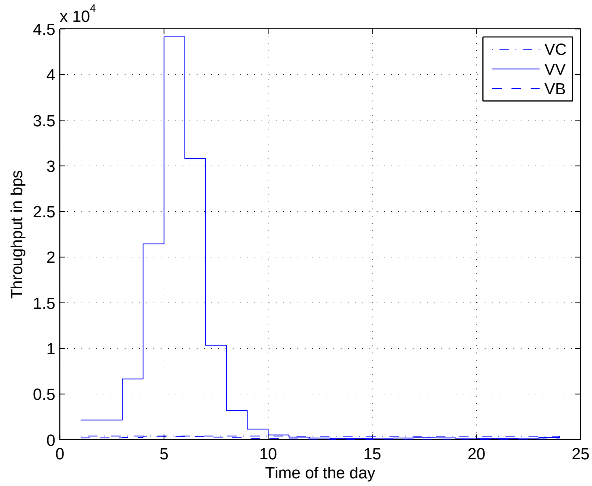


Figure 9: Throughput for CR based DSA in urban with time varying arrival with high competition

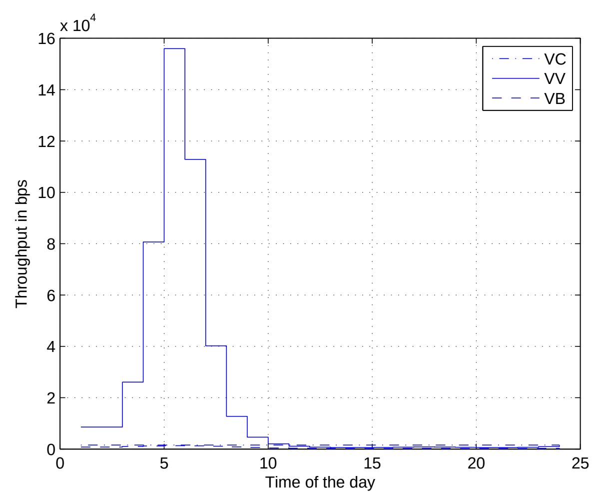


Figure 10: Throughput for CR based DSA in urban with time varying arrival with low PUs arrival

such as bidding in spectrum trading complicates the QoS risks. In dynamic sharing, the QoS risks result from PU and competing SUs' wireless traffic.

In this section, it is assumed that the minimum throughput requirement for dynamic sharing is 1 Kbps, and the risks are calculated by equation 6.1. Further, it is assume that the risks in getting spectrum license, spectrum leasing agreement, and ASA license in urban area is 0.9. In other words, the probability of getting the transmission permission is 0.1. The risks in getting spectrum license, spectrum leasing agreement, and ASA license in rural area is 0.1. Therefore, the probability of getting the transmission permission is 0.9. The parameters that set for urban and rural area aim at showing different levels of competition and license/spectrum availability in different region.

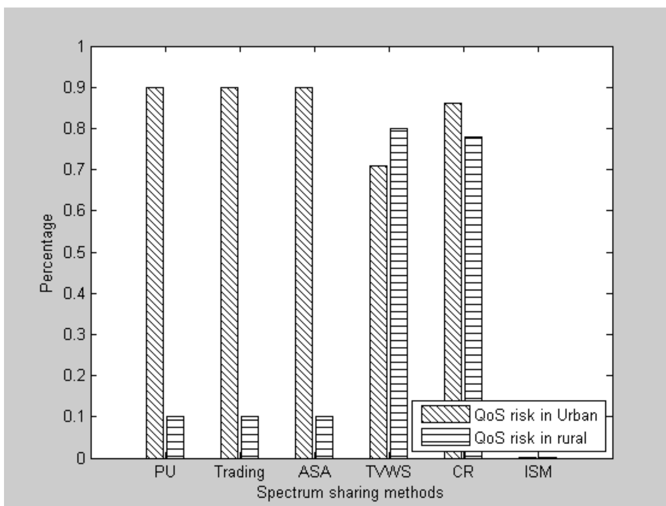


Figure 11: QoS risks with constant throughput requirement

From Figure11, it is clear unlicensed usage show the greatest potential when considering QoS in both urban and rural area. In urban area, dynamic sharing has lower risks than primary usage and quasi-static sharing. It also explains the popularity of the dynamic sharing in high population density region. In rural area, when the QoS risks in primary usage and quasi-static sharing decrease (the availability of spectrum license, leasing agreement, and ASA license increase), TVWS and CR based DSA are not attractive any more.

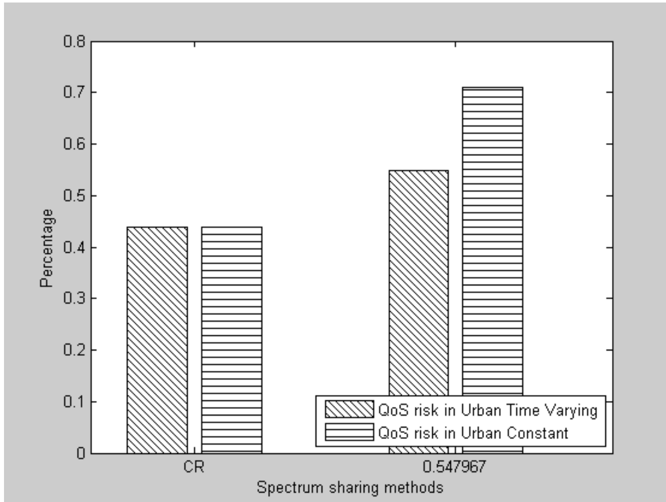


Figure 12: QoS risks with time varying throughput requirement

In Figure12, a different capacity requirement is applied. Instead of constant capacity requirement, the capacity requirement changes with time in this case. Specifically, the capacity requirement between 1-8 am is 1 kbps and 100 bps in the rest of the time. Only the results for CR based DSA and TVWS are shown here. Comparison of Figure12 and 11 shows that when spectrum entrants' QoS requirement can be adjust to the spectrum usage environment, the risks decreases.

7.4 MONETARY ANALYSIS OF EACH SPECTRUM USAGE MODEL

In this section, profits in different situations will be showed and factors that impact profits will be identified. The detailed cost, revenue, and profits are summarized in Appendix C. This section only shows representative figures. The profits shown in this section is the profit that spectrum entrants can get at the 10th year. Three types of profits are shown, best, worst, and risk. Best case in primary usage and quasi-static sharing is the profits that determined by high unit price. Best case in dynamic sharing is the case when maximum throughput is applied. On the contrary, the worst case in primary usage and quasi-static sharing is the profits that determined by low unit price. Worst case in dynamic sharing is the case considering PUs' and competing SUs' time-varying and constant behaviors. Profits under risk assume the probability of obtaining the revenue linearly decreases with the increase of the revenue.

Some conclusions can be made : (1) Spectrum cost is the dominant factor for the profits that spectrum entrants can get in primary usage and quasi-static sharing. (2) Low demand in rural area may not necessarily lead to low profits, due to the low spectrum cost. (3) when the spectrum cost and demand is uniformly distributed across the entire area, the larger the coverage, the higher the profits. However, if the spectrum cost and demand is not uniformly distributed, it may not be true. (4) When low unit price attracts the same amount of demand as large unit price does, low unit price brings lower profits. However, if the low unit price attracts higher demand, this conclusion may not stay the same. (5) Spectrum entrants that cannot precisely predict service demand may lead to either cannot meat the soaring demand or over investigate in infrastructure. However, they have mitigation strategies that will be analyzed in the real options model to remedy these situations. (6) Profits that gain under risk is between best and worst case.

7.4.1 EXPECTED PROFITS

7.4.1.1 PRIMARY USAGE Figure13 shows profits for primary usage in different scenarios. X-ticks represent combinations of area (U for urban, R for Rural)and coverage (L for Large, S for Small). Three bars in each case is the profit when high unit price, low unit price, and risks are applied.

Some observation can be made from Figure13: (1) All cases except rural area large coverage leads to negative profits. Noted here, although the wireless traffic in urban area is larger than in rural area, the total number of resource blocks that have been used is the same for urban area and rural area, due to the limitations of the infrastructure. SUs have the option to implement more infrastructures in order to meet all service demand and increase profits with higher expenses on infrastructure. This will be quantified in next section. (2) Small coverage is less profitable than large coverage, since SUs pay the same amount of spectrum cost even if they target on small coverage and it is assumed that the service demand is uniformly distributed across the entire region. In other words, the revenue in small coverage is much less than the one in large coverage. (3) Low unit price is less profitable than high unit price. It is because we assume that the demand is the same in low unit price and high unit price. In reality, the demand may change with the unit price. For example, the demand is higher when the unit price is low. If it is the case, the revenue for low unit price will increase.

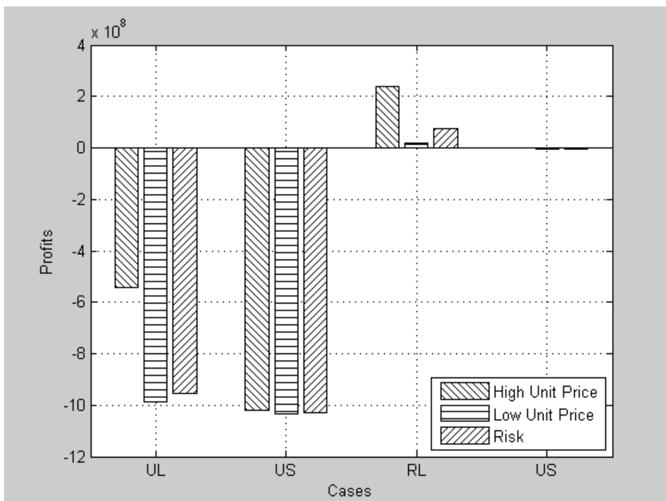


Figure 13: Profits of primary usage

7.4.1.2 COOPERATIVE THROUGH TRADING It is assumed that the average spectrum leasing price is uniformly distributed according time and geographic locations. In other words, the average unit spectrum leasing price equals total spectrum cost divided by license duration, which is 10 years in this case, and divided by the geographic coverage (350 Km^2 for urban area and 150 Km^2 for rural area). X-ticks in the figures represent combinations of area (U for urban, R for Rural), Coverage (L for Large, S for Small), and spectrum leasing charge (A for average).

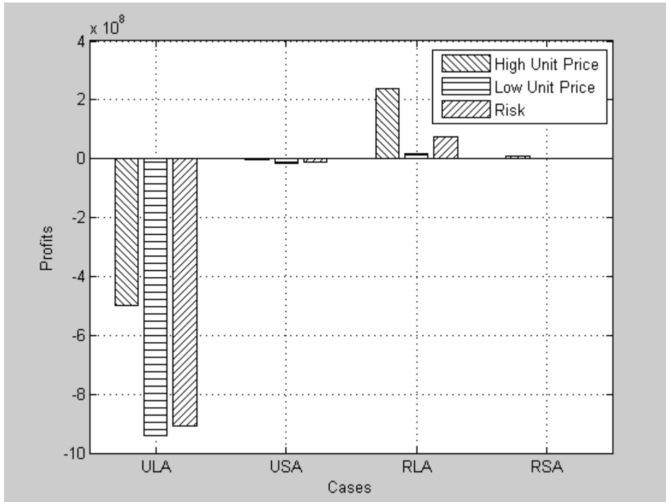


Figure 14: Profits of cooperative sharing through trading

Compare Figure13 with Figure14, it is clear that (1) When the average leasing price is applied, the profits in cooperative through trading is slightly higher than the ones in the primary usage, due to the time discount affect. Therefore, even if spectrum entrants will pay the full price of the spectrum, the time effect in trading provides benefit. However, this benefit is not come without cost. The risk associate with the discounted charge of spectrum is the spectrum leasing agreement availability. There is no guarantee that spectrum entrants can always find operable spectrum leasing agreement. (2) Cooperative sharing through trading provides higher profits in small coverage than primary usage. The reason for this phenomenon is that the spectrum charge that paid by spectrum entrants in this case only cover their demand area, instead of paying the spectrum cost for the entire licensed coverage.

7.4.1.3 ASA In the ASA usage model, there is no spectrum cost. Therefore, the cost of small coverage in urban is the same as the cost of small coverage in rural area. Moreover, it is assumed that the coverage for single base station shrank in ASA because the frequency is higher. Thus, the infrastructure cost in ASA is higher than the one in primary usage and cooperative sharing through trading. X-ticks in the figures represent combinations of area (U for urban, R for Rural) and Coverage (L for Large, S for Small).

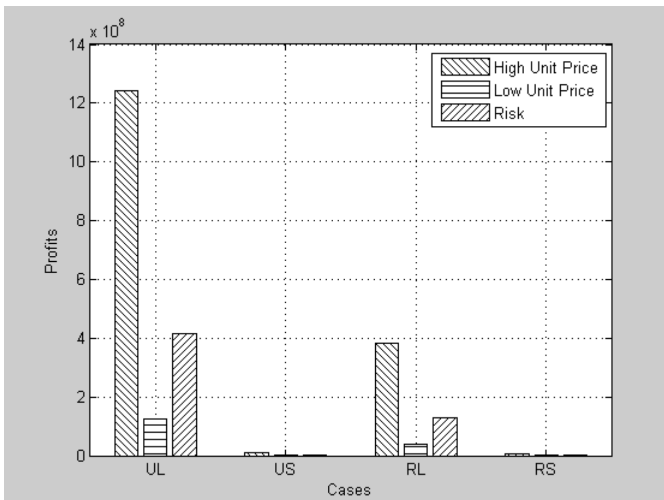


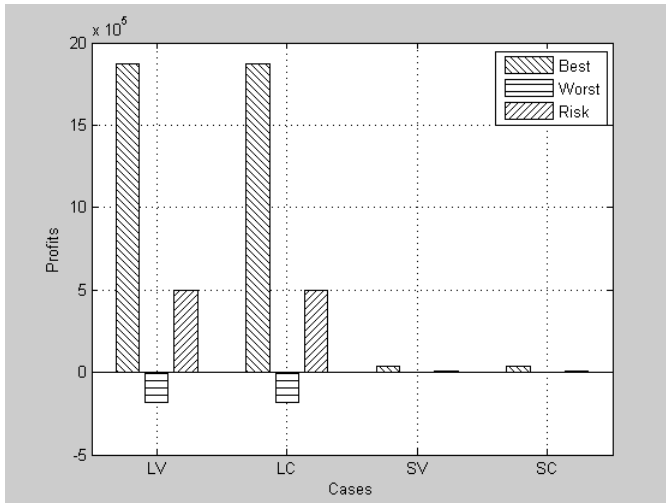
Figure 15: Profits of ASA

Compare Figure15 with Figure13 and Figure14, it can be seen that profits for large coverage in urban area is positive under ASA while it is negative in both primary usage and cooperative sharing through trading. It is because under ASA, there is no license fee. It also proves that license fee is the dominate factor in determining profits for primary usage and quasi-static sharing. It further indicates that spectrum sharing between federal and commercial usage can benefit spectrum entrants, especially when spectrum entrants can operate over large coverage with low spectrum cost.

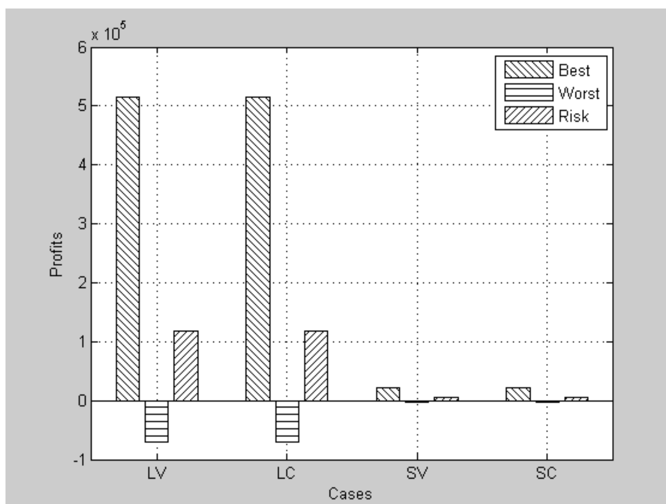
7.4.1.4 TVWS Figure16 shows profits for TVWS in both urban and rural area. Some observations can be made: (1) The expected profits in the best case for the same coverage in both constant and time varying case are the same, since it is assumed that throughput requirement can be met. Therefore, as long as the demand is the same, the profits is the same. The worst case does not necessarily lead to the same profits. Although they are the same in this case, when the pricing method and spectrum utilization change, it may not stay the same. (2) It can be seen that the profits in the best case scenarios are positive and all profits in worst case are negative. That means when worst case occurs, spectrum entrants will lose money. It further shows the importance of considering the risks. (3) The dominant cost factor for spectrum entrants in TVWS is the cost for transmitters and geolocation capabilities, which depends on the coverage. Therefore, the larger the coverage, the higher the cost. (4) Low profits in rural area is due to the less demand.

7.4.1.5 CR based DSA Figure17 shows profits for CR based DSA in both urban and rural areas. Compare the cases in TVWS, it is clear that CR based DSA is less profitable than TVWS, although the throughput in CR based DSA may not be lower than the one in TVWS. It is because the cost of establishing CR based DSA is much higher than the costs for building infrastructure in TVWS. Comparing different groups in Figure17, it can be seen that cases in rural area is less profitable than the one in urban area. Moreover, large coverage is more profitable than small coverage. It is because urban area has larger service demand. Furthermore, due to the assumption of uniform distribution of service demand, large coverage has higher service demand than small coverage.

7.4.1.6 UNLICENSED USAGE Figure18 shows profits for unlicensed usage in both urban and rural area. Some observations can be made: (1) Under the current setting, the 11 channels can meet the service demand in all occasions. It is because the service rate is higher than the arrival rate. Moreover, it is assumed that spectrum entrants can coordinate with each other. If it is not the case, spectrum entrants may experience higher interference and then decrease the throughput. (2) Compare with CR based DSA, the competing SUs have the same arrival rate and traffic shape as PUs in the CR based DSA. However, in

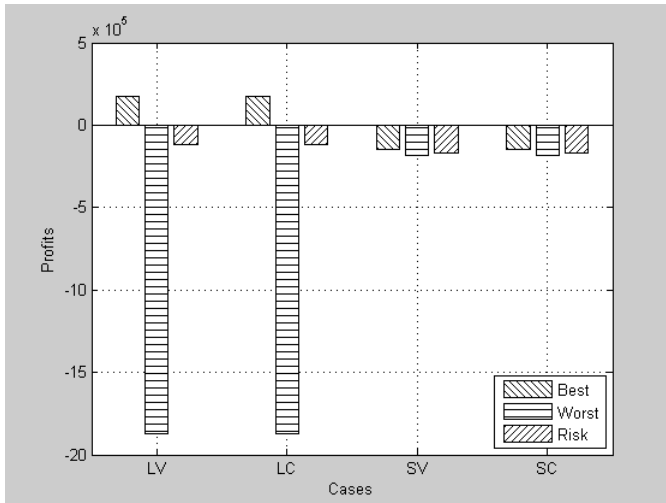


(a) Profits of TVWS in urban area

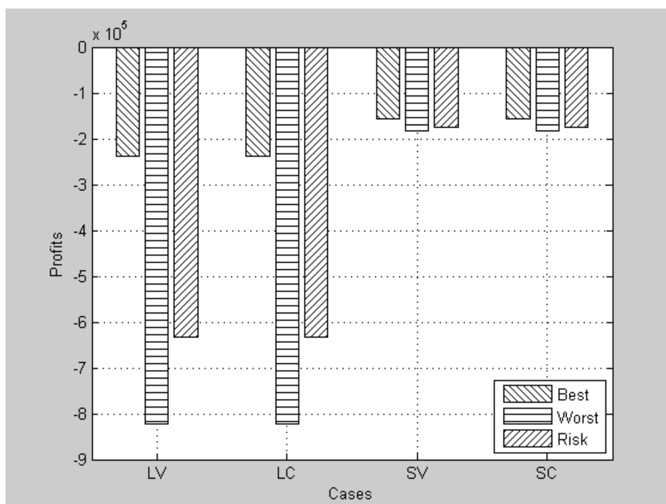


(b) Profits of TVWS in rural area

Figure 16: Profits of TVWS



(a) Profits of CR based DSA in urban area



(b) Profits of CR based DSA in rural area

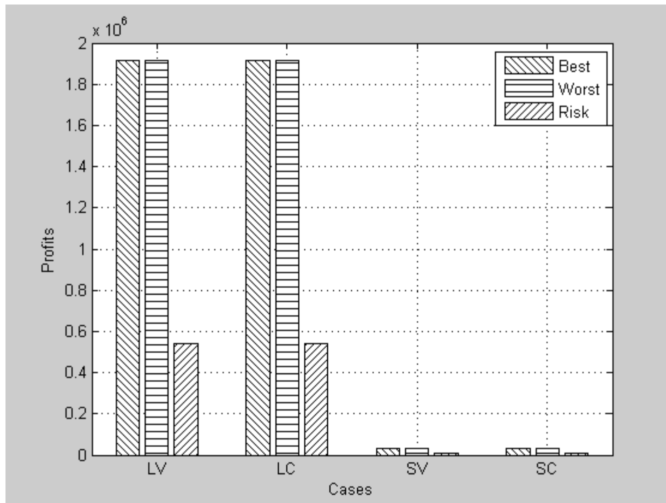
Figure 17: Profits of CR based DSA

unlicensed bands, all users have the same priority, therefore the throughput for focused spectrum entrant is much higher than in the previous case. Both best and worst case in urban area leads to positive profits. Both constant and time varying in urban area leads to positive profits. (3) Urban small coverage has significant less profits than large area due to the assumption of uniform distribution of demand. In reality, spectrum entrants with small area may have higher profits than large coverage since the demand in small area is intense and the demand in large coverage is not far more than in the small area, and the cost for covering larger area increase dramatically. It is also the case for rural area. All situations in the rural area lead to negative profits due to the low demand.

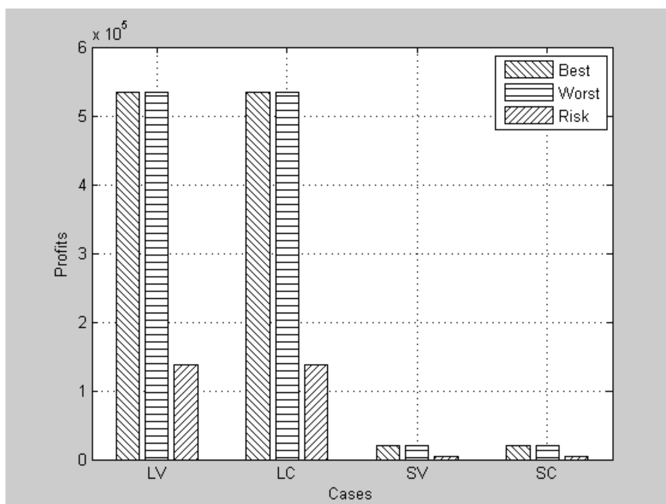
7.4.1.7 SENSITIVITY ANALYSIS The first sensitivity analysis focuses on spectrum leasing price. Spectrum leasing price does not stay the same for all occasions. For example, spectrum leasing price may increase when PUs' demand increase or the competition in getting spectrum leasing agreement is intense. The opposite situations may decrease the spectrum leasing price. In this dissertation, these two situations are tested by high and low unit price. The high unit spectrum leasing price is 1.5 times of the average unit leasing charges, and the low unit spectrum leasing price is 0.67 times of the average unit leasing charge.

Figure19 shows the situation when high leasing price is applied. The result for low leasing price can be found in Appendix C. It can be seen that high spectrum leasing charge leads to low profits than low spectrum leasing charge does. It is because the the demand and service charge are assumed to be the same. It is possible that spectrum entrants that are willing to pay high spectrum leasing charge have higher demand or service charge. In this way, their profits may be even higher than the spectrum entrants that get low spectrum leasing price.

The second sensitivity analysis focuses on ASA license availability. In Figure20 the ASA license availability decreases from 1 to 0.1. Comparison of Figure20 with Figure15 shows that the expected profits is much higher when the ASA license is always available than the ASA license is only available for 10% of the time.



(a) Profits of ISM in urban area



(b) Profits of ISM in rural area

Figure 18: Profits of ISM

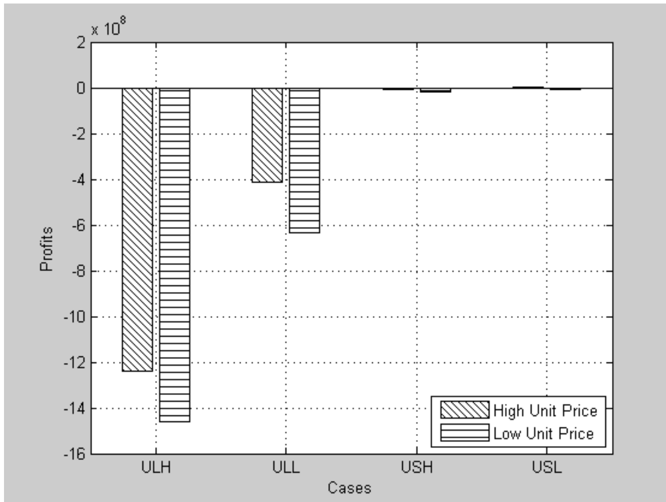


Figure 19: Profits of cooperative sharing through trading with different spectrum cost

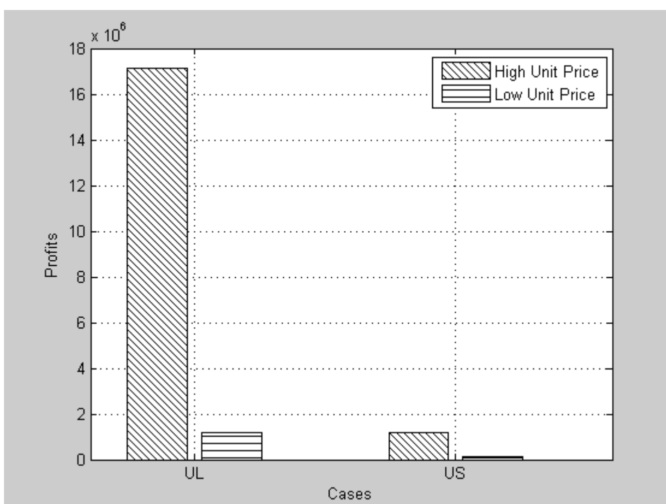


Figure 20: Profits of ASA with low ASA license availability

7.4.2 MONETARY RISKS

This section evaluates the monetary risks. Equation 6.4 is applied. The required profits, PR_i, varies with location and coverage. $\mathrm{PR}_i = 1000000$ for urban area large coverage, $\mathrm{PR}_i = 100000$ for urban area small coverage and rural area large coverage, $\mathrm{PR}_i = 10000$ for rural area small coverage.

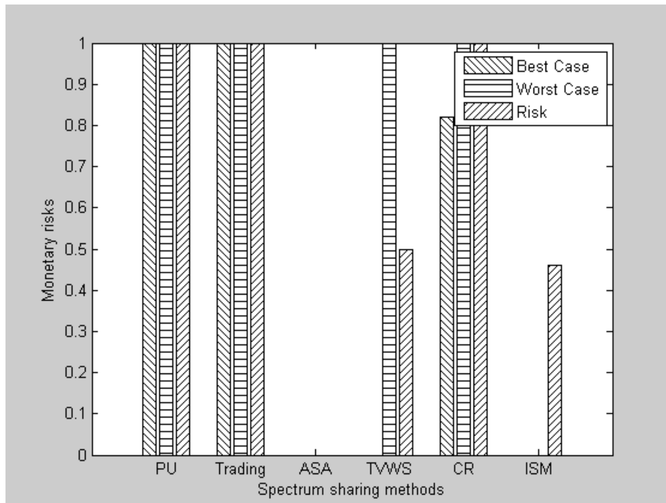
In Figure21 and 22, risks equals to 1 means the spectrum sharing method leads to negative profits, and risks equals to 0 means the expected profit is higher than the required one. From Figure21, it can be seen that (1) ASA does not have monetary risks in neither case. (2) Primary usage and cooperative sharing through trading lead to negative profits. (3) TVWS leads to negative profits in the worst case, while the best case brings positive profits. (4) CR based DSA is more risky than TVWS in the best cases, since the cost for CR based DSA is much higher than TVWS. (5) Unlicensed usage in the ISM bands does not have risks in the large coverage, but the risk is 0.70 in small coverage due to less service demand and different profits requirements.

The monetary risk changes significantly when the location switches from urban to rural. As depicted in Figure22, in rural area, (1) Primary usage and cooperative sharing through trading provides positive profits except primary usage in the worst case. It is because the spectrum cost in rural area is extremely less than the spectrum cost for urban area. (2) CR based DSA leads to negative profits in both large and small coverage due to less demand and high cost. (3) TVWS leads to negative profits in the worst case due to the low throughput and demand.

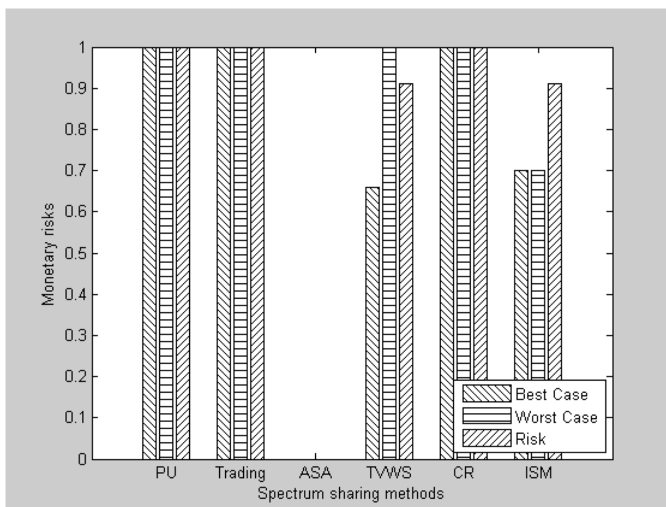
7.4.3 VALUE OF MITIGATION STRATEGIES

In this section, the value of mitigation strategies are quantified for lease (spectrum and infrastructure) and improve by the same sharing method.

7.4.3.1 OPTION OF LEASING The scenario for lease spectrum and infrastructure usually happens when service demand decrease and then profits decrease. From the results that shown below, it is clear that even if demand decrease that spectrum entrants' revenue

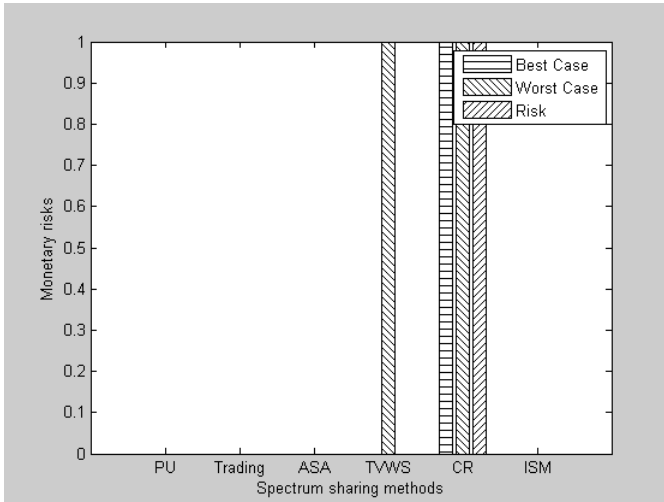


(a) Monetary risks for urban area large coverage

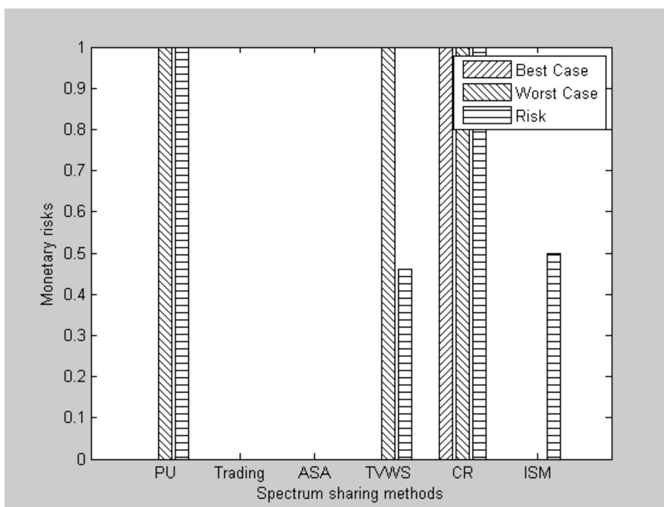


(b) Monetary risks for urban area small coverage

Figure 21: Monetary risks for urban area



(a) Monetary risks for rural area large coverage



(b) Monetary risks for rural area small coverage

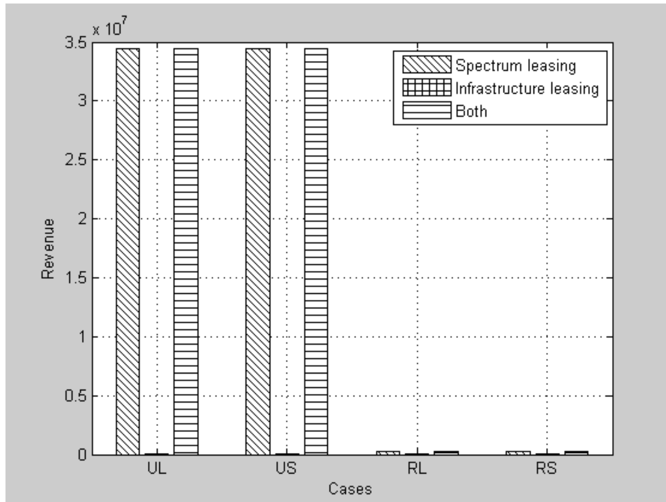
Figure 22: Monetary risks for rural area

that gain from providing wireless services is not in line with cost, it is not necessary that spectrum entrants will have negative profits. Lease spectrum and infrastructure may lead to a positive profits or reduce the loss. In this dissertation, it is assumed that only PUs have the opportunity to lease the spectrum. Spectrum entrants in cooperative through trading does not have the authority to sublease their spectrum. All spectrum users have the opportunity to lease their infrastructure. It is further assumed that the demand for leasing spectrum and infrastructure is a linearly decrease function with increased price, as described in equation 7.6:

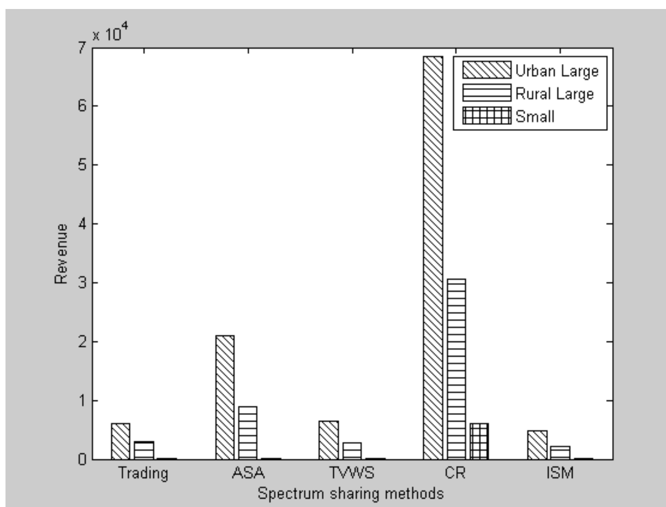
$$f = -2/m^2 \times x + 2/m; \tag{7.6}$$

where m is the maximum price that can be charged for lease spectrum and infrastructure. For spectrum leasing, m equals the spectrum cost per year (spectrum cost divided by ten). For infrastructure leasing, m equals the cost for establishing base stations, all equipment, and maintenance per year. When the competition in getting spectrum and infrastructure is high, maximum price may go beyond these points.

In Figure23b, only infrastructure lease for urban area large coverage (Urban Large), rural area large coverage (Rural Large), and small coverage (Small) are shown. It is because that the infrastructure leasing only depends on the cost of infrastructure. And the cost of infrastructure only depends on the coverage and base station radius in this model. In other words, the small coverage in rural and urban area have the same infrastructure cost, therefore, the leasing revenue is the same for both cases. Figure23a demonstrates this point. It is clear that spectrum leasing brings the largest leasing revenue, since the spectrum cost is much higher than the infrastructure cost in all cases. When compare the infrastructure leasing revenue, it can be seen that CR based DSA has the highest gain. It is because the infrastructure cost in CR based DSA is the highest one due to the large cost in sensors and fusion center. TVWS have higher cost than unlicensed usage due to the cost on geolocation capability. ASA has high infrastructure cost and then higher infrastructure leasing revenue than cooperative sharing through trading. It is because of the assumption that ASA operates on higher frequency bands. Thus, the coverage per base station is smaller and then more base stations are needed to cover the same area.



(a) Revenue for PUs to lease spectrum and infrastructure



(b) Revenue for lease infrastructure

Figure 23: Value of lease spectrum and infrastructure

7.4.3.2 OPTION OF IMPROVING

In the current setting, only ASA and unlicensed usage meet all service requirements. Therefore, improving the current infrastructure and then meet all service demand is the goal for spectrum entrants. Users in primary usage and cooperative sharing through trading can increase the number of base stations to meet service demand in urban and rural area large coverage. Spectrum entrants in TVWS does not have the capability to improve, since the only frequency bands they can use is the TVWS and the availability solely depends on PUs' usage. CR based DSA can improve the throughput by transmitting on a broader frequency bands with more sophisticated transmitters and sensors. Whether the higher number of operable frequency bands can lead to higher profits depends on the extra cost and revenue. In this section, equation 7.6 is applied to quantify the value of option to improving for primary usage, cooperative sharing through trading, and CR based DSA.

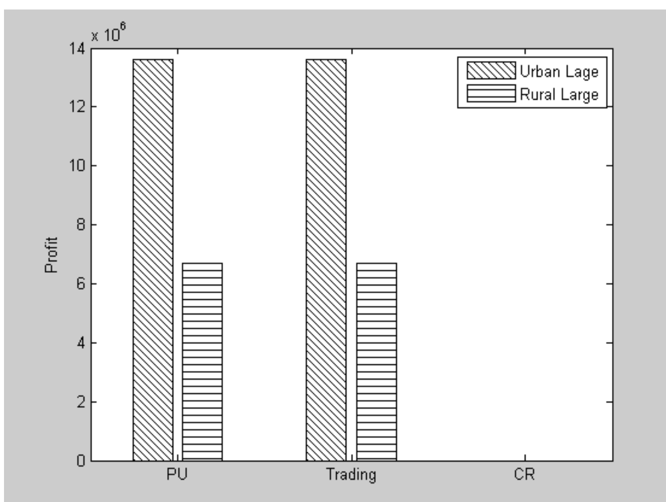


Figure 24: Value of options to improve

Figure24 shows the value of improve. Spectrum entrants in primary usage and cooperative sharing through trading generate positive revenue by establishing more base stations, since they can meet more service demand. However, spectrum entrants in CR based DSA cannot benefit from improving. The revenue that brought by extending operable channels from 11 to 22 cannot justify the cost. This situation may be changed when the cost of infrastructures decrease to a certain level, where SUs can have a desired throughput.

In short, spectrum entrants in dynamic sharing do not have much room to improve by their own spectrum sharing method, since the QoS level is determined by PUs and other SUs in the same band. However, spectrum entrants in dynamic sharing can improve by acquiring more spectrum through other spectrum sharing methods. For example, they can lease spectrum from PUs and become a ASA licensee while keep transmitting dynamically. Similar conclusion applies to quasi-static sharing. Spectrum entrants in cooperative sharing through trading and ASA face limitations when leasing agreement and ASA license are not available. Moreover, competition in getting the leasing agreement and ASA license is intense in profitable areas. When the leasing agreement and ASA license are not available or the frequency bands listed under leasing agreement and ASA license are not enough to support their service demands, spectrum entrants can investigate in TVWS in order to to acquire more spectrum and meet service demand. In summary, for a spectrum entrant that plans to provide continuous wireless service by sharing spectrum, it needs at least one spectrum sharing method from each (quasi-static and dynamic sharing) category.

7.4.3.3 PROFITS WITH RISKS AND MITIGATION STRATEGIES In section 7.4.1, profits are determined based on constant demand for both best and worst case scenarios. However, best and worst cases are not the only disciplines to evaluate the expected profits. When considering the dynamic in the market, service demand can be a decreasing function of the increased of price. In this dissertation, when risks in profits are considered, it is assumed that the probability of gaining a certain amount of revenue decreases with the increase of the amount of the revenue.

Besides the risks, as aforementioned in section 7.4.3, spectrum entrants have the opportunity to mitigate risks. In the current setting, only spectrum entrants in primary usage and cooperative sharing through trading have the possibility to increase the profit by deploying more base stations. Spectrum entrants in TVWS and CR based DSA cannot improve by their own method, however, they can switch to cooperative sharing through trading, primary usage, ASA, and unlicensed usage. The value of the right to switching is not explicitly quantified in the option, since the full analysis of each method is shown in 7.4.

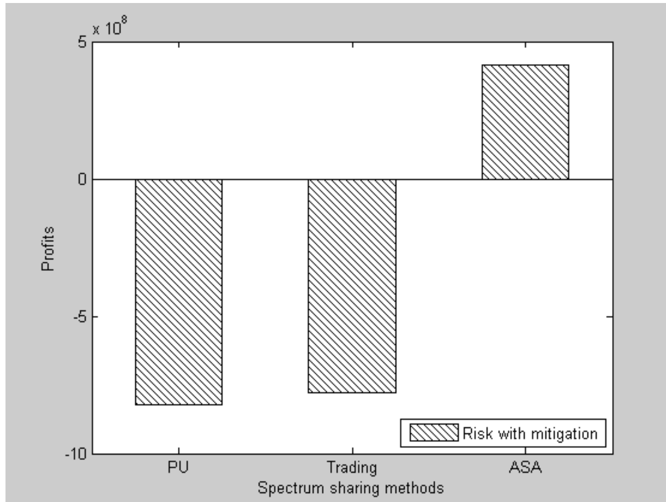
Figure25 26 27 and 28 shows the profits that each method leads to when considering risks and mitigation strategies. In summary, ASA still provide the highest profits in all cases. When considering risks and mitigation strategies, primary usage and cooperative sharing through trading has higher profits than even the best case scenario.

7.5 CASE STUDIES

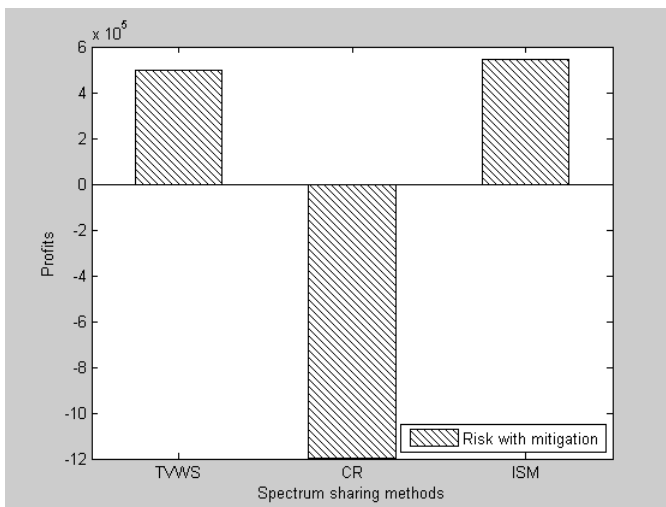
7.5.1 BROADBAND SERVICES

In this section, the target spectrum entrant aims at providing broadband services. Table 12 provides the rank for different combinations of location, coverage, and decision criteria. P represents primary usage, CT represents cooperative sharing through trading, A represents ASA, T represents TVWS, C represents CR based DSA, and I represents unlicensed usage in the ISM bands. Under Criteria column, B indicates profits in the best case scenario, W indicates profits in the worst case scenario, and R indicates profits considering risks and mitigation strategies. The numerical value is the weight for profits W_p that defined in section 6.1. Following four sections will illustrate the situation in each combination of location and coverage in detail.

7.5.1.1 URBAN AREA LARGE COVERAGE When the spectrum entrant aims at providing services in urban area for a large coverage, it is assumed that service provider will provide services to the entire geographic region that lists under the license. Other than directly purchasing licenses from the FCC, spectrum entrants can purchase spectrum leasing agreement from PUs and get ASA license that cover the entire region, or they can choose dynamic sharing to provide the services. If the spectrum entrant chooses to be a dynamic spectrum sharing user, it is assumed that it can perfectly sense PUs' usage and coordinate with other SUs. Perfect sensing does not necessarily requires spectrum entrant's transmitters

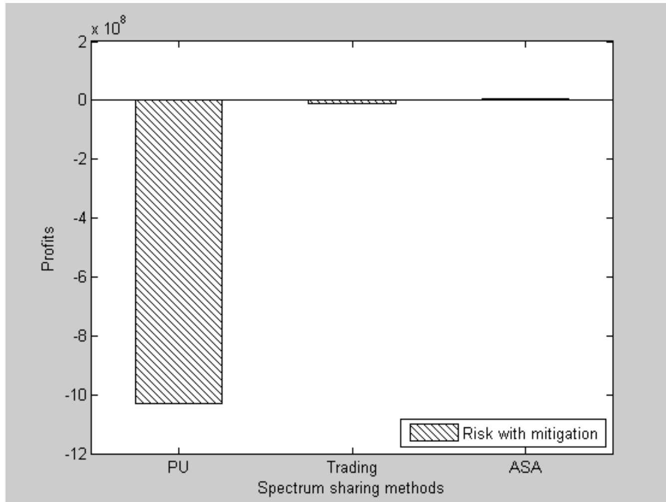


(a) Profits for primary usage and quasi-static sharing in urban area large coverage considering risks and mitigation strategies

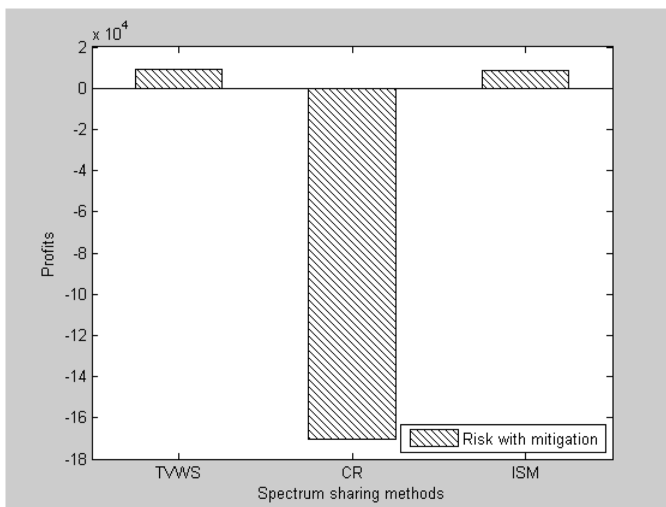


(b) Profits for dynamic sharing in urban area large coverage considering risks and mitigation strategies

Figure 25: Profits for urban area large coverage considering risks and mitigation strategies

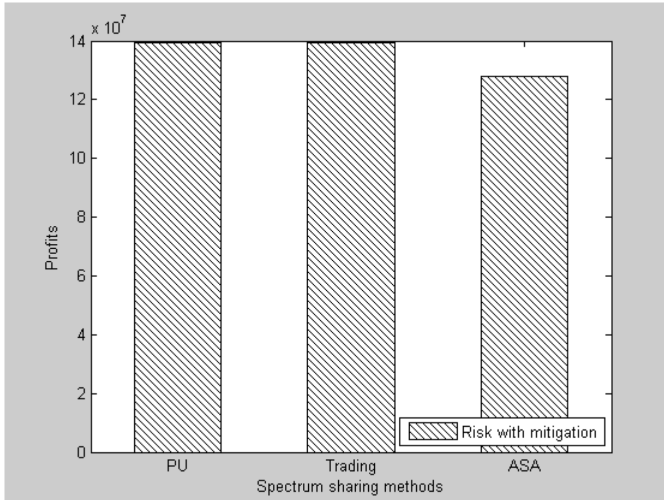


(a) Profits for primary usage and quasi-static sharing in urban area small coverage considering risks and mitigation strategies

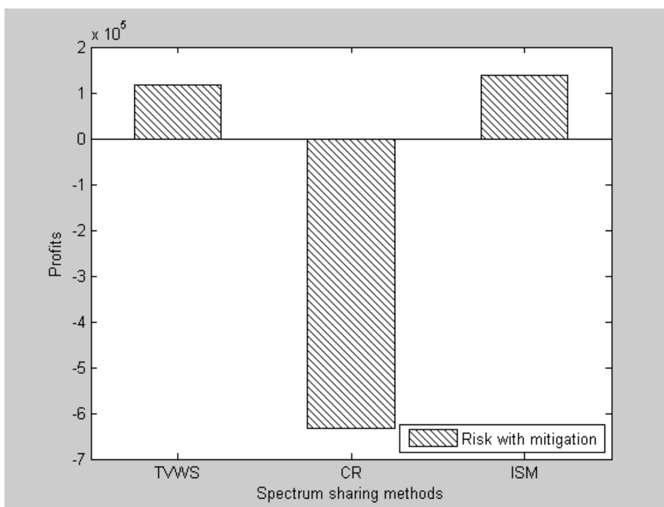


(b) Profits for dynamic sharing in urban area small coverage considering risks and mitigation strategies

Figure 26: Profits for urban area small coverage considering risks and mitigation strategies

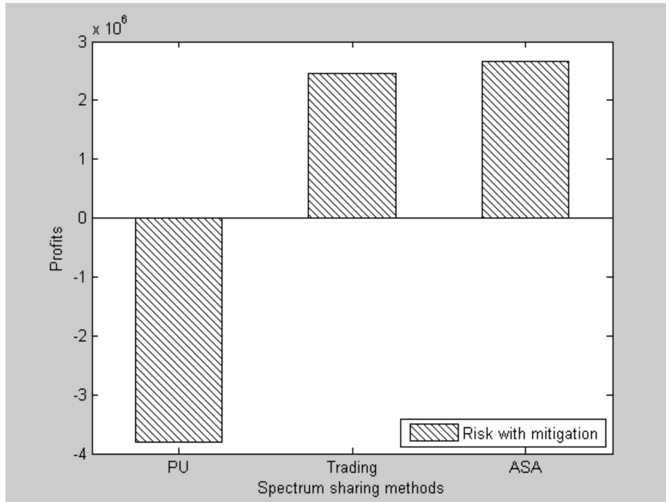


(a) Profits for primary usage and quasi-static sharing in rural area large coverage considering risks and mitigation strategies

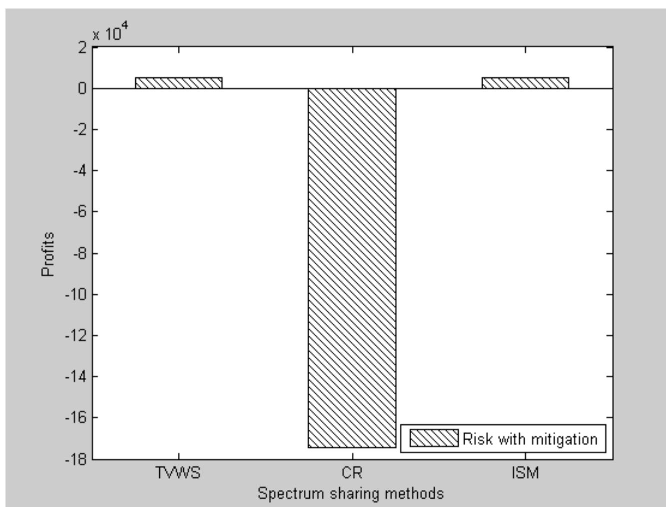


(b) Profits for dynamic sharing in rural area large coverage considering risks and mitigation strategies

Figure 27: Profits for rural area large coverage considering risks and mitigation strategies



(a) Profits for primary usage and quasi-static sharing in rural area small coverage considering risks and mitigation strategies



(b) Profits for dynamic sharing in rural area small coverage considering risks and mitigation strategies

Figure 28: Profits for rural area small coverage considering risks and mitigation strategies

Table 12: SUs' choices based on different decision criteria

Criteria	Urban Large	Urban Small	Rural Large	Rural Small
Profit Max (B)	$A > I > T > C > CT > P$	$A > T > I > C > CT > P$	$A > CT > P > I > T > C$	$A > CT > P > T > I > C$
Profit Max (W)	$A > I > T > C > CT > P$	$A > I > T > C > CT > P$	$A > CT > P > I > T > C$	$A > CT > I > T > C > P$
Profit Max (R)	$A > I > T > C > CT > P$	$A > T > I > C > CT > P$	$A > CT > P > I > T > C$	$A > CT > I > T > C > P$
QoS Risk Min	$I > T > C > P = CT = A$	$I > T > C > P = CT = A$	$I > P = CT = A > C > T$	$I > P = CT = A > C > T$
Mixed (0.5,B)	$I > T > A > C > P = CT$	$I > A > T > C > P = CT$	$I > P = CT = A > T > C$	$I > P = CT = A > T > C$
Mixed (0.5,W)	$I > T > A > C > P = CT$	$I > A > T > C > P = CT$	$I > P = CT = A > T > C$	$I > P = CT = A > C > T$
Mixed (0.3,B)	$I > T > A > C > P = CT$	$I > A > T > C > P = CT$	$I > P = CT = A > T > C$	$I > P = CT = A > T > C$
Mixed (0.3,W)	$I > A > T > C > P = CT$	$I > A > T > C > P = CT$	$I > P = CT = A > T > C$	$I > P = CT = A > C > T$
Mixed (0.7,B)	$I > T > A > C > P = CT$	$A > I > T > C > P = CT$	$I > P = CT = A > T > C$	$I > P = CT = A > T > C$
Mixed (0.7,W)	$I > A > T > C > P = CT$	$A > I > T > C > P = CT$	$I > P = CT = A > C > T$	$I > P = CT = A > C > T$

to be co-located with PUs' transmitters. Frequently checking the database for TVWS and locate sensors close to PUs' transmitters are other means to reduce interference with PUs. In TVWS and unlicensed usage in ISM bands, the transmission power cap limit the reach of each base station. It is possible that the end-to-end communication exceed the coverage of one base station, then a relay of the data by base stations will be scheduled.

In summary, observations from table 12 show that: (1) If the spectrum entrant seeks profit maximization, ASA is the best choice. The rank stays the same for all three decision criteria (best case, worst case, and risk with mitigation strategies). In the best case scenario, the first four strategies (A,I,T,C) provide positive profits; in the worst case scenario, the first two strategies (A,I) provide positive profits; when considering risks and mitigation strategies, the first three strategies (A,I,T) provide positive profits. Moreover, in the current assumption, cost determines the rank. The higher the cost, the lower the rank. (2) If the spectrum entrant seeks QoS risk minimization, unlicensed usage in the ISM bands is the best choice. Primary and quasi-static sharing have higher risks than dynamic sharing, since the competition in getting the license and leasing agreement in urban area is intense. (3) If the spectrum entrant considers mixed strategies with different weight, the first three choices for spectrum entrants are: unlicensed usage in the ISM bands, TVWS, and ASA. Primary usage and cooperative sharing through trading are the least preferred methods due to the low possibility in getting the license and leasing agreement and the negative profits. They will rank higher than TVWS if the license and the leasing agreement are always available.

7.5.1.2 URBAN AREA SMALL COVERAGE In this case, the target spectrum entrant plans to provide wireless service in urban area with a small coverage (5 Km^2). The majority of the application only need one hop (from access point or base station to user device). However, when end-to-end communications occur at the edge of the coverage, base stations may need to relay the data.

When the spectrum entrant only wants to provide services to small area, their infrastructure cost reduces dramatically. However, it is assumed that primary usage still requires the same amount of spectrum licensing fee as large coverage, since the spectrum license is issued based on large geographic area. Compared to primary usage, spectrum entrants in cooperative sharing through trading only pays spectrum cost for the target coverage and operation duration. It is assumed that PUs will divide the licensing fee linearly according to coverage and time. Therefore, the spectrum cost for small coverage in cooperative sharing through trading is much less than primary usage. In addition, it is assumed that the demand is proportion of the coverage. That means the less the coverage, the less the demand. Therefore, the revenue for small coverage is less than the revenue for large coverage. However, it may not be the case in the reality where small coverage has the highest population density. Moreover, with smaller coverage, the availability of spectrum leasing agreement, ASA license, and spectrum holes may changes, which is outside the scope of this dissertation.

In summary, observations from table 12 shows that: (1) If the spectrum entrant is profit maximizing, ASA is the best choice for all three cases. TVWS is slightly better than unlicensed usage in the ISM band in the best case scenario and when considering risks and mitigation strategies, since the total cost for unlicensed usage is higher than TVWS. However, TVWS provides negative profits in the worst case, due to the extremely low throughput. (2) ASA is preferred when the target spectrum entrant emphasizes on profits and unlicensed usage is preferred when QoS risks is the focus.

7.5.1.3 RURAL AREA LARGE COVERAGE There are several distinctions between large coverage in urban and rural area: (1) the spectrum license cost is less in rural area than in urban one; (2) according to the chosen spectrum auction, the geographic coverage in rural (150 Km^2) is smaller than urban (350 Km^2); (3) it is assumed that the demand in rural area is less than in urban, due to the less population density; (4) the availability of spectrum license, ASA license, spectrum leasing agreement, and spectrum hole is higher in rural than in urban due to the less competition.

In summary, observations from table 12 shows that: (1) If the spectrum entrant seeks profit maximization, ASA is the best choice followed by cooperative sharing through trading, primary usage, and then dynamic sharing. CR based DSA leads to negative profits in all cases and TVWS leads to negative profits in the worst case. Among spectrum sharing methods that bring positive profits, the less the cost, the higher the rank. (2) If the spectrum entrant aims at minimize QoS risks, unlicensed usage in the ISM bands is the best choice followed by primary usage quasi-static sharing and then other two methods in dynamic sharing. It is because the QoS risks in primary usage and quasi-static sharing is low in rural area due to less competition in getting license/leasing agreement. As long as spectrum entrants have the transmission permission in primary usage and quasi-static sharing, they have the reservation of the spectrum which lead to higher throughput than CR based DSA and TVWS. (3) If mixed strategy with different weight is applied, unlicensed usage in the ISM bands is preferred. It is followed by primary usage and quasi-static sharing. It is because that these four methods does not have monetary risks, while TVWS and CR based DSA have. Moreover, TVWS and CR based DSA also have QoS risks. In other words, in area that the probability of getting a license is high and the license is not very expensive, transmitting in an exclusive way is preferred. The reason that unlicensed usage in ISM bands ranks high is because there is no QoS risks in the current assumption. Noted here, contrast to exclusive usage, spectrum entrants in the ISM bands has potential QoS risks when more spectrum users transmit in the same bands.

7.5.1.4 RURAL AREA SMALL COVERAGE Similar as urban area small coverage, the spectrum cost for small coverage in rural is the same as large coverage under primary usage, and divided according to coverage and operation duration under cooperative sharing through trading.

In summary, observations from table 12 shows that: (1) If the spectrum entrant seeks profit maximization, ASA is the best choice. The following rank changes with spectrum entrants' risk attitude. If they consider the best case scenario, cooperative sharing through trading and primary usage are the second and third preferred methods. If the spectrum entrant considers worst case scenario or risk with mitigation strategies, unlicensed usage in ISM bands moves up to the third position while primary usage lead to negative profits. (2) If the spectrum entrant seeks QoS risk minimization, unlicensed usage in ISM bands is the best choice followed by primary usage, quasi-static sharing, and then dynamic sharing. (3) If mixed strategy with different weight is applied, unlicensed usage in the ISM bands is still preferred followed by primary usage, quasi-static sharing, and then dynamic sharing. The rank inside dynamic sharing changes with spectrum entrant's attitude. When the best case scenario is considered, TVWS outperformed CR based DSA. When the worst case scenario is considered, CR based DSA outperformed TVWS. It is because spectrum entrants in TVWS have low throughput in worst case, which leads to negative profits.

7.5.2 CONSTANT TRAFFIC

Above decisions are made based on the assumption that the spectrum entrant targets on providing broadband services, which lead to time-varying traffic. When spectrum entrant changes from providing broadband services to services that generate constant wireless traffic, decisions may change. According to the current setting, the profits for time-varying traffic and constant traffic stay the same. However, the QoS risks change as depict in Figure29.

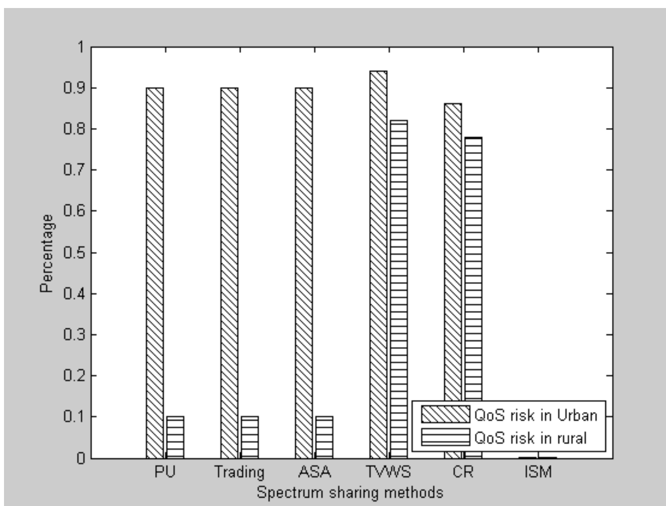


Figure 29: QoS risks

Based on the new QoS risks, the decision for spectrum entrant changes. Only one example is provided here for comparison. In the urban area large coverage scenario, when $W_q = 0.5$, the rank of spectrum usage methods for users have constant traffic is: $I > A > T > C > P = CT$ (best case), $I > A > C > T > P = CT$ (worst case). Due to the increase in the QoS risks of TVWS, the rank of TVWS in decision decreases.

7.5.3 EVENT BASED SERVICES

Operation duration also impacts on QoS and monetary risks. With shorter period of operation time, spectrum entrants may be able to anticipate the spectrum usage environment more accurately. In addition, the event based services usually do not have demand risk. The reason they provide services is due to the large demand, such as wireless services for a conference and sports game. However, large amount of demand does not necessarily lead to high profits due to the large upfront cost for both spectrum and infrastructure.

Appendix C provides cost and revenue for the entire ten years. According to current setting, if spectrum entrants only want to provide services for less than one year, non of the spectrum sharing method can provide positive profits. In other words, infrastructure based spectrum sharing method is not preferred for short-time services. For spectrum entrant that seek to provide event based services, MVNOs may be the best choice.

8.0 CONCLUSION

The rapid proliferation of various forms of mobile devices, coupled with the expansion of wireless Internet services, brought to the limitations of the static command and control approach of spectrum management. Spectrum sharing emerged as a promising method by providing the flexibility needed to respond to temporal and spatial variations of traffic statistics and bandwidth requirements of different services. Therefore, when a potential wireless service provider (spectrum entrant) comes to the market, it has to choose from more than one spectrum usage methods, including primary usage, quasi-static sharing (cooperative sharing through trading and ASA), and dynamic sharing (TVWS, CR based DSA, and unlicensed usage in the ISM band).

Despite of the merits in spectrum sharing, such as providing flexibility, certain level of QoS guarantees, and increasing spectrum utilization efficiency, it has been adopted slowly due to the embedded risks. Thus, the motivation of this research is to transform spectrum sharing from a radical strategy to commercial reality by understanding and minimizing spectrum sharing risks. Two types of risks are modeled in this dissertation: (1) QoS risks: come from competition in spectrum access. For example, mobile offloading and heterogeneous applications may increase the spectrum access demand and reduce spectrum access opportunities; (2) monetary risks: spectrum users' revenue may not be in line with cost due to changes in the spectrum usage environment, QoS levels, and demands.

Specifically, QoS risks are quantified with respect to throughput by a queueing model. In order to provide a realistic spectrum usage environment, a time-varying preemptive resume M/G/C queue was built to model spectrum users with subordinate rights and diurnal behavior. Throughput was calculated based on different traffic models, expected number of spectrum users, and number of accessible channels to reflect sharing in different temporal and spatial domains. Monetary risks in terms of profits consider costs, revenue, and mitigation strategies. In detail, different types of cost and demand functions, as well as wireless traffic models and probabilities of demand, are applied to reflect spectrum usage in different regions. Moreover, spectrum users have mitigation strategies to actively cope with risks. The value of mitigation strategies such as leasing spectrum and infrastructure as well as improving are quantified by the real options method for potential demand and spectrum usage environment changes. The best spectrum usage method is identified according to different decision criteria, such as profit maximization, risk minimization, and mixed strategy that applies distinct weights to monetary and QoS risks, as well as spectrum entrants' incentives, limitations, and risk awareness. Besides the observation that summarized in executive summary (section 7.1), some implications can be drawn:

1. ASA shows great potential in getting high profits due to the lack of spectrum cost and the assumption that they can operate in high transmission power. Because of heavy regulation of exclusive zone, high transmission power may not be allowed. However, due to its great potential, the cooperation between PUs and SUs should be encouraged to allow SUs to operate on high transmission power while protect PUs' services.
2. Comparison of cost and profits in urban and rural area shows that the cost for urban area is higher than rural area. At the same time, it also brings high profits. In other words, the risks for spectrum entrants in urban and rural areas are different. The challenge for spectrum entrants in the urban area is the high spectrum cost, infrastructure cost, and spectrum access opportunities. In rural areas, although the cost requirement is low, the profits may not be enough to justify the low cost due to low service demand. Therefore, the challenge for spectrum entrants in rural area is how to create services with sufficient demand and charge at a optimum price.
3. Although accurate anticipation of demand and wireless traffic is essential, it may be very difficult, if not impossible for spectrum entrants to calculate. In this way, quantifying the value of mitigation strategies that are embedded in each method is critical. Two categories of mitigation strategies are applied here. When spectrum entrants have higher service demand or spectrum usage, they can acquire more spectrum by adopting other spectrum usage methods, or they can change to another spectrum usage method. On

the other hand, when spectrum entrants have low demand, they have the opportunity to lease the spectrum to others (PUs only) and lease their infrastructure.

4. In this dissertation, ASA can be recognized as a special case of quasi-static sharing since it is assumed that the spectrum cost is not applied. Similarly, unlicensed usage in ISM band can be viewed as a special case of dynamic sharing since the expected throughput achieve the maximum. If we do not consider these two special cases, here are some general conclusions: In urban areas, primary usage and quasi-static sharing is less preferred to dynamic sharing. While in rural area, primary usage and quasi-static sharing is preferred than dynamic sharing. It is because in the urban area, spectrum cost is high and the availability of license and leasing agreement is low. Although the dynamic usage in the urban area face high competition and results in low throughput, at least spectrum entrants can provide services and expect positive profits. In rural areas, the low spectrum cost in primary usage and quasi-static sharing provide resource reservation for spectrum entrants, which leads to higher profits and QoS levels.
5. Some mitigation strategies can improve the throughput: (1) transmit on non-peak hours. For example, spectrum entrants can transmit before 8am when PUs' usage is low. (2) when considering the availability of license/leasing agreement in quasi-static sharing and expected throughput in dynamic sharing, at least one spectrum usage method from each category should be applied in order to provide continuous services.
6. The target spectrum entrant in this decision making process have a time-varying behavior. Similar conclusion can be made for spectrum entrant with constant transmission behavior, although the level of QoS risks changes. Moreover, based on the current assumption, event based service providers cannot get profits in any of these methods, due to the heavy initial costs. In other words, infrastructure based spectrum sharing may not be worth for short term services. Wireless service providers may opt to become MVNOs that lease infrastructure or services from Mobile Network Operators (MNOs).

Some assumptions limit the application of this risk and decision analysis model. First, the spectrum hole is assumed to be exogenous. However, in reality, the spectrum hole may be endogenous. PUs can decrease the spectrum hole by transmitting meaningless data. Modeling endogenous spectrum holes and incentivize PUs to share spectrum with SUs are future research directions. Second, spectrum entrants' risk attitude heavily impact on the spectrum decision. In this dissertation, it is assumed that spectrum entrants are risk-neutral. When they are risk-averse and risk-seeking, different spectrum usage choice will be made. Third, in the queueing model, it is assumed that spectrum users can detect others' service and coordinate with each other perfectly. The greedy behavior and interference due to imperfect detection and wireless channels are ignored. This can be improved by replacing the existing static service rate to a function of service rate that depends on distance. Fourth, the distribution in this dissertation, such as the one in the real options analysis, only considers linear distribution. Other distribution of revenue can be applied to achieve realistic results.

The ultimate goal for this dissertation is to cope with uncertainties and risks in technology adoption. Users of technology and regulators benefit from understanding and minimizing risks. Generally speaking, users of technology, such as spectrum users, can model the risk to have a better understanding before adopt the technology. Moreover, they have two methods to actively manage the risk. The first one is decision model that help users to make informed decision after evaluating risks and uncertainties. In this dissertation, risk is a ratio based on the expected and required value. In the future research, the risk can be estimated as a probability distribution. The second one is options and real options. Real options have already been largely applied in electricity generation area. Due to its merit of minimizing risks, it can be applied to other technology adoption field with careful design. For example, the priority access in spectrum sharing between federal and non-federal users in 3.5 GHz can be realized by option [125]. Then, users with priority access have the right but not obligations to exclude others' access. Research questions like the value of the option, implementation, and the impact from SUs at adjacent channel and areas are important.

Regulator is another essential player in technology adoption. The understanding of potential risks, uncertainties, as well as technology users' choices are key to policy interventions. Enforcement is one way to reduce uncertainties and risks for technology users, which is not considered in this dissertation. Thus, enforcement with an associated cost could be one choice for spectrum entrants to share the spectrum, or recognized as a mitigation strategy. At large, it is hoped that in the future, the technology adoption problems due to uncertainties and risks can be solved by decision models and risk minimization tools.

APPENDIX A

SELECTED LICENSE AUCTION STATISTICS

	Frequency bands	Pittsburgh, PA	Washington D.C.	New York, NY
Wireless Communications Service (Auction 14) Applications: Any fixed, mobile, radiolocation or broadcast-satellite (sound) use. Time: 4/15/1997-4/25/1997, License terms: 10 years, renewable. Licensees are required to provide substantial service to their service areas within ten years	2305-2310 MHz paired with 2350-2355 MHz (block A)	$200,000 Region: MEAs	$200,000	$200,000
	2310-2315 MHz paired with 2355-2360 MHz (block B)	$37,335 Region: MEAs	$69,709	$261,243
	2315-2320 MHz (block C)	$54,327 Region: REA	$47,172	as D.C.
	2345-2350 MHz (block D)	$11,021 Region: REA	$700,229	as D.C
Location and Monitoring Services (Auction 21), Applications: Multilateration LMS systems are authorized to transmit status and instructional messages, either voice or non-voice, so long as they are related to the location or monitoring functions of the system. Time: 2/23/1999-3/5/1999, License terms: 10 years, provide multilateration location and monitoring service to one-third of the license areas population within five years of initial license grant and two-thirds of the population within ten years	904-904.75 MHz, and 927.75-928 MHz (block A)	FCC Held Region: EA	$35,783	$114,812
	919.75-921.75 MHz and 927.5-927.75 MHz (block B)	$5,406	$15,000	$43,055
	921.75-927.25 and 927.25-927.5 MHz (block C)	$19,000	$356,000	$158,000
1.4 GHz (Auction 69), Applications: both fixed and mobile services including wireless internet, high speed data as well as advanced two-way mobile and paging services. Time: 2/7/2007-3/8/2007 License terms: 10 years	1390-1392, 1392-1395, 1432-1435 MHz	$668,000 Region: MEA	$857,000	$4,573,000

700 MHz (Auction 73), Applications: flexible fixed, mobile, and broadcast uses, including fixed and mobile wireless commercial services (including FDD- and TDD-based services); fixed and mobile wireless uses for private, internal radio needs; and mobile and other digital new broadcast operations. These uses may include two-way interactive, cellular, and mobile television broadcasting services. Time: 1/24/2008-3/18/2008, License terms:10 years, (1) at least 35 percent of the geographic areas of their licenses within four years of the end of the DTV transition, and (2) at least 70 percent of the geographic areas of their licenses at the end of the license term.	698-704/728-734 MHz (block A)	$8,407,000 Region: EA	$122,688,000	$14,983,000
	704-710/734-740 MHz (Block B)	$76,471,000 Region: CMA	$241,363,000	$883,703,000
	722-728 MHz (Block E)	$3,757,000 Region: EA	$61,108,000	$7,492,000
	746-757/776-787 MHz (Block C)	$1,109,715,000 Region: REA	$502,774,000	As D.C.
	758-763/788-793 MHz (Nationwide, Block D)	$472,042,000 Region: Nationwide		
Advanced Wireless Services (Auction 66), Applications: fixed and mobile terrestrial wireless applications using bandwidth that is sufficient for the provision of a variety of applications including those using voice and data (such as internet browsing, message services, and full-motion video) content. Time: 8/9/2006-9/18/2006 License terms: 15 years,	1710-1720/2110-2120 MHz (Block A)	$10,718,000 Region: CMA	$133,150,000	$396,232,000
	1720-1730/2120-2130 MHz (Block B)	$14,822,000 Region: EA	$146,708,000	$468,178,000
	1730-1735/2130-2135 MHz (Block C)	$6,833,000 Region: EA	$76,066,000	$363,945,000
	1735-1740/2135-2140 MHz (Block D)	$365,445,000 Region: REA	$552,694,000	As D.C.
	1740-1745/2140-2145 MHz (Block E)	$356,780,000 Region: REA	$472,553,000	As D.C.
	1745-1755/2145-2155 MHz (Block F)	$615,923,000 Region: REA	$1335,374,000	As D.C.

220 MHz (Auction 72), Applications: Land mobile operations including voice and data services, such as telemetry and one-way or two-way paging operations on a primary basis and fixed operations on a primary basis. Time: 6/20/2007-6/26/2007 License terms: 10 years, must provide coverage to at least two-thirds of the population of their service areas or that they are otherwise providing "substantial service" to their service areas within 10 years	220-222 MHz (EA license 100 KHz)	-	$6,500,000	-
C and F Block Broadband PCS (Auction 35), <u>Applications</u>: mobile and/or portable radio services, using such devices as small, lightweight, multifunction portable phones, portable fax machines, and advanced devices with two-way data capabilities that are competing with existing cellular, paging, and other land mobile services. <u>Time</u>: 12/12/2000-1/26/2001 <u>License terms</u>: 10 years,	1895-1900/1975-1980 MHz (Block C3)	$97,848,000 Region: BEA	$172,184,000	$1,484,327,000
	1900-1905/1980-1985 MHz (Block C4)	$112,774,000 Region: BEA	$216,743,000	$2,057,010,000
	1905-1910/1985-1990 MHz (Block C5)	$114,232,000 Region: BEA	$217,527,000	$$2,038,316,000
Narrowband PCS (Auction 41), Applications: The Commission broadly defines PCS as mobile and fixed communications offerings that serve individuals and businesses, and can be integrated with a variety of competing networks. Time: 10/3/2001-10/16/2001 License terms: 10 years, required to provide coverage to a composite area of 75,000 square kilometers or 25 percent of the geographic area, or serve 37.5 percent of the population of the service area within five years of the initial license grant; and, construct base stations that provide coverage to a composite area of 150,000 square kilometers or 50 percent of the geographic area, or serve 75 percent of the population of the service area within ten years of the initial license grant.	901.35-901.4 MHz (MTA channel 26)	$4,100 Region: EA	$9,000	$30,000
	901.4-901.45 MHz (MTA channel 27)	$4,100 Region: EA	$9,000	$30,000
	940.4-940.45 MHz (MTA channel 28)	$4,100 Region: EA	$7,800	$36,000

Table 13: Statistics of FCC areas for Pittsburgh, PA, Washington D.C., New York, NY

	BTA	MEA	REA	CMA	EA
Name	350 Pittsburgh, PA	12 Pittsburgh	3 Great Lakes	13 Pittsburgh, PA	53 Pittsburgh, PA-WV
Population		4,148,373	54,327,300	2,035,968	2,971,829
Name	461 Washington, DC	5 Washington	1 Northeast	8 Washington, DC-MD-VA	13 Washington-Baltimore, DC-MD-VA-WV-PA
Population		7,745,433	47,172,015	4,182,658	8,403,130
Name	321 New York, NY	2 New York City	1 Northeast	1 New York, NY-NJ/Nassau-Suffolk, NY/Newark, Jersey City and Paterson-Clifton-Passic, NJ	10 New York-No. New Jer.-Lon Island, NY-NJ-CT-PA-MA-CT
Population		29,027,017	47,172,015	16,134,166	25,712,577

APPENDIX B

VALIDATION OF THE M/G/C QUEUE SIMULATION

There is no analytic solution for state probability in M/G/C queue. Therefore, the validation is done through M/M/C queue with $C = 1$. According to the analytic solution, the state probability for M/M/1 queue can be calculated as following:

$$\Pi_i = (1 - \rho)\rho^i \tag{B.1}$$

where, $\rho = \frac{\lambda}{\mu}$. In this validation, $\lambda = 1$ and $\mu = 2$. Therefore, $\Pi_i = \frac{1}{2^i}$. Following is the comparison of 50 simulation results and analytic results.

	Π_0	Π_1	Π_2	Π_3	Π_4	Π_5
Analytical Results	0.5	0.25	0.125	0.0625	0.03125	0.015265
Simulation Results	0.500707	0.249392	0.125174	0.062451	0.031088	0.015896
Difference	-0.00071	0.000608	-0.00017	4.89e-05	0.000162	-0.00027
	Π_6	Π_7	Π_8	Π_9	Π_10	Π_{11}
Analytical Results	0.007813	0.003906	0.001953	0.000977	0.000488	0.000244
Simulation Results	0.007257	0.003992	0.002117	0.001071	0.000476	0.000158
Difference	0.000556	-8.5e-05	-0.00016	-9.4e-05	1.19e-05	8.64e-05

APPENDIX C

PROFITS CALCULATION

Urban	Year	0	1	2	3	4	5	6	7	8	9	Total Profits
Large Area (350 Km2)	Cost	$1,033,941,200.00	$13,069.31	$12,939.91	$12,811.79	$12,684.94	$12,559.35	$12,435.00	$12,311.88	$12,189.98	$12,069.29	
	High Unit Price Revenue	$51,322,194.00	$50,814,053.47	$50,310,944.03	$49,812,815.87	$49,319,619.67	$48,831,306.60	$48,347,828.32	$47,869,136.95	$47,395,185.10	$46,925,925.84	
	High Unit Price Profits	-$982,619,006.00	$50,800,984.16	$50,298,004.12	$49,800,004.08	$49,306,934.73	$48,818,747.26	$48,335,393.32	$47,856,825.07	$47,382,995.12	$46,913,856.56	-$543,105,261.59
	Low Unit Price Revenue	$5,132,219.40	$5,081,405.35	$5,031,094.40	$4,981,281.59	$4,931,961.97	$4,883,130.66	$4,834,782.83	$4,786,913.70	$4,739,518.51	$4,692,592.58	
	Low Unit Price Profits	-$1,028,808,980.60	$5,068,336.04	$5,018,154.49	$4,968,469.80	$4,919,277.03	$4,870,571.31	$4,822,347.83	$4,774,601.82	$4,727,328.53	$4,680,523.30	-$984,959,370.45
	High Unit Price Demand Change Revenue	$8,553,700.00	$8,469,009.90	$8,385,158.32	$8,302,136.95	$8,219,937.57	$8,138,552.05	$8,057,972.33	$7,978,190.42	$7,899,198.44	$7,820,988.55	
	High Unit Price Demand Change Profits	-$1,025,387,500.00	$8,455,940.59	$8,372,218.41	$8,289,325.16	$8,207,252.63	$8,125,992.71	$8,045,537.33	$7,965,878.55	$7,887,008.46	$7,808,919.27	-$952,229,426.89
Small Area (5 Km2)	Cost	$1,033,880,768.00	$166.34	$164.69	$163.06	$161.44	$159.85	$158.26	$156.70	$155.15	$153.61	
	High Unit Price Revenue	$1,237,221.00	$1,224,971.29	$1,212,842.86	$1,200,834.51	$1,188,945.06	$1,177,173.33	$1,165,518.15	$1,153,978.36	$1,142,552.84	$1,131,240.43	
	High Unit Price Profits	-$1,032,643,547.00	$1,224,804.95	$1,212,678.17	$1,200,671.45	$1,188,783.62	$1,177,013.48	$1,165,359.88	$1,153,821.67	$1,142,397.69	$1,131,086.82	-$1,022,046,929.26
	Low Unit Price Revenue	$123,722.10	$122,497.13	$121,284.29	$120,083.45	$118,894.51	$117,717.33	$116,551.81	$115,397.84	$114,255.28	$113,124.04	
	Low Unit Price Profits	-$1,033,757,045.90	$122,330.79	$121,119.60	$119,920.39	$118,733.06	$117,557.49	$116,393.55	$115,241.14	$114,100.14	$112,970.43	-$1,032,698,679.31
	High Unit Price Demand Change Revenue	$412,407.00	$408,323.76	$404,280.95	$400,278.17	$396,315.02	$392,391.11	$388,506.05	$384,659.45	$380,850.95	$377,080.14	
	High Unit Price Demand Change Profits	-$1,033,468,361.00	$408,157.43	$404,116.26	$400,115.11	$396,153.58	$392,231.26	$388,347.79	$384,502.76	$380,695.80	$376,926.53	-$1,029,937,114.48

Figure 30: Profits for primary usage in urban area

Rural Area	Year	0	1	2	3	4	5	6	7	8	9	Total Profits
Large Area (150 Km2)	Cost	$6,500,600.00	$6,534.65	$6,469.95	$6,405.89	$6,342.47	$6,279.67	$6,217.50	$6,155.94	$6,094.99	$6,034.64	
	High Unit Price Revenue	$25,661,097.00	$25,407,026.73	$25,155,472.01	$24,906,407.93	$24,659,809.83	$24,415,653.30	$24,173,914.16	$23,934,568.48	$23,697,592.55	$23,462,962.92	
	High Unit Price Profits	$19,160,497.00	$25,400,492.08	$25,149,002.06	$24,900,002.04	$24,653,467.36	$24,409,373.63	$24,167,696.66	$23,928,412.54	$23,691,497.56	$23,456,928.28	$238,917,369.21
	Low Unit Price Revenue	$2,566,109.70	$2,540,702.67	$2,515,547.20	$2,490,640.79	$2,465,980.98	$2,441,565.33	$2,417,391.42	$2,393,456.85	$2,369,759.25	$2,346,296.29	
	Low Unit Price Profits	-$3,934,490.30	$2,534,168.02	$2,509,077.25	$2,484,234.90	$2,459,638.51	$2,435,285.66	$2,411,173.92	$2,387,300.91	$2,363,664.27	$2,340,261.65	$17,990,314.78
	High Unit Price Demand Change Revenue	$8,553,700.00	$8,469,009.90	$8,385,158.32	$8,302,136.95	$8,219,937.57	$8,138,552.05	$8,057,972.33	$7,978,190.42	$7,899,198.44	$7,820,988.55	
	High Unit Price Demand Change Profits	$2,053,100.00	$8,462,475.25	$8,378,688.36	$8,295,731.05	$8,213,595.10	$8,132,272.38	$8,051,754.83	$7,972,034.49	$7,893,103.45	$7,814,953.91	$75,267,708.82
Small Area (5 Km2)	Cost	$6,470,768.00	$166.34	$164.69	$163.06	$161.44	$159.85	$158.26	$156.70	$155.15	$153.61	
	High Unit Price Revenue	$837,054.00	$828,766.34	$820,560.73	$812,436.37	$804,392.44	$796,428.16	$788,542.73	$780,735.38	$773,005.33	$765,351.81	
	High Unit Price Profits	-$5,633,714.00	$828,600.00	$820,396.04	$812,273.31	$804,231.00	$796,268.31	$788,384.47	$780,578.68	$772,850.18	$765,198.20	$1,535,066.19
	Low Unit Price Revenue	$83,705.40	$82,876.63	$82,056.07	$81,243.64	$80,439.24	$79,642.82	$78,854.27	$78,073.54	$77,300.53	$76,535.18	
	Low Unit price Profits	-$6,387,062.60	$82,710.30	$81,891.38	$81,080.58	$80,277.80	$79,482.97	$78,696.01	$77,916.84	$77,145.39	$76,381.57	-$5,671,479.76
	High Unit Price Demand Change Revenue	$279,018.00	$276,255.45	$273,520.24	$270,812.12	$268,130.81	$265,476.05	$262,847.58	$260,245.13	$257,668.44	$255,117.27	
	High Unit Price Demand Change Profits	-$6,191,750.00	$276,089.11	$273,355.55	$270,649.06	$267,969.37	$265,316.21	$262,689.31	$260,088.43	$257,513.30	$254,963.66	-$3,803,116.00

Figure 31: Profits for primary usage in rural area

Urban Area	Year	0	1	2	3	4	5	6	7	8	9	Total Profits
Large Area (350 Km2)	High Unit Price Revenue	$51,322,194.00	$50,814,053.47	$50,310,944.03	$49,812,815.87	$49,319,619.67	$48,831,306.60	$48,347,828.32	$47,869,136.95	$47,395,185.10	$46,925,925.84	
	Low Unit Price revenue	$5,132,219.40	$5,081,405.35	$5,031,094.40	$4,981,281.59	$4,931,961.97	$4,883,130.66	$4,834,782.83	$4,786,913.70	$4,739,518.51	$4,692,592.58	
	High Unit Price Demand Change Revenue	$8,553,700.00	$8,469,009.90	$8,385,158.32	$8,302,136.95	$8,219,937.57	$8,138,552.05	$8,057,972.33	$7,978,190.42	$7,899,198.44	$7,820,988.55	
Average Cost	Cost	$103,449,200.00	$102,377,425.74	$101,363,787.86	$100,360,186.00	$99,366,520.80	$98,382,693.86	$97,408,607.78	$96,444,166.12	$95,489,273.38	$94,543,835.03	
	High Unit Price Profits	-$52,127,006.00	-$51,563,372.28	-$51,052,843.84	-$50,547,370.14	-$50,046,901.13	-$49,551,387.25	-$49,060,779.46	-$48,575,029.17	-$48,094,088.28	-$47,617,909.19	-$498,236,686.74
	Low Unit Price Profits	-$98,316,980.60	-$97,296,020.40	-$96,332,693.46	-$95,378,904.42	-$94,434,558.83	-$93,499,563.20	-$92,573,824.95	-$91,657,252.42	-$90,749,754.87	-$89,851,242.45	-$940,090,795.60
	High Unit Price Demand Change Profits	-$94,895,500.00	-$93,908,415.84	-$92,978,629.55	-$92,058,049.06	-$91,146,583.22	-$90,244,141.81	-$89,350,635.45	-$88,465,975.69	-$87,590,074.94	-$86,722,846.48	-$907,360,852.04
High Leasing cost	Cost	$155,143,200.00	$153,559,603.96	$152,039,211.84	$150,533,873.11	$149,043,438.72	$147,567,761.11	$146,106,694.17	$144,660,093.24	$143,227,815.09	$141,809,717.91	
	High Unit Price Profits	-$103,821,006.00	-$102,745,550.50	-$101,728,267.82	-$100,721,057.24	-$99,723,819.05	-$98,736,454.51	-$97,758,865.85	-$96,790,956.29	-$95,832,629.99	-$94,883,792.07	-$992,742,399.31
	Low unit price profits	-$150,010,980.60	-$148,478,198.61	-$147,008,117.44	-$145,552,591.52	-$144,111,476.76	-$142,684,630.45	-$141,271,911.34	-$139,873,179.54	-$138,488,296.58	-$137,117,125.32	-$1,434,596,508.17
	High Unit Price Demand Change Profits	-$146,589,500.00	-$145,090,594.06	-$143,654,053.52	-$142,231,736.16	-$140,823,501.15	-$139,429,209.06	-$138,048,721.84	-$136,681,902.81	-$135,328,616.65	-$133,988,729.35	-$1,401,866,564.61
Low Leasing cost	Cost	$68,986,533.33	$68,255,973.60	$67,580,171.88	$66,911,061.27	$66,248,575.51	$65,592,649.02	$64,943,216.85	$64,300,214.71	$63,663,578.92	$63,033,246.45	
	High Unit Price Profits	-$17,664,339.33	-$17,441,920.13	-$17,269,227.85	-$17,098,245.40	-$16,928,955.84	-$16,761,342.42	-$16,595,388.53	-$16,431,077.75	-$16,268,393.82	-$16,107,320.61	-$168,566,211.69
	Low Unit Price Profits	-$63,854,313.93	-$63,174,568.25	-$62,549,077.48	-$61,929,779.68	-$61,316,613.54	-$60,709,518.36	-$60,108,434.02	-$59,513,301.01	-$58,924,060.41	-$58,340,653.87	-$610,420,320.55
	High Unit Price Demand Change Profits	-$60,432,833.33	-$59,786,963.70	-$59,195,013.56	-$58,608,924.32	-$58,028,637.94	-$57,454,096.97	-$56,885,244.52	-$56,322,024.28	-$55,764,380.48	-$55,212,257.90	-$577,690,376.99
Small Area (5 Km2)	High Unit Price Revenue	$1,237,221.00	$1,224,971.29	$1,212,842.86	$1,200,834.51	$1,188,945.06	$1,177,173.33	$1,165,518.15	$1,153,978.36	$1,142,552.84	$1,131,240.43	
	Low Unit Price Revenue	$123,722.10	$122,497.13	$121,284.29	$120,083.45	$118,894.51	$117,717.33	$116,551.81	$115,397.84	$114,255.28	$113,124.04	
	High Unit Price Demand Change Revenue	$412,407.00	$408,323.76	$404,280.95	$400,278.17	$396,315.02	$392,391.11	$388,506.05	$384,659.45	$380,850.95	$377,080.14	
Average cost	Cost	$1,477,739.43	$1,462,514.29	$1,448,033.95	$1,433,696.98	$1,419,501.96	$1,405,447.48	$1,391,532.16	$1,377,754.61	$1,364,113.48	$1,350,607.41	
	High Unit Price profits	-$240,518.43	-$237,543.00	-$235,191.09	-$232,862.46	-$230,556.89	-$228,274.15	-$226,014.01	-$223,776.25	-$221,560.64	-$219,366.97	-$2,295,663.90
	Low Unit Price Profits	-$1,601,461.53	-$1,585,011.41	-$1,569,318.23	-$1,553,780.43	-$1,538,396.46	-$1,523,164.82	-$1,508,083.98	-$1,493,152.45	-$1,478,368.76	-$1,463,731.45	-$15,314,469.52
	High Unit Price Demand Change Profits	-$1,065,332.43	-$1,054,190.52	-$1,043,752.99	-$1,033,418.81	-$1,023,186.94	-$1,013,056.37	-$1,003,026.11	-$993,095.16	-$983,262.53	-$973,527.26	-$10,185,849.13
High Leasing cost	Cost	$2,216,225.14	$2,193,688.26	$2,171,968.57	$2,150,463.94	$2,129,172.21	$2,108,091.30	$2,087,219.11	$2,066,553.57	$2,046,092.65	$2,025,834.30	
	High Unit Price Profits	-$979,004.14	-$968,716.97	-$959,125.72	-$949,629.42	-$940,227.15	-$930,917.97	-$921,700.96	-$912,575.21	-$903,539.81	-$894,593.87	-$9,360,031.23
	Low Unit Price Profits	-$2,092,503.04	-$2,071,191.13	-$2,050,684.29	-$2,030,380.48	-$2,010,277.71	-$1,990,373.97	-$1,970,667.29	-$1,951,155.74	-$1,931,837.36	-$1,912,710.26	-$20,011,781.28
	High Unit Price Demand Change Profits	-$1,803,818.14	-$1,785,364.50	-$1,767,687.62	-$1,750,185.76	-$1,732,857.19	-$1,715,700.19	-$1,698,713.06	-$1,681,894.12	-$1,665,241.70	-$1,648,754.16	-$17,250,216.45
Low Leasing cost	Cost	$985,415.62	$975,064.97	$965,410.86	$955,852.34	$946,388.45	$937,018.27	$927,740.86	$918,555.31	$909,460.70	$900,456.14	
	High Unit Price Profits	$251,805.38	$249,906.32	$247,432.00	$244,982.18	$242,556.61	$240,155.06	$237,777.29	$235,423.06	$233,092.13	$230,784.29	$2,413,914.31
	Low Unit Price Profits	-$861,693.52	-$852,567.84	-$844,126.57	-$835,768.89	-$827,493.95	-$819,300.94	-$811,189.05	-$803,157.47	-$795,205.42	-$787,332.10	-$8,237,835.74
	High Unit Price Demand Change Profits	-$573,008.62	-$566,741.21	-$561,129.91	-$555,574.17	-$550,073.43	-$544,627.16	-$539,234.81	-$533,895.85	-$528,609.76	-$523,376.00	-$5,476,270.91

Figure 32: Profits for cooperative sharing through trading in urban area

Rural Area	Year	0	1	2	3	4	5	6	7	8	9	Total Profits
Large Area (150 Km2)	High Unit Price Revenue	$25,661,097.00	$25,407,026.73	$25,155,472.01	$24,906,407.93	$24,659,809.83	$24,415,653.30	$24,173,914.16	$23,934,568.48	$23,697,592.55	$23,462,962.92	
	Low Unit Price Revenue	$2,566,109.70	$2,540,702.67	$2,515,547.20	$2,490,640.79	$2,465,980.98	$2,441,565.33	$2,417,391.42	$2,393,456.85	$2,369,759.25	$2,346,296.29	
	High Unit Price Demand Change Revenue	$8,553,700.00	$8,469,009.90	$8,385,158.32	$8,302,136.95	$8,219,937.57	$8,138,552.05	$8,057,972.33	$7,978,190.42	$7,899,198.44	$7,820,988.55	
Average Cost	Cost	$677,600.00	$647,128.71	$640,721.50	$634,377.72	$628,096.75	$621,877.97	$615,720.77	$609,624.52	$603,588.63	$597,612.51	
	High Unit Price Profits	$24,983,497.00	$24,759,898.02	$24,514,750.51	$24,272,030.21	$24,031,713.08	$23,793,775.33	$23,558,193.39	$23,324,943.95	$23,094,003.92	$22,865,350.41	$239,198,155.83
	Low Unit Price Profits	$1,888,509.70	$1,893,573.96	$1,874,825.70	$1,856,263.07	$1,837,884.23	$1,819,687.36	$1,801,670.65	$1,783,832.33	$1,766,170.62	$1,748,683.78	$18,271,101.40
	High Unit Price Demand Change Profits	$7,876,100.00	$7,821,881.19	$7,744,436.82	$7,667,759.23	$7,591,840.82	$7,516,674.08	$7,442,251.56	$7,368,565.90	$7,295,609.81	$7,223,376.05	$75,548,495.45
High Leasing cost	Cost	$1,001,100.00	$967,425.74	$957,847.27	$948,363.63	$938,973.89	$929,677.12	$920,472.40	$911,358.81	$902,335.46	$893,401.44	
	High Unit Price Profits	$24,659,997.00	$24,439,600.99	$24,197,624.74	$23,958,044.30	$23,720,835.94	$23,485,976.18	$23,253,441.76	$23,023,209.66	$22,795,257.09	$22,569,561.48	$236,103,549.15
	Low Unit Price Profits	$1,565,009.70	$1,573,276.93	$1,557,699.93	$1,542,277.16	$1,527,007.09	$1,511,888.21	$1,496,919.02	$1,482,098.04	$1,467,423.80	$1,452,894.85	$15,176,494.72
	High Unit Price Demand Change Profits	$7,552,600.00	$7,501,584.16	$7,427,311.05	$7,353,773.31	$7,280,963.68	$7,208,874.93	$7,137,499.93	$7,066,831.61	$6,996,862.98	$6,927,587.11	$72,453,888.77
Low Leasing cost	Cost	$461,933.33	$433,597.36	$429,304.32	$425,053.78	$420,845.33	$416,678.54	$412,553.01	$408,468.33	$404,424.09	$400,419.89	
	High Unit Price Profits	$25,199,163.67	$24,973,429.37	$24,726,167.70	$24,481,354.15	$24,238,964.51	$23,998,974.76	$23,761,361.15	$23,526,100.15	$23,293,168.46	$23,062,543.03	$241,261,226.96
	Low Unit Price Profits	$2,104,176.37	$2,107,105.31	$2,086,242.88	$2,065,587.01	$2,045,135.66	$2,024,886.79	$2,004,838.41	$1,984,988.52	$1,965,335.17	$1,945,876.41	$20,334,172.53
	High Unit Price Demand Change Profits	$8,091,766.67	$8,035,412.54	$7,955,854.00	$7,877,083.17	$7,799,092.25	$7,721,873.51	$7,645,419.32	$7,569,722.10	$7,494,774.35	$7,420,568.67	$77,611,566.58
Small Area (5 Km2)	High Unit Price Revenue	$837,054.00	$828,766.34	$820,560.73	$812,436.37	$804,392.44	$796,428.16	$788,542.73	$780,735.38	$773,005.33	$765,351.81	
	Low Unit Price Revenue	$83,705.40	$82,876.63	$82,056.07	$81,243.64	$80,439.24	$79,642.82	$78,854.27	$78,073.54	$77,300.53	$76,535.18	
	High Unit Price Demand Change Revenue	$279,018.00	$276,255.45	$273,520.24	$270,812.12	$268,130.81	$265,476.05	$262,847.58	$260,245.13	$257,668.44	$255,117.27	
Average Cost	Cost	$22,334.67	$21,519.47	$21,306.41	$21,095.45	$20,886.59	$20,679.79	$20,475.04	$20,272.32	$20,071.60	$19,872.87	
	High Unit Price Profits	$814,719.33	$807,246.86	$799,254.32	$791,340.91	$783,505.85	$775,748.37	$768,067.69	$760,463.06	$752,933.73	$745,478.94	$7,798,759.07
	Low Unit Price Profits	$61,370.73	$61,357.16	$60,749.67	$60,148.18	$59,552.66	$58,963.03	$58,379.23	$57,801.22	$57,228.93	$56,662.31	$592,213.12
	High Unit Price Demand Change Profits	$256,683.33	$254,735.97	$252,213.84	$249,716.67	$247,244.23	$244,796.26	$242,372.54	$239,972.81	$237,596.84	$235,244.40	$2,460,576.89
High Leasing cost	Cost	$33,118.00	$32,196.04	$31,877.27	$31,561.65	$31,249.16	$30,939.76	$30,633.43	$30,330.13	$30,029.83	$29,732.50	
	High Unit Price Profits	$803,936.00	$796,570.30	$788,683.46	$780,874.72	$773,143.28	$765,488.40	$757,909.31	$750,405.25	$742,975.50	$735,619.30	$7,695,605.52
	Low Unit Price Profits	$50,587.40	$50,680.59	$50,178.81	$49,681.99	$49,190.09	$48,703.05	$48,220.85	$47,743.41	$47,270.71	$46,802.68	$489,059.57
	High Unit Price Demand Change Profits	$245,900.00	$244,059.41	$241,642.98	$239,250.47	$236,881.65	$234,536.29	$232,214.15	$229,915.00	$227,638.61	$225,384.77	$2,357,423.33
Low Leasing cost	Cost	$15,145.78	$14,401.76	$14,259.17	$14,117.99	$13,978.21	$13,839.81	$13,702.78	$13,567.11	$13,432.78	$13,299.78	
	High Unit Price Profits	$821,908.22	$814,364.58	$806,301.56	$798,318.38	$790,414.23	$782,588.35	$774,839.95	$767,168.27	$759,572.54	$752,052.02	$7,867,528.11
	Low Unit Price Profits	$68,559.62	$68,474.87	$67,796.90	$67,125.65	$66,461.04	$65,803.01	$65,151.49	$64,506.43	$63,867.75	$63,235.40	$660,982.16
	High Unit Price Demand Change Profits	$263,872.22	$261,853.69	$259,261.07	$256,694.13	$254,152.61	$251,636.24	$249,144.80	$246,678.02	$244,235.66	$241,817.49	$2,529,345.93

Figure 33: Profits for cooperative sharing through trading in rural area

Urban Area	Year	0	1	2	3	4	5	6	7	8	9	Total Profits
Large area (350 Km2)	Cost	$214,200.00	$45,742.57	$45,289.68	$44,841.26	$44,397.29	$43,957.71	$43,522.49	$43,091.57	$42,664.92	$42,242.50	
	High Unit Price Revenue	$129,972,087.00	$128,685,234.65	$127,411,123.42	$126,149,627.15	$124,900,620.94	$123,663,981.13	$122,439,585.27	$121,227,312.15	$120,027,041.74	$118,838,655.18	
	High Unit Price Profits	$129,757,887.00	$128,639,492.08	$127,365,833.74	$126,104,785.88	$124,856,223.65	$123,620,023.41	$122,396,062.78	$121,184,220.58	$119,984,376.81	$118,796,412.68	$1,242,705,318.62
	Low Unit price Revenue	$12,997,208.70	$12,868,523.47	$12,741,112.34	$12,614,962.71	$12,490,062.09	$12,366,398.11	$12,243,958.53	$12,122,731.22	$12,002,704.17	$11,883,865.52	
	Low unit price Profits	$12,783,008.70	$12,822,780.89	$12,695,822.66	$12,570,121.45	$12,445,664.80	$12,322,440.40	$12,200,436.04	$12,079,639.64	$11,960,039.25	$11,841,623.02	$123,721,576.85
	High Unit Price Demand Change Revenue	43317900	42889009.9	42464366.24	42043926.97	41627650.46	41215495.51	40807421.3	40403387.42	40003353.88	39607281.07	
	High Unit Price Demand Change Profits	$43,103,700.00	$42,843,267.33	$42,419,076.56	$41,999,085.70	$41,583,253.17	$41,171,537.79	$40,763,898.81	$40,360,295.85	$39,960,688.96	$39,565,038.57	$413,769,842.74
Small Area (5 Km2)	Cost	$768.00	$166.34	$164.69	$163.06	$161.44	$159.85	$158.26	$156.70	$155.15	$153.61	
	High Unit Price Revenue	$1,237,221.00	$1,224,971.29	$1,212,842.86	$1,200,834.51	$1,188,945.06	$1,177,173.33	$1,165,518.15	$1,153,978.36	$1,142,552.84	$1,131,240.43	
	High Unit Price Profits	$1,236,453.00	$1,224,804.95	$1,212,678.17	$1,200,671.45	$1,188,783.62	$1,177,013.48	$1,165,359.88	$1,153,821.67	$1,142,397.69	$1,131,086.82	$11,833,070.74
	Low Unit price Revenue	$123,722.10	$122,497.13	$121,284.29	$120,083.45	$118,894.51	$117,717.33	$116,551.81	$115,397.84	$114,255.28	$113,124.04	
	Low unit price Profits	$122,954.10	$122,330.79	$121,119.60	$119,920.39	$118,733.06	$117,557.49	$116,393.55	$115,241.14	$114,100.14	$112,970.43	$1,181,320.69
	High Unit Price Demand Change Revenue	412407	408323.7624	404280.9528	400278.1711	396315.0209	392391.1098	388506.0493	384659.4548	380850.9453	377080.1439	
	High Unit Price Demand Change Profits	$411,639.00	$408,157.43	$404,116.26	$400,115.11	$396,153.58	$392,231.26	$388,347.79	$384,502.76	$380,695.80	$376,926.53	$3,942,885.52
Rural Area	Year	0	1	2	3	4	5	6	7	8	9	Total Profits
Large Area (150 Km2)	Cost	$91,800.00	$19,603.96	$19,409.86	$19,217.68	$19,027.41	$18,839.02	$18,652.50	$18,467.82	$18,284.97	$18,103.93	
	High Unit Price Revenue	$40,204,269.00	$39,806,206.93	$39,412,086.07	$39,021,867.40	$38,635,512.27	$38,252,982.45	$37,874,240.05	$37,499,247.57	$37,127,967.89	$36,760,364.25	
	High Unit Price Profits	$40,112,469.00	$39,786,602.97	$39,392,676.21	$39,002,649.71	$38,616,484.86	$38,234,143.43	$37,855,587.55	$37,480,779.76	$37,109,682.93	$36,742,260.32	$384,333,336.74
	Low Unit price Revenue	$4,020,426.90	$3,980,620.69	$3,941,208.61	$3,902,186.74	$3,863,551.23	$3,825,298.24	$3,787,424.00	$3,749,924.76	$3,712,796.79	$3,676,036.43	
	Low unit price Profits	$3,928,626.90	$3,961,016.73	$3,921,798.75	$3,882,969.05	$3,844,523.82	$3,806,459.22	$3,768,771.51	$3,731,456.94	$3,694,511.82	$3,657,932.50	$38,198,067.24
	High Unit Price Demand Change Revenue	13395300	13262673.27	13131359.67	13001346.21	12872620.01	12745168.33	12618978.54	12494038.16	12370334.81	12247856.25	
	High Unit Price Demand Change Profits	$13,303,500.00	$13,243,069.31	$13,111,949.81	$12,982,128.52	$12,853,592.60	$12,726,329.30	$12,600,326.04	$12,475,570.34	$12,352,049.84	$12,229,752.32	$127,878,268.09
Small Area (5 Km2)	Cost	$768.00	$166.34	$164.69	$163.06	$161.44	$159.85	$158.26	$156.70	$155.15	$153.61	
Large coverage per base station	High Unit Price Revenue	$837,054.00	$828,766.34	$820,560.73	$812,436.37	$804,392.44	$796,428.16	$788,542.73	$780,735.38	$773,005.33	$765,351.81	
	High Unit Price Profits	$836,286.00	$828,600.00	$820,396.04	$812,273.31	$804,231.00	$796,268.31	$788,384.47	$780,578.68	$772,850.18	$765,198.20	$8,005,066.19
	Low Unit price Revenue	$83,705.40	$82,876.63	$82,056.07	$81,243.64	$80,439.24	$79,642.82	$78,854.27	$78,073.54	$77,300.53	$76,535.18	
	Low unit price Profits	$82,937.40	$82,710.30	$81,891.38	$81,080.58	$80,277.80	$79,482.97	$78,696.01	$77,916.84	$77,145.39	$76,381.57	$798,520.24
	High Unit Price Demand Change Revenue	279018	276255.4455	273520.2431	270812.1219	268130.8138	265476.0532	262847.5775	260245.1262	257668.4418	255117.2691	
	High Unit Price Demand Change Profits	$278,250.00	$276,089.11	$273,355.55	$270,649.06	$267,969.37	$265,316.21	$262,689.31	$260,088.43	$257,513.30	$254,963.66	$2,666,884.00

Figure 34: Profits for ASA in high ASA license availability

Urban Area	Year	0	1	2	3	4	5	6	7	8	9	
Large Area (350 Km2)	Cost	$214,200.00	$45,742.57	$45,289.68	$44,841.26	$44,397.29	$43,957.71	$43,522.49	$43,091.57	$42,664.92	$42,242.50	
	High Unit price Revenue	$12,997,208.70	$12,868,523.47	$12,741,112.34	$12,614,962.71	$12,490,062.09	$12,366,398.11	$12,243,958.53	$12,122,731.22	$12,002,704.17	$11,883,865.52	
	High Unit Price Profits	$12,783,008.70	$12,822,780.89	$12,695,822.66	$12,570,121.45	$12,445,664.80	$12,322,440.40	$12,200,436.04	$12,079,639.64	$11,960,039.25	$11,841,623.02	$123,721,576.85
	Low Unit price Revenue	$1,299,720.87	$1,286,852.35	$1,274,111.23	$1,261,496.27	$1,249,006.21	$1,236,639.81	$1,224,395.85	$1,212,273.12	$1,200,270.42	$1,188,386.55	
	Low unit price Profits	$1,085,520.87	$1,241,109.77	$1,228,821.56	$1,216,655.01	$1,204,608.92	$1,192,682.10	$1,180,873.36	$1,169,181.55	$1,157,605.49	$1,146,144.05	$11,823,202.67
Small Area (5 Km2)	Cost	$768.00	$166.34	$164.69	$163.06	$161.44	$159.85	$158.26	$156.70	$155.15	$153.61	
	High Unit Price Revenue	$123,722.10	$122,497.13	$121,284.29	$120,083.45	$118,894.51	$117,717.33	$116,551.81	$115,397.84	$114,255.28	$113,124.04	
	High Unit Price Profits	$122,954.10	$122,330.79	$121,119.60	$119,920.39	$118,733.06	$117,557.49	$116,393.55	$115,241.14	$114,100.14	$112,970.43	$1,181,320.69
	Low Unit price Revenue	$12,372.21	$12,249.71	$12,128.43	$12,008.35	$11,889.45	$11,771.73	$11,655.18	$11,539.78	$11,425.53	$11,312.40	
	Low unit price Profits	$11,604.21	$12,083.38	$11,963.74	$11,845.29	$11,728.01	$11,611.89	$11,496.92	$11,383.09	$11,270.38	$11,158.80	$116,145.69

Figure 35: Profits for ASA in low ASA license availability

		Year	0	1	2	3	4	5	6	7	8	9	Total Profits
City time varying	Large coverage	Cost	$144,144.00	$5,489.11	$5,434.76	$5,380.95	$5,327.68	$5,274.93	$5,222.70	$5,170.99	$5,119.79	$5,069.10	
	Best case	High Constant Demand Revenue	$215,550.72	$213,416.55	$211,303.52	$209,211.41	$207,140.01	$205,089.11	$203,058.53	$201,048.05	$199,057.47	$197,086.61	
		High Constant Demand Profits	$71,406.72	$207,927.45	$205,868.76	$203,830.45	$201,812.33	$199,814.19	$197,835.83	$195,877.06	$193,937.68	$192,017.51	$1,870,327.97
	Demand Change	High Unit Price Revenue	$71,850.20	$71,138.81	$70,434.47	$69,737.10	$69,046.63	$68,363.00	$67,686.14	$67,015.98	$66,352.45	$65,695.50	
		High Unit Price Profits	-$72,293.80	$65,649.70	$64,999.71	$64,356.14	$63,718.95	$63,088.07	$62,463.44	$61,844.99	$61,232.66	$60,626.40	$495,686.27
	Worst case	High Constant Demand Revenue	$778.38	$770.67	$763.04	$755.49	$748.01	$740.60	$733.27	$726.01	$718.82	$711.70	
		High Constant Demand Profits	-$143,365.62	-$4,718.44	-$4,671.72	-$4,625.47	-$4,579.67	-$4,534.33	-$4,489.43	-$4,444.98	-$4,400.97	-$4,357.40	-$184,188.03
City constant arrival	Large coverage	Cost	$144,144.00	$5,489.11	$5,434.76	$5,380.95	$5,327.68	$5,274.93	$5,222.70	$5,170.99	$5,119.79	$5,069.10	
	Best case	High Constant Demand Revenue	$215,550.72	$213,416.55	$211,303.52	$209,211.41	$207,140.01	$205,089.11	$203,058.53	$201,048.05	$199,057.47	$197,086.61	
		High Constant Demand Profits	$71,406.72	$207,927.45	$205,868.76	$203,830.45	$201,812.33	$199,814.19	$197,835.83	$195,877.06	$193,937.68	$192,017.51	$1,870,327.97
	Demand Change	High Unit Price Revenue	$71,850.20	$71,138.81	$70,434.47	$69,737.10	$69,046.63	$68,363.00	$67,686.14	$67,015.98	$66,352.45	$65,695.50	
		High Unit Price Profits	-$72,293.80	$65,649.70	$64,999.71	$64,356.14	$63,718.95	$63,088.07	$62,463.44	$61,844.99	$61,232.66	$60,626.40	$495,686.27
	Worst case	High Constant Demand Revenue	$778.38	$770.67	$763.04	$755.49	$748.01	$740.60	$733.27	$726.01	$718.82	$711.70	
		High Constant Demand Profits	-$143,365.62	-$4,718.44	-$4,671.72	-$4,625.47	-$4,579.67	-$4,534.33	-$4,489.43	-$4,444.98	-$4,400.97	-$4,357.40	-$184,188.03
City time varying	Small coverage	Cost	$2,184.00	$83.17	$82.34	$81.53	$80.72	$79.92	$79.13	$78.35	$77.57	$76.80	
	Best case	High Constant Demand Revenue	$3,849.12	$3,811.01	$3,773.28	$3,735.92	$3,698.93	$3,662.31	$3,626.05	$3,590.14	$3,554.60	$3,519.40	
		High Constant Demand Profits	$1,665.12	$3,727.84	$3,690.93	$3,654.39	$3,618.21	$3,582.38	$3,546.91	$3,511.80	$3,477.03	$3,442.60	$33,917.20
	Demand Change	High Unit Price Revenue	$1,283.00	$1,270.30	$1,257.72	$1,245.27	$1,232.94	$1,220.73	$1,208.64	$1,196.68	$1,184.83	$1,173.10	
		High Unit Price Profits	-$901.00	$1,187.13	$1,175.37	$1,163.74	$1,152.22	$1,140.81	$1,129.51	$1,118.33	$1,107.26	$1,096.29	$9,369.66
	Worst case	High Constant Demand Revenue	$13.90	$13.76	$13.63	$13.49	$13.36	$13.22	$13.09	$12.96	$12.84	$12.71	
		High Constant Demand Profits	-$2,170.10	-$69.41	-$68.72	-$68.04	-$67.37	-$66.70	-$66.04	-$65.38	-$64.74	-$64.10	-$2,770.58
City constant arrival	Small coverage	Cost	$2,184.00	$83.17	$82.34	$81.53	$80.72	$79.92	$79.13	$78.35	$77.57	$76.80	
	Best case	High Constant Demand Revenue	$3,849.12	$3,811.01	$3,773.28	$3,735.92	$3,698.93	$3,662.31	$3,626.05	$3,590.14	$3,554.60	$3,519.40	
		High Constant Demand Profits	$1,665.12	$3,727.84	$3,690.93	$3,654.39	$3,618.21	$3,582.38	$3,546.91	$3,511.80	$3,477.03	$3,442.60	$33,917.20
	Demand Change	High Unit Price Revenue	$1,283.00	$1,270.30	$1,257.72	$1,245.27	$1,232.94	$1,220.73	$1,208.64	$1,196.68	$1,184.83	$1,173.10	
		High Unit Price Profits	-$901.00	$1,187.13	$1,175.37	$1,163.74	$1,152.22	$1,140.81	$1,129.51	$1,118.33	$1,107.26	$1,096.29	$9,369.66
	Worst case	High Constant Demand Revenue	$13.90	$13.76	$13.63	$13.49	$13.36	$13.22	$13.09	$12.96	$12.84	$12.71	
		High Constant Demand Profits	-$2,170.10	-$69.41	-$68.72	-$68.04	-$67.37	-$66.70	-$66.04	-$65.38	-$64.74	-$64.10	-$2,770.58

Figure 36: Profits for TVWS in urban area

		Year	0	1	2	3	4	5	6	7	8	9	Total Profits
Rural time varying arrival	Large coverage	Cost	$59,976.00	$2,352.48	$2,329.18	$2,306.12	$2,283.29	$2,260.68	$2,238.30	$2,216.14	$2,194.20	$2,172.47	
	Best case	Low Constant Demand Revenue	$62,145.79	$61,530.49	$60,921.27	$60,318.09	$59,720.88	$59,129.59	$58,544.15	$57,964.50	$57,390.60	$56,822.37	
		Low Constant Demand Profits	$2,169.79	$59,178.01	$58,592.09	$58,011.97	$57,437.60	$56,868.91	$56,305.85	$55,748.36	$55,196.40	$54,649.90	$514,158.88
	Demand Change	High Unit Price Revenue	$20,715.30	$20,510.20	$20,307.13	$20,106.07	$19,907.00	$19,709.90	$19,514.75	$19,321.53	$19,130.23	$18,940.82	
		High Unit Price Profits	-$39,260.70	$18,157.72	$17,977.94	$17,799.94	$17,623.71	$17,449.21	$17,276.45	$17,105.40	$16,936.04	$16,768.35	$117,834.07
	Worst case	Low Constant Demand Revenue	$1,035.76	$1,025.51	$1,015.35	$1,005.30	$995.35	$985.49	$975.74	$966.08	$956.51	$947.04	
		Low Constant Demand Profits	-$58,940.24	-$1,326.97	-$1,313.83	-$1,300.82	-$1,287.94	-$1,275.19	-$1,262.56	-$1,250.06	-$1,237.69	-$1,225.43	-$70,420.73
Rural constant arrival	Large coverage	Cost	$59,976.00	$2,352.48	$2,329.18	$2,306.12	$2,283.29	$2,260.68	$2,238.30	$2,216.14	$2,194.20	$2,172.47	
	Best case	Low Constant Demand Revenue	$62,145.79	$61,530.49	$60,921.27	$60,318.09	$59,720.88	$59,129.59	$58,544.15	$57,964.50	$57,390.60	$56,822.37	
		Low Constant Demand Profits	$2,169.79	$59,178.01	$58,592.09	$58,011.97	$57,437.60	$56,868.91	$56,305.85	$55,748.36	$55,196.40	$54,649.90	$514,158.88
	Demand Change	High Unit Price Revenue	$20,715.30	$20,510.20	$20,307.13	$20,106.07	$19,907.00	$19,709.90	$19,514.75	$19,321.53	$19,130.23	$18,940.82	
		High Unit Price Profits	-$39,260.70	$18,157.72	$17,977.94	$17,799.94	$17,623.71	$17,449.21	$17,276.45	$17,105.40	$16,936.04	$16,768.35	$117,834.07
	Worst case	Low Constant Demand Revenue	$1,035.76	$1,025.51	$1,015.35	$1,005.30	$995.35	$985.49	$975.74	$966.08	$956.51	$947.04	
		Low Constant Demand Profits	-$58,940.24	-$1,326.97	-$1,313.83	-$1,300.82	-$1,287.94	-$1,275.19	-$1,262.56	-$1,250.06	-$1,237.69	-$1,225.43	-$70,420.73
Rural time varying arrival	Small coverage	Cost	$2,184.00	$83.17	$82.34	$81.53	$80.72	$79.92	$79.13	$78.35	$77.57	$76.80	
	Best case	Low Constant Demand Revenue	$2,589.41	$2,563.77	$2,538.39	$2,513.25	$2,488.37	$2,463.73	$2,439.34	$2,415.19	$2,391.27	$2,367.60	
		Low Constant Demand Profits	$405.41	$2,480.60	$2,456.04	$2,431.72	$2,407.65	$2,383.81	$2,360.21	$2,336.84	$2,313.70	$2,290.79	$21,866.78
	Demand Change	High Unit Price Revenue	$863.14	$854.59	$846.13	$837.75	$829.46	$821.25	$813.11	$805.06	$797.09	$789.20	
		High Unit Price Profits	-$1,320.86	$771.42	$763.78	$756.22	$748.74	$741.32	$733.98	$726.72	$719.52	$712.40	$5,353.24
	Worst case	Low Constant Demand Revenue	$43.16	$42.73	$42.31	$41.89	$41.47	$41.06	$40.66	$40.25	$39.85	$39.46	
		Low Constant Demand Profits	-$2,140.84	-$40.44	-$40.04	-$39.64	-$39.25	-$38.86	-$38.48	-$38.10	-$37.72	-$37.34	-$2,490.71
Rural constant arrival	Small coverage	Cost	$2,184.00	$83.17	$82.34	$81.53	$80.72	$79.92	$79.13	$78.35	$77.57	$76.80	
	Best case	Low Constant Demand Revenue	$2,589.41	$2,563.77	$2,538.39	$2,513.25	$2,488.37	$2,463.73	$2,439.34	$2,415.19	$2,391.27	$2,367.60	
		Low Constant Demand Profits	$405.41	$2,480.60	$2,456.04	$2,431.72	$2,407.65	$2,383.81	$2,360.21	$2,336.84	$2,313.70	$2,290.79	$21,866.78
	Demand Change	High Unit Price Revenue	$863.14	$854.59	$846.13	$837.75	$829.46	$821.25	$813.11	$805.06	$797.09	$789.20	
		High Unit Price Profits	-$1,320.86	$771.42	$763.78	$756.22	$748.74	$741.32	$733.98	$726.72	$719.52	$712.40	$5,353.24
	Worst case	Low Constant Demand Revenue	$43.16	$42.73	$42.31	$41.89	$41.47	$41.06	$40.66	$40.25	$39.85	$39.46	
		Low Constant Demand Profits	-$2,140.84	-$40.44	-$40.04	-$39.64	-$39.25	-$38.86	-$38.48	-$38.10	-$37.72	-$37.34	-$2,490.71

Figure 37: Profits for TVWS in rural area

		Year	0	1	2	3	4	5	6	7	8	9	Total Profits
City constant	Large coverage	Cost	$1,526,800.00	$41,584.16	$41,172.43	$40,764.79	$40,361.17	$39,961.56	$39,565.90	$39,174.16	$38,786.30	$38,402.27	
		High Constant Demand Revenue	$215,550.72	$213,416.55	$211,303.52	$209,211.41	$207,140.01	$205,089.11	$203,058.53	$201,048.05	$199,057.47	$197,086.61	
	Best case	High Constant Demand Profits	-$1,311,249.28	$171,832.40	$170,131.09	$168,446.62	$166,778.83	$165,127.56	$163,492.63	$161,873.89	$160,271.18	$158,684.33	$175,389.24
		High Unit Price Revenue	$71,850.20	$71,138.81	$70,434.47	$69,737.10	$69,046.63	$68,363.00	$67,686.14	$67,015.98	$66,352.45	$65,695.50	
	Demand Change	High Unit Price Profits	-$1,454,949.80	$29,554.65	$29,262.03	$28,972.31	$28,685.46	$28,401.44	$28,120.24	$27,841.82	$27,566.16	$27,293.23	-$1,199,252.46
		High Constant Demand Revenue	$1,676.51	$1,659.91	$1,643.47	$1,627.20	$1,611.09	$1,595.14	$1,579.34	$1,563.71	$1,548.22	$1,532.90	
	Worst case	High Constant Demand Profits	-$1,525,123.49	-$39,924.25	-$39,528.96	-$39,137.59	-$38,750.09	-$38,366.42	-$37,986.56	-$37,610.45	-$37,238.07	-$36,869.38	-$1,870,535.26
	Higher number of		$3,592.51	$3,556.94	$3,521.73	$3,486.86	$3,452.33	$3,418.15	$3,384.31	$3,350.80	$3,317.62	$3,284.78	
	available channel		-$1,523,207.49	-$38,027.22	-$37,650.71	-$37,277.93	-$36,908.84	-$36,543.41	-$36,181.59	-$35,823.36	-$35,468.67	-$35,117.50	
	Small coverage	Cost	$177,400.00	$594.06	$588.18	$582.35	$576.59	$570.88	$565.23	$559.63	$554.09	$548.60	
		High Constant Demand Revenue	$3,849.12	$3,811.01	$3,773.28	$3,735.92	$3,698.93	$3,662.31	$3,626.05	$3,590.14	$3,554.60	$3,519.40	
	Best case	High Constant Demand Profits	-$173,550.88	$3,216.95	$3,185.10	$3,153.56	$3,122.34	$3,091.43	$3,060.82	$3,030.51	$3,000.51	$2,970.80	-$145,718.86
		High Unit Price Revenue	$1,283.04	$1,270.34	$1,257.76	$1,245.31	$1,232.98	$1,220.77	$1,208.68	$1,196.71	$1,184.87	$1,173.13	
	Demand Change	High Unit Price Profits	-$176,116.96	$676.28	$669.58	$662.95	$656.39	$649.89	$643.45	$637.08	$630.78	$624.53	-$170,266.03
		High Constant Demand Revenue	$29.94	$29.64	$29.35	$29.06	$28.77	$28.48	$28.20	$27.92	$27.65	$27.37	
	Worst case	High Constant Demand Profits	-$177,370.06	-$564.42	-$558.83	-$553.30	-$547.82	-$542.39	-$537.02	-$531.71	-$526.44	-$521.23	-$182,253.23
City time varying	Large coverage	Cost	$1,526,800.00	$41,584.16	$41,172.43	$40,764.79	$40,361.17	$39,961.56	$39,565.90	$39,174.16	$38,786.30	$38,402.27	
		High Constant Demand Revenue	$215,550.72	$213,416.55	$211,303.52	$209,211.41	$207,140.01	$205,089.11	$203,058.53	$201,048.05	$199,057.47	$197,086.61	
	Best case	High Constant Demand Profits	-$1,311,249.28	$171,832.40	$170,131.09	$168,446.62	$166,778.83	$165,127.56	$163,492.63	$161,873.89	$160,271.18	$158,684.33	$175,389.24
		High Unit Price Revenue	$71,850.20	$71,138.81	$70,434.47	$69,737.10	$69,046.63	$68,363.00	$67,686.14	$67,015.98	$66,352.45	$65,695.50	
	Demand Change	High Unit Price Profits	-$1,454,949.80	$29,554.65	$29,262.03	$28,972.31	$28,685.46	$28,401.44	$28,120.24	$27,841.82	$27,566.16	$27,293.23	-$1,199,252.46
		High Constant Demand Revenue	$1,676.51	$1,659.91	$1,643.47	$1,627.20	$1,611.09	$1,595.14	$1,579.34	$1,563.71	$1,548.22	$1,532.90	
	Worst case	High Constant Demand Profits	-$1,525,123.49	-$39,924.25	-$39,528.96	-$39,137.59	-$38,750.09	-$38,366.42	-$37,986.56	-$37,610.45	-$37,238.07	-$36,869.38	-$1,870,535.26
	Small coverage	Cost	$177,400.00	$594.06	$588.18	$582.35	$576.59	$570.88	$565.23	$559.63	$554.09	$548.60	
		High Constant Demand Revenue	$3,849.12	$3,811.01	$3,773.28	$3,735.92	$3,698.93	$3,662.31	$3,626.05	$3,590.14	$3,554.60	$3,519.40	
	Best case	High Constant Demand Profits	-$173,550.88	$3,216.95	$3,185.10	$3,153.56	$3,122.34	$3,091.43	$3,060.82	$3,030.51	$3,000.51	$2,970.80	-$145,718.86
		High Unit Price Revenue	$1,283.04	$1,270.34	$1,257.76	$1,245.31	$1,232.98	$1,220.77	$1,208.68	$1,196.71	$1,184.87	$1,173.13	
	Demand Change	High Unit Price Profits	-$176,116.96	$676.28	$669.58	$662.95	$656.39	$649.89	$643.45	$637.08	$630.78	$624.53	-$170,266.03
		High Constant Demand Revenue	$29.94	$29.64	$29.35	$29.06	$28.77	$28.48	$28.20	$27.92	$27.65	$27.37	
	worst case	High Constant Demand Profits	-$177,370.06	-$564.42	-$558.83	-$553.30	-$547.82	-$542.39	-$537.02	-$531.71	-$526.44	-$521.23	-$182,253.23

Figure 38: Profits for CR based DSA in urban area

		Year	0	1	2	3	4	5	6	7	8	9	Total Profits
Rural constant	Large coverage	Cost	$677,200.00	$17,821.78	$17,645.33	$17,470.62	$17,297.65	$17,126.38	$16,956.81	$16,788.92	$16,622.70	$16,458.12	
		Low Constant Demand Revenue	$62,145.79	$61,530.49	$60,921.27	$60,318.09	$59,720.88	$59,129.59	$58,544.15	$57,964.50	$57,390.60	$56,822.37	
	Best case	Low Constant Demand Profits	-$615,054.21	$43,708.70	$43,275.95	$42,847.47	$42,423.24	$42,003.21	$41,587.33	$41,175.58	$40,767.90	$40,364.26	-$236,900.58
		High Unit Price Revenue	$20,715.30	$20,510.20	$20,307.13	$20,106.07	$19,907.00	$19,709.90	$19,514.75	$19,321.53	$19,130.23	$18,940.82	
	Demand Change	High Unit Price Profits	-$656,484.70	$2,688.42	$2,661.80	$2,635.44	$2,609.35	$2,583.51	$2,557.94	$2,532.61	$2,507.53	$2,482.71	-$633,225.39
		Low Constant Demand Revenue	$1,035.76	$1,025.51	$1,015.35	$1,005.30	$995.35	$985.49	$975.74	$966.08	$956.51	$947.04	
	Worst case	Low Constant Demand Profits	-$676,164.24	-$16,796.27	-$16,629.97	-$16,465.32	-$16,302.30	-$16,140.89	-$15,981.08	-$15,822.85	-$15,666.19	-$15,511.08	-$821,480.19
	Small coverage	Cost	$177,400.00	$594.06	$588.18	$582.35	$576.59	$570.88	$565.23	$559.63	$554.09	$548.60	
		Low Constant Demand Revenue	$2,589.41	$2,563.77	$2,538.39	$2,513.25	$2,488.37	$2,463.73	$2,439.34	$2,415.19	$2,391.27	$2,367.60	
	Best case	Low Constant Demand Profits	-$174,810.59	$1,969.71	$1,950.21	$1,930.90	$1,911.78	$1,892.85	$1,874.11	$1,855.56	$1,837.18	$1,818.99	-$157,769.29
		High Unit Price Revenue	$863.14	$854.59	$846.13	$837.75	$829.46	$821.25	$813.11	$805.06	$797.09	$789.20	
	Demand Change	High Unit Price Profits	-$176,536.86	$260.53	$257.95	$255.40	$252.87	$250.37	$247.89	$245.43	$243.00	$240.60	-$174,282.83
		Low Constant Demand Revenue	$43.16	$42.73	$42.31	$41.89	$41.47	$41.06	$40.66	$40.25	$39.85	$39.46	
	Worst case	Low Constant Demand Profits	-$177,356.84	-$551.33	-$545.87	-$540.47	-$535.12	-$529.82	-$524.57	-$519.38	-$514.24	-$509.14	-$182,126.77
Rural time varying	Large coverage	Cost	$677,200.00	$17,821.78	$17,645.33	$17,470.62	$17,297.65	$17,126.38	$16,956.81	$16,788.92	$16,622.70	$16,458.12	
		Low Constant Demand Revenue	$62,145.79	$61,530.49	$60,921.27	$60,318.09	$59,720.88	$59,129.59	$58,544.15	$57,964.50	$57,390.60	$56,822.37	
	Best case	Low Constant Demand Profits	-$615,054.21	$43,708.70	$43,275.95	$42,847.47	$42,423.24	$42,003.21	$41,587.33	$41,175.58	$40,767.90	$40,364.26	-$236,900.58
		High Unit Price Revenue	$20,715.30	$20,510.20	$20,307.13	$20,106.07	$19,907.00	$19,709.90	$19,514.75	$19,321.53	$19,130.23	$18,940.82	
	Demand Change	High Unit Price Profits	-$656,484.70	$2,688.42	$2,661.80	$2,635.44	$2,609.35	$2,583.51	$2,557.94	$2,532.61	$2,507.53	$2,482.71	-$633,225.39
		Low Constant Demand Revenue	$1,035.76	$1,025.51	$1,015.35	$1,005.30	$995.35	$985.49	$975.74	$966.08	$956.51	$947.04	
	Worst case	Low Constant Demand Profits	-$676,164.24	-$16,796.27	-$16,629.97	-$16,465.32	-$16,302.30	-$16,140.89	-$15,981.08	-$15,822.85	-$15,666.19	-$15,511.08	-$821,480.19
	Small coverage	Cost	$177,400.00	$594.06	$588.18	$582.35	$576.59	$570.88	$565.23	$559.63	$554.09	$548.60	
		Low Constant Demand Revenue	$2,589.41	$2,563.77	$2,538.39	$2,513.25	$2,488.37	$2,463.73	$2,439.34	$2,415.19	$2,391.27	$2,367.60	
	Best case	Low Constant Demand Profits	-$174,810.59	$1,969.71	$1,950.21	$1,930.90	$1,911.78	$1,892.85	$1,874.11	$1,855.56	$1,837.18	$1,818.99	-$157,769.29
		High Unit Price Revenue	$863.14	$854.59	$846.13	$837.75	$829.46	$821.25	$813.11	$805.06	$797.09	$789.20	
	Demand Change	High Unit Price Profits	-$176,536.86	$260.53	$257.95	$255.40	$252.87	$250.37	$247.89	$245.43	$243.00	$240.60	-$174,282.83
		Low Constant Demand Revenue	$43.16	$42.73	$42.31	$41.89	$41.47	$41.06	$40.66	$40.25	$39.85	$39.46	
	Worst case	Low Constant Demand Profits	-$177,356.84	-$551.33	-$545.87	-$540.47	-$535.12	-$529.82	-$524.57	-$519.38	-$514.24	-$509.14	-$182,126.77

Figure 39: Profits for CR based DSA in rural area

		Year	0	1	2	3	4	5	6	7	8	9	Total Profits
City constant arrival	Large coverage	Cost	$94,552.00	$5,299.01	$5,246.54	$5,194.60	$5,143.17	$5,092.24	$5,041.83	$4,991.91	$4,942.48	$4,893.55	
	Best case	High Constant Demand Revenue	$214,588.44	$212,463.80	$210,360.20	$208,277.43	$206,215.27	$204,173.54	$202,152.02	$200,150.51	$198,168.82	$196,206.76	
		High Constant Demand Profits	$120,036.44	$207,164.79	$205,113.66	$203,082.83	$201,072.11	$199,081.29	$197,110.19	$195,158.61	$193,226.34	$191,313.21	$1,912,359.46
	Demand Change	High Unit Price Revenue	$71,529.50	$70,821.29	$70,120.09	$69,425.83	$68,738.44	$68,057.86	$67,384.02	$66,716.86	$66,056.29	$65,402.27	
		High Unit Price Profits	-$23,022.50	$65,522.28	$64,873.54	$64,231.23	$63,595.28	$62,965.62	$62,342.20	$61,724.95	$61,113.81	$60,508.72	$543,855.13
	Worst case	High Constant Demand Revenue	$214,588.44	$212,463.80	$210,360.20	$208,277.43	$206,215.27	$204,173.54	$202,152.02	$200,150.51	$198,168.82	$196,206.76	
		High Constant Demand Profits	$120,036.44	$207,164.79	$205,113.66	$203,082.83	$201,072.11	$199,081.29	$197,110.19	$195,158.61	$193,226.34	$191,313.21	$1,912,359.46
	Small coverage	Cost	$1,484.00	$83.17	$82.34	$81.53	$80.72	$79.92	$79.13	$78.35	$77.57	$76.80	
	Best case	High Constant Demand Revenue	$3,367.98	$3,334.63	$3,301.62	$3,268.93	$3,236.56	$3,204.52	$3,172.79	$3,141.38	$3,110.27	$3,079.48	
		High Constant Demand Profits	$1,883.98	$3,251.47	$3,219.27	$3,187.40	$3,155.84	$3,124.59	$3,093.66	$3,063.03	$3,032.70	$3,002.67	$30,014.61
	Demand Change	High Unit Price Revenue	$1,122.66	$1,111.54	$1,100.54	$1,089.64	$1,078.85	$1,068.17	$1,057.60	$1,047.13	$1,036.76	$1,026.49	
		High Unit Price Profits	-$361.34	$1,028.38	$1,018.19	$1,008.11	$998.13	$988.25	$978.46	$968.78	$959.19	$949.69	$8,535.84
	Worst case	High Constant Demand Revenue	$3,367.98	$3,334.63	$3,301.62	$3,268.93	$3,236.56	$3,204.52	$3,172.79	$3,141.38	$3,110.27	$3,079.48	
		High Constant Demand Profits	$1,883.98	$3,251.47	$3,219.27	$3,187.40	$3,155.84	$3,124.59	$3,093.66	$3,063.03	$3,032.70	$3,002.67	$30,014.61
City time varying	Large coverage	Cost	$94,552.00	$5,299.01	$5,246.54	$5,194.60	$5,143.17	$5,092.24	$5,041.83	$4,991.91	$4,942.48	$4,893.55	
	Best case	High Constant Demand Revenue	$214,588.44	$212,463.80	$210,360.20	$208,277.43	$206,215.27	$204,173.54	$202,152.02	$200,150.51	$198,168.82	$196,206.76	
		High Constant Demand Profits	$120,036.44	$207,164.79	$205,113.66	$203,082.83	$201,072.11	$199,081.29	$197,110.19	$195,158.61	$193,226.34	$191,313.21	$1,912,359.46
	Demand Change	High Unit Price Revenue	$71,529.50	$70,821.29	$70,120.09	$69,425.83	$68,738.44	$68,057.86	$67,384.02	$66,716.86	$66,056.29	$65,402.27	
		High Unit Price Profits	-$23,022.50	$65,522.28	$64,873.54	$64,231.23	$63,595.28	$62,965.62	$62,342.20	$61,724.95	$61,113.81	$60,508.72	$543,855.13
	Worst case	High Constant Demand Revenue	$214,588.44	$212,463.80	$210,360.20	$208,277.43	$206,215.27	$204,173.54	$202,152.02	$200,150.51	$198,168.82	$196,206.76	
		High Constant Demand Profits	$120,036.44	$207,164.79	$205,113.66	$203,082.83	$201,072.11	$199,081.29	$197,110.19	$195,158.61	$193,226.34	$191,313.21	$1,912,359.46
	Small coverage	Cost	$1,484.00	$83.17	$82.34	$81.53	$80.72	$79.92	$79.13	$78.35	$77.57	$76.80	
	Best case	High Constant Demand Revenue	$3,367.98	$3,334.63	$3,301.62	$3,268.93	$3,236.56	$3,204.52	$3,172.79	$3,141.38	$3,110.27	$3,079.48	
		High Constant Demand Profits	$1,883.98	$3,251.47	$3,219.27	$3,187.40	$3,155.84	$3,124.59	$3,093.66	$3,063.03	$3,032.70	$3,002.67	$30,014.61
	Demand Change	High Unit Price Revenue	$1,122.66	$1,111.54	$1,100.54	$1,089.64	$1,078.85	$1,068.17	$1,057.60	$1,047.13	$1,036.76	$1,026.49	
		High Unit Price Profits	-$361.34	$1,028.38	$1,018.19	$1,008.11	$998.13	$988.25	$978.46	$968.78	$959.19	$949.69	$8,535.84
	Worst case	High Constant Demand Revenue	$3,367.98	$3,334.63	$3,301.62	$3,268.93	$3,236.56	$3,204.52	$3,172.79	$3,141.38	$3,110.27	$3,079.48	
		High Constant Demand Profits	$1,883.98	$3,251.47	$3,219.27	$3,187.40	$3,155.84	$3,124.59	$3,093.66	$3,063.03	$3,032.70	$3,002.67	$30,014.61

Figure 40: Profits for ISM in urban area

		Year	0	1	2	3	4	5	6	7	8	9	Total Profits
Rural constant arrival	Large coverage	Cost	$40,704.00	$2,281.19	$2,258.60	$2,236.24	$2,214.10	$2,192.18	$2,170.47	$2,148.98	$2,127.71	$2,106.64	
	Best case	Low Constant Demand Revenue	$62,145.79	$61,530.49	$60,921.27	$60,318.09	$59,720.88	$59,129.59	$58,544.15	$57,964.50	$57,390.60	$56,822.37	
		Low Constant Demand Profits	$21,441.79	$59,249.30	$58,662.67	$58,081.85	$57,506.79	$56,937.41	$56,373.68	$55,815.52	$55,262.89	$54,715.73	$534,047.63
	Demand Change	High Unit Price Revenue	$20,715.30	$20,510.20	$20,307.13	$20,106.07	$19,907.00	$19,709.90	$19,514.75	$19,321.53	$19,130.23	$18,940.82	
		High Unit Price Profits	-$19,988.70	$18,229.01	$18,048.52	$17,869.83	$17,692.90	$17,517.72	$17,344.28	$17,172.55	$17,002.53	$16,834.18	$137,722.82
	Worst case	Low Constant Demand Revenue	$62,145.79	$61,530.49	$60,921.27	$60,318.09	$59,720.88	$59,129.59	$58,544.15	$57,964.50	$57,390.60	$56,822.37	
		Low Constant Demand Profits	$21,441.79	$59,249.30	$58,662.67	$58,081.85	$57,506.79	$56,937.41	$56,373.68	$55,815.52	$55,262.89	$54,715.73	$534,047.63
	Small coverage	Cost	$1,484.00	$83.17	$82.34	$81.53	$80.72	$79.92	$79.13	$78.35	$77.57	$76.80	
	Best case	Low Constant Demand Revenue	$2,265.73	$2,243.30	$2,221.09	$2,199.10	$2,177.32	$2,155.77	$2,134.42	$2,113.29	$2,092.37	$2,071.65	
		Low Constant Demand Profits	$781.73	$2,160.13	$2,138.74	$2,117.57	$2,096.60	$2,075.84	$2,055.29	$2,034.94	$2,014.79	$1,994.84	$19,470.49
	Demand Change	High Unit Price Revenue	$755.24	$747.77	$740.36	$733.03	$725.77	$718.59	$711.47	$704.43	$697.45	$690.55	
		High Unit Price Profits	-$728.76	$664.60	$658.02	$651.50	$645.05	$638.66	$632.34	$626.08	$619.88	$613.74	$5,021.12
	Worst case	Low Constant Demand Revenue	$2,265.73	$2,243.30	$2,221.09	$2,199.10	$2,177.32	$2,155.77	$2,134.42	$2,113.29	$2,092.37	$2,071.65	
		Low Constant Demand Profits	$781.73	$2,160.13	$2,138.74	$2,117.57	$2,096.60	$2,075.84	$2,055.29	$2,034.94	$2,014.79	$1,994.84	$19,470.49
Rural time varying	Large coverage	Cost	$40,704.00	$2,281.19	$2,258.60	$2,236.24	$2,214.10	$2,192.18	$2,170.47	$2,148.98	$2,127.71	$2,106.64	
	Best case	Low Constant Demand Revenue	$62,145.79	$61,530.49	$60,921.27	$60,318.09	$59,720.88	$59,129.59	$58,544.15	$57,964.50	$57,390.60	$56,822.37	
		Low Constant Demand Profits	$21,441.79	$59,249.30	$58,662.67	$58,081.85	$57,506.79	$56,937.41	$56,373.68	$55,815.52	$55,262.89	$54,715.73	$534,047.63
	Demand Change	High Unit Price Revenue	$20,715.30	$20,510.20	$20,307.13	$20,106.07	$19,907.00	$19,709.90	$19,514.75	$19,321.53	$19,130.23	$18,940.82	
		High Unit Price Profits	-$19,988.70	$18,229.01	$18,048.52	$17,869.83	$17,692.90	$17,517.72	$17,344.28	$17,172.55	$17,002.53	$16,834.18	$137,722.82
	Worst case	Low Constant Demand Revenue	$62,145.79	$61,530.49	$60,921.27	$60,318.09	$59,720.88	$59,129.59	$58,544.15	$57,964.50	$57,390.60	$56,822.37	
		Low Constant Demand Profits	$21,441.79	$59,249.30	$58,662.67	$58,081.85	$57,506.79	$56,937.41	$56,373.68	$55,815.52	$55,262.89	$54,715.73	$534,047.63
	Small coverage	Cost	$1,484.00	$83.17	$82.34	$81.53	$80.72	$79.92	$79.13	$78.35	$77.57	$76.80	
	Best case	Low Constant Demand Revenue	$2,265.73	$2,243.30	$2,221.09	$2,199.10	$2,177.32	$2,155.77	$2,134.42	$2,113.29	$2,092.37	$2,071.65	
		Low Constant Demand Profits	$781.73	$2,160.13	$2,138.74	$2,117.57	$2,096.60	$2,075.84	$2,055.29	$2,034.94	$2,014.79	$1,994.84	$19,470.49
	Demand Change	High Unit Price Revenue	$755.24	$747.77	$740.36	$733.03	$725.77	$718.59	$711.47	$704.43	$697.45	$690.55	
		High Unit Price Profits	-$728.76	$664.60	$658.02	$651.50	$645.05	$638.66	$632.34	$626.08	$619.88	$613.74	$5,021.12
	Worst case	Low Constant Demand Revenue	$2,265.73	$2,243.30	$2,221.09	$2,199.10	$2,177.32	$2,155.77	$2,134.42	$2,113.29	$2,092.37	$2,071.65	
		Low Constant Demand Profits	$781.73	$2,160.13	$2,138.74	$2,117.57	$2,096.60	$2,075.84	$2,055.29	$2,034.94	$2,014.79	$1,994.84	$19,470.49

Figure 41: Profits for ISM in rural area

APPENDIX D

THROUGHPUT IN DYNAMIC SHARING

	Self	Others	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
City	Time varying	constant	659.7242	659.7242	2019.328	6472.147	13315.99	9285.084	3135.871	979.4741	356.0157	158.1416	86.53358	58.18765	47.61067	46.33985	51.20681	59.19032	64.43397	61.83104	54.03996	47.54583	46.27676	52.84793	72.97014	123.5091
		time varying	1737.626	1737.626	9644.603	54726.86	149113.9	91459.71	18747.11	3194.533	666.182	184.9319	69.81375	36.23452	25.86232	24.70421	29.24424	37.28306	42.94205	40.09648	32.01489	25.80275	24.64722	30.83793	52.76103	124.3873
		both	419.1432	419.1432	1538.269	5541.802	11956.17	8156.993	2514.401	669.8926	196.5743	68.59964	29.80641	16.72566	12.36216	11.86151	13.80759	17.15612	19.45021	18.3026	14.97474	12.33648	11.83679	14.48072	23.32741	49.03237
	Constant	constant	122.0877	122.0877	122.0877	122.0877	122.0877	122.0877	122.0877	122.0877	122.0877	122.0877	122.0877	122.0877	122.0877	122.0877	122.0877	122.0877	122.0877	122.0877	122.0877	122.0877	122.0877	122.0877	122.0877	122.0877
		time varying	321.9698	321.9698	588.0177	1086.963	1589.769	1314.292	742.2581	399.2024	228.5331	142.7723	98.5003	76.03333	66.32822	65.09609	69.7331	76.90798	81.37112	79.17827	72.33645	66.26574	65.0345	71.2492	88.27958	122.9557
		both	77.52955	77.52955	92.92736	104.3998	109.4252	107.0901	97.79615	83.45086	67.39026	52.95578	42.05772	35.10234	31.7109	31.26142	32.93029	35.39558	36.86176	36.14761	33.84077	31.68821	31.23884	33.46278	39.03625	48.46788
Rural	Time varying	constant	608.9835	608.9835	610.31	609.9823	607.1916	596.7476	567.5577	508.6053	426.353	348.4431	299.8744	289.4357	315.7266	365.8407	403.4898	390.8307	341.5353	299.478	289.4287	317.6778	381.7786	465.5986	539.6253	584.192
		time varying	742.576	742.576	745.1038	744.479	739.1662	719.4001	665.1514	560.189	424.5949	308.7807	243.3661	230.0336	264.1132	333.5152	389.2825	370.1956	299.1466	242.855	230.0246	266.708	356.7544	487.6598	614.6388	695.8852
		both	292.5116	292.5116	293.3365	293.1327	291.398	284.9217	266.9558	231.3184	183.235	139.7993	113.9837	108.5813	122.2903	149.2968	170.2557	163.149	136.0633	113.7775	108.5777	123.321	158.1037	205.92	249.9582	277.1693
	Constant	constant	429.4322	429.4322	429.4322	429.4322	429.4322	429.4322	429.4322	429.4322	429.4322	429.4322	429.4322	429.4322	429.4322	429.4322	429.4322	429.4322	429.4322	429.4322	429.4322	429.4322	429.4322	429.4322	429.4322	429.4322
		time varying	523.6655	523.6655	524.3064	524.1481	522.7986	517.7206	503.2917	472.9915	427.6614	380.5567	348.5244	341.3146	359.2419	391.4913	414.3119	406.7603	376.141	348.2528	341.3096	360.5426	401.2864	449.7809	489.1385	511.5578
		both	206.2325	206.2325	206.3643	206.3318	206.054	205.0023	201.9595	195.2934	184.559	172.3108	163.2582	161.1322	166.3571	175.2618	181.2078	179.2712	171.0996	163.1788	161.1307	166.7283	177.8485	189.9172	198.8936	203.7127

Figure 42: Throughput for TVWS

	Self	Others	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
City	Time varying	constant	398.1325	398.1325	398.6284	398.9213	399.0339	398.9826	398.7594	398.3399	397.7152	396.9302	396.1046	395.4104	395.0043	394.9464	395.1563	395.4431	395.6019	395.5256	395.2653	395.0014	394.9434	395.2205	395.8229	396.6212
		time varying	2169.002	2169.002	6690.286	21590.5	44418.43	30997.99	10420.34	3228.937	1165.604	514.7688	280.2902	187.7657	153.3091	149.1724	165.0191	191.0344	208.134	199.6447	174.2485	153.0981	148.9671	170.3649	235.9891	401.2609
		both	194.291	194.291	257.0682	309.3719	333.7729	322.322	278.6881	217.4266	157.59	111.6793	81.9348	65.15396	57.59119	56.61924	60.26376	65.82691	69.23716	67.56662	62.2934	57.54196	56.57059	61.44725	74.4348	98.91887
	Constant	constant	396.6058	396.6058	396.6058	396.6058	396.6058	396.6058	396.6058	396.6058	396.6058	396.6058	396.6058	396.6058	396.6058	396.6058	396.6058	396.6058	396.6058	396.6058	396.6058	396.6058	396.6058	396.6058	396.6058	396.6058
		time varying	2149.868	2149.868	6555.007	20715.26	41782.34	29470.83	10142.55	3189.649	1160.088	514.2908	280.5895	188.1598	153.7001	149.5615	165.4137	191.4276	208.5195	200.0346	174.6441	153.489	149.356	170.7603	236.3513	401.2452
		both	193.7661	193.7661	256.0154	307.7859	331.9116	320.5919	277.4247	216.7223	157.3102	111.6301	81.98295	65.23593	57.6828	56.71182	60.35239	65.90784	69.31242	67.64475	62.37944	57.63362	56.66322	61.5344	74.50009	98.91691
Rural	Time varying	constant	880.2279	880.2279	880.2333	880.232	880.2206	880.1773	880.0498	879.7599	879.2592	878.6302	878.1198	877.9938	878.2993	878.7878	879.0935	878.9957	878.5643	878.1152	877.9937	878.3204	878.9227	879.5146	879.9184	880.1236
		time varying	1250.067	1250.067	1252.81	1252.132	1246.363	1224.772	1164.442	1042.668	872.9299	712.3574	612.3743	590.8986	644.9967	748.1949	825.7868	799.6918	698.1313	611.5586	590.884	649.0129	781.0356	953.8924	1106.732	1198.82
		both	259.3786	259.3786	259.6397	259.5753	259.0251	256.9476	250.9823	238.152	218.1778	196.4212	181.049	177.5261	186.2435	201.5624	212.1156	208.6499	194.3296	180.9168	177.5237	186.8705	206.1213	228.0422	245.0407	254.411
	Constant	constant	879.2805	879.2805	879.2805	879.2805	879.2805	879.2805	879.2805	879.2805	879.2805	879.2805	879.2805	879.2805	879.2805	879.2805	879.2805	879.2805	879.2805	879.2805	879.2805	879.2805	879.2805	879.2805	879.2805	879.2805
		time varying	1248.467	1248.467	1251.196	1250.522	1244.782	1223.303	1163.273	1042.05	872.9509	712.8328	613.0517	591.6107	645.6154	748.5823	825.9571	799.939	698.6394	612.2374	591.5962	649.6239	781.3354	953.6281	1105.834	1197.482
		both	259.2254	259.2254	259.4855	259.4213	258.8734	256.8046	250.8638	238.0837	218.1805	196.4909	181.1592	177.6447	186.3406	201.6172	212.138	208.6832	194.4051	181.0273	177.6423	186.966	206.1625	228.0109	244.9459	254.2786

Figure 43: Throughput for CR based DSA

	Self	Others	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
City	Time varying	constant	999996.3	999996.3	999996.4	999996.5	999996.5	999996.5	999996.5	999996.4	999996.2	999996	999995.8	999995.6	999995.5	999995.4	999995.5	999995.6	999995.6	999995.6	999995.5	999995.5	999995.4	999995.5	999995.7	999995.9
		time varying	1000000	1000000	1000000	1000000	1000000	1000000	1000000	1000000	1000000	999998.8	999981	999896.2	999762.8	999735.3	999823.8	999903.4	999932.4	999919.5	999858.9	999761.5	999733.9	999845.3	999960.2	999996.1
		both	999918.2	999918.2	999975.4	999989.2	999992.3	999991	999982.7	999949.2	999804.9	999230.5	997508.6	994241.9	991036.3	990475.2	992378.2	994451.5	995378.9	994950.9	993232	991008.9	990446	992891.4	996450.9	998772.9
	Constant	constant	999995.9	999995.9	999995.9	999995.9	999995.9	999995.9	999995.9	999995.9	999995.9	999995.9	999995.9	999995.9	999995.9	999995.9	999995.9	999995.9	999995.9	999995.9	999995.9	999995.9	999995.9	999995.9	999995.9	999995.9
		time varying	1000000	1000000	1000000	1000000	1000000	1000000	1000000	1000000	1000000	999998.7	999981.5	999901.4	999776.7	999751	999833.6	999908.1	999935.4	999923.3	999866.4	999775.4	999749.7	999853.6	999961.7	999996.1
		both	999912.5	999912.5	999972.7	999987.6	999991.1	999989.6	999980.6	999945	999796.4	999222.8	997540	994392.2	991327.9	990793.1	992608.5	994593.2	995484	995072.7	993424.8	991301.7	990765.3	993099.1	996516.8	998772.3
Rural	Time varying	constant	999999.9	999999.9	999999.9	999999.9	999999.9	999999.9	999999.9	999999.9	999999.9	999999.9	999999.9	999999.9	999999.9	999999.9	999999.9	999999.9	999999.9	999999.9	999999.9	999999.9	999999.9	999999.9	999999.9	999999.9
		time varying	1000000	1000000	1000000	1000000	1000000	1000000	1000000	1000000	999999.9	999999.7	999999.4	999999.3	999999.6	999999.8	999999.9	999999.8	999999.7	999999.4	999999.3	999999.6	999999.8	999999.9	1000000	1000000
		both	999975.4	999975.4	999975.5	999975.5	999975.3	999974.4	999971.7	999964.4	999948.3	999919.3	999886.6	999877	999899.2	999927.6	999941.7	999937.5	999915.6	999886.3	999877	999900.6	999934.1	999957.2	999968.6	999973.3
	Constant	constant	999999.9	999999.9	999999.9	999999.9	999999.9	999999.9	999999.9	999999.9	999999.9	999999.9	999999.9	999999.9	999999.9	999999.9	999999.9	999999.9	999999.9	999999.9	999999.9	999999.9	999999.9	999999.9	999999.9	999999.9
		time varying	1000000	1000000	1000000	1000000	1000000	1000000	1000000	1000000	999999.9	999999.7	999999.5	999999.4	999999.6	999999.8	999999.9	999999.8	999999.7	999999.5	999999.4	999999.6	999999.8	999999.9	1000000	1000000
		both	999975.1	999975.1	999975.2	999975.2	999974.9	999974.1	999971.3	999964.2	999948.3	999920.1	999888.4	999879	999900.5	999928.2	999941.9	999937.7	999916.5	999888	999879	999901.9	999934.5	999957	999968.3	999972.9

Figure 44: Throughput for unlicensed usage in ISM bands

			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
City with low PU arrival (Amax=150)	Time varying	constant	1595.273	1595.273	1599.217	1601.55	1602.448	1602.039	1600.26	1596.922	1591.959	1585.739	1579.218	1573.749	1570.557	1570.102	1571.751	1574.007	1575.257	1574.656	1572.608	1570.534	1570.079	1572.256	1576.997	1583.296
		time varying	8584.136	8584.136	26100.71	80671.86	155975.7	112840.2	40203.88	12733.38	4630.95	2052.661	1120.508	752.0149	614.6497	598.1521	661.3429	765.0413	833.1766	799.3522	698.1373	613.8079	597.333	682.6555	944.1309	1601.68
		both	781.6465	781.6465	1033.572	1243.497	1341.444	1295.479	1120.342	874.4858	634.3764	450.1437	330.7571	263.3799	233.0049	229.1006	243.7399	266.0824	279.7768	273.0686	251.8917	232.8071	228.9052	248.4932	300.6466	398.931
City with more available channels (C=22)	Time varying	constant	800.564	800.564	801.555	802.1402	802.3652	802.2628	801.8167	800.9784	799.7299	798.1611	796.5112	795.1238	794.3122	794.1965	794.6161	795.1893	795.5066	795.3541	794.8339	794.3064	794.1906	794.7444	795.9483	797.5436
		time varying	4339.204	4339.204	13309.87	42299.41	85099.71	60167.94	20648.18	6449.938	2336.311	1034.25	564.322	378.6722	309.4836	301.1746	333.0012	385.2339	419.5564	402.5174	351.5338	309.0596	300.7621	343.7358	475.4535	806.842
		both	391.7638	391.7638	517.733	622.6309	671.5545	648.5965	561.0982	438.1975	318.0755	225.8312	166.0116	132.2337	117.001	115.0429	122.3848	133.5888	140.4552	137.0918	126.4729	116.9019	114.9448	124.7686	150.9182	200.1753
City with more competition (Aselfmax = 2*60)	Time varying	constant	396.9863	396.9863	397.9747	398.5593	398.7843	398.6819	398.236	397.3994	396.1558	394.5973	392.9631	391.5929	390.793	390.679	391.0923	391.6575	391.9706	391.8201	391.307	390.7873	390.6732	391.2188	392.4067	393.9851
		time varying	2154.623	2154.623	6646.226	21450.6	44137.42	30799.11	10352.01	3207.573	1157.855	511.3329	278.4122	186.5037	152.2768	148.1677	163.9087	189.7505	206.7363	198.3035	173.0765	152.0671	147.9637	169.2188	234.4059	398.5788
		both	193.897	193.897	256.7281	309.1241	333.5817	322.1031	278.3813	217.0447	157.1966	111.3249	81.63191	64.89075	57.34868	56.37952	60.01372	65.56195	68.96352	67.29719	62.0378	57.29959	56.33102	61.19395	74.14862	98.58381

Figure 45: Sensitivity analysis of throughput for CR based DSA

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