TECHNICAL ARCHITECTURES AND ECONOMIC CONDITIONS FOR VIABLE SPECTRUM TRADING MARKETS

by

Carlos Enrique Caicedo Bastidas

Bachelor of Engineering in Electronics, Universidad del Cauca, 1996

Master of Science in Electrical Engineering, Universidad de los Andes, 1999

Master of Science in Engineering, University of Texas at Austin, 2003

Submitted to the Graduate Faculty of

School of Information Sciences in partial fulfillment

of the requirements for the degree of

Doctor of Philosophy in Information Science

University of Pittsburgh

2009

UNIVERSITY OF PITTSBURGH

SCHOOL OF INFORMATION SCIENCES

This dissertation was presented

by

Carlos Enrique Caicedo Bastidas

It was defended on

July 15, 2009

and approved by

Dr. David Tipper, Associate Professor, Telecommunications, SIS

Dr. Prashant Krishnamurthy, Associate Professor, Telecommunications, SIS

Dr. Kuldeep Shastri, Roger S. Ahlbrandt Sr. Endowed Chair in Finance, PITT Business

Dr. Andreas Blume, Professor, Department of Economics, University of Pittsburgh

Dissertation Advisor: Dr. Martin Weiss, Associate Professor, Telecommunications, SIS

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Carlos Enrique Caicedo Bastidas, Ph.D.

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The growing interest from telecommunication services providers to offer wireless based services has spurred an also growing demand for wireless spectrum. This has made the tasks related to spectrum management more complicated, especially those related to the allocation of spectrum between competing uses and users. Economically efficient spectrum allocation and assignment requires up to date information on the value of spectrum. Consequently, many spectrum management authorities are or have been elaborating regulations in order to increase the use of market based mechanisms for spectrum management, thus reducing their emphasis on command and control methods.

Spectrum trading (ST) is a market based mechanism where buyers and sellers determine the assignment of spectrum and its uses. That is, it can address both the allocation and assignment aspects of spectrum use. The assignment of spectrum licenses through spectrum trading markets can be used as a mechanism to grant access to spectrum to those who value it most and can use it more efficiently. For it to be optimally effective, a secondary market must exist that allows spectrum users to optimally choose between capital investment and spectrum use on a continuous basis, not just at the time of initial assignment.

This research identifies the different technical architectures for ST markets and studies the possible behaviors and interactions in spectrum trading markets with the use of Agent based Computational Economics (ACE). The research objective is to understand and determine the

conditions that lead to viable spectrum trading markets. This analysis is valuable because it can help regulators prepare for plausible future scenarios and create policy instruments that promote these markets. It is also of value to wireless service providers as they can use the results of this work to understand the economic behavior of different ST market implementations and prepare strategies to participate in these markets.

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PREFACE

I would like to thank my parents for their continuous love, support, encouragement and sacrifice during my Ph.D. studies and I dedicate this work to them. I would also like to thank my dissertation advisor, Dr. Martin Weiss for his great advice and support. I hope to carry on his approach to the analysis of research problems and his friendship into the future. My sincere thanks to the members of my committee, Dr. David Tipper, Dr. Prashant Krishnamurthy, Dr. Andreas Blume and Dr. Kuldeep Shastri for their help and comments.

I am also very grateful to my friend Libia Giovanna Delgado for her support and sponsorship during the start of my Ph.D. program. Finally, I would like to express my gratitude to the dean, faculty members and staff of the School of Information Sciences that have provided me valuable comments and support during my studies. In particular, my thanks to Dr. James Joshi, Dr. Richard Thompson, Kelly Shaffer and Theresa Benedek.

1.0 INTRODUCTION

The growing interest from telecommunication service providers to offer wireless based services has spurred an also growing demand for wireless spectrum. This has made the tasks related to spectrum management more complicated, especially those related to the allocation of spectrum between competing uses and users. Economically efficient spectrum allocation and assignment requires up to date information on the value of spectrum. Consequently, many spectrum management authorities are or have been elaborating regulations in order to increase the use of market based mechanisms for spectrum management, thus reducing their emphasis on command and control methods.

This chapter provides a brief background on some of the issues surrounding spectrum management and introduces the concept of spectrum trading markets which are the focus of this dissertation.

1.1 BACKGROUND

1.1.1 Spectrum Management

Radio spectrum is a highly regulated resource whose management is usually deferred to a government agency in most countries. Spectrum management encompasses all activities related to regulating this resource including the allocation and assignment of spectrum along with the enforcement of related regulations. In this dissertation, spectrum allocation refers to defining acceptable uses of certain bands (e.g. FM radio) whereas; spectrum assignment is the process of granting rights to particular users in a band that has been allocated (e.g. a radio station).

Traditional spectrum allocation and assignment mechanisms have focused on avoiding interference between users and on the type of use given to spectrum rather than on the efficient use of spectrum and the maximization of economic benefits. Due to this, most of the spectrum is used sub-optimally most of the time with low average occupancy values (less than 6% as reported in [1]).

Managing spectrum has become increasingly difficult for regulatory agencies due to the new technologies and uses for spectrum that are continuously emerging and that place increasing demands on this resource. Thus, more flexible assignment mechanisms have to be put in place to adjust to this new reality while still achieving the best usage of spectrum possible under economic or social welfare considerations.

However, before looking at the ways that spectrum trading can improve spectrum management, the basic traditional models for spectrum management will be explained. These models are: command and control, the commons model and the market model. I will describe each of them in order to provide an understanding of their characteristics and then proceed to discuss some of the problems and issues related to their use.

1.1.1.1 Command and control

Under this model, the Spectrum Management Authority (SMA) specifies all details as to how the spectrum should be used, among which are:

- Allowed uses of the spectrum

- Technologies to be used
- Transmitter parameters: power, location, antenna height
- Bandwidth and frequency

Typically, the SMA will make decisions on spectrum allocation first and this impacts its later decisions on assignment. Usually, no changes to allocations or assignments are allowed through secondary market activity in this model. To be granted use of a specific frequency band, an organization must obtain a license or right of use from the SMA which defines the obligations of the licensee and the technical parameters to provide service.

Although this model is effective in managing the use of spectrum to prevent harmful interference among users, it places a lot of responsibility on the SMA since its choice of allocations, technologies and uses for spectrum bands has a great impact on the provision of wireless services. However, the SMAs may sometimes have limited information about the potential uses and/or user markets for spectrum and their value. This limitation grows as rapid changes in technology and service requirements take place, to which an SMA might react rather slowly.

In general, this model doesn’t allow flexible reconfiguration and use of the spectrum for new technologies and incurs in spectrum waste when the same service can be provided over a smaller amount of spectrum (i.e., broadcast television) and when guard bands between spectrum segments could be given some use with interference control methods. This has led to the formulation of service and technology neutral spectrum management scenarios and initiatives where the restrictions on spectrum use are reduced and usage rights can be traded in order to provide more efficient use of the spectrum [2].

1.1.1.2 Market model

The most common alternative to the command and control model is the market model. This model requires the clear definition of exclusive spectrum rights over defined geographic areas which are granted to licensees through methods such as auctions, beauty contests or lotteries.

Many SMAs use this model but place restrictions on the assigned spectrum. One common restriction is that once a wireless operator is granted a license he cannot resell it or trade it without the SMAs authorization. Additionally, change of use for the spectrum covered by the license is not allowed. These restrictions contribute to create an apparent scarcity in spectrum for new operators and generate low average uses in current spectrum assignments[1].

In a more liberalized regulatory regime, usage rights ideally should be technology and service neutral with the SMA basically defining the maximum acceptable levels of interference and the extension of the spectrum block granted with the rights. If liberalization of use and ownership is supported, the initial spectrum assignments can be modified by using spectrum trading to transfer the usage right to another licensee who can determine what services and technology he will use to deliver services[3].

1.1.1.3 Commons model

In this model there are no exclusive usage rights and multiple users can share access to a single frequency band. It does not give any service guarantees to its users and cannot be used easily in scenarios where service providers want to be compensated. Users have to comply with technical parameters or standards that define the power limits and operational restrictions for unlicensed devices to control interference within the spectrum band [4]. However, it is a very flexible way to assign and allocate spectrum, as usage varies dynamically with technology capability and user applications.

This model has had some success in short range, low-power applications such as wireless LANs and Bluetooth connectivity. Long range, high power applications are unlikely to be implemented over this model since they require investments in infrastructure that need to be recovered over time. However, technologies and concepts in the field of mesh networks could be used in the provision of wireless services over wide areas in a commons model but with several quality limitations [5].

Additionally, spectrum allocated through this model runs the risk of suffering the "tragedy of the commons" where there is an inefficient overuse of a limited set of resources that are held in common [6].

1.1.2 Which management model to use?

Fixed spectrum allocation found in models such as the command and control model provide for an environment where spectrum will be distributed sub-optimally. As mentioned before, for a spectrum allocation to be effective, the SMA that manages spectrum under a command and control regime would need to know all the possibilities for consumer demand and production, a task that is better left for market interactions to determine.

An example of inefficiency in the command and control model arises in the way that guard bands[1] are defined and managed. In this model, the SMA defines guard bands based on its knowledge of the systems that will be deployed. The guard bands are not included in the licensed bandwidth so ownership of the bands remains with the SMA. In a regime where change of use is allowed, guard bands should be managed by the operators of spectrum [7].

[1] A guard band is a small frequency band between adjacent channels or segments of spectrum that is kept unused to prevent the channels to overlap and cause interference to the users or uses of each channel.

Market based models can take care of these inefficiencies, leaving the SMA only with the problem of determining the initial allocation of spectrum and enforcing rules for fair spectrum trading. Coase's theorem which states that "the initial allocation of a good does not matter from an efficiency perspective so long as property rights are clearly defined and the goods can be freely exchanged – because, provided that there are no frictions in the trading process, exchange will lead to an efficient outcome"[2] provides from an economic theory perspective, a justification for letting market forces come into play in the determination of what services should be provided over tradable segments of spectrum.

Each spectrum management model has its place depending on the social and economic goals of a regulatory entity that manages spectrum. However, the proper management and allocation of commercial spectrum requires gathering information about the true value of spectrum for each user which is a difficult task that is better left to market forces.

In particular, the commons model should be employed wherever it provides benefits despite the interference characteristics of its use. For other frequency bands, spectrum usage rights should be clearly defined and distributed to users through the use of market based mechanisms and there should be as few restrictions as possible on how spectrum may be used[8].

Market based mechanisms within a regulatory environment that allows flexible use and assignment of a spectrum segment can enhance the assignment of spectrum to those who value it more [3]. These mechanisms liberate the regulator from micro-managing spectrum assignments and they promote social welfare by allowing innovation and high diversity of products and services.

[2] Coase R, "The Problem of Social Cost", Journal of Law and Economics 1 (1961)

1.2 MOTIVATION

With a growing demand for spectrum, the tasks related to spectrum management have grown more complicated, especially those related to the allocation of spectrum between competing uses and users. A proper allocation requires information on how valuable spectrum is to all the different users, which is a difficult task to accomplish [9]. As a result, many spectrum management authorities (SMA) are using market based mechanisms (most notably auctions) for spectrum management to align assignment and allocation more closely with economic value. This encourages efficient spectrum use and requires spectrum users to make tradeoffs between technology investments (which may reduce spectrum use) and spectrum.

But auctions are useful for initial assignments only. By analogy with the stock market, auctions are like an initial public offering (IPO). Long term technical and economic efficiency requires a secondary market (like a stock or commodities exchange) so that spectrum market participants can continually evaluate the balance of technology and spectrum investments in their portfolio.

In a pure secondary spectrum market, buyers and sellers determine the assignments of spectrum and possibly also its uses. That is, it can address both the allocation and assignment aspects of spectrum use. Spectrum usage rights are transferred from one user to another for a certain price. Thus, it differs from traditional systems where the spectrum is returned to the SMA and then reassigned [8]. A trade will occur when the spectrum is worth more to another user than to the current owner of the usage right.

Spectrum trading is a market based mechanism where, ideally, buyers and sellers determine the assignments of spectrum and its uses. That is, it can address both the allocation and assignment aspects of spectrum use. The allocation aspect often has "public interest" consequences that will not be addressed in this dissertation. Trading transactions are initiated voluntarily by a spectrum holder and the sums paid by the new owner of the spectrum usage right are retained (in full or in part) by the previous owner[8].

Spectrum trading results in a more dynamic, competitive and efficient communications market than is possible under the traditional regimes implemented so far. Businesses have better knowledge than regulators about their spectrum requirements and valuations. Trading should also enable a faster rate of innovation and growth in the number of uses and users of spectrum [10].

Figure 1 illustrates a trading scenario based on the use of a spectrum exchange and shows some of the information flows. In this scenario, the exchange collects the offers to sell (asks) and offers to buy (bids) for spectrum, determines the winning bid and transfers the right of use of spectrum from the selling license holder to the new owner of the right.

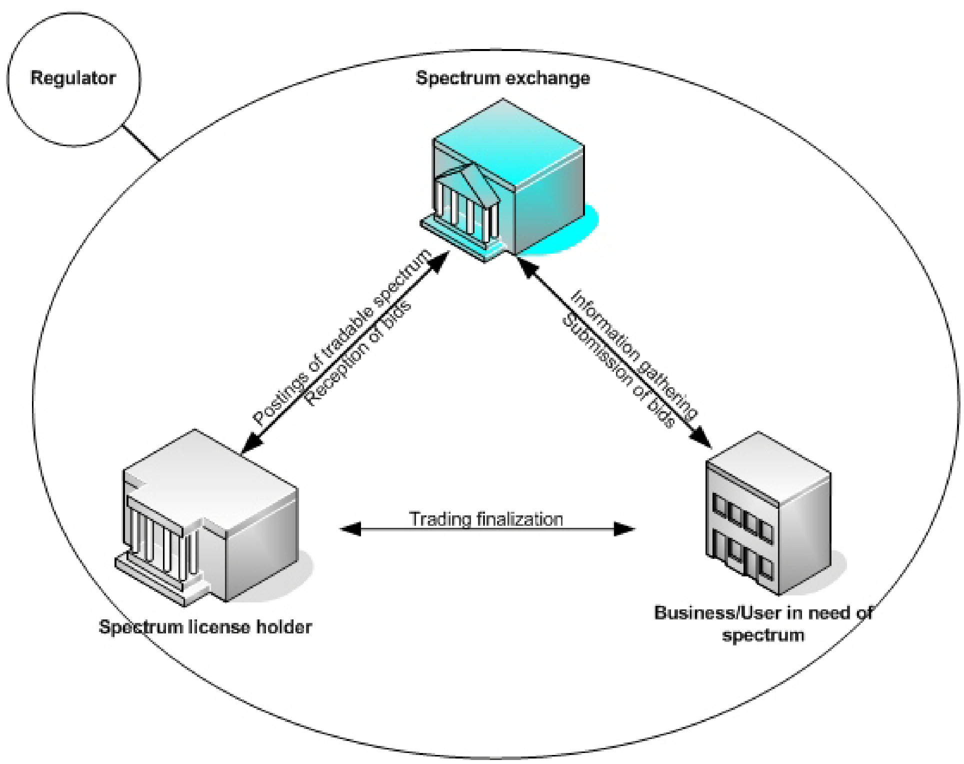

Figure 1. Spectrum trading scenario

The assignment of spectrum licenses through spectrum trading markets can be used as a mechanism to grant spectrum to those who value it most and can use it more efficiently. For it to be optimally effective, a secondary market must exist that allows spectrum users to optimally choose between capital investment and spectrum use on a continuous basis, not just at the time of initial assignment.

Spectrum trading initiatives are being considered or implemented by the regulatory bodies of many countries due to the growing demand for wireless services from consumers and also from the interest of wireless service providers in:

- Providing new revenue generating services
- Serve geographical regions where spectrum resources are needed in order to provide service to a number of customers that is larger than that which can be accommodated by a provider's own resources.
- Having alternative mechanisms to handle peak loads more dynamically
- Being able to provide wireless services without big initial investments on infrastructure and spectrum licenses such as in the case of Mobile Virtual Network Operators (MVNO).
- Allow for the provision of new services to customers.
- Obtain economic gains from spectrum that is unused (i.e. speculation)

Despite its benefits, a secondary market for spectrum poses a number of challenges. These include:

- Establishment of regulatory provisions to allow spectrum transfers and trades with flexible use of spectrum (no restrictions on the use of spectrum). In general, flexibility is desirable to “achieve a continuous improvement in spectrum usage and accommodate rapidly changing technologies and services”[11].

- Incorporation of social preferences and values may be difficult or costly if allocation and assignment is done purely by market mechanisms. For example, a social desire for diversity in media ownership may require governmental intervention in the market; so may spectrum for public safety communications.
- The parameters under which a secondary spectrum market might emerge are unknown. Even if the previous two items could be successfully addressed, it is not clear that spectrum users would participate in such a market. Factors that could affect the emergence of such a market include:
  - Amount of available spectrum for trading
  - Market structure
  - Market liquidity

Because of the potential benefits and unknown pitfalls of spectrum trading (ST) markets, further understanding of how spectrum trading can be implemented, and what kind of spectrum trading approaches lead to liquid and sustainable markets is required. Research that addresses these issues would be of interest to regulators as it would help them prepare for plausible future scenarios. It would also be of interest to wireless service providers as they can use the results of this work to make more informed decisions as to the economic benefits of different ST market implementations. ST, if implemented correctly can change the interactions of wireless service provisioning and the impact of these services on society.

1.3 PROBLEM STATEMENT

The viability of ST markets depends on several technical and economic conditions which can be impacted upon through regulatory and policy decisions but which must be determined through careful study of how these markets work and the sets of interactions that are present in them. Since no data on the operation of a true "liberalized[3]" spectrum trading market exists, this research work will make use of agent-based models for studying such markets. In general, the focus of this research is driven by the following questions:

- How can ST markets be implemented? What are the technical architectures for ST markets?
- What set of market parameters lead to ST markets that are viable?
  - Are these parameter combinations likely in practice?
  - How can policy decisions influence the viability of these markets?

This research studies the technical and economic issues related to the implementation of ST markets. It proposes a classification for the technical and market architectures of these markets and determines the sets of conditions for the markets to be viable (liquid and sustainable). Study of the economic characteristics of the proposed ST markets is done through the use of agent-based computational economics (ACE) methods and tools. We expect that the outcomes of this dissertation will help ST market participants and policy makers understand the requirements for viable spectrum trading markets and how to prepare towards creating and/or participating in them.

[3] Liberalized spectrum markets are those that have provisions to allow spectrum transfers and trades and that also allow flexible use of spectrum (no restrictions on the use of spectrum).

1.4 DISSERTATON OUTLINE

This dissertation is structured as follows: Chapter 2.0 provides a background on spectrum management and describes the current state of spectrum trading and its benefits. Chapter 3.0 describes the research questions and research methodology used for this dissertation. Chapter 4.0 describes the proposed classification of architectures for the implementation of ST environments, the technical issues related to implementing them are discussed in Chapter 5.0 . Chapter 6.0 describes the analysis of the proposed market structures for ST. Chapter 7.0 explains the impact of technical and economic architecture on the economic behavior of a ST market. Chapter 8.0 describes the agent-based modeling of ST markets and the development and specifications of the ACE tool developed to study these markets. Chapter 9.0 mentions the results obtained from this work. Finally, chapter 10.0 mentions the conclusions of this research and topics for future work.

2.0 SPECTRUM TRADING: BENEFITS AND LIMITATIONS

Static spectrum assignment leads to inefficiencies which grow as technology evolves. Spectrum trading can improve the efficiency of the initial distributions of spectrum by allowing the licensees to be those who value its use the most and can employ the technology that provides the best economic gains. In essence, spectrum trading puts licensees on a scenario where they can choose to transfer their rights of use for spectrum or keep them depending on the value it has for them.

Competition among service providers is expected to increase under a market that supports spectrum trading since new companies could have access to spectrum. However, adequate trading regulations have to be in place to avoid spectrum hoarding and to provide low transactions costs for spectrum access. Economic efficiency and innovation should increase as efficient companies making good use of acquired radio spectrum displace less efficient companies and as entrepreneurs who wish to offer new services acquire spectrum that may have been previously used to offer low value services or used through old technologies [9, 15].

Technological innovation should also be stimulated since there would be an interest to have intelligent software defined radio (SDR) or cognitive radio based systems[4] to make as much use of tradable spectrum as possible and offer several services over it. Additionally,

[4] Cognitive radio extends SDR technology to incorporate knowledge of a user's usage patterns, context awareness (location, type of service most likely to be requested by user, etc), and environmental factors (available services, link conditions) in the provision of wireless services.

technological developments or changes in consumer behavior that were not envisioned when the spectrum was initially assigned can be taken into account by any new operator that comes into the market to offer services [16].

Consumers would benefit from spectrum trading by having cheaper prices for those services that are most popular since there would be an incentive for the existence of several providers providing those services given that any provider can acquire extra capacity for its service offerings through spectrum trading at a cheaper price than that of owning a license for a spectrum block [9].

Also, scenarios where a user and his communication device are not attached to a specific wireless service provider would become more viable with ST. In these scenarios, users have the freedom of choosing and joining a service provider of their convenience at any time and geographical location [17]. This contrasts with the vendor-central systems used today where a user is locked to a specific service provider and a specific wireless standard on his/her wireless terminal. SDR or cognitive radio technologies combined with a spectrum trading environment will be key enablers of a user-centric wireless service infrastructure. However, for spectrum trading mechanisms to be fully effective, licensees should not be needlessly constrained in their use of spectrum.

In general, welfare benefits would be produced by spectrum trading and spectrum liberalization due to increases in efficiency [18] because of:

- Increased value of the services offered from a given unit of spectrum since the owner of the spectrum would be the one that can make the best use of it.
- Increased knowledge and transparency of the true value of spectrum and the reduction of market entry barriers.

- Increased level of competition
- Rapid incorporation and adoption of new technologies and services which in turn stimulates innovation.

The realization of these benefits over a well designed regulatory framework requires the implementation of a spectrum trading infrastructure under technical architectures that can satisfy social welfare goals and support the widest range of trading interactions possible at an acceptable level of economic efficiency.

Despite its benefits, spectrum trading may be limited by several factors which have led several countries to be cautious and take slow steps towards implementing it, among these factors are [2, 18] :

- Transaction costs: If transaction costs are high the welfare gains obtained through a more efficient use of spectrum may not arise since these costs would inhibit trading.
- Market failure: Spectrum trading could displace services of value to a community or foster anti-competitive behavior, all of which would make the welfare losses exceed the gains obtained from trading. Also, geographic specificity is a limitation and characteristic in ST as the usefulness of the traded spectrum is tied to the geography which affects market liquidity.
- Conflicts with public policy: Spectrum trading can conflict with government policy goals which can delay or eliminate initiatives to enable such trading.
- Conflicting with efforts for international harmonization in the use of spectrum, especially in the borders between countries.
- Inadequate distribution and/or content of market information about trading opportunities.

- Low spectrum trading activity
- Windfall gains
- Increased interference between services with disruptive effects on consumers

Although these factors can be avoided or attenuated by having an adequate regulatory framework for spectrum trading with spectrum liberalization, more experiences in real ST market deployments will be required to determine the methods that lead to stable and profitable markets. Some of the regulatory requirements as wells as some of the current initiatives to implement spectrum trading based markets are discussed in the next section.

2.1 TRADABLE SPECTRUM USAGE RIGHTS

To enable spectrum trading, regulation has to be put in place that defines a set of spectrum usage rights. Such definition reduces the risk for spectrum trading transactions. Additionally, spectrum usage rights should be defined in a technology neutral way by means of power emission masks and other parameters that don't lock a provider into a particular technology or set of transmission methods.

Ofcom[5] proposes a regulatory regime where two types of rights over spectrum are defined, Spectrum Management Rights (SMR) and Spectrum Usage Rights (SUR) [7]. In this scenario, the SMR owners would have the right to issue SURs that are in sync with their SMR limits. These rights would cover large blocks of spectrum to reduce transaction costs and span a

[5] Regulator for the communication industry in the United Kingdom

large geographic area. A SUR would define the right to transmit and/or receive at a specific service area within specified technical limits.

Rights to transmit or receive signals over spectrum can be defined in relation to four parameters [7]:

- Geographical area (space)
- Duration and time of access (time)
- Spectrum endowment – amount of bandwidth to which access is granted (frequency)
- Protection from interference (power)

In more detail, [10] proposes that transmission rights should be defined in terms of

- Time
- Geographic boundaries
- Frequency boundaries
- In-band power limits
- Out-of-band power limits
- Interference mitigation factors

In addition an indication of what constitutes unacceptable interference could be defined based on Power Flux Density (PFD) or EIRP[6] so that interactions among different systems can be controlled.

[6] EIRP (Effective isotropic radiated power) is the amount of power that would have to be emitted by an isotropic antenna (an antenna that evenly distributes power in all directions – it's a theoretical device) to produce the peak power density observed in the direction of maximum antenna gain

2.2 SPECTRUM TRADING AND SECONDARY SPECTRUM MARKET INITIATIVES

Spectrum trading has been introduced to some extent in countries such as Australia, New Zealand, Guatemala, El Salvador, the USA, the UK and Canada. Each of them has defined a framework for spectrum trading in a different way but in general they have benefited from it.

In the year 2000, the FCC issued several policy statements [19, 20] indicating its guidelines for promoting efficient use of the radio spectrum through the development of secondary markets. It also mentioned the need to make spectrum more available and use radio agile equipment to make use of it, along with promoting market processes through the establishment of private spectrum exchanges and brokers.

In 2003, the FCC issued regulation on spectrum leasing that specified some of the methods to enter into leasing arrangements for wireless radio licensees with exclusive rights to their assigned spectrum [21]. The leasing arrangements have flexibility in terms of the geographic area that may be covered and the amount of time for which they are valid, as long as they are in sync with the terms of the licensee. In September 2004, the FCC released a follow up report and order that extended the availability of spectrum leasing to more wireless services and devices, clarified the rules for cases where leasing parties may enter dynamic spectrum leasing arrangements in which more than one entity could share the use of the same spectrum segment through the use of software radio or cognitive radio devices. It also established a “private commons” option for cases where a licensee wishes to provide spectrum access to individual users or groups of users through the use of advanced devices [22].

A special case in spectrum trading is that of the many federal entities that have licenses to operate in the public sector spectrum. This is the part of spectrum used for public safety purposes by state and local governments as well as for military and Federal government use. Under the current regulations, the licensees of this spectrum have no incentive to put their assigned spectrum into trading markets since they cannot retain any revenue that might result from sharing it with other users. However, licensees of the public sector can lease their spectrum usage rights to other entities of the public sector and to entities that provide communications that support public sector operations.

Worldwide, over the last couple of years, countries such as the UK and Germany have launched detailed technical and regulatory studies to determine the framework for the introduction or extension of secondary use markets in those countries. The EU in general allows secondary trading under EC legislation but with constraints regarding change of use in many of the bands where trading is allowed. Ofcom in the UK established trading for certain sets of spectrum frequencies in December 2004 [23, 24].

2.3 MECHANISMS AND INSTANCES FOR SPECTRUM TRADING

Spectrum trading can be accomplished through several mechanisms:

1. Bilateral negotiations + SMA authorization
2. Auctions
3. Exchange based trading
4. Broker based trading

In SMA based trading, the SMA receives a request for approval of a spectrum trade after the buyer and seller of a spectrum right have determined that they wish to execute a trade. The SMA analyzes the trade implications, charges a fee for its services and approves or denies the trade. If the trade is approved, the SUR of the traded spectrum is transferred to the buyer and the SMA updates its databases of spectrum assignments. A problem with this kind of trading is that the SMA may be too slow to approve the trade and thus affect the dynamism of a ST market.

When using auctions to trade spectrum, the owner of a SUR can decide on the rules for the auction [8]. The auction winner gets the SUR after paying the winning bid amount.

In exchange based trading, another entity enters in the trading transaction, the spectrum exchange, which can be a company delegated by the SMA to handle spectrum assignments on its behalf, charge the respective fees for spectrum and update any required database. The exchange acts as a central point in the collection of all the bids (buy requests) and asks (sell requests) in the market and the establishment of trades. In broker based trading, spectrum brokers act on behalf of a service provider and search the market to find a matching buyer/seller with which to do a transaction.

Each mechanism does not exclude the use of another, so there could be environments where several of them could be used. When there are a sufficient number of trading transactions, brokerage services or spectrum exchanges may arise. In the U.S. in particular, the Cantor Fitzgerald company has set up a spectrum & tower exchange marketplace service acting as an intermediary between buyers and sellers (bids & offers) of spectrum rights, tower assets and tower/rooftop space. Additionally, other private companies like Spectrum Bridge[7] are starting to offer capabilities to sell and lease unused spectrum assets.

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[7] http://www.spectrumbridge.com

A trade in a ST market implies the transfer of spectrum usage rights from one user entity to another for a certain price. Trading will only take place if the spectrum is worth more to the new user than to its former user thus providing a series of economic benefits and more efficient use of spectrum as mentioned before.

A spectrum trade can take several forms, these are listed below:

a. Sale: Complete transfer of the spectrum usage right to another party.
b. Sale + buy back: Usage right is sold to another party but with the agreement that the seller will buy back the usage right at a pre-determined point of time in the future.
c. Lease: Ownership and obligations related to the usage right remain with the leaser but the right to profit from the usage right is transferred to another party for a pre-defined period of time.
d. Mortgage or security: The usage right is used as collateral for a loan.

To reason more clearly about spectrum trading, we begin with a taxonomy for the trading instances that may arise in a spectrum trading market and which is based on the classification proposed in [10]. This taxonomy classifies trading instances based on three aspects: mode, duration and extent.

Mode: Refers to the range of actions that a buyer has at his disposal with the spectrum that he has acquired. The actions can be classified as:

a. Change of ownership
b. Change of use: This includes the capability of aggregating and/or disaggregating spectrum for a particular use along with providing a service over the spectrum that is different to that to which the spectrum was previously assigned to.

Extent: It's the degree to which a spectrum licenses' rights and obligations are transferred to the buyer, which can be:

a. Complete transfer: Rights and obligations of seller are completely transferred to the buyer
b. Shared: Rights and obligations are shared (bear upon) both seller and buyer.

Duration: Refers to the length of time of the trade which could take the form of:

a. Short term lease
b. Long term lease
c. Sale and buy back
d. Permanent: Sale until the end of license term

Several combinations of mode, extent and duration are possible. In practice, the details will depend on the regulatory decisions of each country that implements spectrum trading and on the technical infrastructure that supports and monitors the trading arrangements.

Additionally, the trading interactions in a ST market will also depend on the types of participants present in the market. These may include [9] :

- Brokers / Exchanges: Register bids and offers for spectrum
- Market makers: Hold inventories and provide liquidity to the market
- License owners: Offer surplus spectrum for trading
- Spectrum management organizations: Manage blocks of spectrum for dynamic service provision.
- Speculators: Entities that seek monetary gains in short-term prices changes of spectrum.

A spectrum trade will occur if buyer and seller have enough information regarding the condition of the spectrum to be traded and if an information exchange between them (or through a trusted entity) can take place that guarantees the success of a trading interaction. This requires that information systems be in place to facilitate the interactions among buyers and sellers. Part of the information systems will have to handle the economic aspects of an interaction (trade), other parts will allow buyers and sellers to find each other and match their needs and yet others will be used to configure the infrastructure that will implement the specifications of the trade. Brokers or spectrum exchange entities can facilitate to potential traders access to the information about bids and asks being posted for spectrum usage rights (licenses) and thus provide a mechanism to give price transparency.

Greater detail on the role of each market participant is given in chapter 6.0

3.0 RESEARCH QUESTIONS AND EXPERIMENTAL DESIGN

The objective of this dissertation is to determine how spectrum trading markets can be implemented and the combination of attributes that lead to viable spectrum trading markets. Viability will be determined mostly on the basis of liquidity and sustainability characteristics of the market. This analysis is valuable because it will help regulators prepare for plausible future scenarios. It is also of value to wireless service provider as they can use the results of this work to make more informed decisions as to the economic benefits of different ST market implementations.

ST markets can be implemented via different technical architectures but precise operating principles must be established beforehand and a clear understanding of market structure is required. In order to gain ground in the understanding of these markets, we propose a classification for the architectures that can be used to implement them from a technical perspective and also a classification of the market structures that can support ST.

Additionally, to study the possible behaviors and interactions in ST markets we propose the use of Agent based Computational Economics (ACE) to model and study them. ACE provides us with the tools to analyze the consequences of implementing these new markets, which would be difficult to analyze with conventional statistical and analytical tools due to the range of parameters than can be changed and also due to the lack of empirical data on spectrum trading in a liberalized regulatory framework.

A Spectrum Trading market modeling tool (SPECTRAD) has been developed as part of this research work. The tool works on top of REPAST (Recursive Porous Agent Simulation Toolkit) developed by the Argonne National Laboratory [25, 26]. In SPECTRAD, we make use of ACE concepts and techniques to model different types of ST market scenarios and address some of the research questions related to this dissertation.

The deliverables of this dissertation will be presented in the remaining chapters in the following way:

Chapter 4.0 describes a proposed classification of architectures for the technical implementation of ST markets. Chapter 5.0 analyzes several of the technical implementation issues of ST markets. Chapter 6.0 describes the roles of the participants in a ST market and a proposed classification for ST market organization from the point of view of the economic behavior of its participants. Chapter 7.0 explains the effect of technical architecture and market structure parameters on the economic behavior of a ST market.

The tool and experiments used to model and simulate ST market scenarios (SPECTRAD) is described in chapter 8.0 . The analysis of the simulation results is mentioned in chapter 9.0 . Chapter 10.0 contains the conclusions from this research and suggestions for future work.

3.1 RESEARCH QUESTIONS

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

1. How can ST markets be implemented? How can technical architectures for ST be characterized?

2. What set of parameter values lead to ST markets that are liquid and sustainable? Where the set of parameters is determined by:
   - *Number of market participants (N)* : The market participants are the entities that can buy and/or sell spectrum which will be referred to as ***spectrum users*** **(SU)** throughout this work. They include spectrum license holders (SLH) and spectrum license requestors (SLR) which are acting as wireless service providers. Other market participants are entities such as market makers and speculators.
   - *Available spectrum (S)*: Number of *Basic Bandwidth Units* (**BBU**) of spectrum that are available in the market for trading.
   - *Distribution of spectrum users' valuation of spectrum (L)*: We will assume that spectrum users have a choice of investing in the acquisition of spectrum (BBU units) or investing in a unit of transmission of an alternate technology (**AT**). Thus, when spectrum prices are too high, the spectrum user would acquire AT units instead to satisfy its traffic requirements. We will consider that there are three categories of spectrum users. Each category is defined based on their level of valuation for spectrum. These levels are *L=[low, medium, high]*. As an example, users with a low level valuation will have lower valuations of spectrum than other users (at other levels) and will be more inclined to invest in ATs than to acquire BBUs. In our simulations, the population of spectrum users

in the market is distributed over the three levels of *valuation* in different pre-defined proportions.

- *Market structure (M)*: This defines the allowed behaviors for the entities participating in the market. The set of market structures to be considered is mentioned in more detail in chapter 6.0 .

3. How does each parameter of the set (*N*, *S*, *L*, *M*) affect market behavior? Where market behavior is measured in terms of its liquidity and sustainability. We assume that liquidity is measured by the extent of the relative bid-ask spread (the smaller the relative bid-ask spread, the more liquid the market is). Sustainability is determined by observing that a given market structure provides a running market that continues to operate and allow trades for a big number of time units (t > 1000). In detail, this question will be addressed by exploring the following sub-questions:

   3.1. Over which values of **R** = S/N = *average amount of spectrum per user* -- are ST markets liquid and sustainable?

   3.2. What type of market structure provides better market behavior in terms of sustainability and spectrum use efficiency?

   3.3. What is the effect of the distribution of the valuation levels in a ST market?

4. Are we likely to see the conditions / parameters for a feasible ST market arise in the real world? How do we achieve them if not currently present?

5. How can the conditions for having a liquid and sustainable ST market be obtained or helped with policy changes?

The following assumptions and restrictions will be made in this work as we explore the previously mentioned questions:

- The trading environment used supports spectrum property or quasi-property rights. This means that regulations are in place to enable spectrum trading markets without excessive regulator interaction.
- Spectrum liberalization is in place. That is, a chunk of spectrum can be given any use a provider wants. No restrictions on use are in place.
- Only one wireless standard is being used to make use of the traded spectrum. OFDM based operation over the traded spectrum has guided some of the technical thinking of this work and will continue to do so.
- Spectrum trading is conducted over an exchange based market environment.
- The trading interactions to be studied are being conducted over urban environment conditions.
- The opportunity cost of not serving a traffic requirement is very high and will be avoided by a spectrum user if the market allows it. As mentioned in question #2. We will assume that spectrum users have a choice of investing in the acquisition of spectrum (BBU units) or investing in a unit of transmission of an alternate technology (AT). Thus, when spectrum prices are too high, the spectrum user will acquire AT units instead to satisfy its traffic requirements.

3.2 EXPERIMENTAL DESIGN

Question 1 is addressed with the deliverables presented in chapters 4.0 and 5.0 . An overview of the framework, tool and theoretical basis for addressing questions 2 and 3 is presented in chapter 8.0 , the results and analysis to support our conclusions to answer these questions are included in chapter 9.0 . Questions 4 and 5 require the analysis of the simulation results derived from questions 2 and 3 and also the interpretation of current regulatory statues and trends in the regulation of spectrum markets. This analysis is also included in chapter 9.0 .

To perform statistical testing for the analysis of research questions 2 and 3, we perform several simulation experiments by varying the values of parameters in the parameter set P=[*N*, *S*, *L*, *M*] as shown in Table 1 to perform a full factorial experiment design with 100 replications per data point:

Table 1. Parameter values for simulations

<table>
<tr><th>Parameter</th><th>Values</th></tr>
<tr><td>Number of market participants (N_{su})</td><td>4, 5, 6, 10, 20, 50</td></tr>
<tr><td>Distribution of spectrum users' valuation level (L)
Table indicates proportion of the spectrum users within a given valuation level</td><td><table><tr><th>Case</th><th>Low</th><th>Medium</th><th>High</th></tr><tr><td>1</td><td>⅓</td><td>⅓</td><td>⅓</td></tr><tr><td>2</td><td>½</td><td>¼</td><td>¼</td></tr><tr><td>3</td><td>¼</td><td>¼</td><td>½</td></tr></table></td></tr>
<tr><td>Available Spectrum (S_{BBU}^{Total})
Values indicate the number of BBUs available for trading</td><td>5*N_{su}, 10*N_{su}, 15*N_{su}, 20*N_{su}, 25*N_{su}.
The amounts of spectrum where chosen for each value of N_{su} in order to have R=S/N_{su} in the set [5, 10, 15, 20, 25]</td></tr>
<tr><td>Market architecture (M)
The characteristics of the market architectures to be considered are mentioned chapter 6.0</td><td>Two market architectures will be considered: band manager based exchange (BM), no band manager based exchange (NOBM)</td></tr>
<tr><td>Total # of experiments</td><td>6x3x5x2x100 = 18,000</td></tr>
</table>

In each experiment we measure the average of the bid-ask spread, number of trades conducted over time, BBU (spectrum) inventory level, AT inventory levels, bid prices, ask prices among other parameters. A detailed discussion on how the behavior of each scenario is quantified a qualified is given in chapters 8.0 and 9.0 .

Questions 2 and 3 will be addressed by analyzing the information on the relative bid-ask spread (as an indicator of market liquidity [27, 28]), the bid prices, ask prices, spectrum and AT inventory levels and other parameters to determine liquidity and sustainability criteria to identify viable markets. The 90% confidence intervals around the average values for a given parameter will be used in order to determine if a given parameter within a market scenario complies with a viability criteria or not.

Questions 4 and 5 will make use of the data gathered in the experiments conducted in this research and the analysis provided to questions 2 and 3 in order to elaborate a comprehensive view of the elements required to have liquid and sustainable ST markets. This information along with a study of the spectrum regulation of the U.S. and U.K (as examples of regulatory environments with advances in the implementation of spectrum trading) will be used to elaborate recommendations on how to achieve working ST markets.

4.0 A CLASSIFICATION OF ARCHITECTURES FOR THE IMPLEMENTATION OF SPECTRUM TRADING MARKETS

In order to address the questions of this research, we need to understand how spectrum trading (ST) markets are implemented from a technical perspective. This chapter presents a classification of the technical architectures for ST elaborated for this research and presented in [12]. The classification is based on four *dimensions*, namely: infrastructure, configuration method, activation and flexibility. For each of them, I provide an analysis of some of the technical requirements needed to support a given dimension.

4.1 INFRASTRUCTURE

Spectrum obtained via a trade can be used by the buyer through a *shared* infrastructure such as a pooling point where several licensees (those that have participated in trades and obtained spectrum) can make use of their awarded spectrum for transmissions. A licensee could also use its own equipment *(not shared)* to make use of his spectrum. Figure 2 shows examples of shared and not shared infrastructures.

Technical requirements:

<u>*Shared*</u>: These ST architectures require the installation of pooling points that can be used to provide wireless service to geographic areas of interest. Although the use of a shared pooling

point reduces infrastructure costs for the wireless service providers (WSPs) that use it (permanently or sporadically), optimal geographic coverage may not be achieved.

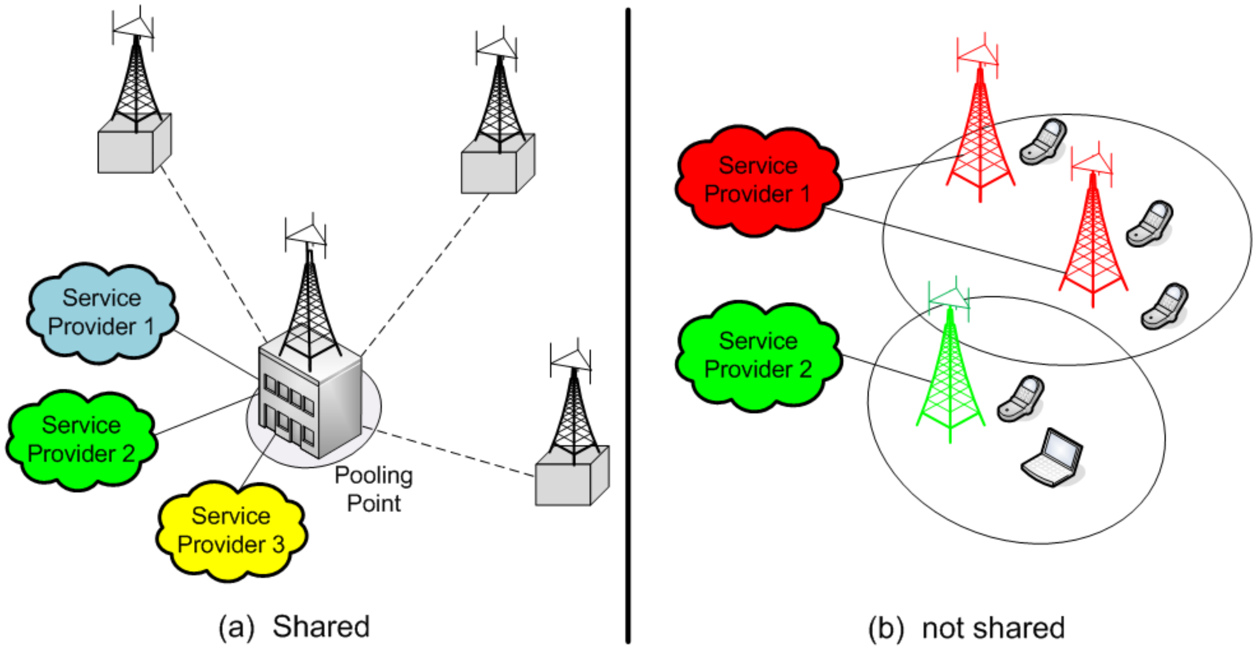

Figure 2. Infrastructure options for ST architectures

Another way of implementing a shared infrastructure is through the use of Radio Infrastructure Providers (RIPs) which are companies that could have sets of reconfigurable radio base stations either at fixed locations or mobile (truck mounted) whose transmission capacity is leased to a WSP. Backhaul links from the pooling points or RIP devices to the WSP network would carry the collected traffic that has to go a particular WSP. These links could be wired or wireless and either owned or leased by the WSP.

Not shared: When the WSP owns the radio infrastructure the only requirement here is that its infrastructure should support some degree of re-configurability of the operational frequencies that it uses or be based on SDR technology in order to benefit from ST interactions. Further description of the technical requirements for this dimension is provided in section 5.1.

4.2 CONFIGURATION METHOD

Configuration of traded spectrum over a region can be done in a *centralized* or *distributed* manner. In an architecture that uses centralized configuration a spectrum exchange entity is in charge of spectrum configuration for a region, configures all the technical parameters of each trade and controls the infrastructure required for the use of the spectrum.

In a distributed configuration architecture, the exchange gives permission over a specific area to a service provider to use the spectrum that has been traded. This permission would specify the technical parameters of the allowed operations over the spectrum. The configuration of the equipment that allows transmission/reception over the traded spectrum is done by other means not in direct control of the exchange. In this case the exchange is acting more like a broker.

Technical requirements:

Centralized: An infrastructure for delivering configuration commands from a spectrum exchange to the reconfigurable radio base stations (RRBS) is required. The RRBS are the devices that will enable the use of spectrum defined in a given trade. Communication from the exchange with the RRBS includes wired/wireless channels for the transmission of commands plus the management platforms (software/hardware) that can enable the issuing of such commands.

Distributed: In this case, transmission of the spectrum use permissions from the spectrum exchange to the WSP is needed but the infrastructure required to do this should be less complicated than that required in the centralized case.

4.3 ACTIVATION

The requests for spectrum to be acquired through ST can be *provider initiated* and/or *user initiated*. A provider initiated request is one where the entity that wants to provide a service initiates the request to obtain the necessary spectrum from a spectrum broker/exchange. A user initiated request is one where the user's terminal equipment determines the need to acquire spectrum to support the services required by the user. An architecture could also support both types of requests. In this case, medium to long term use of the spectrum is managed through provider initiated requests, while short term and/or bursty behavior is handled through user initiated trades.

Technical requirements:

Provider initiated: Requires a communication channel between the WSP and the spectrum broker/exchange. The channel can be defined by the exchange so that all WSPs that want to use the services of the exchange have to use the same channel.

Provider + User initiated: In this case, configuration channels to support Mobile Node (MN) to RRBS messages are required and the channels that the RRBS uses to configure the mobile nodes (MN) can be used to carry the confirmations of the MN to RRBS interactions. User initiated requests have to be relayed by the RRBS to the spectrum exchange through the same type of channels mentioned in the *provider initiated* case.

4.4 FLEXIBILITY

Flexibility refers to the range of wireless standards that can be used to support services over the traded spectrum. When several wireless protocols can be used, we refer to a *Multi-protocol* architecture. When only one wireless MAC protocol is allowed, we have a *Single protocol* architecture.

Technical requirements:

The fewer protocols supported, the easier it is to determine interference interactions among users but the less flexible the system becomes. Also, as a larger number of standards/protocols is supported the logical processing requirements of the trading infrastructure increase and thus its design must take this into account. Further analysis on the implications of flexibility in ST architectures has been included in section 5.5.

4.5 CLASSIFICATION SUMMARY

Figure 3 summarizes the dimensions for spectrum trading architectures. A particular architecture for implementing a ST infrastructure would gather an attribute from each dimension. The choice of architecture defines the set of possible trading interactions from a technical perspective. Also, each architecture will require a different set of technical elements, protocols and capabilities for implementation which will have consequences in terms of number of information flows for a trade, transaction costs and complexity.

Table 2 summarizes some of the technical consequences/requirements for each dimension of the proposed ST architecture classification.

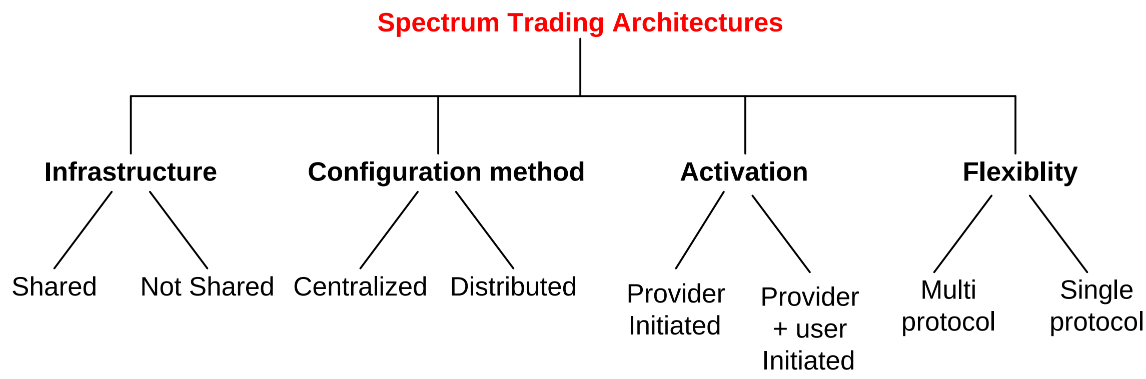

Figure 3. ST architectures

Table 2. ST architecture dimensions summary

	Categories	Comments
Infrastructure	Shared	Infrastructure costs for each provider would be reduced but optimal placement/coverage may not be achieved.
	Not Shared	Placement/coverage goals are easier to fulfill but at a higher cost.
Configuration	Centralized	Flexibility is limited to those protocols that the central exchange allows and is able to configure
	Distributed	Allows for high flexibility in providing several wireless protocols over a region
Activation	Provider initiated	Requires a configuration channel from Base Stations (BS) to Mobile Node (MN)
	Provider + user initiated	Requires configuration channels to support BS to MN and MN to DB requests
Flexibility	Multi-protocol	As fewer protocols are supported, interference prediction and control improves
	Single protocol	

5.0 SPECTRUM TRADING IMPLEMENTATION ISSUES

This chapter presents some of the issues related to the technical implementation of spectrum trading markets. It further discusses the effect of the parameters that form part of the definition of a technical architecture for ST.

5.1 ACCESS TO SPECTRUM

Dynamic Spectrum Access (DSA) techniques are key enablers for spectrum trading. In particular [11] proposes a form of DSA labeled as *Coordinated Dynamic Spectrum Access*, where the access to the spectrum in a region is controlled and coordinated by a centralized spectrum broker through the use of a segment of spectrum referred to as the Coordinated Access Band (CAB) over which access to chunks of spectrum are statistically multiplexed thus improving spectrum access and spectrum utilization.

Although infrastructures that enable dynamic spectrum access (DSA) such as the one proposed in [29] can support several flexibility and activation scenarios of a ST implementation, it is relevant to mention that as more wireless protocols are supported for transmission in a region, the more complicated it will be to manage interference and spectrum assignment functions.

We consider that in a scenario where a single wireless standard is used (i.e. WiMAX, or any OFDM based technology), interference is more predictable, spectrum assignment more manageable and spectrum trading can give way to *Wireless Bandwidth/Capacity Trading* where trading requests are mapped to a convenient amount of spectrum bandwidth based on the capacity requirement, QoS needs and propagation conditions.

If the segment of spectrum available for trading activities coincides with that traditionally assigned to a specific telecommunications service (i.e. GSM, PCS 1900), the radio base stations developed to provide the service could be used to make use of the traded spectrum as long as their configuration times do not impose long delays in the activation of the spectrum.

From a technical perspective, an ideal spectrum trading market would offer the opportunity for service operators to obtain and operate spectrum for any use over a wide range of frequencies and with minimal and/or controlled interference levels from other users of spectrum. Since the segment of spectrum a particular service provider might be operating on can change from trade to trade, the infrastructure required to make use of the spectrum must be able to operate in different frequencies.

Fully configurable radio systems based on Software Defined Radios (SDR) which we have referred to Reconfigurable Radio Base Stations (RRBS) should satisfy these requirements if they can provide an infrastructure of radio systems that are adaptable, reconfigurable and multifunctional in terms of modes of operation, radio frequency bands, waveforms used and air interfaces supported. These devices are starting to appear in the wireless communications market[30]. Additionally, most modern day commercial radio base stations are making use of some SDR functionalities and while not being full SDR systems, they do provide enough capabilities to operate at different frequencies within a given transmission standard (i.e. GSM) to also support limited ST scenarios.

5.2 INFORMATION MANAGEMENT

In trading interactions, information related to the transaction and the participants in the transaction is crucial. The way trading information flows also affects how a market interaction starts, how it develops and in general how the market works by affecting the confidence of potential buyers and sellers and determining the way buyers and sellers gather information for a successful trade [15].

Pricing and spectrum availability information are key to a successful ST market. Adequate access to this information promotes price transparency, can reduce transaction costs, promote market entry and higher volumes of trading [10]. In terms of spectrum availability, buyers need information on the usage rights that are available for trading and the trades that have taken place. This information can be specified in terms of [2]:

- Spectrum endowment
- Geographical area of endowment
- Duration of rights (license term)
- Imposed obligations
    - Service restrictions
    - Required interference protection measures
- Current spectrum neighbors (for interference determination)

If this kind of information is not available or has a high retrieval cost, many efficient trades might not take place. In order to reduce the cost of obtaining this information and ensuring adequate information flow, registries of spectrum usage rights and trades should be created.

However, details in the way information is managed have to be clearly defined in the policies that implement a ST market. For example revealing the current holders of a spectrum license might reveal information about the business plans and objectives of a given provider but information openness also promotes high confidence in the market and tends to eliminate information imbalances among market participants.

In general, the information flows required for enabling a ST market will cover aspects such as:

- Buyer / seller announcement and discovery + obtaining pricing information
- Configuration commands for radio equipment (Base stations and user terminals)
- Handling of spectrum requests from radio equipment to spectrum manager
- Updates of spectrum occupancy information
- Reports on interference power levels

Each one of these aspects requires the design of a protocol over the elements of the architecture that implement the trading functions.

5.3 PROTOCOLS IN ST ENVIRONMENTS

Several sets of protocols will be required in a ST environment, among them are:

Physical / wireless layer protocols: This set of protocols encompasses all the protocols required by the wireless standards that will be supported in the trading environment

Trading information management protocol: This is a high level trading protocol that would define how each entity that wants to use the ST trading infrastructure to participate in trades should register and define the sets of capabilities it possess. These entities include:

- Buyers wanting to post bids for spectrum
- Licensees of spectrum wanting to offer their spectrum for trading
- Radio Infrastructure Providers that want to announce the availability and location of their equipment to activate spectrum acquired through by others through trading.

*Protocols for enabling spectrum trade*s: This set of protocols can be sub-divided in:

- Radio Configuration Protocols: These are protocols that carry configuration information for SDR based radio devices. Protocols in this area should operate at two levels
    - User level: Protocol between user device and exchange/pooling point
    - Provider level: Protocol between a provider's radio base stations and an exchange / pooling point.
- Spectrum exchange configuration protocol: A protocol that passes technical information between the spectrum requester or seller and the spectrum exchange

For the purposes of the spectrum trading markets modeled in this work, we will assume that the information flows among entities participating in the market are supported by an adequate protocol. The details of protocol specification are left for further research.

5.4 INTERFERENCE MANAGEMENT

The transmission rights of users that participate in a ST market have to be protected against unwanted interference. Enforcement of interference rules along with monitoring is a complicated task that requires the deployment of an infrastructure (sensors) to keep users accountable for the interference they generate. This sensor based infrastructure could be complemented or replaced by user terminal systems that report on their interference environment measurements to a spectrum management entity.

In addition to the use of technical mechanisms to control interference, economic based mechanisms can also be used. In particular, a fee or tax on the amount of generated interference could be applied to the price of a traded spectrum license by the spectrum management entity [31]. The tax could be based on the out of band interference and spectrum profile of the wireless standard that is being used for the transmission or based on the output profile of a particular transmitter and antenna configuration.

However, the simpler the set of metrics to characterize interference the easier it will be to specify interference related costs. In particular, the use of metrics such as *interference temperature* proposed in [32] could be used to manage interference considering only the capabilities and interference limits of the transmitters and the receivers involved in communication interactions within a given area.

5.5 IMPLICATIONS OF FLEXIBILITY

Supporting more than one wireless standard in a spectrum trading area would provide a greater diversity of service choices but at a higher cost in infrastructure. A SDR based RRBS could support several wireless standards and have transmissions on different standards active at the same time. In this case factors such as to the load imposed by the processing of each standard and the transmission resources used to attend each user should be analyzed in order to determine the combinations of standards and number of transmissions that can be supported over a given set of computational capabilities of the RRBS. The costs incurred because of the freedom of choices at the MAC and physical levels have to be weighed against the benefit of having such freedom.

Additionally, interference management gets more complicated as the number of wireless standards operating over a region grows. Sharing of spectrum for TDMA/FDMA based standards with other CDMA standards will generally require splitting the total tradable spectrum in segments where one kind of transmission method is allowed in each, and the incorporation of guard bands between them.

Predictability of the interference caused by each transmission is enhanced when the number of supported standards is low since each one and the interactions among them can be characterized. Thus, the tradeoffs of managing several standards versus restricting their number to only a few should be carefully analyzed in a spectrum trading environment.

6.0 MARKET STRUCTURES FOR SPECTRUM TRADING

Spectrum trading (ST) will be attractive to wireless service providers if it can provide fast and economic access to spectrum resources. This access can be used, among other things to:

- Serve geographical regions where spectrum resources are needed in order to provide service to a number of customers that is larger than that which can be accommodated by a provider's own resources.
- Support peak demand periods where a provider's spectrum holdings become insufficient to attend its customers.
- Allow for the provision of new services to customers.
- Obtain economic gains from spectrum that is unused (i.e. speculation)

Trading systems that satisfy these requirements can be implemented via different technical architectures such as the ones proposed in chapter 4.0 , but precise market operating principles must be established beforehand and a clear understanding of the market structure is required.

A description of the structure of future spectrum trading markets and their related technical implementations is provided in this chapter. The description includes the roles of market participants and a classification of the market types that can support spectrum trading.

6.1 PARTICIPANTS IN A SPECTRUM TRADING MARKET

To understand the organization of and interactions in a ST market we need to know what entities participate in such a market. The following sections describe these entities and some of their functions.

6.1.1 Spectrum license holders (SLH)

Entity that owns a spectrum license which has been acquired either through an auction, spectrum trading or direct assignment by a regulatory agency and that offers its license for trading in exchange of financial compensation.

This entity can be:

- A wireless service provider which has a license for the use of spectrum acquired either through a government led auction or the ST market.
- A spectrum exchange which has been assigned a spectrum trading band by a regulatory agency.
- A market maker

In general, SLHs hold spectrum for speculation or for their own use.

6.1.2 Spectrum license requestors (SLR)

Entity that submits bids for spectrum licenses to the ST market with the intent of acquiring the license. Spectrum license requestors obtain spectrum for speculation or their own use.

An entity that acts as a SLR can be:

- A wireless service provider that wants to acquire spectrum for its own use
- A market maker
- A company/enterprise that acquires spectrum on behalf of another

6.1.3 Spectrum regulator

Government entity that oversees the ST market and defines the regulations for its operation. It is also responsible for providing a spectrum availability and assignment database which is updated every time a spectrum trade is completed to register the identity of the new holder of spectrum.

6.1.4 Market makers

A market maker is basically a dealer that holds an inventory of spectrum and stands ready to execute a transaction when a SLR (buyer) or SLH (seller) desires. A market maker facilitates trading; it does not provide services using the spectrum. It gets revenue through the spread between ask prices and bid prices for spectrum, and holds a spectrum inventory for negotiating and speculating.

6.1.5 Spectrum broker

An entity present in over-the-counter spectrum markets (section 6.2.1). It matches bids and asks of spectrum from different SLH and SLR and receives a fee for each trade matched. A spectrum broker does not hold any spectrum.

6.1.6 Spectrum exchange

An entity present in exchange based markets (described later) which provides and maintains a market place or facilities for bringing together buyers and sellers of spectrum in which spectrum trading transactions can take place. It also publicizes prices and anonymizes trading entities.

6.2 SPECTRUM TRADING MARKET TYPES

Figure 4 shows the two types of trading market structures over which we will classify ST markets. An explanation of each market type is given in the following sub-sections.

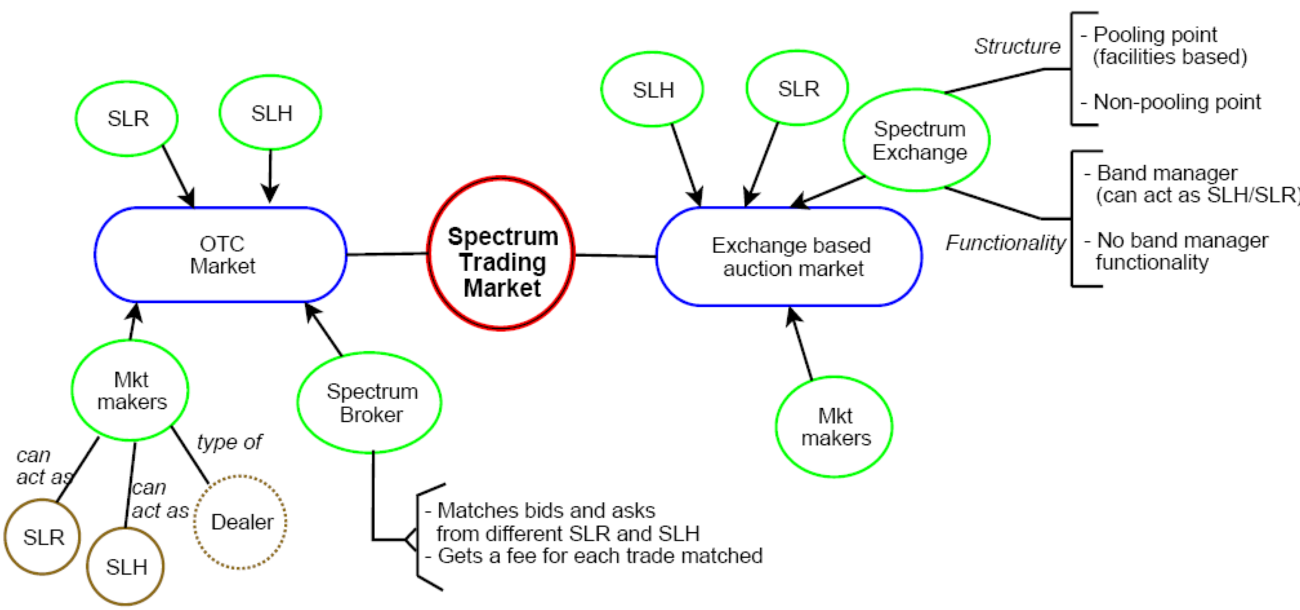

Figure 4. Spectrum trading market types

6.2.1 Over-the-counter (OTC) market

In this kind of market, there is no central trading facility. A SLR can place a bid (buy offer) for a spectrum license or a SLH can place an ask (sell offer) for a license either through a market maker or a broker. Market makers act as dealers who stand ready to buy or sell spectrum on request thus providing immediate access to this resource. On the other hand, when a transaction goes through a broker, the broker acts as an agent in executing the transaction and collects a commission. The broker searches for the entity that will complete the other side of the transaction and charges a fee for making a match in the transaction. The fee is usually a percentage of the sale price.

When compared to brokers, market makers offer immediacy in the completion of a transaction. The market maker allows the SLR or SLH to make the transaction when he or she desires, rather than waiting to locate a party who wants to complete the transaction as when using a broker.

Within the context of an OTC market, the functions of a spectrum broker are:

- Receive and organize offers of spectrum to be traded from spectrum license holders
- Receive and organize bids for spectrum from spectrum license requestors
- Charge fees for each completed spectrum trade
- Update the regulator’s spectrum availability and assignment database (or a similar system to register spectrum assignments) once the transaction has cleared
- Grant a spectrum license to the winning spectrum requestor. This authorizes the SLR to configure its equipment to work in the granted spectrum.

For a market maker, the functions are:

- Update the regulator’s spectrum availability and assignment database (or a similar instrument) once a transaction (buy or sell) has cleared.
- Grant spectrum license to a SLR that has bought a license from the market maker.
- In the case of buying spectrum from a SLH, the market maker should incorporate the spectrum into its holdings and prepare to make it available for a future sell.

6.2.2 Exchange based market

In this market, the spectrum exchange is the central entity. Following and adapting definitions of an exchange such as those of [33], a spectrum exchange is defined for our purposes as an organization made up of entities whether incorporated or unincorporated, which provide and maintain a market place or facilities for bringing together buyers and sellers of spectrum in which spectrum trading transactions can take place. For our purposes, we assume that spectrum exchanges make use of continuous double auctions as a mechanism to match buyers and sellers.

In general, an exchange denotes the idea of a central facility where buyers and sellers can transact. In the traditional sense, an exchange is usually involved in the delivery of the product. However, for a spectrum exchange to allow use of traded spectrum, the required devices do not need to be co-located in the exchange so the exchange might not be involved in the delivery of service.

We will consider that the spectrum exchange acts as a pooling point (POOL) if its facilities house the communication equipment that enable the delivery of wireless services through spectrum acquired by a buyer in the exchange. This kind of exchange also takes care of the configuration of equipment required to make the spectrum usable to the new license holder. A non-pooling point exchange (NOPOOL) only delivers the authorization for use of spectrum to the buying party in a spectrum trade. The new SLH must then use this authorization to configure its devices to make use of the spectrum it has just acquired.

From a functional perspective a spectrum exchange can be a band manager (BM) for a given segment of spectrum over a region or have no band manager functionality (NOBM). An exchange with BM functionality can support transactions where it grants spectrum licenses to a SLR and then have these licenses returned to it if the trading terms so specify, as in the case of spectrum leasing transactions. Thus leasing arrangements in addition to permanent license transfers can be supported on this exchange. In contrast to BM exchanges, a NOBM exchange will only facilitate the trading of spectrum among entities in the market without holding any spectrum inventory itself. Leasing arrangements in NOBM exchanges will require coordination between the lessee, lessor and the exchange and thus could have higher transaction costs.

Some additional functionalities of any type of spectrum exchange are:

- Receive and organize offers of spectrum to be traded from spectrum license holders
- Receive and organize bids for spectrum from spectrum requestors
- Charge exchange membership fees
- Charge transaction related fees, such as:
    - Listing fee
    - Clearing and settlement fee
    - Maintain an updated spectrum availability and assignment database

From the previous discussion, the proposed classification generates four types of spectrum exchanges which can be used to implement a ST market. These are listed in Table 3.

Table 3. Types of exchanges

Exchange type	Characteristics
POOL_BM	*Pooling point + band manager functionality* • Use of traded spectrum is enabled and configured through equipment/infrastructure owned by the exchange. • All tradable spectrum is held by the exchange • All tradable spectrum returns to or is given by the exchange
POOL_NOBM	*Pooling point only, no band manager functionality* • Use of traded spectrum is enabled and configured through equipment/infrastructure owned by the exchange. • Different *segments* of spectrum can be activated and configured through the equipment/infrastructure of the exchange • No spectrum inventory is held by the exchange
NOPOOL_BM	*Non-pooling point + band manager functionality* • All tradable spectrum is held by the exchange • All tradable spectrum returns to or is given by the exchange • Exchange grants authorizations for use of spectrum (no equipment configuration is done by the exchange)
NOPOOL_NOBM	*Non-pooling point, no band manager functionality* • Exchange grants authorizations for use of spectrum (no equipment configuration is done by the exchange) • No spectrum inventory is held by the exchange

6.3 RELATING TECHNICAL ARCHITECTURES TO MARKET TYPES

For the work in this proposal, we will assume a subset of the architectures proposed in chapter 4.0 Our focus will be ST market implementations where we use a single technology for wireless transmission. We further assume that bids and asks for spectrum are not user (mobile node) initiated. This leaves open architectural choices in the way the ST infrastructure will be owned/operated and the configuration method to be used. These choices are explained in the following sections and related to market structures.

6.3.1 Infrastructure ownership

Traded spectrum can be used by a SLH through a shared infrastructure by deploying a pooling point to which several SLH are connected. In contrast, a market implementation can also be based on having each SLH use their own equipment (not shared) to enable the use of acquired spectrum.

When infrastructure is not shared, the only technical requirement for the SLH's equipment is that its base stations should be reconfigurable and able to operate over a range of frequencies in order to benefit from ST interactions. In this kind of infrastructure, the SLH obtains a spectrum license grant from a market entity (exchange or broker) and configures its RBSs accordingly to the license parameters.

As mentioned in section 4.1, the shared infrastructure case requires the installation of pooling points that can be used to provide wireless service to geographic areas of interest. The wireless service providers that want to use a particular pooling point, connect to it through transmission links that could be wired or wireless and either owned or leased by the WSP. These links would carry the signals collected at the pooling point that have to go to a particular WSP and are also used by the WSP to send the signals that have to be distributed by the pooling point infrastructure.

Pooling points can be deployed as a site where several RBS and their associated antennas are placed (co-located). A pooling point's control center would house the links to remote RBS located through a service area as well as links to the WSPs interested in using this infrastructure. Figure 5 illustrates a possible pooling point setup.

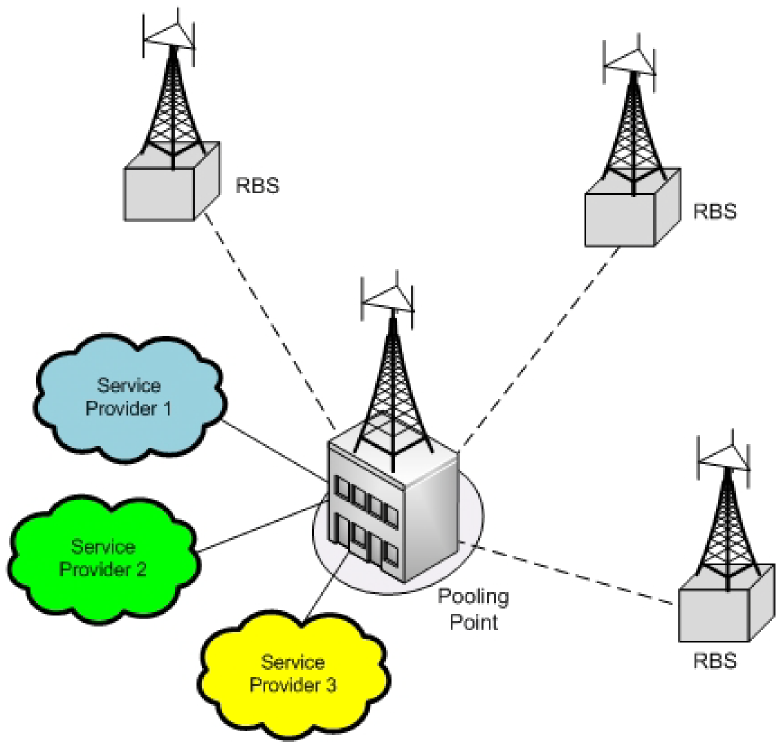

Figure 5. A pooling point

An alternative pooling point implementation would be to deploy only antennas around a geographic area and with the use of Radio over Fiber (RoF) links send and receive the wireless service signals to/from these antennas at the control center. Radio over fiber enables the cost effective transport of wireless signals over optical fibers providing distribution of radio signals to simplified base stations denoted as remote antenna units (RAUs) [34]. This provides for a reconfigurable system that is flexible to the kinds of services it can provide, has centralized maintenance and is cheaper than deploying a set of full-scale base stations.

A limitation in the use of RoF is that this technology is better suited for operating RAUs with small area coverage (radius < 1 km) [35]. It is then better to employ RoF for covering urban areas where traffic density is high. Thus, many RAUs would have to be deployed to cover a big area.

The devices of the shared infrastructure (antennas, RBSs, etc) can be provided by a spectrum exchange acting as a pooling point or through the use of Radio Infrastructure Providers (RIPs) which are companies that could have sets of reconfigurable radio base stations either at fixed locations or mobile (truck mounted) and whose transmission capacity is leased to an exchange.

6.3.2 Configuration method

A ST market infrastructure can use centralized or distributed configuration mechanisms to enable the use of traded spectrum. In an architecture that uses centralized configuration an entity such as an spectrum exchange or broker is in charge of spectrum configuration for a region and configures all the technical parameters of each trade. When distributed configuration is used, the exchange/broker sends permission to the SLH to use the traded spectrum over a specific area. The permission message specifies the technical parameters of the allowed operations over the spectrum. The SLH can then proceed to configure the equipment that allows it to operate over the traded spectrum.

For centralized configuration, an infrastructure for delivering configuration commands from a spectrum exchange/broker to the radio base stations (RBS) is required. For distributed configuration, a transmission of the spectrum use permissions from the spectrum exchange/broker to the new SLH is needed but the infrastructure required to do this should be less complicated than that required in the centralized case.

6.3.3 Technical architectures vs. market types

From the discussion in the two previous subsections we can now relate the subset of technical architectures we are considering to the different market types we have proposed. Specifically, for OTC spectrum trading markets, all architectures in the subset can operate in such a market since the characteristics of the architectures do not restrict any type of OTC operation and the operation of these markets do not require a specific arrangement of technical elements.

For exchange based markets, architectures that make use of shared infrastructure are better aligned with markets where there is an exchange that acts as a pooling point. In these markets, the exchange acting as a central point where trading requests are collected and where radio equipment is housed will be involved in the delivery of spectrum. Thus, the exchange is an active part of the technical operation of the market and its structure must be correctly aligned with the set of trading behaviors it wishes to establish.

Table 4 lists the market types supported by a given architecture defined by the infrastructure ownership and configuration options discussed previously.

Table 4. Architectures vs. Market types

Architecture		**Supported Market Type**	
Infrastructure type	**Configuration method**	**OTC**	**Exchange**
Shared	Centralized	Yes	POOL_BM, POOL_NOBM
Shared	Distributed	Yes	POOL_BM, POOL_NOBM
Not shared	Centralized	Yes	NOPOOL_BM, NOPOOL_NOBM
Not shared	Distributed	Yes	NOPOOL_BM, NOPOOL_NOBM

How spectrum is organized and made available to participants in a ST market is important. We will focus on *exchange based ST markets* to treat this topic. For scenarios where the exchange has a BM functionality, the SLRs will send a request for spectrum to the exchange which, if possible, will assign spectrum to the requesting entity in the form of a timed lease within the band managed by the exchange. The spectrum band assigned to the exchange could be managed in a manner similar to a Coordinated Access Band (CAB) as proposed in [29].

For a spectrum exchange that has no band manager functionality (NOBM), the entire spectrum it will handle for trading will come from market participants that use the exchange and make bids and offers of spectrum. It's worth mentioning that unless the market has defined a basic amount of bandwidth as a spectrum trading unit it will be very complicated to match bids and offers of spectrum without incurring in wasteful assignment of this resource.

Although giving a particular structure to the way the spectrum trading band should be segmented will limit its operational flexibility, it also provides benefits in terms of simplifying the specifications to characterize a particular spectrum trade and managing interference between ST users.

7.0 TECHNICAL ARCHITECTURE VS. ECONOMIC BEHAVIOR

The objective of this chapter is to provide an understanding of how the parameters that define a technical architecture for the implementation of a ST market affect its economic behavior. This analysis will serve as a guide to define criteria for the selection of parameters of the scenarios to be modeled using Agent-Based Computational Economics (ACE) where we are interested in modeling the running behavior of a market, that is, the trading behavior of a market assuming the infrastructure required for its operation has been deployed.

Sections 7.1 and 7.2 provide examples to explain how different technologies can work over an ST architecture and implicitly illustrate the merits of the technical classification developed in this work. Section 7.3 proposes a cost model to evaluate the costs of the technical architectures for ST. Section 7.4 uses the qualitative analysis of costs to determine which aspects of a technical architecture impact the running behavior of a ST market.

7.1 SPECTRUM TRADING AND WIMAX

7.1.1 WiMAX background

The IEEE 802.16 Working Group on Broadband Wireless Access Standards developed the standard for wireless metropolitan area network communications commercially known as

WiMAX (Worldwide Interoperability for Microwave Access). This standard is also officially trademarked as WirelessMAN by the IEEE.

WiMAX is a last mile technology that offers wireless broadband access at rates of up to 40 Mbps over a cell of 3 to 10 Km. in radius [36]. This kind of capacity allows this technology to be an alternative to DSL and cable technologies in the provision of broadband services.

The 802.16 standard over which WiMAX is based has had several revisions over the years. The 802.16d standard approved in June 2004 and known as 802.16-2004 is the basis for most of today's commercial products that support WiMAX. This standard defines the physical (PHY) and Medium Access Control (MAC) layers for broadband wireless communications as well as support for point-to-point and mesh network structures using this technology.

Although a single MAC layer is defined in the 802.16 standard, there are several choices for the PHY layer. Each one of these choices is referred to as an air interface and they are listed in Table 5. The WirelessMAN-SC and WirelessMAN-SCa interfaces are based on a single carrier technology, thus, only one carrier occupies the whole bandwidth for transmission under these air interfaces. WirelessMAN-OFDM employs Orthogonal Frequency Division Multiplexing to overcome multipath propagation effects. In this air interface 256 OFDM subcarriers are defined, out of which only 200 are used and the rest are not active (guard bands).

Table 5. IEEE 802.16 Air interfaces

Air interface	**Frequency Band of operation**
WirelessMAN-SC	10 – 66 GHz
WirelessMAN-SCa	< 11 GHz
WirelessMAN-OFDM	< 11 GHz
WirelessMAN-OFDMA	< 11 GHz
WirelessHUMAN	< 11 GHz

WirelessMAN-OFDMA employs orthogonal frequency division multiple access (OFDMA) to provide resistance for multipath propagation effects and also support multiple access, that is, having several users operating at the same time over the wireless system. Wireless HUMAN stands for Wireless High Speed Unlicensed Metropolitan Access and is the name given to the 802.16 air interfaces to be used for unlicensed bands.

7.1.2 ST architectures for WiMAX

From the ST architecture classification presented in chapter 4.0 , a total of 16 combinations of the dimension parameters can be obtained. Each combination defines an architecture. We will only consider eight architectures as we are focusing on scenarios with only one wireless standard (single protocol in the *Flexibility* dimension of the classification). The architectures to be considered are listed in Table 6.

Table 6. Architectures to analyze

#	Infrastructure	Flexibility	Configuration	Activation
1	Shared	Single protocol	Centralized	Provider Initiated
2	Shared	Single protocol	Centralized	User+Provider
3	Shared	Single protocol	Distributed	Provider Initiated
4	Shared	Single protocol	Distributed	User+Provider
5	Not shared	Single protocol	Centralized	Provider Initiated
6	Not shared	Single protocol	Centralized	User+Provider
7	Not shared	Single protocol	Distributed	Provider Initiated
8	Not shared	Single protocol	Distributed	User+Provider

When using WirelessMAN-OFDM, all the bandwidth is allocated to a specific user device, also known as a Subscriber Station (SS). Multiuser access is achieved by specifying the time interval (timeslot) during which the bandwidth should be used by a user's SS. With WirelessMAN-OFDMA, different groups of subcarriers can be assigned to different users thus making capacity assignment more fine grained.

Of the set of architectures, those that support User+Provider based activation imply a higher degree of complexity in the protocols that control ST interactions since a protocol that allows for a user to initiate a capacity request must be included.

The air interface in the 802.16-2004 standard can be implemented through the use of many different options. Standardized sets of options are referred to as *system profiles*. Each profile lists MAC and PHY features that can be used in typical implementations. The physical layer profiles that are defined in the standard are mentioned in the following tables.

Table 7. WirelessMAN-OFDM and WirelessHUMAN-OFDM [37]

Profile Id	Channel bandwidth	Licensed/unlicensed
ProfP3_1.75	1.75 MHz	Licensed
ProfP3_3.5	3.5 MHz	Licensed
ProfP3_7	7 MHz	Licensed
ProfP3_3	3 MHz	Licensed
ProfP3_5.5	5.5 MHz	Licensed
ProfP3_10	10 MHz	Unlicensed

Table 8. WirelessMAN-OFDMA and WirelessHUMAN-OFDMA [37]

Profile Id	Channel bandwidth	Licensed/unlicensed
OFDMA_ProfP1	1.25 MHz	Licensed
OFDMA_ProfP2	3.5 MHz	Licensed
OFDMA_ProfP3	7 MHz	Licensed
OFDMA_ProfP4	8.75 MHz	Licensed
OFDMA_ProfP5	14 MHz	Licensed
OFDMA_ProfP6	17.5 MHz	Licensed
OFDMA_ProfP7	28 MHz	Licensed
OFDMA_ProfP8	10 MHz	Unlicensed
OFDMA_ProfP9	20 MHz	Unlicensed

ST can be applied to the WiMAX system profiles that require licensed operation. In these cases, the license can be used by an entity that is different than the original owner of the license at times and/or geographic locations where the original owner cannot make full use of it. Thus the architectures for ST mentioned on Table 6 can be implemented to support the previously mentioned set of system profiles.

7.2 SPECTRUM TRADING FOR GSM/EDGE BASED NETWORKS

GSM is the most popular mobile radio standard in the world. Originally introduced in the mid-1980s, it has evolved to the point of being able to provide 2.5G and 3G services. The Global Mobile Suppliers Association (GSA)[8] states that as of May 2009, there were 413 GSM/EDGE networks in 177 countries.

EDGE is a mobile data standard that can operate over GSM networks. It allows data transmission speeds up to 384 Kbps. This capacity is achieved within the same GSM channel bandwidth of the 800 MHz, 900MHz, 1800MHz and 1900MHz air interfaces defined for GSM [38]. A GSM channel has a bandwidth of 200KHz.

For spectrum trading over GSM/EDGE networks, the set of architectures mentioned in Table 6 of the previous section will also be considered. The element of a GSM/EDGE network that will make the spectrum obtained via trading operational will be the base transceiver station (BTS). A BTS contains one or more transceivers to provide the required call handling capacity in its coverage area.

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[8] http://www.gsacom.com

For spectrum trading the BTS should have the capabilities of a RRBS (Reconfigurable radio base station) mentioned in section 5.1. Mainly, it should allow that the operational frequency of its transceivers to be changed by software easily. Fortunately, mobile radio equipment manufacturers are already incorporating SDR technology into their BTS products which would provide for flexible operational frequency assignment and enhanced capabilities such as software based operation/migration to more advanced wireless standards [30].

In a GSM/EDGE network, a group of BTSs are connected to a Base Station Controller (BSC) which manages the radio resources for them. Thus, for spectrum trading the BSC should have enough "intelligence" to be able to interact with and use the resources provided by the ST market. In the case of *shared* ST architectures, the BSC would be shared by several service providers and would be the key component of a spectrum pooling point.

7.3 A COST MODEL FOR THE EVALUATION OF TECHNICAL ARCHITECTURES

The technical architectures used to implement a ST market, can impact the economic behavior of the market. In order to study that impact we will develop a cost model to evaluate a ST technical architecture. We propose that the technical implementation of a ST architecture can be evaluated over three cost dimensions: Trade, infrastructure and information overhead costs.

Trade costs

These are the costs incurred by the market participants (spectrum buyer or seller) for being allowed to participate in trading interactions and for each trading transaction completed over the ST infrastructure. Trading costs should be low enough to make ST attractive. Regulatory or economic impositions (fees) are a part of these costs. These fees are the following:

- Per trade fee: This is paid to the exchange and/or given to a SMA. It is charged every time a trade is successfully completed in the ST system.
- ST system registration fee: Fee charged by a SMA or the spectrum exchange/broker to any entity that wants to be registered and considered as a potential participant of trading interactions that take place in the ST system.
- ST information system access fee: Fee charged to a market participant that scans the current set of bids or offers in a ST market and proceeds to either post a bid or offer for spectrum. This fee could be charged on a per transaction basis or on a subscription basis (per month, per year)

Infrastructure costs

Costs incurred for the installation and configuration of the ST market infrastructure. Infrastructure costs consider the costs of deploying the information systems and hardware that will make a ST implementation operationally viable. These include the costs of the Reconfigurable Radio Base Stations (RBS) and the spectrum exchange or broker infrastructure among others. These costs are incurred by the spectrum broker/exchange and recovered through the fees imposed to spectrum buyers/sellers or through compensation agreements with the SMA.

Information overhead costs

These costs arise from the amount of information that needs to flow among the entities involved in a spectrum trade. Basically, the number of operation and management protocols and the information flows required for each architecture define an amount of additional information exchanges (overhead) in a ST environment that would not be present in a traditional (command and control) wireless operation environment. Thus, this overhead must be taken into account since a large amount of overhead will imply a longer service (trade) activation time and reduce the performance of a ST infrastructure. Economically, these are deadweight losses.

Cost model parameters

From the previous discussion on costs, a set of cost parameters for evaluating ST interactions can be defined. These are listed in Table 9.

The costs for each dimension can be represented as:

Trade costs: $T_{tot} = \left(N_{trade} \times Trade_{fee}\right) + Reg_{fee} + Info_{fee} + (I_{type} \times RIP_{fee}) + Sconf_{fee}$

Infrastructure costs: $I_{tot} = I_{type} \times (N_{RBS} \times P_{RBS}) \times \gamma \times \eta + SDB_{cost} + RFI_{cost}$

Information overhead cost: $IOVH_{tot} = \left((TIP_{ovh} + RCP_{ovh}) \times \gamma_{ovh}\right) \times (1 + \sigma_{ovh} \times C_{method})$

Where the following are indicator variables:

- Infrastructure type indicator (I_{type})

  =1 shared

  =0 not-shared

- Configuration method indicator (C_{method})

  =0 Centralized

  =1 Distributed

Table 9. Cost model parameters

Cost parameter	Name	Comment
Trade		
Per trade fee	$Trade_{fee}$	Recurrent cost, paid once on every trade to be executed
Number of spectrum trades	N_{trade}	Number of completed trades over a given time period
ST system registration fee	Reg_{fee}	Paid once only
Information system access fee	$Info_{fee}$	Paid on a regular basis to access trading information (offers and bids)
RIP equipment use fee	RIP_{fee}	Fee charged by a Radio Infrastucture Provider (RIP) for the use of its equipment. It is applicable only when the ST architecture is implemented over a *shared* infrastructure with the use of RIPs
Service request/configuration fee	$Sconf_{fee}$	When service is user initiated, fee goes to the user
Infrastructure costs		
Reconfigurable base stations (RBS)	N_{RBS}	Number of reconfigurable base stations
	P_{RBS}	Price of RBS
Housing and maintenance of spectrum allocation database	SDB_{cost}	
Other radio infrastructure (backhaul links, tower permits, etc)	RFI_{cost}	
Flexibility cost increase factor	*Gamma* (γ)	Cost increase based on the number of supported wireless standards. Affects the cost of RRBS mainly
User service activation capability cost increase factor	*Eta* (η)	Cost increase factor for ST system that allow the user to initiate a spectrum request
Information overhead		
From trading information management protocol	TIP_{ovh}	
From radio configuration protocols	RCP_{ovh}	
Flexibility overhead increase factor	γ_{ovh}	Overhead increase factor due to supporting wireless protocol flexibility in a ST infrastructure
Configuration type overhead increase factor	σ_{ovh}	Overhead increase for architectures that use distributed configuration.

The cost equations provide us with a way to qualify the impact of each of the spectrum trading architecture dimensions on each of the cost dimensions. The analysis is summarized in Table 10.

Table 10. Architecture dimensions vs. Cost

Architecture Dimension	Value choices	Cost dimension it affects	Specific parameter	Effect
Infrastructure	Shared vs. not shared	Trade	RIP equipment use fee	Higher cost for *shared*
	Shared vs. not shared	Infrastructure	Radio infrastructure cost	Lower cost for *shared*
Activation	Provider only vs. User+provider	Infrastructure	Radio infrastructure cost	Higher cost for *user+provider*
	Provider only vs. User+provider	Overhead		Higher cost for *user+provider*

When the ST *infrastructure* is shared in a ST environment there will be higher costs for establishing a ST transaction when compared to a not-shared environment due to the RIP equipment use fee. However the new user of the spectrum will have lower radio infrastructure costs since it makes use of the shared infrastructure instead of deploying its own. The use of a shared infrastructure will remain attractive to an entity requiring spectrum as long as all other transaction and information overhead related costs are low enough to compensate for the opportunity costs of deploying its own radio infrastructure. A service provider with its own infrastructure can provide and plan for better coverage and QoS levels than one that shares infrastructure and is limited by the geographic position of the shared radio equipment (RRBS) and capacity of the backhaul links of such infrastructure.

Shared ST infrastructures would benefit new entrants to the wireless services market by making it easy for them to acquire spectrum and use radio infrastructure. Incumbents of this market have the following choices:

- Offer their unused spectrum into the ST market and thus collect on the fees for this concept.
- Deploy or adapt their infrastructure so that it can make use of spectrum acquired through the ST market. This would benefit the provider in those areas where excessive service demand occurs and/or to cover areas where demand is so low that it doesn't merit the deployment of its own radio infrastructure.

These choices are not exclusive as there might be service areas where one makes better sense than the other.

In terms of service activation, when supporting user+provider based activation the ST infrastructure must contain devices with the adequate intelligence to support and understand user based activation requests in addition to provider based requests. This implies higher costs in infrastructure due to the added intelligence. Also information overhead is increased as protocols between the subscriber device and the base station must be enhanced to support user initiated interactions.

When matching these cost behaviors to the set of architectures selected and mentioned in Table 6 and by taking architecture #1 as the base reference, a qualitative cost comparison can be achieved which is summarized in Table 11.

Table 11. Cost comparison of architectures

	Architecture dimensions			Cost dimensions		
#	**Infrastructure**	**Configuration**	**Activation**	**Trade**	**Infrastructure**	**Info overhead**
1	Shared	Centralized	Provider Initiated	N/A	N/A	N/A
2	Shared	Centralized	User+Provider	Same	Higher	Higher
3	Shared	Distributed	Provider Initiated	Same	Same	Higher
4	Shared	Distributed	User+Provider	Same	Higher	Higher
5	Not shared	Centralized	Provider Initiated	Lower	Higher	Same
6	Not shared	Centralized	User+Provider	Lower	Higher	Higher
7	Not shared	Distributed	Provider Initiated	Lower	Higher	Higher
8	Not shared	Distributed	User+Provider	Lower	Higher	Higher

The selection of the *best* architecture will depend on the environment in which a spectrum trading infrastructure is to be deployed and the way that a WSP wants to manage its costs. For example, depending on the value of the RIP_{fee} a WSP could have to consider whether it is more beneficial (from a cost perspective) to deploy its own radio infrastructure to serve an area than to depend on a shared ST infrastructure. In this case, the WSP would not incur a trade cost but would incur an infrastructure cost, so one cost dimension diminishes while the other one increases. A cost minimization strategy would indicate an inflection point where the WSP would be better off changing its strategy to owning its radio infrastructure.

Functional aspects of a wireless technology can complicate the cost analysis of a given ST architecture. In the case of WiMAX, its set of profiles for the PHY layer offer a choice of OFDM vs. OFDMA operation. The latter offers capabilities for having multiple subscriber transmissions simultaneously (multiple access) which means higher efficiency in spectrum use. This comes at the expense of added complexity in the assignment and handling of spectrum to the subscriber stations when compared to OFDM. The effects of these characteristics have not yet been captured in the parameters of the cost model.

7.4 IMPLICATIONS FOR THE MODELING OF ST MARKETS

The cost comparison among architectures mentioned in Table 11 will hold for a ST architecture that employs one wireless standard such as WiMAX or GSM/EDGE in which the operational requirements of the standard do not impose any special elements or benefits to a particular architecture dimension. In WiMAX and GSM/EDGE operation an Operational Support System (OSS) can be in place over which the radio network infrastructure is controlled. In a ST environment the OSS would issue commands to the RBS in order to make use of resource acquired in the market.

In order to answer questions 2 and 3 related to the research focus of this dissertation (see chapter 3.0) we are interested on the effect of the technical architecture characteristics in the ST market behavior once the market is active and conducting trades.

From the analysis of the previous sections and under the assumption of ST markets with single protocol operation and provider initiated activation we can see that most of the relationships between technical architecture parameters and costs will affect the startup costs to set up a ST market. However, the focus of this research is on the running behavior of a market (market behavior assuming its infrastructure has been deployed) and the only cost dimension that affects the running behavior of a market is the *trade* dimension.

Trade costs affect the running behavior of the market due to the payment of fees that a WSP would have to incur in order to make use of shared infrastructure. These fees would affect the bid-ask spread in the market but if kept small the effect would be lessened.

However, trade costs are related to the technical infrastructure type selected to implement the ST market. These costs will remain the same as those for the reference architecture chosen in Table 11 when using a *shared* infrastructure (technical) and will be lower when using a not shared infrastructure.

Additionally, from Table 4 we see that there is a relationship between the choice of infrastructure and type of exchange to be used, however the only differentiating factor between the exchange types is whether the exchange is organized to work as a band manager (BM) or not (NOBM).

Thus, under the following assumptions/restrictions:

- One wireless standard is being used in the market
- Provider initiated activation of spectrum trading request is supported
- Interference between spectrum units (BBUs) traded in the market does not impact the services provided over a BBU
- Trading takes place over an exchange entity.

The result of this analysis for the modeling of the running behavior ST markets is that when modeling these markets, two types of market operation should be considered and clearly differentiated: Markets with a spectrum exchange organized to work as a band manager (BM) or those with a pure spectrum exchange (NOBM).

In order to proceed with the analysis of ST markets and address questions 2 and 3 of this research through the use of agent-based modeling, we will consider only market scenarios operating with the previously mentioned exchange types and assumptions.

8.0 AGENT-BASED MODELING OF ST MARKETS

As defined by Tesfatsion in [39], agent-based computational economics (ACE) is “the computational study of economic processes modeled as dynamic systems of interacting agents”. An agent in an ACE model is a software entity with defined data and behavior. Agents can represent individuals, institutions, firms and physical entities.

A complete ACE model must specify the initial state of the economic system being modeled, the characteristics of the agents and the methods of interaction among agents. The specification of an agent includes its public (accessible to other agents) and private behavioral methods and attributes.

When modeling markets, the agents representing market participants have limited (if any) knowledge of the decisions and state of other market participants (bounded rationality). Agents adapt their behavior based on their goals, their interaction with the market and/or other agents. A key fact in ACE modeling is that once initial conditions have been specified, the evolution of an ACE model is only dependant on the interactions among agents. Thus ACE models provide a tool to observe the aggregate behaviors that emerge on a system from the individual behaviors of its components (agents). Analyzing these aggregate behaviors can provide insights into the behavior and characteristics of new markets, the effect of economic policies and the roles of institutions.

8.1 MODEL OVERVIEW

In order to study the possible behaviors and interactions in spectrum trading markets we make use of ACE to model and study these markets. In our case, we use ACE to determine the conditions over which spectrum trading markets are viable where viability is determined by the liquidity and sustainability of the market. For this study, the agents incorporated into our models represent the market participants present in exchange based markets and mentioned in section 6.1. The list of agents is shown in Table 12.

Table 12. Agents in ACE model

Agent	Comments
Spectrum User	This agent models a wireless service provider that participates in the ST market as a seller of spectrum (SLH) or buyer (SLR)
Market Maker	Entity that provides liquidity to the market. It will be present only in scenarios in which the exchange does not act as a band manager (NOBM scenarios)
Spectrum Exchange	Centralized entity that gathers and matches bids and asks for spectrum. It will act as a band manager in BM scenarios and not in this capacity in NOBM scenarios
Spectrum Regulator	Manages a spectrum availability and assignment database.

A Spectrum Trading market modeling tool (SPECTRAD) has been developed as part of this research work and makes use of ACE concepts [39, 40]. The tool works on top of REPAST (Recursive Porous Agent Simulation Toolkit) platform developed by the Argonne National Laboratory [25, 26]. REPAST provides a set of tools for the development of agent based models in Java along with data collection, data analysis and error reporting capabilities.

A market scenario simulation starts with a set of specified initial conditions that are selected to match the experimental design mentioned in chapter 3.0 . The parameters for the scenarios to be considered are:

- Number of market participants (Spectrum Users + Market Maker) (N)
- Distribution of spectrum users' valuation level (L)
- Available Spectrum (S)
- Market type (M)

A description of the behavior of agents and the statistics collected is detailed in the next sections of this chapter.

8.2 GENERAL MARKET SETUP AND MODEL ASSUMPTIONS

We assume that spectrum trading will take place over a single geographic area over which the wireless services providers (modeled by Spectrum User agents) can provide services, have enough radio base stations (RBS) to cover the area and can trade spectrum with the help of a spectrum exchange. Wireless service requests manifest to each spectrum user (SU) as traffic requests (traffic to be served) for which the SU has to determine if it has sufficient resources. The SUs can obtain resources to serve traffic either by acquiring spectrum in the form of Basic Bandwidth Units (BBUs) or by using a unit of transmission of an Alternate Technology (AT).

Investment in AT transmission units can resemble investing in equipment to make better use of spectrum already owned by the SU, thus avoiding further buying of BBUs. The choice between BBUs or ATs will be based on the economic benefit that a given SU might receive from making a selection as it tries to *minimize* its costs for providing wireless service. Each SU will have a fixed price for its choice of AT unit which does not change during the life of the market. Thus, if a SU is acting as a spectrum license requestor (SLR i.e. buyer) when the market price for BBU is higher than the AT price, the SU will buy ATs and when BBU prices are lower or equal to the AT price, the SU will buy BBUs.

However, in order to make the behavior of a scenario more consistent with realistic parameters, once an AT unit is bought; it cannot be put into service immediately. We assume a one *time tick* delay (which can be mapped to an hour, a day, or a week depending on the time scale of choice) from the moment the AT unit is bought until it can be used. We also assume that the *opportunity cost* of not serving a given request for traffic is too high for the SU to incur. Thus, a SU can buy BBUs at a price higher than its AT choice price in order to get the transmission resources to serve traffic requests until its AT units are usable (activated). After the ATs are activated, the SU will put back in the market the BBUs for which it overpaid. AT units have a finite lifetime after which they become unusable. Further details on the buying and selling behavior of the SU are given in section 8.3.

The behavior of the spectrum exchange depends on the type of scenario being simulated (NOBM vs. BM). Details of its behavior are given in section 8.4. The market maker is active only in NOBM scenarios, its behavior is described in section 8.5.

A regulator agent models a regulator entity and oversees the trades being conducted in the market and updates a spectrum assignment database so that ownership of a given BBU could be verified if needed. In the scenarios considered in this research, we assume a liberalized spectrum environment (spectrum can be given any use and owned by any SU) thus the regulator does not restrict any trading interaction.A summary of the parameters that apply to all market scenarios is provided in Table 13.

Table 13. General market simulation parameters

Parameter	**Symbol**
Size (bandwidth) of a BBU	BW_{BBU}
Traffic capacity of a BBU	C_{BBU}
Traffic capacity of an AT transmission unit	C_{AT}
AT lifetime	AT_{Life}
Total simulated market lifetime	T_{max}
Total number of BBUs for trading	$\boldsymbol{S_{BBU}^{Total}}$
Total number of SUs in market	N_{su}

8.3 SPECTRUM USER AGENT BEHAVIOR

Spectrum users (SU) are the agents that model wireless service providers (WSPs) and which buy and sell spectrum in order to attend traffic requests (buy) or obtain economic gain (sell). When buying spectrum, the SUs behavior is that of a spectrum license requestor (SLR). When the SU sells spectrum the SU is acting as a spectrum license holder (SLH). Each SU serves the aggregate traffic demand of its customers in a geographic area. The traffic to be served can be mapped to a spectrum requirement that specifies the number of basic bandwidth units (BBUs) required by the SU.

For our analysis we model the aggregate traffic demand for each SU within the ST service area with an exponential distribution with a mean of $\mu_{traffic}$. The interval between changes of traffic demand is modeled as an exponential distribution with a mean of $\mu_{tchange}$.

8.3.1 SU behavior with a NOBM exchange based market

In an exchange based market, the SUs submit requests to buy (bids) or sell (asks) to the exchange. The exchange collects these requests and if it finds the best match between requests to establish a trade. The SU can query the exchange for its current market *quote* , which contains the minimum ask and the maximum bid price posted in the market. SUs can use this information in their market activities.

Additionally, a SU can post *limit* orders to buy/sell (limit bid / limit ask) or market orders to buy/sell. Market orders are buy/sell orders that should be filled at the best price currently available in the market (the quote price). A limit order specifies to the exchange the desire of the SU to acquire/sell BBUs at the best price possible but in no event pay more than or sell for less than a specified limit price when buying or selling spectrum, respectively.

The traffic capacity that a SU must serve varies in time. If the SU's inventory of BBUs and AT units is more than enough to service the traffic capacity required by its customers, the SU can sell part of its spectrum inventory, thus becoming a SLH and prepare to post an offer to sell (ask) to the market. If the SU has less spectrum than that required to serve its customers, it will buy spectrum, thus becoming a SLR and prepare to post a bid to the market. However, the buying decision is also affected by the AT price set by the SU. A general algorithmic description of the SU's buying and selling behavior is detailed here:

Pre-condition: An aggregate traffic demand ($T_{traffic}$) value from the SU's service area customers has been received

Steps:

1. Calculate the maximum traffic demand ($M_{traffic}$) value that can be supported with the current inventory of BBU units (S_{BBU}) and AT units (A_{AT})

$$M_{traffic} = (S_{BBU} \times C_{BBU}) + (A_{AT} \times C_{AT})$$

Where C_{AT} and C_{BBU} are the traffic capacities of an AT unit and a BBU respectively.

2. Calculate the difference ($D_{traffic}$)between $M_{traffic}$ and $T_{traffic}$

$$D_{traffic} = T_{traffic} - M_{traffic}$$

3. Determine **if** ($D_{traffic} > 0$)

3.1 *True:* Determine **if** price per AT unit (P_{AT}) is greater than the current price per BBU (P_{BBU})

3.1.1. *<u>True</u>*: Post a market bid to buy a number of BBUs (S'_{BBU}) so that the SU can serve the additional amount of traffic determined by $D_{traffic}$

$$S'_{BBU} = ceiling\left(\frac{D_{traffic}}{C_{BBU}}\right)$$

3.1.2. *<u>False</u>*: Buy a number of AT units (A'_{AT}) so that the SU can serve the additional amount of traffic determined by $D_{traffic}$

$$A'_{AT} = ceiling\left(\frac{D_{traffic}}{C_{AT}}\right)$$

3.2 *False*: Sell BBU in a quantity given by S''_{BBU} where:

$$S''_{BBU} = max\left[ceiling\left(\frac{|D_{traffic}|}{C_{BBU}}\right) - 1, 0\right]$$

A flow chart illustrating the behavior of spectrum users in NOBM scenarios is shown in Appendix A.

The prices posted by a SU agent for buying or selling BBUs are calculated following the ZIP bidding strategy [41], a description of this strategy is included in Appendix B. The ZIP procedure makes use of a learning algorithm which allows the SU to adapt its bid or ask price in order for them to be competitive in the market. Every time after the spectrum exchange receives a bid or ask for spectrum (*a shout*), it announces its value and whether a trade could be conducted or not based on the shout's values and the market's quote for spectrum. All SU agents will use this information to adapt their prices.

Although in most cases, a SU will buy BBUs only if it can buy them at a price lower than its AT price, there is an exception to this rule. Since we assume that the opportunity cost of not serving either part or all of a traffic request is very high, this cost must be avoided by the SUs if possible. Thus, when an SU determines that the price per BBU is higher than its AT costs, it will buy enough AT units in order to satisfy a traffic request. However, since AT units cannot be activated in the same time tick (time period) in which they are bought, the SU has to buy BBUs at a market price higher than its AT price (i.e. limit price) until the AT units become active. After the AT units become active, the SU will sell back the "overpriced" (from the SU's perspective) BBUs at an initial price equal to the average price at which the set of BBUs were bought.

After a SU has bought AT units, it is aware that they have a finite lifetime and that they should be decommissioned in the future based on their mean lifetime. Before the decommissioning time arrives, and if the SU does not have an active bid in the market, the SU posts a preventive bid for spectrum to acquire BBUs that can be used in place of the AT units that will be decommissioned. In this way, if the bid is successful, the SU does not incur the risk of having unmet traffic capacity that was being served by the AT units at the time of their decommission.

8.3.2 SU behavior in a BM based exchange market

In a market with a BM exchange, the SUs post bids for spectrum and depending on the amount of spectrum in the exchange's band and the amount of spectrum required by the SUs, the exchange determines a cutoff price. The SUs with bid prices above the cutoff price get assigned spectrum. Section 8.4.2 provides more details on the BM exchange's behavior.

SUs with winning bids get assigned spectrum leases for a time period T_{lease} after which they must submit a new bid if it wants the spectrum again. Each bid for spectrum is for a number of BBUs that allows the SU to serve its traffic demand. If a SU already has AT units in its inventory these will help reduce the number of BBUs to bid for. The bid price is selected to be below the SU's alternate technology (AT) price. If the bid price is too low and the SU does not make the cutoff price announced by the BM exchange, the SU will adapt its price following the ZIP procedure to announce a new bid price in the next bidding round.

After the BM announces the end of the bidding rounds, if a SU did not get any or all of the BBUs it needed it will buy AT transmission units which will become active after an activation delay (usually 1 time period). Over the course of the activation delay, the SUs that did not get spectrum will not be able to satisfy its traffic requirements. After activation, AT units have a finite lifetime.

A flow chart illustrating the behavior of spectrum users in BM scenarios is shown in Appendix A.

8.4 EXCHANGE BEHAVIOR

8.4.1 NOBM Exchange

In NOBM exchange based market scenarios, the market initialization is done via a call market[9] trading session after which a continuous order-driven market is started. In the call market session, the SU agents engage in a series of mock auctions (several rounds of posts of bids and asks with no actual trading) to reach stable initial trading prices following a procedure similar to that in [42]. Once the prices have stabilized and been posted in the market, the bids and asks that are marketable are matched and a trade takes place.

After these initial trades, the market behavior switches to that of a continuous order-driven market in which spectrum users may trade at anytime they choose. Spectrum users can post either limit orders or market orders. After each post, the exchange updates its order book and if a trade can take place, it transfers the spectrum license from the seller (SLH) to the buyer (SLR) and records the details of the trading transaction. It also informs the Regulator agent about the trade so that it can keep track of who is the owner of each BBU in the market.

The exchange's order book keeps a record of the bids and asks currently active in the market and sorted by price. After each trade or if there was no trade, the exchange announces the *market quote* informing market participants of the current market ask price (best price at which spectrum is being sold in the market) and the current market bid price (it's the price of the best

[9] In a call market, "all trades take place only when the market is called". In a continuous market, "traders can trade anytime the market is open and traders may continuously attempt to arrange their trades" [28] L. Harris, *Trading and Exchanges: Market Microstructure for Practitioners*: Oxford University Press, USA, 2003.

offer to sell spectrum in the market). This way, market participants can adapt their price behavior to make competitive bids or asks in the future.

A flow chart illustrating the behavior of a NOBM exchange is shown in Appendix A

8.4.2 BM exchange

An exchange with band manager functionality will lease the BBUs in its managed band to SUs during t_{lease} time periods. After the leasing period ends, all SUs must submit a new set of bids in order to have spectrum assigned to them. A bid for spectrum is accepted by the exchange and BBUs are assigned to the bidder if the bid price is above the exchange's *cutoff* price.

To determine the cutoff price, all SUs that require spectrum, submit at the start of a time period the amount of spectrum they need (in BBUs) and the price they want to pay for each BBU. The exchange seeks to maximize spectrum efficiency, that is, it seeks to assign as much of the spectrum from its band as it can and to the users that value it the most. Thus, when it receives the bids for spectrum it will organize the bids according to price, if spectrum demand is greater than the amount of spectrum in the band, the cutoff price will be that of the bid with which the band manager gets to assign all the spectrum. Several bidding rounds are conducted until the cutoff price variation is less than 1% from one round to another or until a maximum number of bidding rounds is reached.

All SUs with bid prices greater than or equal to the final cutoff price get assigned their requested BBUs and pay the exchange that price for each BBU. If spectrum demand is less than the amount of spectrum in the band, the cutoff price becomes the minimum cutoff price ($P_{minCutoff}$) for sustainable operation of the band manager and all SUs that posted bids get assigned their requested BBUs and pay $P_{minCutoff}$ for each of them. A flow chart illustrating the behavior of a NOBM exchange is shown in Appendix A.

8.5 MARKET MAKER BEHAVIOR

As explained in section 6.1 the market maker provides liquidity to the market and corrects market imbalances. The behavior of the market maker agent implemented in the models used in this research is that of an entity that stands ready to make bids for spectrum if no SU is posting a bid and it posts an ask offer if no SU is on the selling side of the market. This makes the market maker a very reactive entity that only intervenes in the market when there is a severe imbalance in it (no buyers or no sellers) with the objective of keeping the market alive. Similarities with of our implemented behavior can be found in references such as [43]. Using a simplified market maker allows us to determine which market scenarios are viable without excessive intervention from entities that do not make use of spectrum (entities that do not provide wireless services).

The market maker has an initial inventory of BBUs assigned to it (S_{BBU}^{mm}), it uses that inventory to keep a bid-ask spread present at all times in the market. Only if its inventory is exhausted will it desist in making the market and when this happens, trades in the market will not be completed depending on where the market imbalance is located. That is, a bidder will not be able to find an ask offer if there are no sellers or a seller will not be able to find a bid offer if there are no buyers. When the market maker cannot act in the market, there will be unserved traffic capacity for at least one SU in the market.

When the MM must intervene in the market, it chooses between 10% – 25% of its current spectrum inventory to be offered for selling (ask) or for buying (bid). It posts an initial price for the BBUs in its ask or bid such that the market's bid-ask spread becomes BA_{mm}. This way the MM's intervention is rather moderate as it will not set to offer all its spectrum for trading and thus provoke large price changes in the market. When posting a bid, the MM's intervention signals a lack of buying activity in the market while there may be a lot of offers to sell spectrum, thus prices for BBUs should come down. When posting an ask, the MM's intervention signals a lack of selling activity thus prices for spectrum should increase.

Keeping in line with this behavior, if the MM's bid or ask becomes marketable (a SU buys from the MM or sells to the MM) the MM will decrease or increase its BBU price in the next bid or ask respectively in order to signal abundance or lack of spectrum being offered in the market.

When market intervention by the MM is not required after T_{no_mm} consecutive time periods, the MM will issue a bid or ask with the objective of getting its spectrum inventory back to its reference level which is the same as its initial spectrum inventory amount. Since the MM does not make use of spectrum it is convenient for the market if it sell any excess inventory that it may possess. If the MM's spectrum inventory is below its initial level it will post a bid to bring it back to its initial level so that the MM is better prepared to intervene the market when it is required.

8.6 ST MARKET MODELING WITH SPECTRAD

Appendix C shows a detailed report of the behavior of a NOBM and a BM based market. Both reports illustrate the capabilities of SPECTRAD and give an example of the wide array of parameters that can be tracked and measured when modeling a ST market with this tool.

The code for SPECTRAD has been developed in Java and operates over the REPAST Symphony agent based modeling platform developed by Argonne National laboratories and implements all of the agent behaviors described in this chapter. It also includes code that uses the data reporting capabilities of REPAST to generate statistically significant data for the analysis of the market scenarios of this research. The API of SPECTRAD is not included in this document due to its length. It is however available as a separate document.

8.7 MODEL VALIDATION:

The analysis of SPECTRAD reports such as those included in appendix C can be used to validate the correct behavior of the modeling logic used in SPECTRAD. Many of these reports have been analyzed to debug and verify SPECTRAD's behavior by the author. A more summarized way of looking at the behavior of SPECTRAD is to look at the correlation values among several measured parameters.

8.7.1 Model validation of NOBM market behavior

Table 14 lists the parameters measured for NOBM scenarios and Table 15 lists the correlation values between the parameters. The values indicated in yellow illustrate the correlation among variables that should change in the same way in a ST market. That is, their correlation is expected to be positive and high (close to 1.0) and validate in part the behavior of the models. The values indicated in green are correlation values that reflect an interesting behavior among variables and can be interpreted as results from the market behavior. These values will be explained in chapter 9.0 .

Table 14. Measured parameters for NOBM scenarios

Parameter	Description
BASpread	Bid ask spread. It is the difference between the minimum ask price and the maximum bid price.
MinAskP	Minimum ask price
MaxBidP	Maximum bid price
TotTrades	Total number of trades conducted
ATInv	Average number of AT units in inventory per spectrum user
MmPrice	Market maker's BBU price
MmInv	Market maker's BBU inventory
OfferedSp	Amount of spectrum offered for sale
Markets	Percentage of markets that were able to run
MktNoBA	Percentage of markets that had no bid ask spread
MidPrice	Mid-point price of a BBU. The mid-point price between the minimum ask price and the maximum bid price

The correlation values in Table 15 show that the maximum bid price and minimum ask price move together (have a high correlation). This is consistent with market behavior in the sense that when supply for a good (spectrum) is scarce, offer (selling) prices go up and so do the bid (buy) prices otherwise trades would not take place and prices have to come down. The market maker's price is highly correlated to the mid point price, max bid price and mid ask price. This indicates that the market maker's prices are not out of sync with the market prices, thus the market maker is posting prices that are consistent with the market's behavior.

The average number of AT units per spectrum user is highly correlated to the BBU price values of the market (maximum bid, minimum ask, mid point, and market maker's) which is an expected result since when BBU prices are high, only those entities (spectrum users) that can afford them would buy BBUs and the rest would buy AT units, increasing their AT inventory levels.

Table 15. Correlation values for NOBM market parameters

	BASpread	*minAskP*	*maxBidP*	*TotTrades*	*ATInv*	*mmPrice*	*mmInv*	*OfferedSp*	*Markets*	*MktNoBA*	*midPrice*
BASpread	1.0000										
minAskP	0.8278	1.0000									
maxBidP	0.8038	0.9989	1.0000								
TotTrades	0.0243	-0.1490	-0.1628	1.0000							
ATInv	0.7610	0.9485	0.9505	-0.0778	1.0000						
mmPrice	0.8310	0.9980	0.9970	-0.1512	0.9573	1.0000					
mmInv	-0.6946	-0.5437	-0.5262	0.4301	-0.4335	-0.5491	1.0000				
OfferedSp	-0.6273	-0.5962	-0.5879	0.6813	-0.5051	-0.6069	0.9220	1.0000			
Markets	0.2114	0.1365	0.1220	0.7205	0.1740	0.1210	0.2032	0.4247	1.0000		
MktNoBA	0.6727	0.7063	0.7049	0.0069	0.8156	0.7171	-0.3274	-0.3732	0.2771	1.0000	
midPrice	0.8170	0.9998	0.9995	-0.1539	0.9491	0.9976	-0.5353	-0.5916	0.1332	0.7032	1.0000

8.7.2 Model validation of BM market behavior

Table 16 lists the parameters measured for BM scenarios and Table 17 lists the correlation values between the parameters. The values indicated in yellow illustrate the expected high correlation among some variables which validates in part the behavior of the models.

Table 16. Measured parameters for BM scenarios

Parameter	Description
ATInv	Average number of AT units in inventory per spectrum user
BBU_Assig	Number of BBUs assigned to spectrum users
CutoffP	Cutoff Price
DGs	Percentage of markets where demand is greater than supply
BidListEmpty	Probability that there are no spectrum buyers in a trading round.
PercAssigBBU	Percentage of the band manager's spectrum band that has been assigned to spectrum users

The correlation values show that the cutoff price is highly correlated to the percentage of markets where demand is greater than supply. This is an expected behavior since high cutoff prices will be present when there is competition for acquiring spectrum among the SUs leading to a cutoff price that is above the minimum cutoff price. Also when the cutoff is high, those entities that cannot acquire spectrum because of price will acquire AT units instead. The correlation values show a good degree of correlation between the cutoff price and AT units per spectrum user which is consistent with this other expected behavior.

Table 17. Correlation values for BM market parameters

	ATInv	*BBU_Assig*	*CutoffP*	*dGs*	*bidListEmpty*	*PercAssigBBU*
ATInv	1.0000					
BBU_Assig	-0.3944	1.0000				
CutoffP	0.6950	-0.0439	1.0000			
dGs	0.6685	-0.0125	0.9894	1.0000		
bidListEmpty	0.5515	-0.2359	0.1013	0.0699	1.0000	
PercAssigBBU	0.6640	0.0909	0.7625	0.7904	0.1025	1.0000

The percentage of assigned BBUs is correlated with the cutoff price and the percentage dGS value, this also validates the model's behavior since high values of dGS indicate competition for the spectrum in the band manager's inventory which will be completely assigned to spectrum users when demand is greater than supply.

9.0 RESULTS AND DISCUSSION

The main goal of this research can be re-stated as finding the *region* where ST markets are viable, where by "region" we mean the combination of parameters that lead to viable markets. Finding this "region of viability" would solve research questions 2 and 3 mentioned in chapter 3.0 . We make use of SPECTRAD and the agent behaviors specified in the previous chapter to simulate several market scenarios and determine the values of the parameters that make a market viable. In this chapter, section 9.2 and 9.3 describe the setup, experiments and results for NOBM and BM exchange scenarios respectively. Section 9.4 looks at the behavior of both scenario types (NOBM and BM) and provides additional analysis on the conditions for viable ST markets.

9.1 GENERAL MARKET SCENARIO PARAMETERS

In all market scenarios the spectrum users (SUs) represent wireless service providers that have traffic demands (from their customers) in the geographic area over which the spectrum trading exchange can provide trading services. We assume that each SU has enough infrastructure in the area so that it can make use of traded spectrum. Table 18 presents the default values for parameters that are common to all (BM and NOBM) market scenarios.

Table 18. Values for common scenario parameters

Parameter	Symbol	Value
General parameters		
Size (bandwidth) of a BBU	BW_{BBU}	200 KHz
Traffic capacity of a BBU	C_{BBU}	384 Kbps
Traffic capacity of an AT transmission unit	C_{AT}	384 Kbps
AT lifetime	AT_{Life}	Uniformly distributed between (90, 110) time ticks.
Total simulated market lifetime	T_{max}	5000 time ticks (3000 time ticks for warmup period, 2000 time ticks for active data collection of market behavior)
SU Parameters		
Mean traffic demand	$\mu_{traffic}$	4.0 Mbps
Mean length for intervals between traffic demand changes	$\mu_{tchange}$	Uniformly distributed between (10, 25) time ticks

Different market scenarios will be simulated by varying the values of the amount of tradable spectrum in the market $\left(S_{BBU}^{Total}\right)$, the number of spectrum users present in the market (N_{su}) and the distribution of spectrum users' valuations. The variation of the tradable spectrum amount and number of spectrum users are related in such a way that the value of the *BBUs per SU ratio (R)* is in the set [5, 10, 15, 20, 25]. Table 19 lists the characteristics of the market scenarios that will be simulated.

100 runs for each scenario will be performed in order to get statistically meaningful data. Thus by considering all factors in combination (full factorial experiment design), we will have to perform: $6 \times 3 \times 5 \times 2 \times 100 = 18000$ experiment (simulation) runs.

Table 19. Scenario parameters

<table>
<tr><th>Parameter</th><th>Values</th></tr>
<tr><td>Number of spectrum users (N_{su})
(For NOBM scenarios, this number includes one market maker)</td><td>4, 5, 6, 10, 20, 50</td></tr>
<tr><td>Distribution of spectrum users' valuation level (L)
Table indicates proportion of the spectrum given to users of a valuation level</td><td><table><tr><th>Case</th><th>Low</th><th>Medium</th><th>High</th></tr><tr><td>1</td><td>⅓</td><td>⅓</td><td>⅓</td></tr><tr><td>2</td><td>½</td><td>¼</td><td>¼</td></tr><tr><td>3</td><td>¼</td><td>¼</td><td>½</td></tr></table></td></tr>
<tr><td>Available Spectrum (S_{BBU}^{Total})
Values indicate the number of BBUs available for trading</td><td>5*N_{su}, 10*N_{su}, 15*N_{su}, 20*N_{su}, 25*N_{su}.
The amounts of spectrum where chosen for each value of N_{su} in order to have R=S/N_{su} in the set [5, 10, 15, 20, 25]</td></tr>
<tr><td>Spectrum exchange architecture</td><td>The spectrum exchange can act either as a band manager (BM) or have no band manager functionality (NOBM)</td></tr>
</table>

9.2 NOBM EXCHANGE SCENARIOS

In all market scenarios with a NOBM exchange, one market maker (MM) will be present and counted in the set of spectrum users. The set of configuration parameters for a MM is given in Table 20.

Table 20. Market maker parameters

Parameter	Symbol	Value
Initial spectrum inventory (BBUs)	S_{BBU}^{mm}	Same as that given to SUs in each scenario
Bid-ask spread for market intervention	BA_{mm}	10
Number of time periods to wait before initiating inventory stabilization procedures.	T_{no_mm}	15

9.2.1 Selected parameters for determining market viability

SPECTRAD was configured to run the NOBM experiments mentioned in Table 19. For every market scenario, 100 runs were attempted and the average of all runs per time period as well as the standard deviation and 90% confidence intervals were collected for several parameters that describe the behavior of a given market. As mentioned in Table 18, each run was executed for 5000 time periods (time ticks) but data was collected only the final 2000 time periods, the rest were for the warm up phase. Appendix C shows a graph for the collected data of a particular NOBM scenario. For the analysis of each scenario, the data from the 2000 time ticks was averaged so that a single representative value describing the time averaged behavior for a particular factor of interest was obtained.

From the set of parameter observations collected for each market scenario, Table 21 lists those that will be taken into account to derive measures for the evaluation of the viability of a NOBM market.

Table 21. Measured parameters

No.	Factor	Symbol
1	Bid-ask spread	BA_{avg}
2	Minimum ask price	$minAsk_{avg}$
3	Maximum bid price	$maxBid_{avg}$
4	Market Maker's BBU inventory	$mmBBU_{avg}$
5	BBUs being offered for sale	$bbuOffered_{avg}$
6	Number of complete market runs	$numMkt_{avg}$

The following is a qualitative description of the usefulness of each of these factors in determining the viability of a ST market :

Factors 1, 2 and 3 are combined to produce a value for the *relative bid/ask spread* (relBA) of the market, in the following way:

$$relBA = \frac{BA_{avg}}{\left(\frac{minAsk_{avg} + maxBid_{avg}}{2}\right)}$$

The usefulness of this factor in determining the viability of a market is that the *relBA* value can be used as an indicator for the liquidity of a market [27, 28]. If the *relBA* value for a market is high, it indicates that the separation between bid and ask prices is large relative to the price of a spectrum BBU (actually, relative to the mid-point price of a BBU). Thus, there would be high resistance in the market to go from a buying position to a selling position. When *relBA* is low, the resistance to conduct a trade is low because with a small change in price (relative to the mid-point BBU price) it would be easy for a market participant to establish a trade. In other words, high values of *relBA* indicate low liquidity in the market while low values of *relBA* would indicate high liquidity.

Factors 2 and 3: The factors can be combined to produce the mid-point BBU price $midPrice_{BBU}$ specified by the following equation:

$$midPrice_{BBU} = \left(\frac{minAsk_{avg} + maxBid_{avg}}{2}\right)$$

This price gives an indication of the average price at which a BBU is being valued in the market. Low values of this measure would indicate an excess in supply or low spectrum demand in the market, while high values would indicate low supply or high demand for spectrum.

Factor 4: *Market Maker's BBU inventory* ($mmBBU_{avg}$) . If the value of this factor differs substantially from the reference inventory level of the Market Maker, it would signal problems in the buying or selling side of the market. Let's define the Market maker's inventory difference with its reference level as:

$$MMInvDiff = \frac{mmBBU_{avg} - mmBBU_{reference}}{mmBBU_{reference}}$$

If in a market the MM is accumulating BBU inventory and can't release it, this implies that the MM always has to act as a buyer to make the market. This indicates that there is low demand for spectrum in that market and the value for *MMInvDiff* would be positive. If the MM is holding low levels of spectrum when compared to its reference level, it would indicate that there are problems in the supply of spectrum in the market and the value for *MMInvDiff* would be negative.

Factor 5: *BBUs being offered for sale ($bbuOffered_{avg}$)*. Expressing this value as a percentage of the total spectrum available in the market using the following equation:

$$bbuOffered_{avg}\,\% = \frac{bbuOffered_{avg}}{S_{BBU}^{Total}} \times 100$$

we have that if this percentage is high, the majority of the tradable spectrum is not in use by the SUs and thus it is being offered for sale. This would indicate low spectrum efficiency. In general, the lower the value of this percentage, the more efficiency there is in terms of spectrum use.

Factor 6: Number of complete market runs *($numMkt_{avg}$)*. For the collection of statistics to analyze each market scenario, 100 runs of the scenario are performed in SPECTRAD. However, in NOBM scenarios activity in each market starts with a series of mock auction so that the SUs can find an initial starting price at which to start trading. If this initial phase is not successful in finding a starting price, the market does not proceed to actual spectrum trading. This factor counts how many of the attempted market runs where successful in finding a stable starting price and thus initiate spectrum trading.

This factor is useful as an indicator of market viability since a high percentage of complete market runs, indicates that initiating trading is feasible without difficulty. In contrast, having a low percentage of complete market runs would indicate that the market structure is not well suited to support sustainable trading.

Table 22 summarizes the set of factors that will be taken into account to determine the viability of NOBM exchange based markets.

Table 22. Factors for NOBM market evaluation

Factor	***Symbol***
Relative bid-ask spread	*relBA*
Mid-point BBU price	$MidPrice_{BBU}$
Relative difference of the MM's inventory to its reference level	*mmInvDiff*
Percentage of spectrum being offered for sale	*bbuOffered%*
Percentage of completed market runs	*numMkt %*

9.2.2 Results

This section displays the results from the modeled NOBM market scenarios using SPECTRAD. The behavior of the market scenarios for each of the previously mentioned factors will be shown based on the number of SUs for each scenario, the user distribution and the R value. Where R is the average number of BBUs per spectrum user $\left(\frac{S_{BBU}^{Total}}{numSU}\right)$. It is worth mentioning that for all scenarios, when R is equal to 10, on average every spectrum user has enough spectrum to serve its average traffic requirement value (see Table 18). Thus lower values of R indicate an under-supply of spectrum, while higher values would lead to an over-supply of this resource to attend the average traffic needs of a SU.

Table 23 shows the structure of the distribution of users in a scenario by indicating which proportions of SUs in a market have low, medium or high valuations for spectrum:

Table 23. Spectrum user distributions

userDist	**Low**	**Medium**	**High**
1	⅓	⅓	⅓
2	½	¼	¼
3	¼	¼	½

Percentage of completed market runs: As mentioned in the experimental design section of chapter 3.0 , a total of 100 runs were executed for each market scenario. However, a market may not be able to start trading activities if its participants can't agree on an initial trading price for spectrum. This happens if the valuations for spectrum between the SUs are divergent enough that there can't be a common starting price. It is also affected by the desire of the SUs to either start buying or start selling spectrum and the number of market participants.

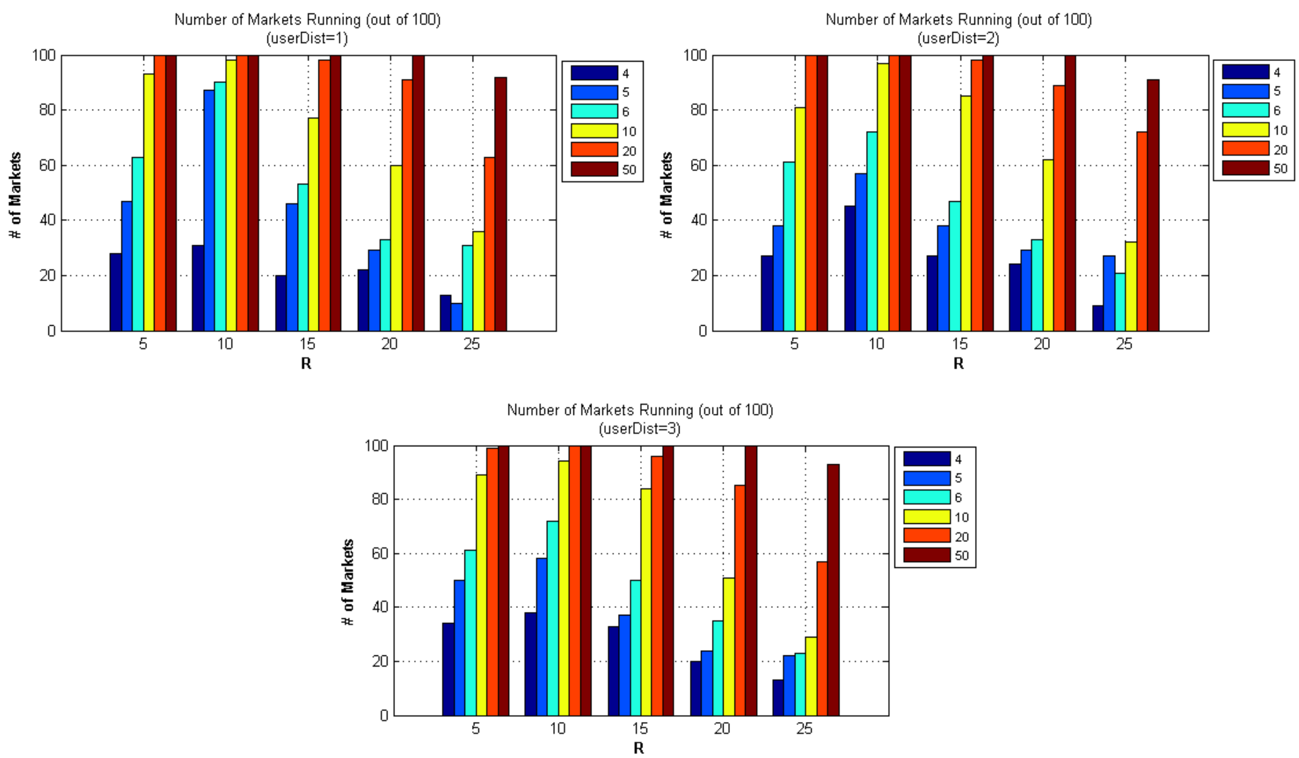


Figure 6. Number of successful market runs

Figure 6 shows the percentage of completed market runs for several scenarios. It can be seen that markets with small number of SUs have less probability of successfully starting than those with a higher number. In particular markets where the number of SU is equal to 4 have problems getting a trading market started, irrespective of user distribution and R value.

As the number of users increases, so does the possibility of having a trading market. For high values of R (>=20) and with SUs <=10 the number of running markets is still lower than in other scenarios. At R=10, all spectrum users have an initial spectrum inventory (10 BBUs) which would allow them to serve most of their average traffic demands. Most scenarios have their peak number of running markets at R=10. At higher R values the SUs have more than enough spectrum to serve their average traffic requests, thus their probability of entering the market as a buyer of spectrum is lower which could be a factor in the number of markets that run.

<u>Relative bid-ask spread and BBU Price</u>: Figure 7 shows the behavior of the relative bid-ask spread for several market scenarios. Figure 9 shows the mid-point BBU price behavior.

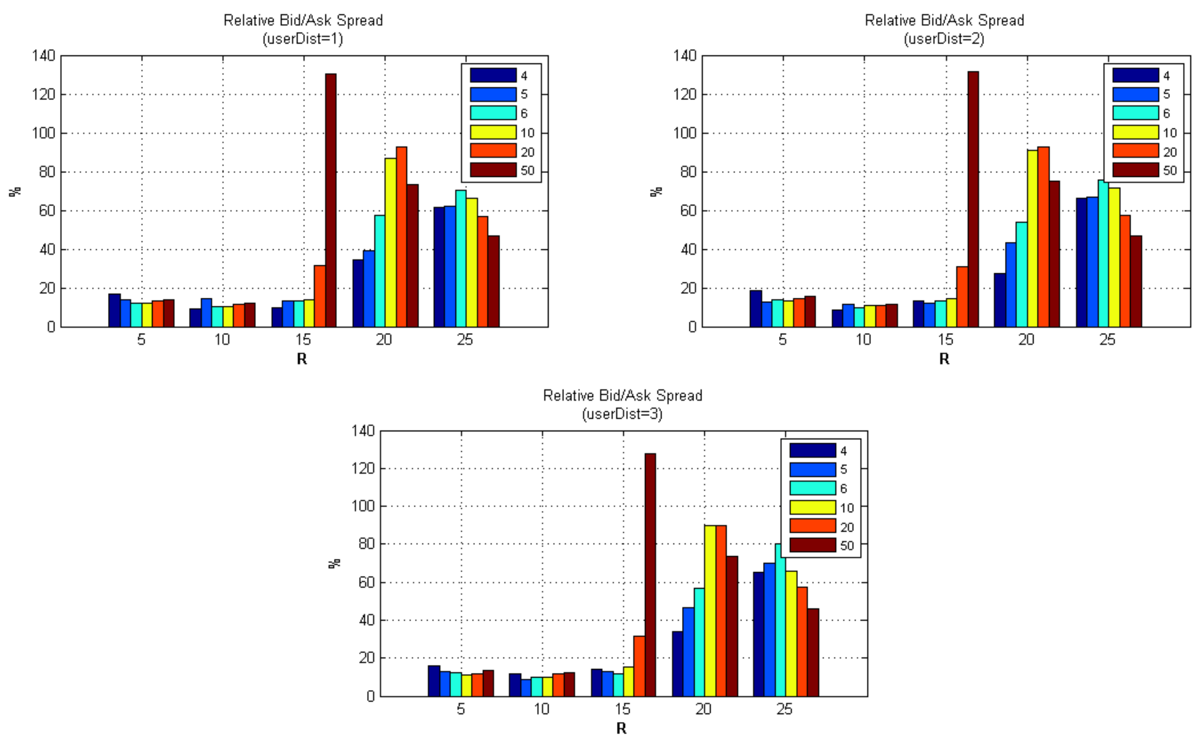


Figure 7. Relative Bid-ask spread

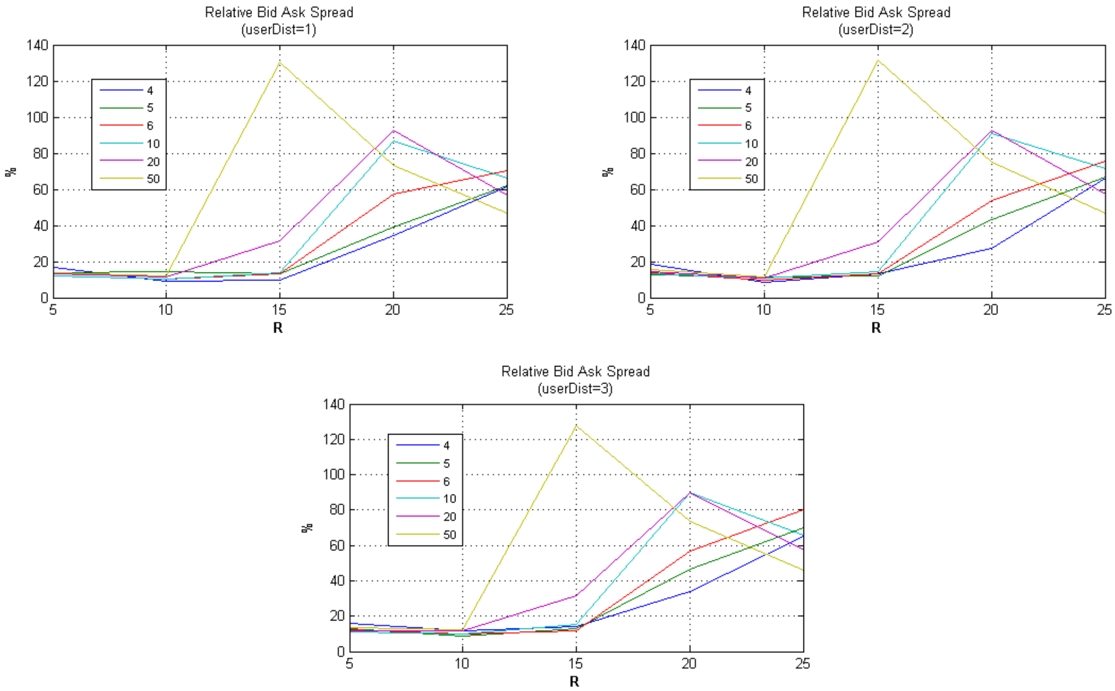


Figure 8. Relative Bid-ask spread (line version)

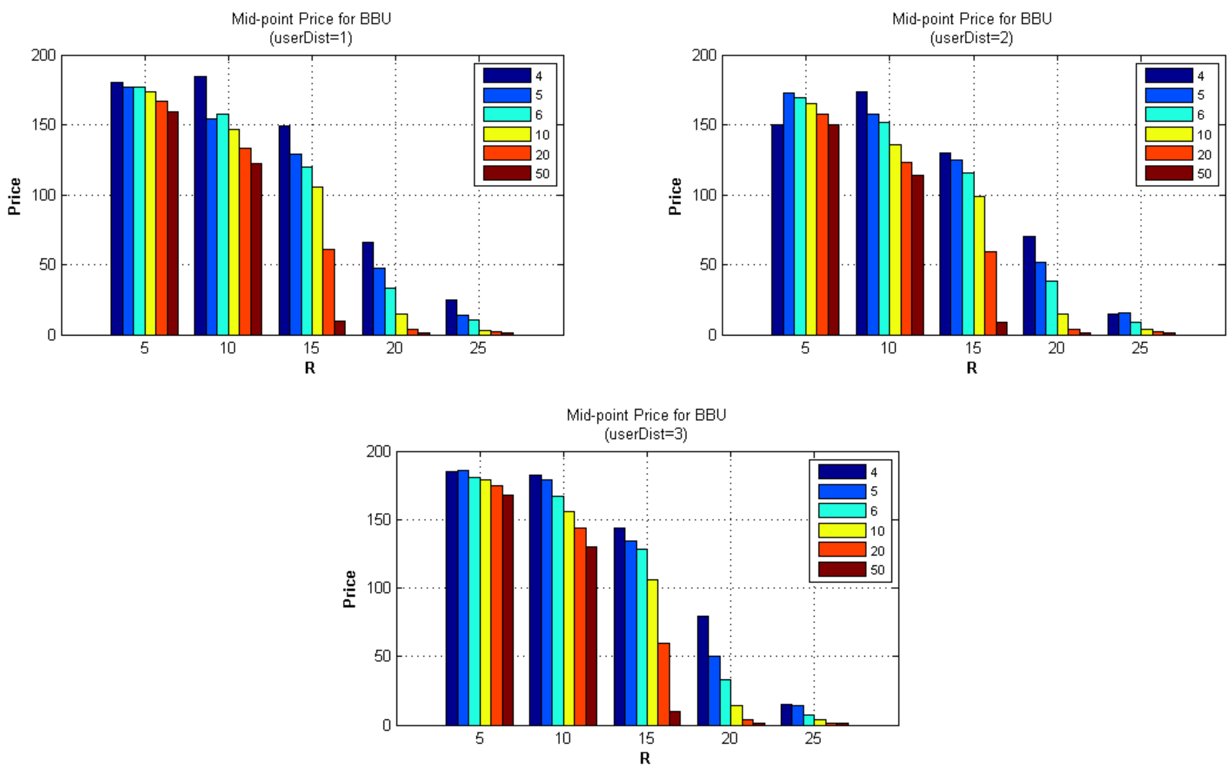


Figure 9. (Mid-Point) BBU Price

R values of 5 and 10 produced markets with a relative bid-ask spread < 20% regardless of the values of number of SU and user distribution. For R=15, only the cases where SU<=10 also generated a relative bid-ask spread < 20%. The higher the value of this factor, the higher the resistance in the market to conduct a trade. In other words, liquidity in the market is greater when the relative bid-ask spread is low and vice versa.

The sharp peak at R=15 and SU=50 arises because the numeric value of the bid-ask spread in that scenario is almost equivalent to the value of the mid-point price for spectrum which as seen in Figure 9 is very low. This combination of values gives a relative bid-ask spread that is high in value.

It should be noted that the transition from R=10 to R=20 produces a sharp drop in the mid-point price of BBU for all scenarios. For most scenarios, the transition occurs when going from R=15 to R=20 except for scenarios with num SUs=50 where the price drop occurs when going from R=10 to R=15. As the number of SUs increases, so does the possibility of having sell offers for spectrum, which brings down the price, especially at high values of R. This price behavior produces peaks in the relative bid ask spread as seen in Figure 8. The peaks are noticeable for some market scenarios, they just occur at different R values.

Additionally, as part of the parameters used for all scenarios modeled, the price for buying an AT transmission unit was always above 100 monetary units. Thus, market scenarios that generated mid-point BBU prices less than 100 will have SUs that are not using price as a differentiator to select between buying spectrum or an AT unit which in turn is an indicator of over-supply of spectrum. This means that scenarios with R>=20 are in an oversupply situation where spectrum prices have dropped below the point where an SU will have to make a choice between using a BBU or an AT based on price.

<u>Relative difference of the market maker's inventory to its reference level *(mmInvDiff)*</u>: Figure 10 shows the mean number of BBUs in the market maker's inventory. A market maker's "normal" inventory level has been defined for the purpose of this work as the numerical equivalent of R BBU units, which is also the initial spectrum assignment for the market maker and all SUs. Thus a market maker with more than R units of spectrum in its inventory indicates a market where the market maker is buying more spectrum than it sells in order to keep the market alive. Excessive amounts of inventory also indicate lack of liquidity in the market and an over-supply of spectrum.

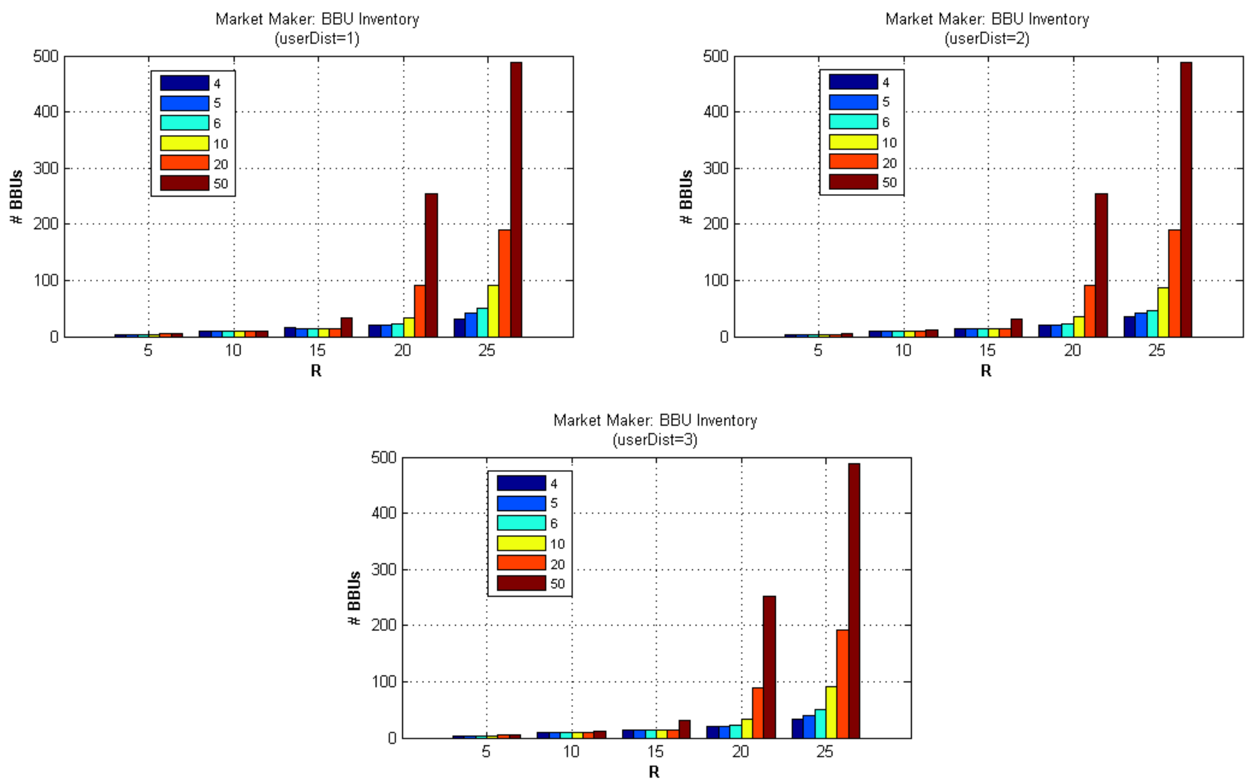


Figure 10. Market maker: BBU inventory

Figure 11 shows the market maker's inventory difference when taking its "normal" level as a reference. For R<=10, the mean MM inventory does not vary in more than 25% from its reference level. That is, the MM is not working with too little or too much spectrum from that which was originally allocated to it. For R>=20, and SU>=10, the MM has a 50% excess on the average number of BBUs in its inventory. If numSU>=20 the excess inventory difference is well above 100% indicating the trouble the market maker is having to keep the market alive.

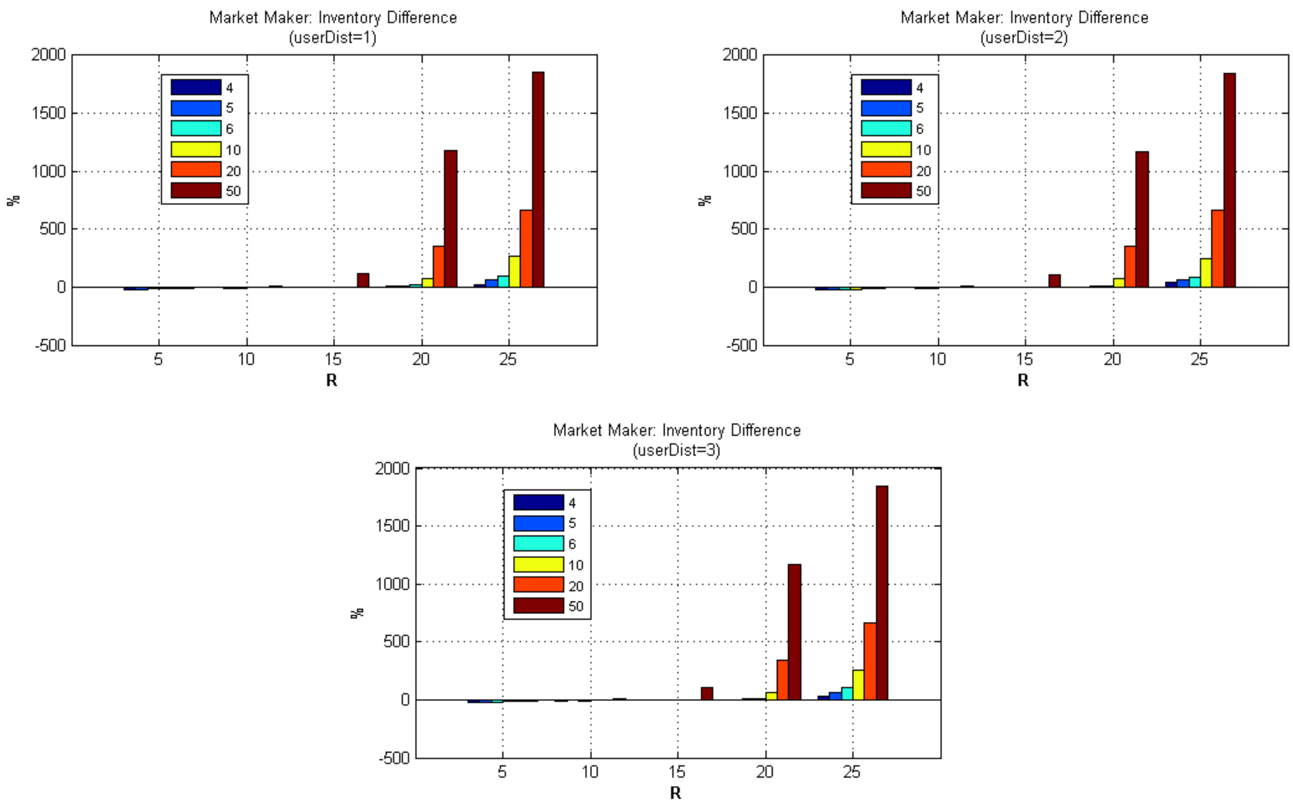


Figure 11. Market Maker: Inventory difference from reference level

<u>Percentage of offered spectrum *(bbuOffered%)*</u>: The amount of spectrum being offered for selling purposes as a percentage of the total amount of spectrum in an scenario is shown in Figure 12. If spectrum is being sold, it means that it is not being used by the SU. Thus knowing how much spectrum is being sold gives an idea as to how efficiently spectrum is being used. The figure shows that the amount of offered spectrum will be between 23%-52% of the total traded spectrum with lower offered spectrum percentages as the number of SUs increases.

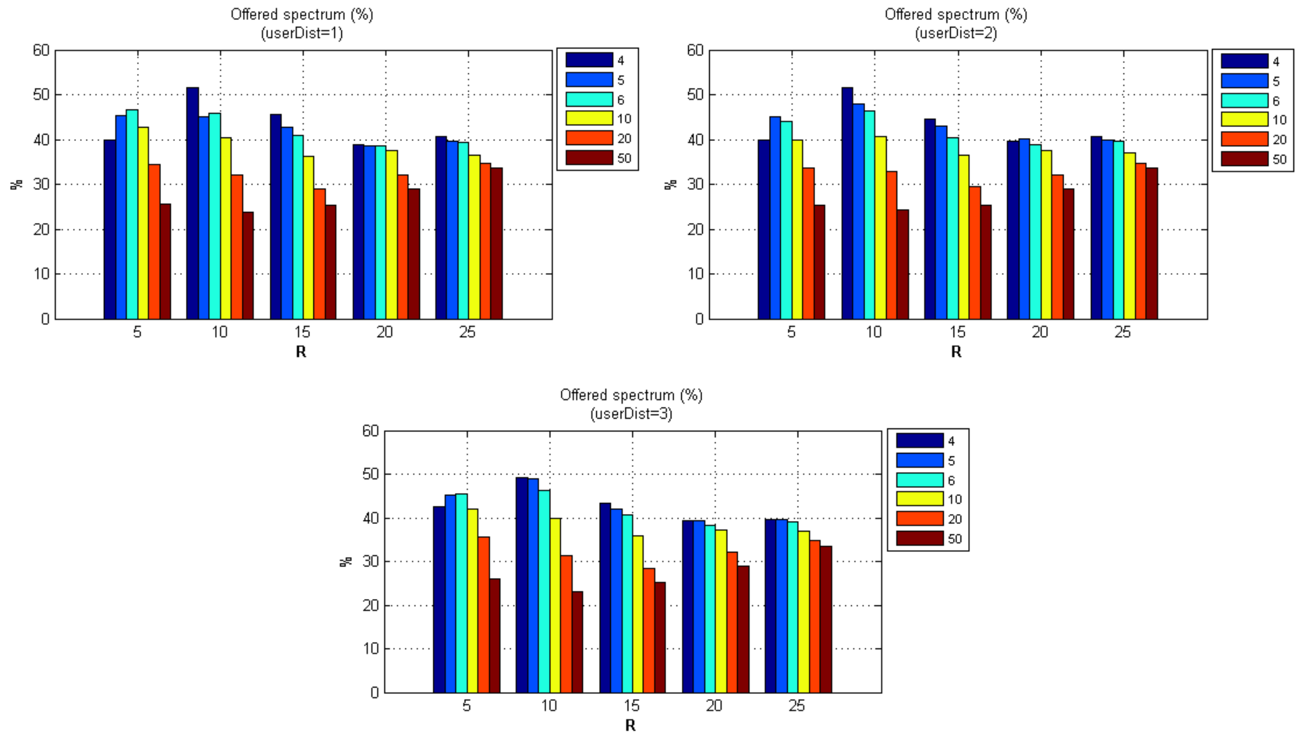


Figure 12. Percentage of offered spectrum

9.2.3 Criteria for viable NOBM markets

In order to determine the viable NOBM markets based on the factors mentioned in Table 22, we need to develop decision criteria to determine if the behavior of a particular factor in a market is to be considered as desirable/acceptable (positive) or undesirable/unacceptable (negative). Additionally, in order to keep track of the aggregate behavior characteristics of a market we will give a score to each factor with a positive value when the market complies positively with the desired behavior characteristic or negative when it complies with the undesirable behavior criteria. Based on the total scores for a market's behavior a final list of viable markets will be determined.

Criteria for the percentage of completed market runs *(numMkt%)*: A low percentage of completed market runs is an indication of the difficulty such a market scenario would have in starting trading interactions. For our purposes, values of *numMkt%* that are less than 50% indicate scenarios that have an unacceptable number of market failures since the probability of having a running market in such scenario is less than that of flipping a coin. These scenarios probably require additional market intervention mechanisms to get started. Scenarios where more than 70% of the markets instantiated lead to trading will be considered acceptable since they indicate scenarios with a high tendency to have a running spectrum trading market. Additionally, the aggregate data collected for the scenarios shows a gap between values of *numMkt%* at 70%. For market viability, the characteristic of being able to start trading activity in a market is of great importance. Because of this, market scenarios that pass/fail this criteria will receive a score of +2/-2 instead of the +1/-1 score that will be used for other criteria.

Criteria for relative bid-ask spread (*relBA*): low values of *relBA* indicate more liquid markets [44, 45]. A value of *relBA* that is less than 20% will be considered acceptable. The aggregate data set of the scenarios analyzed supports choosing this value as it is the mid-point in a gap of values for the *relBA* where several scenarios are below and not close to 20% and others are above and not close to 20%. Values of *relBA* > 50% indicate scenarios with low liquidity and thus, high resistance for trading interactions. These scenarios will be considered unacceptable as they indicate a situation where on average a SU will have to modify its price at least in 50% to reach the mid-point price in the market for a BBU when moving from a buying position to a selling position or viceversa. The SU would need to modify its price even further (after reaching the mid-point price) to reach a price at which a trade can be established.

Criteria for average mid-point BBU price *(midPrice$_{BBU}$)*: The BBU price has a role in a ST market by acting as a differentiator between those who value spectrum the most and the supply/demand conditions of a market. For all the scenarios modeled, the price to acquire an AT transmission unit price is above 100 monetary units and it is independently set by each SU depending on their valuation level. Thus, markets where the BBU price is above 100 will be markets in which spectrum assignment follows the valuation level of a SU which can choose between investing in spectrum or AT units. BBU prices well below 100 indicate markets where the price of spectrum is low due to over-supply or not enough demand conditions.

Scenarios where *midPriceBBU >100* will be considered acceptable since price will act as a differentiator in the market because it will drive the investment decisions of the SUs. We will consider that scenarios with *midPriceBBU* below 25 have unacceptable price behavior since market activity has driven the BBU price to a level well below the point where it is a useful factor for the decisions of a SU. Additionally, the selection of this lower bound is also due to the fact that there is a value gap around this value in the collected scenario data.

Criteria for the relative difference of the MM's inventory to its reference level (*mmInvDiff*): If the *mmInvDiff* value is high it indicates that the MM is either accumulating spectrum inventory which it cannot sell or having problems going back to its reference inventory level because it cannot buy back spectrum. This would happen in scenarios where the market maker is having trouble acting on the market because of liquidity problems in the market. For our purposes we will assume that a *mmInvDiff* value <=25% is acceptable and if >=100% it's unacceptable. The excessive accumulation of BBU inventory by a MM negatively impacts the spectrum efficiency of the market as the MM does not make use of spectrum for transmission purposes. The limits chosen for this factor are based on this analysis and the value gaps centered around these limits found in the aggregate data of simulation results.

Criteria for the percentage of spectrum offered for selling *(bbuOfffered%)*: We will consider as undesirable if the amount of spectrum offered for selling in a scenario is >=38%. This would mean that less than 62% of the available traded spectrum is being used. This value was chosen as it is the average value for *bbuOffered%* in the collected data.

Table 24 summarizes the criteria to be used to evaluate and give score to the different scenarios studied in this work.

Table 24. Criteria for NOBM scenario evaluation

Criteria	Factor	Symbol	Pass	Fail	Score Pass/Fail
C1	Percentage of completed market runs	*numMkt %*	>=70%	<=50%	2/-2
C2	Relative bid-ask spread	*relBA*	<=20%	>=50%	1/-1
C3	Mid-point BBU price	$MidPrice_{BBU}$	>=100	<=25	1/-1
C4	Relative difference of the MM's inventory to its reference level	*mmInvDiff*	<=25%	>=100%	1/-1
C5	Percentage of spectrum being offered for sale	*bbuOffered%*	N/A	>=38%	0/-1

9.2.4 Viable NOBM Markets

Appendix D lists the scores obtained by each of market scenarios studied based on the evaluation criteria defined in the previous section. Figure 13 shows the total scores in graphical form.

The viable NOBM markets can be considered those with scores greater than 0. Scenarios with this condition meet several of the desirable conditions for a viable market. Additionally there is a gap in the score values with many scenarios with scores less than or equal to 0 and others with scores greater than or equal to 2. The scenarios with scores greater than 0 (equivalent to saying greater than or equal to 2 due to gap in score values) all have a percentage of running markets >50% which is a very desirable feature.

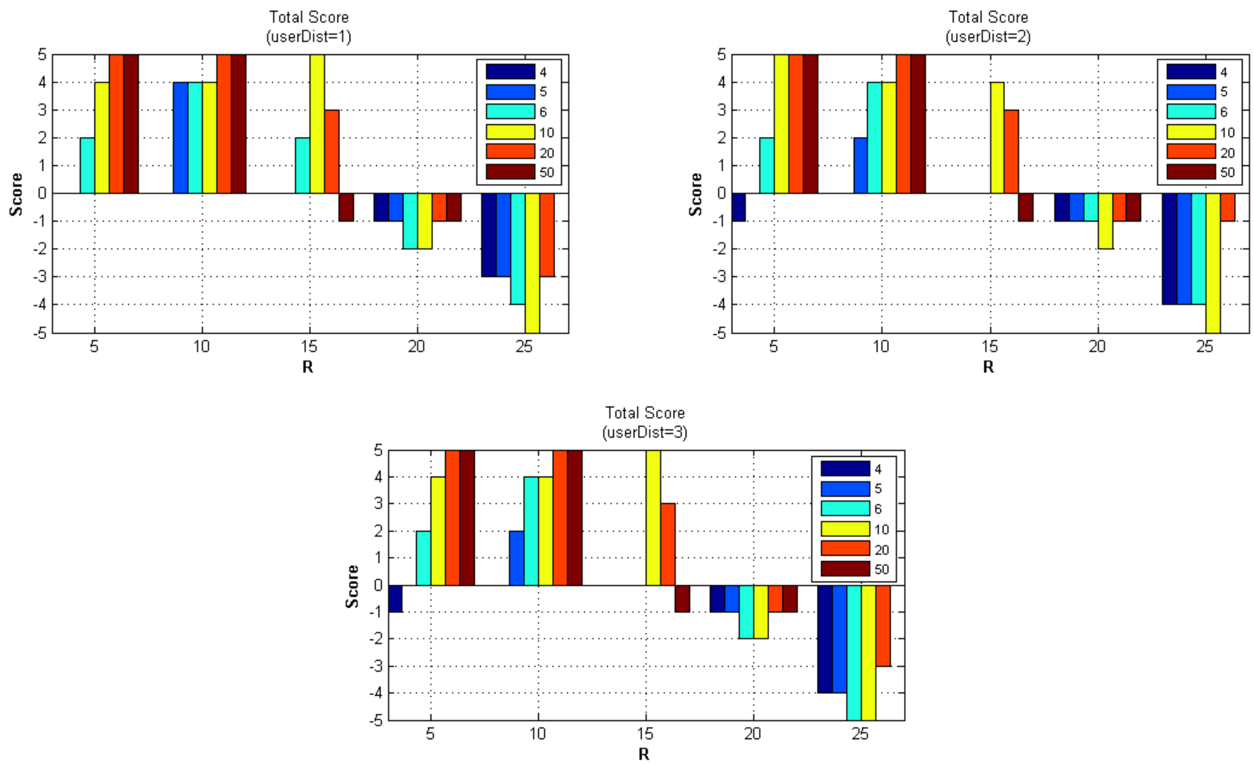


Figure 13. Scores for NOBM market scenarios

Table 25 shows the scores of the viable scenarios. Based on the scores, we can say that most of the viable market scenarios are those that have R values that meet the condition $5 \leq R \leq 10$ and a number of spectrum users (numSU) such that $6 \leq numSU \leq 50$. When R=15, the viable scenarios are those with $10 \leq numSU \leq 20$.

Table 25. Viable NOBM market scenarios

Scenario Descriptors				Criteria					
nsuids	nbbus	UserDist	R	C1	C2	C3	C4	C5	Total score
6	30	1	5	0	1	1	1	-1	2
6	30	2	5	0	1	1	1	-1	2
6	30	3	5	0	1	1	1	-1	2
10	50	1	5	2	1	1	1	-1	4
10	50	2	5	2	1	1	1	0	5
10	50	3	5	2	1	1	1	-1	4
20	100	1	5	2	1	1	1	0	5
20	100	2	5	2	1	1	1	0	5
20	100	3	5	2	1	1	1	0	5
50	250	1	5	2	1	1	1	0	5
50	250	2	5	2	1	1	1	0	5
50	250	3	5	2	1	1	1	0	5
5	50	1	10	2	1	1	1	-1	4
5	50	2	10	0	1	1	1	-1	2
5	50	3	10	0	1	1	1	-1	2
6	60	1	10	2	1	1	1	-1	4
6	60	2	10	2	1	1	1	-1	4
6	60	3	10	2	1	1	1	-1	4
10	100	1	10	2	1	1	1	-1	4
10	100	2	10	2	1	1	1	-1	4
10	100	3	10	2	1	1	1	-1	4
20	200	1	10	2	1	1	1	0	5
20	200	2	10	2	1	1	1	0	5
20	200	3	10	2	1	1	1	0	5
50	500	1	10	2	1	1	1	0	5
50	500	2	10	2	1	1	1	0	5
50	500	3	10	2	1	1	1	0	5
6	90	1	15	0	1	1	1	-1	2
10	150	1	15	2	1	1	1	0	5
10	150	2	15	2	1	0	1	0	4
10	150	3	15	2	1	1	1	0	5
20	300	1	15	2	0	0	1	0	3
20	300	2	15	2	0	0	1	0	3
20	300	3	15	2	0	0	1	0	3

9.2.5 Viability implications

NOBM spectrum trading markets are viable under the criteria used in this work for markets with a range of market participants (spectrum users) with a low limit of 6 (although cases where 5 SUs where present also were viable when R=10) and a high limit of 50. Viability in these cases holds as long as there is no oversupply of spectrum, that is, when R=5 and R=10.

A value of R=5 indicates scenarios where on average there is 50% less spectrum per SU to serve the SU's average traffic requirement. A value of R=10 is the "reference" scenario where the amount of spectrum per user is very close to being enough to serve a SU's average traffic requirement and is where most of the viable scenarios are found. When R=15, there is a 50% oversupply of spectrum and in this case, the viable markets are those with 10 to 20 spectrum users.

Thus, if there is little or no oversupply of spectrum and with a number of spectrum users >=6, most NOBM spectrum trading markets will be viable.

The implication of these findings for regulators is that they should allow trading in wireless service areas where there will be enough market participants (>=6) and sufficient spectrum use such that the amount of spectrum that can be traded won't lead to oversupply situations or excessive undersupply. Regulators should also define the rules for the operation of market makers. Simple market makers as providers of liquidity, like the ones used in the models of this work, help in the establishment of viable markets by holding a spectrum inventory with which they can transact. Since a market maker does not make use of its spectrum assigning too much inventory to a market maker would decrease spectrum efficiency. However, the greater the inventory level of the market maker the better prepared it would be to intervene in the market if there is a lack of spectrum offerings. Thus regulators should carefully define rules to determine the spectrum holdings of a market maker and balance market viability vs. spectrum efficiency.

9.3 BM EXCHANGE SCENARIOS

A band manager (BM) exchange will lease the BBUs within its band for T_{lease} time periods by conducting a call auction in which it receives the bids for spectrum from the SUs. After all bids have been received, it determines the cutoff price that allows the exchange to assign all of the spectrum in the band to the highest bidders. Several rounds of bidding up to *maxRounds* will be conducted if needed to determine a stable cutoff price. At each round each SU can modify its bidding price to better improve its chance of buying spectrum.

Table 26 lists the operational parameters for the BM exchange considered in the scenarios studied in this work.

Table 26. Parameters for a BM exchange

Parameter	Symbol	Value
Duration of BBU lease	T_{lease}	1 time period
Maximum number of bidding rounds	*maxRounds*	20
Minimum cutoff price.	$P_{minCutoff}$	50

9.3.1 Selected parameters for determining market viability

SPECTRAD was configured to run the NOBM experiments mentioned in Table 19. For every market scenario, the average of its 100 runs per time period as well as the standard deviation and

90% confidence intervals were collected for several parameters that describe the behavior of a given market. Appendix C shows graphs of the output that SPECTRAD generates for a particular BM scenario. As mentioned in Table 18, each run was executed for 5000 time periods (time ticks) but data was collected only the final 2000 time periods, the rest were for the warm up phase. For the analysis of each scenario, the data from the 2000 time ticks was averaged so that a single representative value describing the time averaged behavior for a particular factor of interest was obtained.

From the set of parameter observations collected for each market scenario, Table 27 lists those that will be taken into account to derive measures for the evaluation of the viability of a NOBM market.

Table 27. Factors for BM market evaluation

No.	Factor	Symbol
1	Probability of an empty bid list	P_{noBids}
2	Probability that demand is greater than supply	P_{dGs}
3	Average cutoff price	$avgPrice_{cutoff}$
4	Average number of assigned BBUs	$numBBU_{assigned}$
5	Average number of AT's per SU	AT_{su}

The following is a qualitative description of the usefulness of each of these factors in determining the viability of a BM exchange based ST market :

Factor 1 (P_{noBids}): In a BM scenario, the SUs who's bidding price is below the cutoff price for a given time period will buy AT transmission units to serve their traffic demand requirements. As the market progresses, the AT inventory of a SU may be more than enough to satisfy its demand requirements and if this happens for all SUs in a market, none of them will need to request spectrum from the BM. The value of P_{noBids} indicates the average probability that in a given time period there are no SUs making bids for spectrum. High values of this factor indicate that there is not enough activity in the market.

Factor 2 (P_{dGs}): Since a spectrum lease lasts for T_{lease} time periods, when SUs present their bids for spectrum to the BM exchange, their total requested spectrum may not be enough for the BM to make the assignment of all the spectrum in its band. The value of P_{dGs} indicates the average probability that in a given time period the demand for spectrum is not enough to fill the spectrum band.

Factor 3 ($avgPrice_{cutoff}$): The average cutoff price ($avgPrice_{cutoff}$) gives an indication of the valuation of spectrum in a BM scenario. During a BM's operation, all SUs whose bid price was above the cutoff price during that time period get assigned spectrum by the BM after they pay the cutoff price for each BBU. When there is not enough demand to fill the spectrum band, the cutoff price is *minCutoff* thus, if $avgPrice_{cutoff}$ is very close in value to *minCutoff* it indicates a market where there was not enough trading activity to drive the BBU price above *minCutoff*.

Factor 4 ($numBBU_{assigned}$): The average number of BBUs assigned ($numBBU_{assigned}$) will be used to determine the percentage of spectrum assigned in a scenario. Thus if the total number of BBUs a band manager is in charge of is given by $TotBM_{BBU}$, then the value for the average percentage of assigned spectrum ($BBU_{assigned}\%$) is equal to:

$$BBU_{assigned}\ \% = \frac{numBBU_{assigned}}{TotBM_{BBU}} \times 100$$

High values of this percentage indicate a high degree of efficiency in the use of the spectrum given to the BM, while low values indicate the opposite.

Factor 5 (AT_{su}): The average number of ATs per spectrum user (AT_{su}) can be used as an indicator of the difficulty or easiness to get spectrum in a market. On average a SU needs a total of 10 BBU or 10 AT units to serve its traffic requirements. If a SU is keeping an AT inventory above 10 units it would mean that on average it satisfies its traffic requirements only with AT transmission units and does not make use of spectrum.

9.3.2 Results

This section displays the results from the BM market scenarios modeled using SPECTRAD. The behavior of the market scenarios for each of the previously mentioned factors will be shown based on the number of SUs for each scenario, the user distribution and the R value. Where R is the average number of BBUs per Spectrum User $\left(\frac{S_{BBU}^{Total}}{numSU}\right)$. Table 23 indicates how SUs are distributed by specifying which proportion of the number of SUs in a market have low, medium or high valuations for spectrum.

<u>Probability of an empty bid list (P_{noBids})</u>: Figure 14 shows the probability of an empty bid list for the BM scenarios studied in this work.

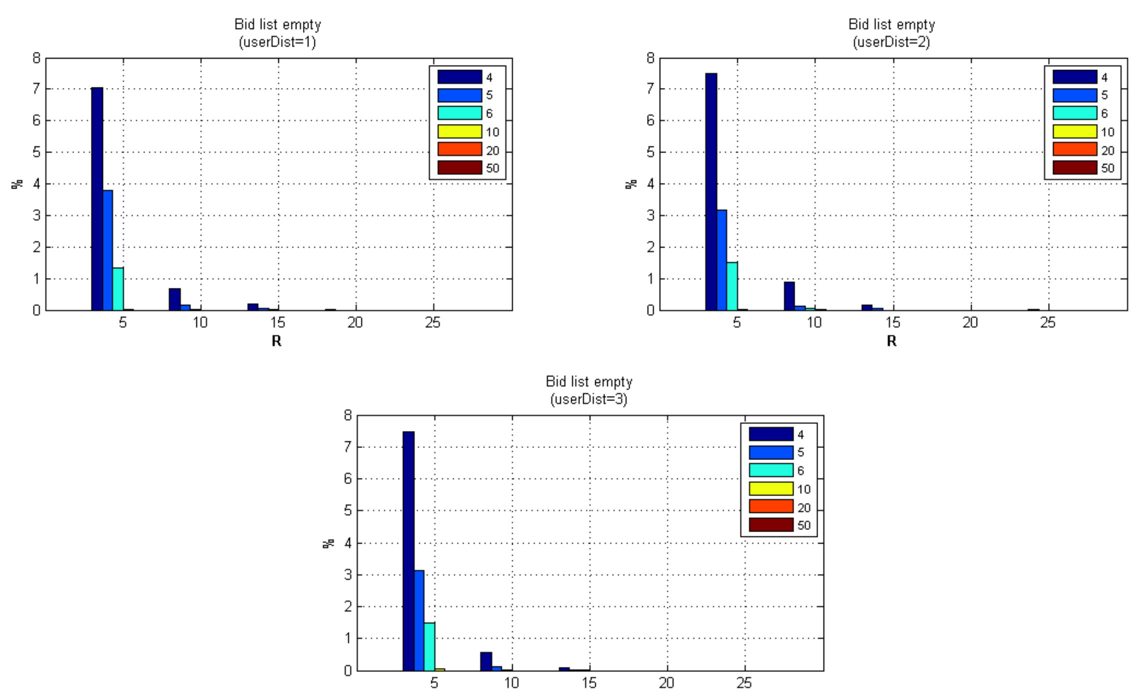


Figure 14. Probability of empty bid list

P_{noBids} is higher for scenarios with low numbers of users (<10) and R<15. As the number of spectrum users increases this probability decreases. Also, as the amount of available spectrum increases, this probability decreases.

<u>Probability that demand is greater than supply (P_{dGs})</u>: The results for P_{dGs} are shown in Figure 15. The lower the value of R, the higher the value of P_{dGs}, this is consistent with the fact that at low R values there is less spectrum available per SU thus demand should be greater than supply more often. As R increases and exceeds 20, there is an over-supply of spectrum which significantly reduces the number of instances where demand exceeds supply, thus the BM exchange would have low activity in these scenarios.

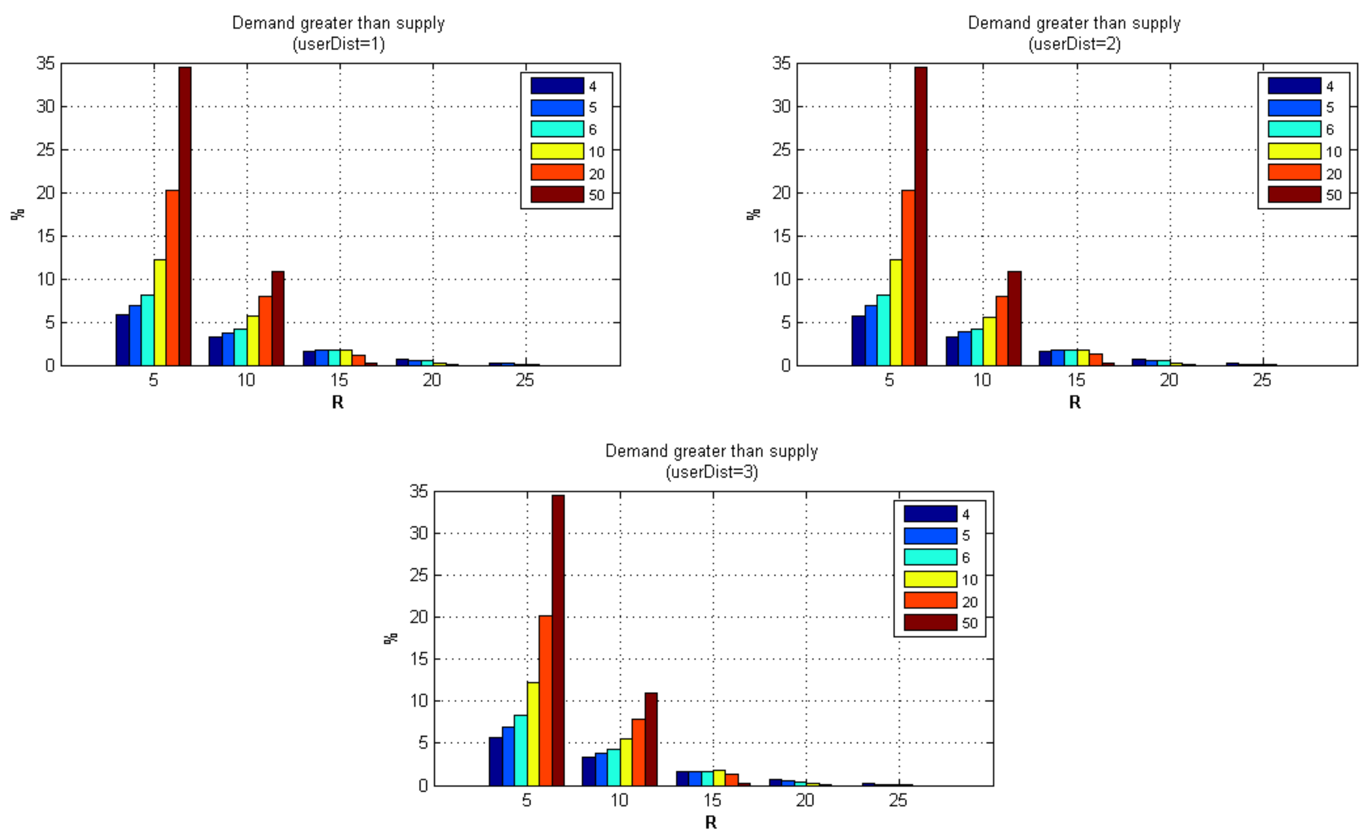


Figure 15. Probability of having demand greater than supply

Average cutoff price (*avgPrice*$_{cutoff}$): Figure 16 shows the values for the average cutoff price. As the value of R increases and there is more spectrum available per user, the cutoff price gets smaller and closer to the minimum cutoff price of the BM exchange which is 50 monetary units. In a BM scenario, when demand is not greater than supply in a trading session, the cutoff price for that session is the minimum cutoff price. Thus, scenarios that have higher probability that demand is greater than supply will have cutoff prices above the minimum since in their sessions the cutoff price won't be the minimum price.

Comparing with the price behavior of NOBM scenarios (see Figure 9) we can see that prices in BM scenarios are dominated mostly by the probability that demand is greater than supply and the minimum cutoff price. NOBM scenarios prices reflect a more competitive price settlement structure when compared to BM scenarios.

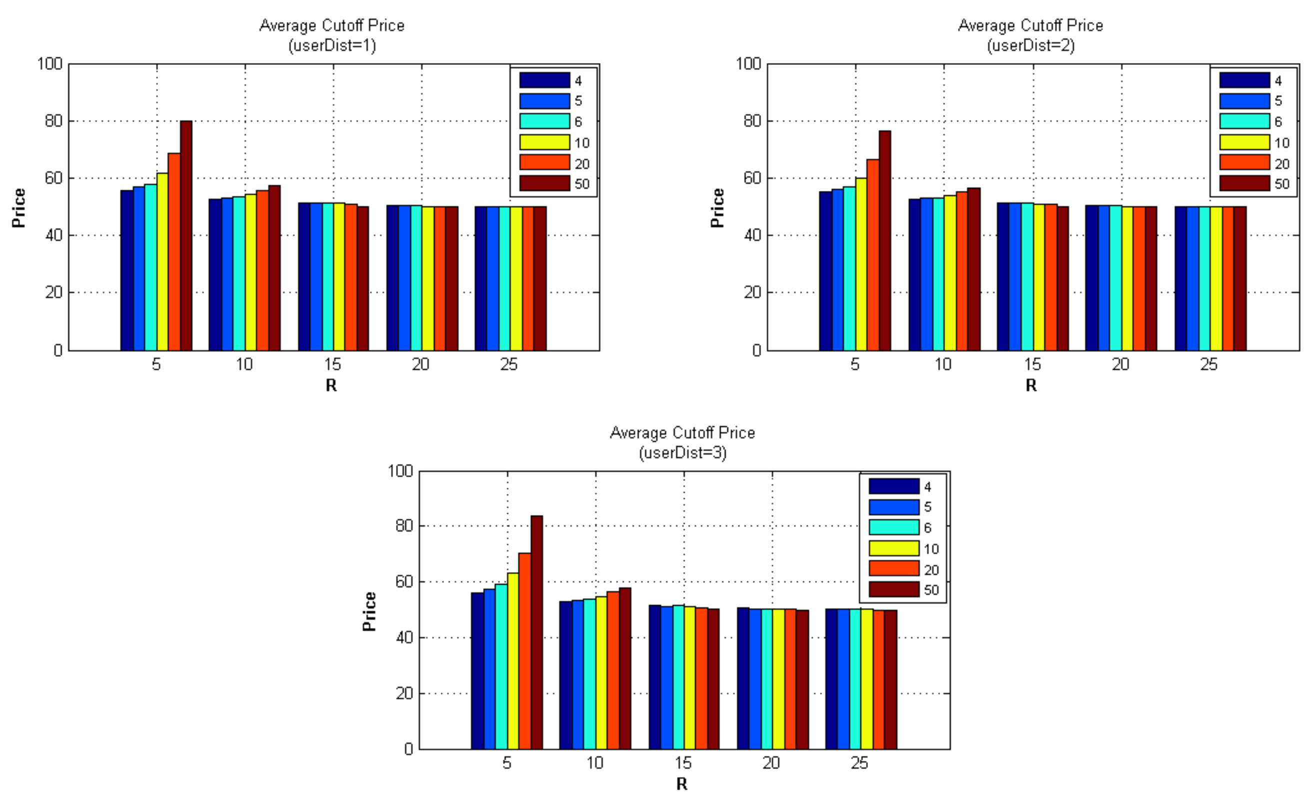


Figure 16. Average cutoff price

Percentage of assigned spectrum ($BBU_{assigned}\%$): Figure 17 shows the percentages of assigned spectrum for each scenario. From the results, it can be seen that the higher the number of spectrum users in the market, the higher the value of $BBU_{assigned}\%$. Additionally, as R increases $BBU_{assigned}\%$ decreases specially for R>=20 since in those scenarios there is an over-supply of spectrum.

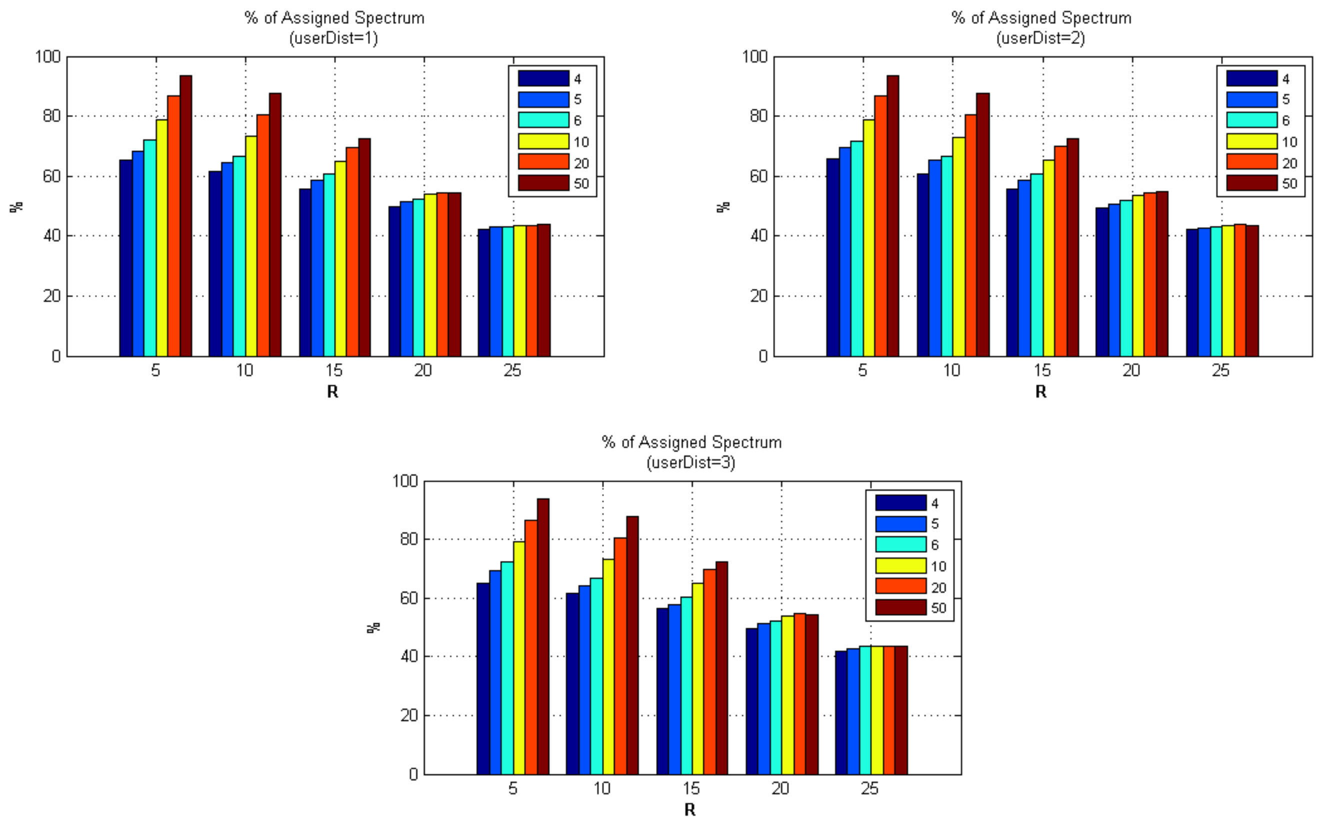


Figure 17. Percentage of assigned spectrum

Average number of ATs per spectrum user (AT_{su}): Figure 18 shows the average number of ATs per SU. A number of ATs above 10 signals that on average, the SU has had to accumulate ATs to serve most of its traffic demands. From the figure, it can be seen that as spectrum becomes more available (increasing R), the number of ATs held on an SU’s inventory decreases.

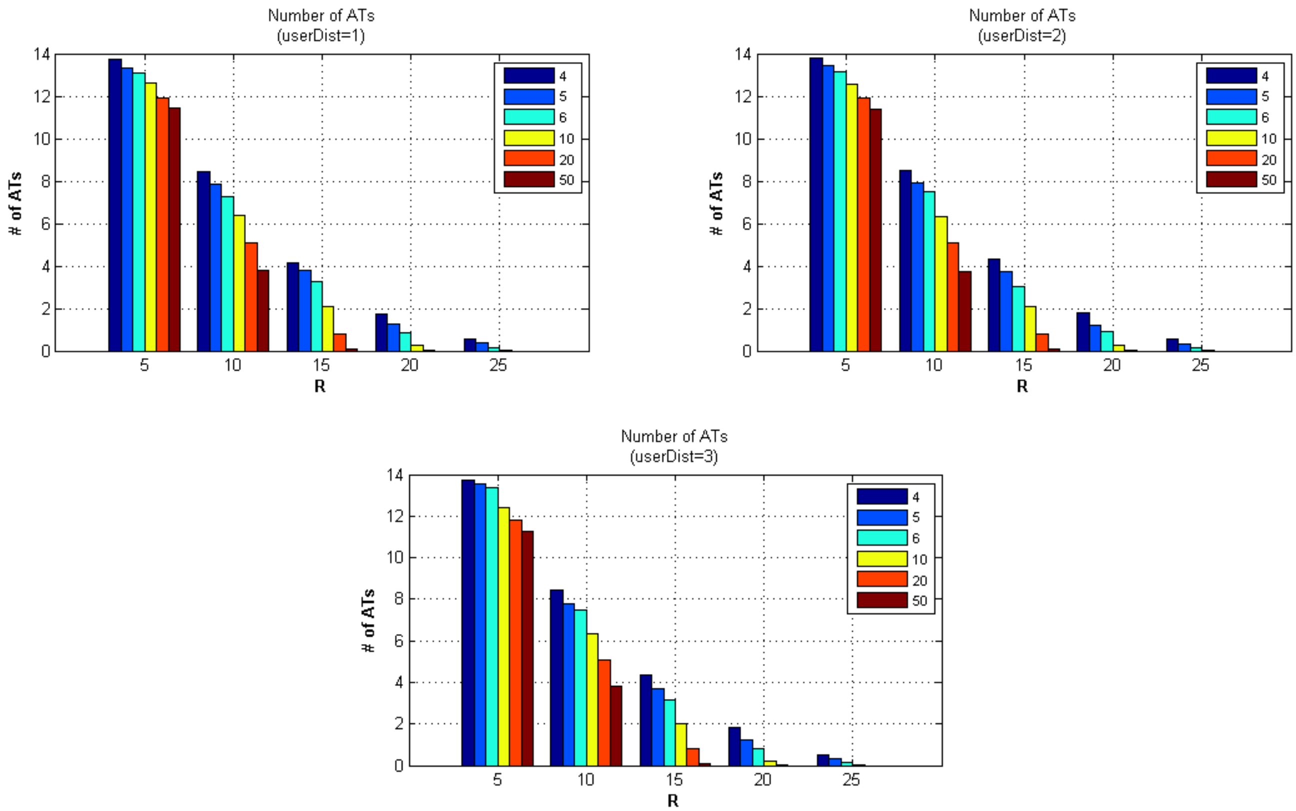


Figure 18. Average number of ATs per spectrum user

9.3.3 Criteria for viable BM markets

In order to determine the viable BM markets based on the factors mentioned in Table 27, we will develop decision criteria to determine if the behavior of a particular factor in a market is to be considered as desirable/acceptable (positive) or undesirable/unacceptable (negative). Additionally, in order to keep track of the aggregate behavior characteristics of a market, and in a manner similar to the analysis used for the study of NOBM markets, we will give a score to each factor with a positive value when the market complies positively with the desired behavior characteristic or negative when it complies with the undesirable behavior criteria. Based on the total scores for a market's behavior a final list of viable markets will be determined.

Criteria for the probability of having an empty bid list (P_{noBids}): Instances where there is an empty bid list in a BM market are undesirable as they signal the lack of need for spectrum from the SUs and thus the lack of need for spectrum trading as well as low levels of trading activity. We will consider that a market behaves in a desirable way when its P_{noBids} value is 0 and has an undesirable behavior if P_{noBids} is greater than 0.

Criteria for the probability that demand is greater than supply (P_{dGs}): If demand is greater than supply at a bidding round in a BM market, the BM exchange will assign spectrum based on the valuations bid by the spectrum users. Thus high values of P_{dGs} indicate a market where there is interest to trade spectrum and where the BM will be actively determining cutoff prices based on the bidding activity of the SUs. When the value for P_{dGs} is low, it indicates a market where spectrum assignment won't be influenced by price signals from the market. For our purposes and based on the aggregate result data, we will consider that scenarios where P_{dGs} > 10% have a positive behavior regarding trading activity and those with P_{dGs} < 1% have a negative behavior.

Criteria for the average cutoff price $avgPrice_{cutoff}$: The minimum cutoff price is 50 monetary units, thus values of $avgPrice_{cutoff}$ close to 50 indicate a market where trading activity was low and the BM opted for assigning spectrum at the minimum cutoff price. We will consider that market with $avgPrice_{cutoff}$ < 51 have undesirable cutoff price behavior.

Criteria for the percentage of assigned spectrum ($BBU_{assigned}\%$): Markets where most of the spectrum held by the BM is assigned will have higher spectrum efficiency than those with low values for $BBU_{assigned}\%$. We will consider that a market has a desirable spectrum efficiency if its value for $BBU_{assigned}\%$ is greater than 62% and an undesirable efficiency if it's below this value. This limit was chosen since it is the average value for this parameter as found in the data. Additionally there is a gap of values centered around this limit in the collected data.

Criteria for the average number of ATs per SU: With the model parameters used in the scenarios a SU will be able to satisfy its average traffic request with 10 BBUs or 10 ATs, thus markets where the number of ATs is greater than 10 will be considered undesirable.

Table 28 summarizes the criteria to be used for evaluating BM markets.

Table 28. Criteria for the evaluation of BM markets

Criteria	Factor	*Symbol*	Pass	Fail	Score Pass/Fail
C1	Probability of empty bid list	P_{noBids}	= 0	> 0	1/-1
C2	Probability that demand is greater than supply	P_{dGs}	>=10%	< 1%	1/-1
C3	Average cutoff price	$avgPrice_{cutoff}$	N/A	< 51	0/-1
C4	Percentage of assigned spectrum	$BBU_{assigned}\%$	>=62%	<=62%	1/-1
C5	Average number of AT's per SU	AT_{su}	N/A	>=10	0/-1

9.3.4 Viable BM Markets

Appendix E lists the scores obtained by each of the BM market scenarios studied based on the evaluation criteria defined in the previous section. Figure 19 shows the total scores in graphical form.

The viable BM markets can be considered those with scores greater or than 0 since these scenarios do not meet many of the undesirable criteria (only C5 is met but by scenarios with R=5 which is expected as these are scenarios with undersupply of spectrum and thus more prone to accumulate AT), additionally all viable scenarios have a percentage of assigned spectrum > 62%. The list of viable scenarios is shown in Table 29.

The largest grouping of viable scenarios satisfy the conditions that $5 \leq R \leq 10$ and that the number of users is such that $10 \leq numSU \leq 50$. Other viable scenarios are found for the cases where R=10 and $5 \leq numSU \leq 10$ and when R=15 and $10 \leq numSU \leq 20$, irrespective of user distribution. Using the value of R as a grouping variable, we can also say that R=10 generates has the greatest number of viable markets. Viability is met when $5 \leq numSU \leq 50$.

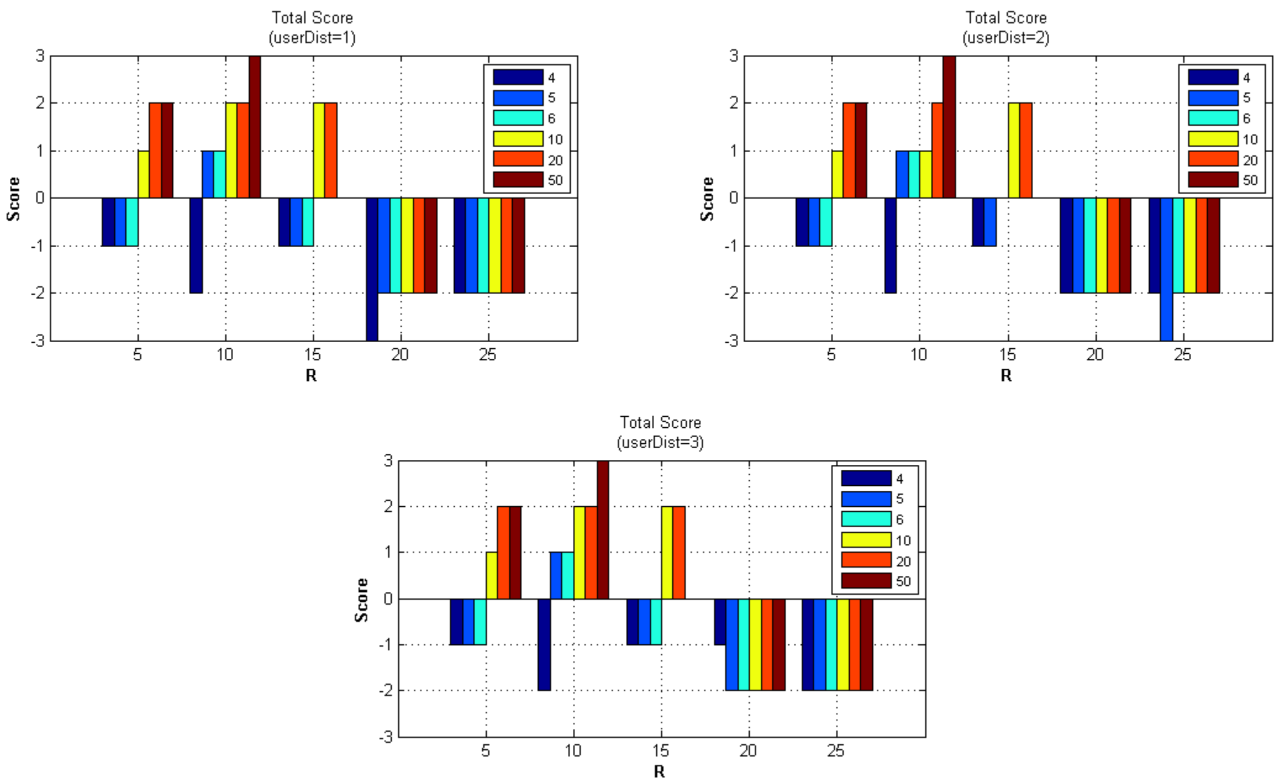


Figure 19. Scores for BM scenarios

9.3.5 Viability implications

BM spectrum trading markets are viable under the criteria used in this work for markets with a range of market participants (spectrum users) with a low limit of 5 and a high limit of 50 when R=10 which is the value of R at which there is no spectrum oversupply or undersupply. Thus a well balanced amount of spectrum in the market (enough spectrum to meet the average traffic demands of the SUs) produces viable markets in BM scenarios.

Table 29. Scores for viable BM scenarios

nsuids	nbbus	UserDist	R	C1	C2	C3	C4	C5	Tot Score
10	50	1	5	0	1	0	1	-1	1
10	50	2	5	0	1	0	1	-1	1
10	50	3	5	0	1	0	1	-1	1
20	100	1	5	1	1	0	1	-1	2
20	100	2	5	1	1	0	1	-1	2
20	100	3	5	1	1	0	1	-1	2
50	250	1	5	1	1	0	1	-1	2
50	250	2	5	1	1	0	1	-1	2
50	250	3	5	1	1	0	1	-1	2
5	50	1	10	0	0	0	1	0	1
5	50	2	10	0	0	0	1	0	1
5	50	3	10	0	0	0	1	0	1
6	60	1	10	0	0	0	1	0	1
6	60	2	10	0	0	0	1	0	1
6	60	3	10	0	0	0	1	0	1
10	100	1	10	1	0	0	1	0	2
10	100	2	10	0	0	0	1	0	1
10	100	3	10	1	0	0	1	0	2
20	200	1	10	1	0	0	1	0	2
20	200	2	10	1	0	0	1	0	2
20	200	3	10	1	0	0	1	0	2
50	500	1	10	1	1	0	1	0	3
50	500	2	10	1	1	0	1	0	3
50	500	3	10	1	1	0	1	0	3
10	150	1	15	1	0	0	1	0	2
10	150	2	15	1	0	0	1	0	2
10	150	3	15	1	0	0	1	0	2
20	300	1	15	1	0	0	1	0	2
20	300	2	15	1	0	0	1	0	2
20	300	3	15	1	0	0	1	0	2

A value of R=5 indicates a scenario where on average there is 50% less spectrum per SU to serve the SU’s average traffic requirement. Viable markets when R=5 where found when

$10 \leq numSU \leq 50$. Scenarios with 50% of spectrum oversupply (R=15) were found viable if the number of SUs ranges from 10 to 20.

From the viability region identified for BM scenarios we can say that BM markets will be viable even with a number of spectrum users as low as 5 if the amount of spectrum available in the market is enough to meet the average traffic needs of market participants. In undersupply or oversupply situations, the number of spectrum users should be >=10. The implication of these findings for regulators is that they should allow band manager based spectrum trading in wireless service areas where the amount of tradable spectrum is well balanced with the traffic needs of the spectrum users. Otherwise, enough market participants must be present (>=10) to support oversupply or undersupply of spectrum in the market.

9.4 VIABILITY IMPLICATIONS FROM NOBM AND BM SCENARIOS

The viability implications for NOBM scenarios were mentioned in section 9.2.5 and those for BM scenarios in section 9.3.5. However, when looking at the viability conditions for both scenarios at the same time we can make the following observations:

Behavior trends are independent of user distribution: Behavior trends for all markets analyzed are the same independently of the user distribution. There were very few exceptions where a deviation of the behavior for a particular parameter in a market was affected by the user distribution. For most cases, for the user distributions used in this work, we can consider that user distributions did not affect market behavior.

Effect of spectrum oversupply: Oversupply of spectrum negatively affected all market scenarios considered. In particular R values greater than 20 generate unviable markets irrespective of market type (BM or NOBM). Thus, an oversupply of 100% above the level of spectrum that SUs need to serve their average traffic leads to unviable markets.

Viability with no oversupply of spectrum: Spectrum trading is viable in markets with no oversupply (R=5 and R=10) for a wide range of spectrum user values. Thus, if enough market participants are present in a ST market and there is no oversupply of spectrum, the market can be viable. However, when the number of spectrum users (*numSU*) is less than 6, NOBM markets are unviable. When *numSU* is less than 10, BM markets are unviable except for R=10 where markets are unviable when n*umSU* is less than 5.

Spectrum efficiency analysis: Figure 20 and Figure 21 can be used to compare the spectrum efficiency obtained in NOBM and BM scenarios. Figure 20 shows the percentage of spectrum that is not being offered for sale in a NOBM scenario. This is the spectrum that is being used by the SUs in those scenarios. Figure 21 shows the percentage of spectrum assigned for use by SUs in a BM scenario.

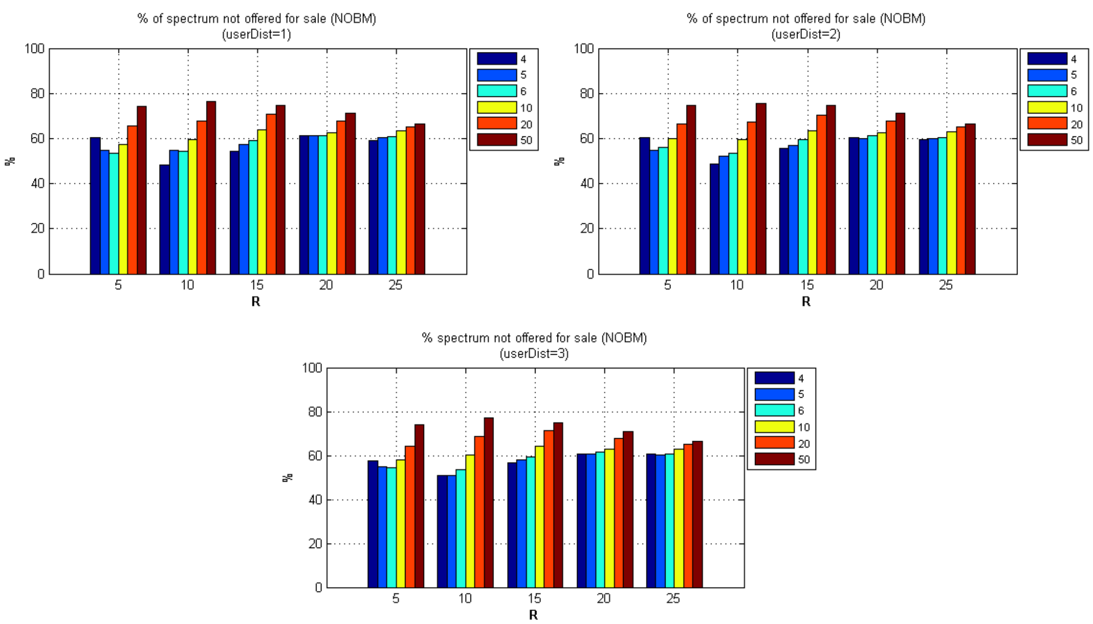


Figure 20. Percentage of spectrum not offered for sale in NOBM scenarios

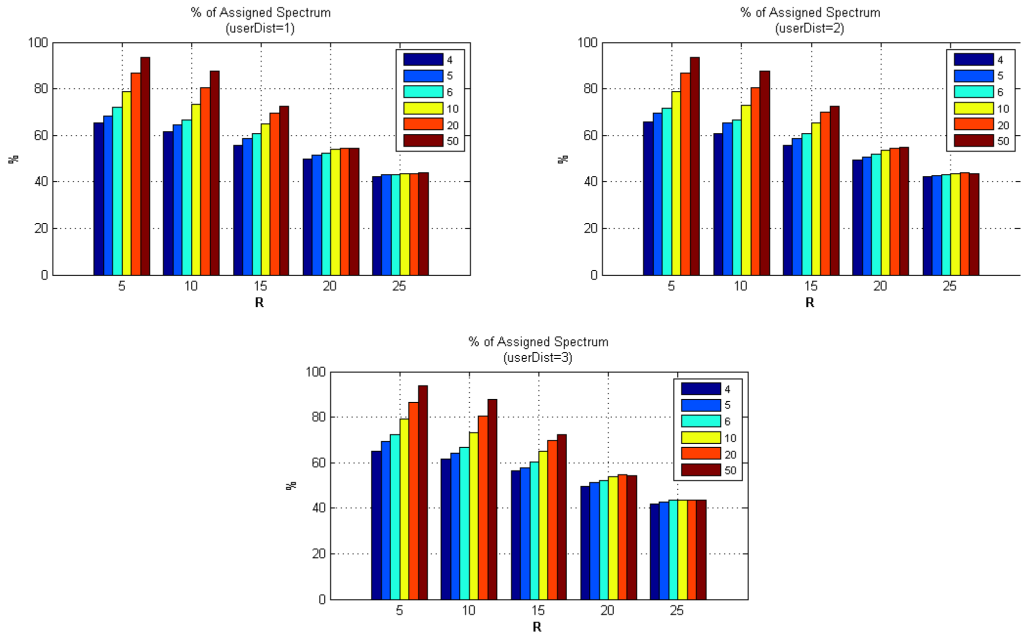


Figure 21. Percentage of assigned spectrum in BM scenarios

From the figures, it can be seen that BM based markets achieve higher spectrum efficiency than NOBM markets for R ≤ 10, and similar efficiency for R=15. Since no viable markets where identified for R ≥ 20 in NOBM and BM scenarios a comparison for spectrum efficiency in those cases is irrelevant.

Spectrum trading in the viable NOBM markets provided for spectrum efficiencies between 51% and 77% and for the viable BM cases, the efficiencies were between 78% and 93%. These values are higher than the average spectrum occupancy values reported in studies of spectrum use efficiency such as [1]. These results show a positive characteristic of spectrum trading markets that is of great interest to regulators and spectrum users.

<u>*Number of users in a viable ST market*</u>: Viable NOBM markets have a number of spectrum users in the range of $6 \leq numSU \leq 50$, while for BM markets $10 \leq numSU \leq 50$ when $5 \leq R \leq 10$. For R=15, viability is present when $10 \leq numSU \leq 20$ for both market types and for BM cases viability is also present when $5 \leq numSU < 10$ and R=10. The main

difference between these values is that NOBM markets can support undersupply conditions better than BM markets but BM markets can operate with a lower number of spectrum users when the amount of tradable spectrum closely matches the amount required to serve their average traffic needs. BM markets are more sensible to oversupply and undersupply conditions than NOBM markets.

10.0 CONCLUSIONS AND FUTURE WORK

Spectrum trading (ST) is a market based mechanism where buyers and sellers determine the assignment of spectrum and its uses. That is, it can address both the allocation and assignment aspects of spectrum use. The assignment of spectrum licenses through spectrum trading markets can be used as a mechanism to grant access to spectrum to those who value it most and can use it more efficiently.

In this dissertation we have focused on determining the set of conditions that lead to viable spectrum trading markets. These conditions define a "viability region" which can be used to structure the technical, economical and regulatory mechanisms to implement these markets. The identification of viable spectrum trading markets was driven in this research by the following questions:

1. How can spectrum trading markets be implemented? How can technical architectures for ST be characterized?
2. What set of parameter values lead to ST markets that are viable (liquid and sustainable)?
3. How does each parameter affect market behavior?
4. Are we likely to see the conditions for viable ST markets arise in the real world? How do we achieve them if not currently present?

5. How can the conditions for having viable ST markets be obtained or helped with policy changes?

One of the contributions of this work is the identification of the different types of technical architectures that can be used to implement spectrum trading markets and how architecture parameters can affect the economic behavior of a particular ST market. This contribution provides answers to question 1 of this research.

Another contribution of this work has been the development of a spectrum trading modeling tool – SPECTRAD – which makes use of agent-based computational economics concepts and an agent-based modeling platform to model the interactions in these markets. SPECTRAD was used in the analysis and modeling of the scenarios considered in this dissertation but its capabilities can be used in the analysis of other scenarios and the study of the effects of different market and regulatory conditions in spectrum trading markets.

In answering questions 2 and 3 the sets of conditions for viable spectrum markets were determined. From this research it was identified that an oversupply of spectrum negatively affects spectrum trading markets. An oversupply ($R \geq 20$) that exceeds in more than 100% the average amount of BBUs required per SU will lead to an unviable market irrespective of the number of participants in the market. Markets with a supply of spectrum that ranged from a 50% undersupply to a 50% oversupply of the amount of spectrum required to satisfy the average spectrum needs of a spectrum user where found viable when there were 6 spectrum users (including a market maker) in NOBM scenarios and 10 spectrum users in BM. This result suggests that ST markets could be implemented over real-world service areas with a mix of the wireless service providers that currently exist in the wireless market (i.e. Verizon, Sprint, AT&T, T-mobile, and MVNOs). In particular, BM markets where viable for scenarios with 5 to 50 spectrum users when there was no spectrum oversupply or undersupply (R=10). Thus with careful spectrum planning BM markets are viable for a large range of spectrum users.

In general, our results suggest that urban environment locations in which combination of wireless services providers (facilities based and mobile virtual network operators) are present in enough quantity to meet the criteria of the viability region identified in this work would have viable ST markets.

In terms of spectrum efficiency, viable BM and NOBM markets produce spectrum efficiencies higher than 50% and in the case of BM markets, as high as 93%, these results suggest that viable ST markets should be supported by regulators in order to have markets that make efficient use of spectrum resources. However, future research is needed to determine the impact of trading frictions (transaction costs) in a ST market and how they can impact spectrum efficiency and prices.

The answers to questions 4 and 5 related to how to achieve market environments that meet the conditions of the viability region identified in this work lead us to suggest that regulators should allow trading in wireless service areas where the number of market participants will be large enough (>=6 for NOBM scenarios, >=10 for BM scenarios) and where the amount of spectrum available for trading won't generate oversupply situations. BM based markets are more sensible to spectrum undersupply and oversupply conditions than NOBM markets but if spectrum is available at an amount enough to serve the average traffic demands of the SUs, then NOBM scenarios can work with a number of users as low as 5.

An undersupply of 50% below the average amount of spectrum required to serve the average traffic load can be tolerated in some BM and NOBM markets thus exact spectrum planning is not required for having a viable spectrum market as long as there are enough market participants but as mentioned before, NOBM markets operate better (with lower number or equal number of users) in spectrum undersupply or oversupply conditions than BM markets.

For the case of NOBM scenarios, the simple behavior of the market maker agent used in the scenarios studied in this work was able to provide enough liquidity to keep several markets running. Regulators seeking to define policies for these markets could just define regulations and reporting requirements for simple market maker operation and let market participants decide whether more rules should be imposed on the behavior of these entities if required. The study of market behavior under more elaborate market maker rules is left for further research.

In general, the dynamics of spectrum trading market could interest entities not traditionally involved in the use spectrum resources to start making use of this resource. Thus, new types of businesses could be developed around the easiness of getting spectrum which would increase the number of market participants in a given market enhancing the viability of such a market as long as the amount of spectrum available for trading does not lead to severe undersupply or oversupply conditions.

The market scenarios studied in this research assumed a liberalized spectrum market where a set of spectrum units (BBUs) could be given any use desired by the spectrum use. Further research is needed to determine the impact of restrictions on spectrum use, as well as limitations in the use of spectrum due to interference limits between different wireless services or protocols.

This work and the related tool developed for the study of spectrum trading markets (SPECTRAD) open the doors for future research ideas and questions, among them are:

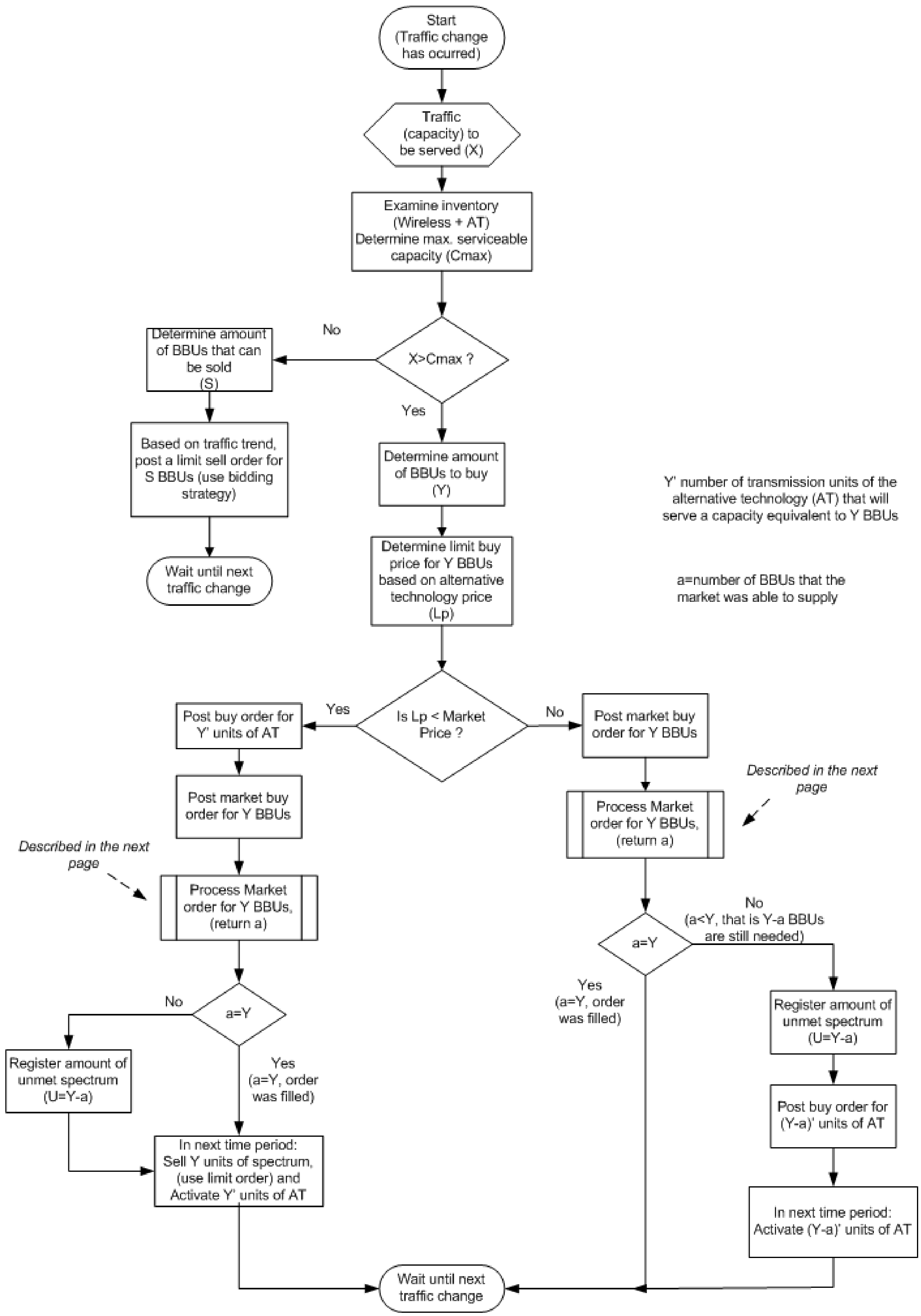
1. What is the impact of speculative behavior in a ST market? Studying the behavior of spectrum trading markets when speculation is allowed would provide another set of interactions that can modify price behavior and market viability.
2. How does having to support more than one wireless technology (GSM, LTE, etc) affect the viability of ST markets? The scenarios analyzed in this research work assumed that only one wireless technology was being used by all SUs. Supporting different wireless technologies would require a different definition of a BBU and of how granular (how many BBUs in a trade) can a trade be.
3. What are the costs associated to trading in a spectrum trading market? Elaborating models to study the transaction costs related to spectrum trading would enhance the understanding of the economic behavior of ST markets.
4. How can spectrum trading enhance next generation wireless service provision and mobility scenarios? Most of the literature related to future wireless environments does not address how these environments can be implemented or affected by the existence of spectrum trading markets. Research in this direction would help in the understanding of the role spectrum trading can have in future mobile environments.
5. How can protocols for enabling spectrum trading interactions over a range of wireless technologies be enabled and designed?

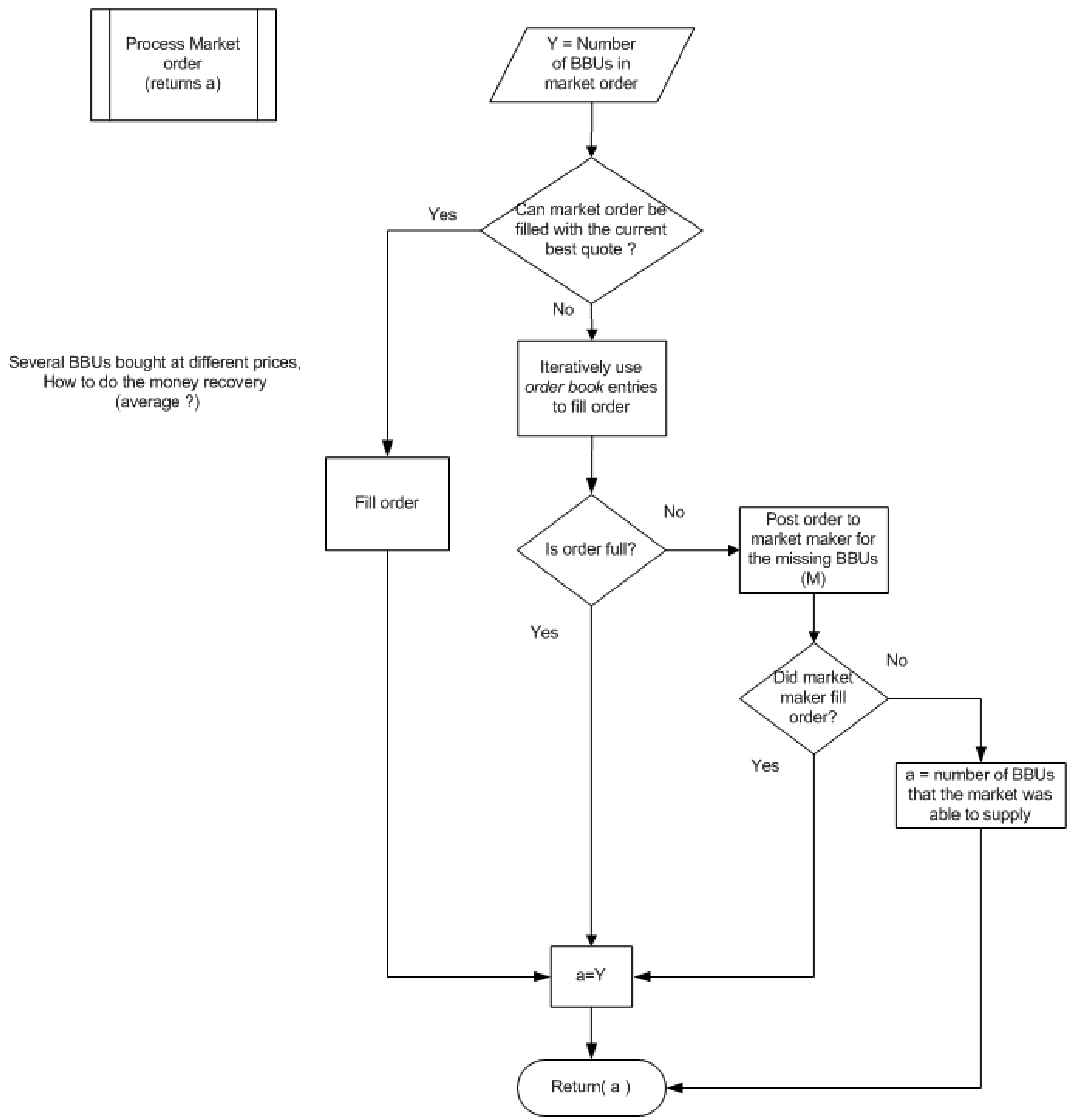
In general the study of spectrum trading markets provides for an interesting set of scenarios that can be studied from their technical and economic characteristics. The future adoption and incorporation of software radio systems that can work over several wireless protocols and be easily upgraded, as well as the continued interest in providing innovative wireless services should be strong drivers for continued research of spectrum trading and the development of regulations that can facilitate these markets.

APPENDIX A

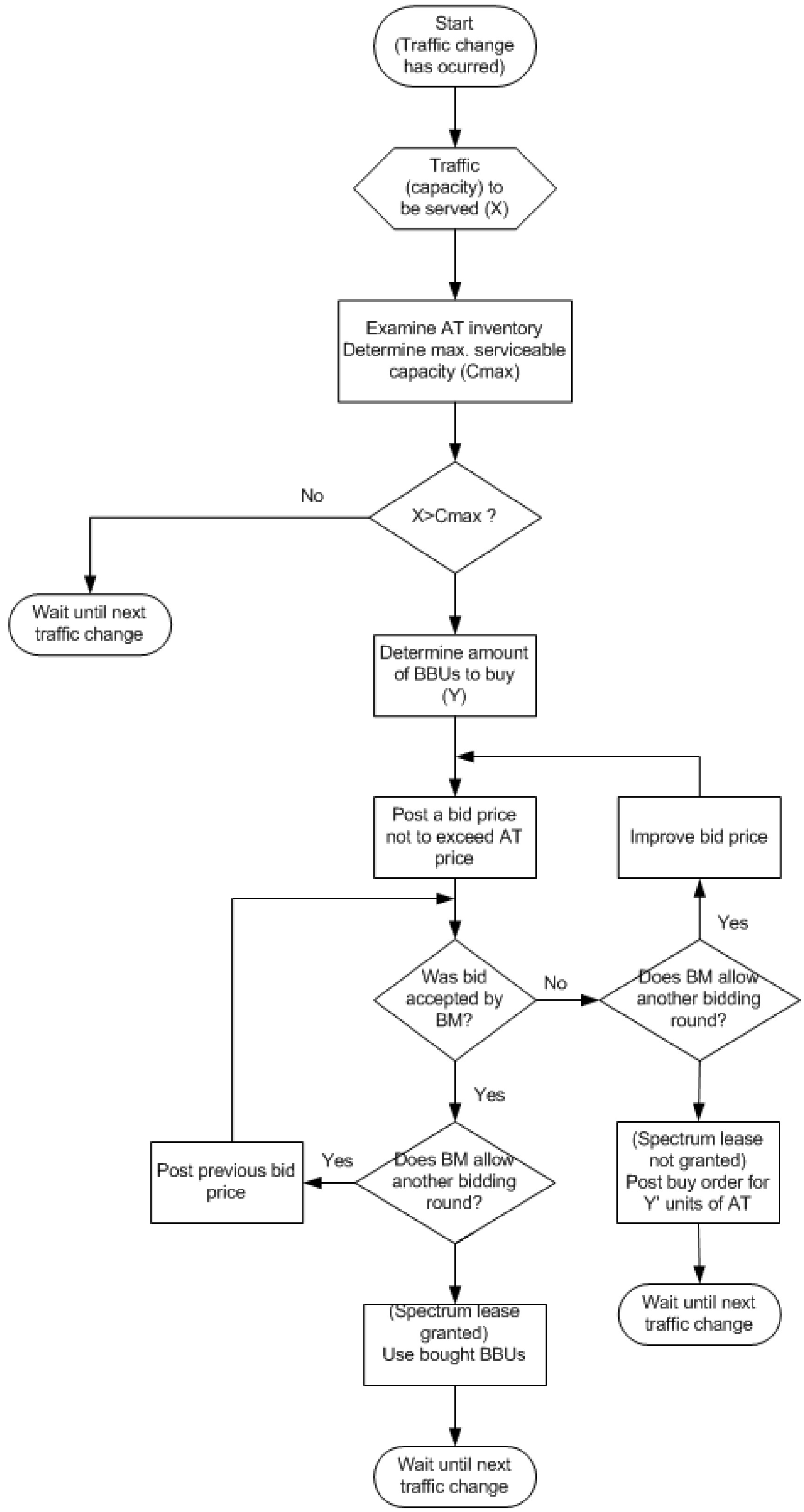
HIGH-LEVEL FLOWCHART DIAGRAMS OF THE BEHAVIOR OF SPECTRAD AGENTS

SPECTRUM USER BEHAVIOR IN NOBM SCENARIOS

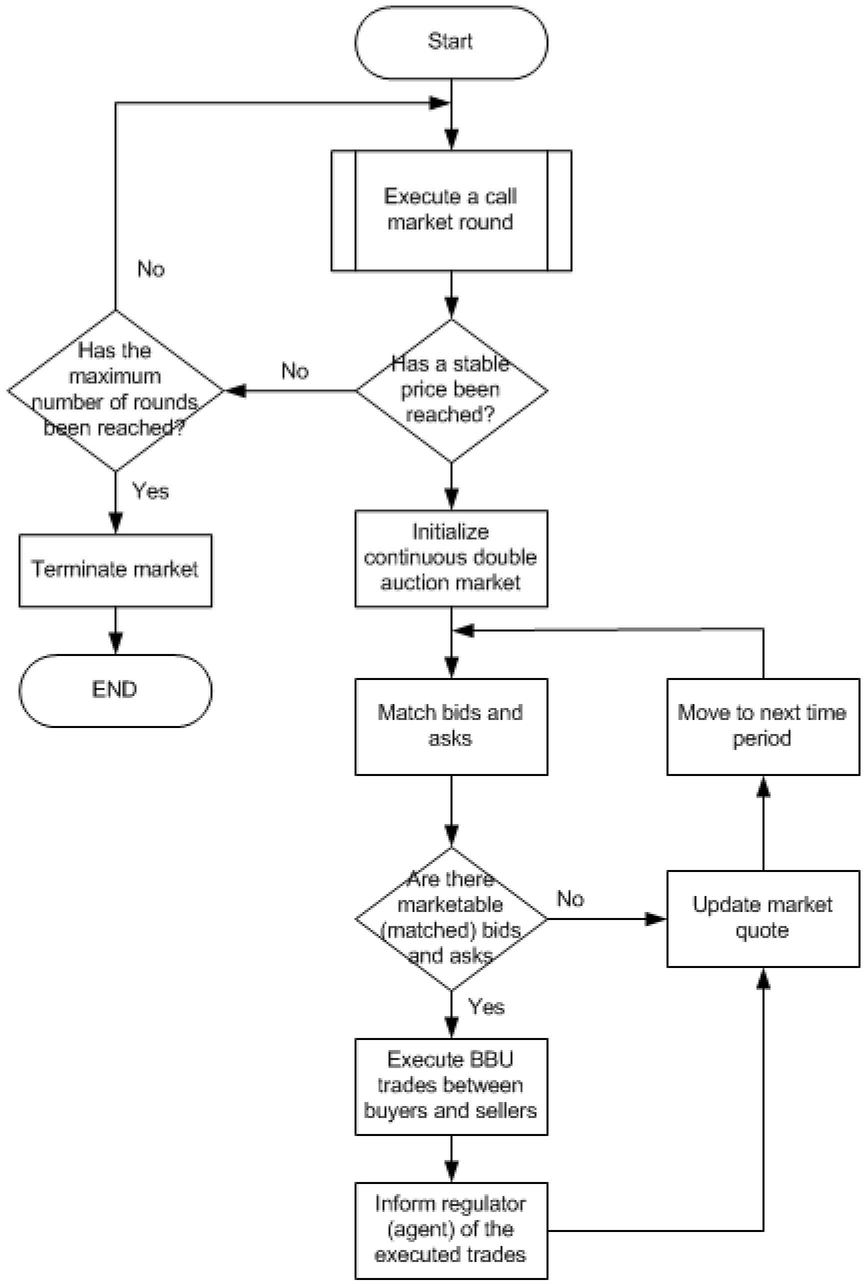



Process Market order (returns a)
Y = Number of BBUs in market order
Can market order be filled with the current best quote ?
Yes
No
Several BBUs bought at different prices, How to do the money recovery (average ?)
Iteratively use *order book* entries to fill order
Fill order
Is order full?
No
Post order to market maker for the missing BBUs (M)
Yes
Did market maker fill order?
No
Yes
a = number of BBUs that the market was able to supply
a=Y
Return(a)

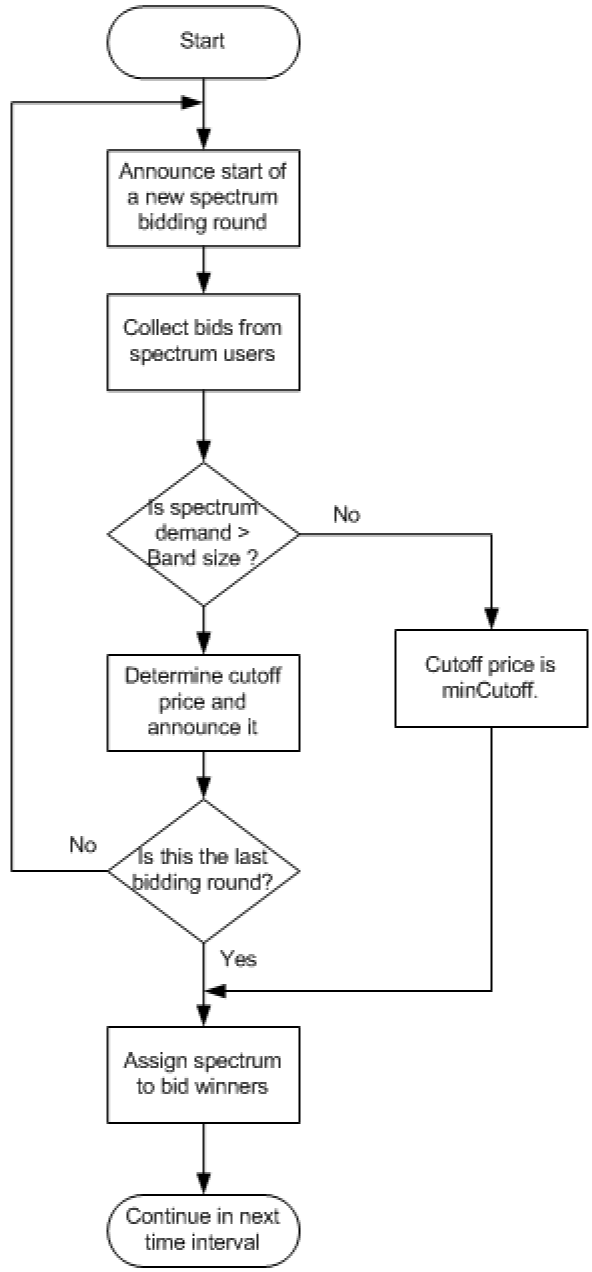
SPECTRUM USER BEHAVIOR IN BM SCENARIOS



NOBM EXCHANGE BEHAVIOR



BM EXCHANGE BEHAVIOR



APPENDIX B

ZIP BIDDING STRATEGY

The zero-inteligence-plus (ZIP) bidding strategy was developed by Cliff and Bruten [41]. This strategy can be used to implement software based traders (agents) that can have similar performance to human traders while also being a strategy that is not computationally intensive.

In ZIP, each trader agent as a profit margin μ, which determines the difference between the agent's limit price (reservation price) and the shout price, where a shout is a bid or ask to be submitted. In a trading market with many ZIP based agents each agent alters its profit margin based on four factors:

- Trading state of the agent: An agent is *active* in the market if it can still make a transaction or *inactive* if it has sold or bought all the units of goods it needed and will not be participating in the market for the rest of a trading period.
- Last shout type: Indicates whether the last shout was a bid or an ask
- Last shout price: This price is traditionally denoted by q
- Last shout status: Indicates if the last shout resulted in a transaction or not.

During a market's operation, if there was a transaction in the last trading round and the agent was not the winner or there was no transaction, the agent will decrease his profit margin for the current round. If the agent was the winner, he would increase his profit margin in the current round. The procedures to adjust the profit margin when the agent's bid or ask price is p are explained in the following pseudo-code:

For a SELLER agent:

If the last shout was accepted at price q **then**

any seller for which $p \leq q$ should raise his profit margin

if the last shout was a bid **then**

any active seller for which $p \geq q$ should lower his margin

endif

else

if the last shout was an ask **then**

any active seller for which $p \geq q$ should lower his margin

endif

endif

For a BUYER agent:

If the last shout was accepted at price q **then**

any buyer for which $p \geq q$ should raise his profit margin

if the last shout was an ask **then**

any active buyer for which $p \leq q$ should lower his margin

endif

else

if the last shout was a bid **then**

any active buyer for which $p \leq q$ should lower his margin

endif

endif

The adjustments to the profit margin are done by the following adaptation mechanism: At a given time t, an individual ZIP trader (trader *i*) calculates the shout price $p_i(t)$ for a unit *j* with limit price $L_{i,j}$ using the profit margin $\mu_i(t)$ according to the following equation:

$$p_i(t) = L_{i,j}(1 + \mu_i(t))$$

The basic aim of the ZIP strategy is that the value of μ_i for each trader should change dynamically in response to the actions of other trader in the market. It should increase or decrease to make the trader's shout-price competitive when compared to the shouts of other traders. The adaptation or update rule for the trader is based on a simple machine learning rule, the Widrow-Hoff "delta rule". Based on this rule, an update for the profit margin μ_i on the transition from time *t* to *t+1* is done with the following equations:

$$\mu_i(t+1) = \frac{\left(p_i(t) + \Delta_i(t)\right)}{L_{i,j}} - 1$$

Using $\Gamma_i(t)$ in place of $\Delta_i(t)$ the update rule becomes:

$$\mu_i(t+1) = \frac{\left(p_i(t) + \Gamma_i(t)\right)}{L_{i,j}} - 1$$

Where:

$$\Gamma_i(t+1) = \gamma_i \Gamma_i(t) + (1 - \gamma_i)\Delta_i(t)$$

$$\Delta_i(t) = \beta_i(\tau_i(t) - p_i(t))$$

$$\tau_i(t) = R_i(t)q(t) + A_i(t)$$

$\tau_i(t)$ is known as the *target price*, β_i as the *learning rate* and γ_i as the *momentum coefficient*. $R_i(t)$ and $A_i(t)$ are random reals and $q(t)$ is the last shout value. When the intention is to increase the agent's shout price $R_i(t) > 1.0$ and $A_i(t) > 0.0$; when the intention is to decrease the shout price, $0.0 < R_i(t) < 1.0$ and $A_i(t) < 0.0$.

Every time the agent's profit margin is altered, the target price is calculated using new and randomly generated values of R_i and A_i, which are independent and identically distributed for all agents.

For the scenarios analyzed in this research work, R_i is uniformly distributed over the range [1.0, 1.05] for price increases and over the range [0.95, 1.0] for price decreases. A_i is uniformly distributed over [0.0, 5.0] for increases and [-5.0, 0.0] for decreases. β_i is fixed at 0.3 and γ_i has a value of 0.05. The initial profit margins μ_i, are randomly generated to be within 5% and 35% for buyers and sellers.

APPENDIX C

SPECTRAD SCENARIO REPORT EXAMPLES

The figures in this appendix are an example the set of parameters that can be measured with SPECTRAD to characterize the behavior of NOBM and BM market scenarios. The reports that SPECTRAD generates are controlled by a set of input parameters which are listed below:

- Sequence number (seqnum): Identification number to identify the scenario
- Number of runs (num_sweeps): Number of scenario instances that were executed and averaged to generate data points and scenario results
- Number of time periods (num_ticks): Number of time periods after the warmup period over which scenario data was collected.
- Number of spectrum values (num_spectrumvalues): Data collection can be done for more than one scenario in a SPECTRAD execution. Each scenario can have a different value for the total amount of BBUs being traded. When collecting data for a single scenario the value of this variable should be 1.
- Number of spectrum user values (num_suvalues): Data collection can be done for more than one scenario in a SPECTRAD execution. Each scenario can have a different value for the number of spectrum users that are trading spectrum. When collecting data for a single scenario the value of this variable should be 1.
- Number of spectrum users in scenario (num_su_ids): This value is constant if num_suvalues is 1, otherwise it will change for each simulated scenario
- Number of BBUs in scenario (num_bbus): This value is constant if num_spectrumvalues is 1, otherwise it will change for each simulated scenario
- Sampling period: Detailed behavior data per spectrum user will be captured every *sampling* time ticks.

- Warmup period : Number of time ticks used for warmup of an scenario. No data is collected during warmup.

The values for the previously mentioned parameters for the scenarios shown in this appendix are:

num_sweeps = 100

num_ticks = 2000

num_spectrumvalues = 1

num_suvalues = 1

num_su_ids = 10

num_bbus = 100

sampling = 5

Warmup period = 3000

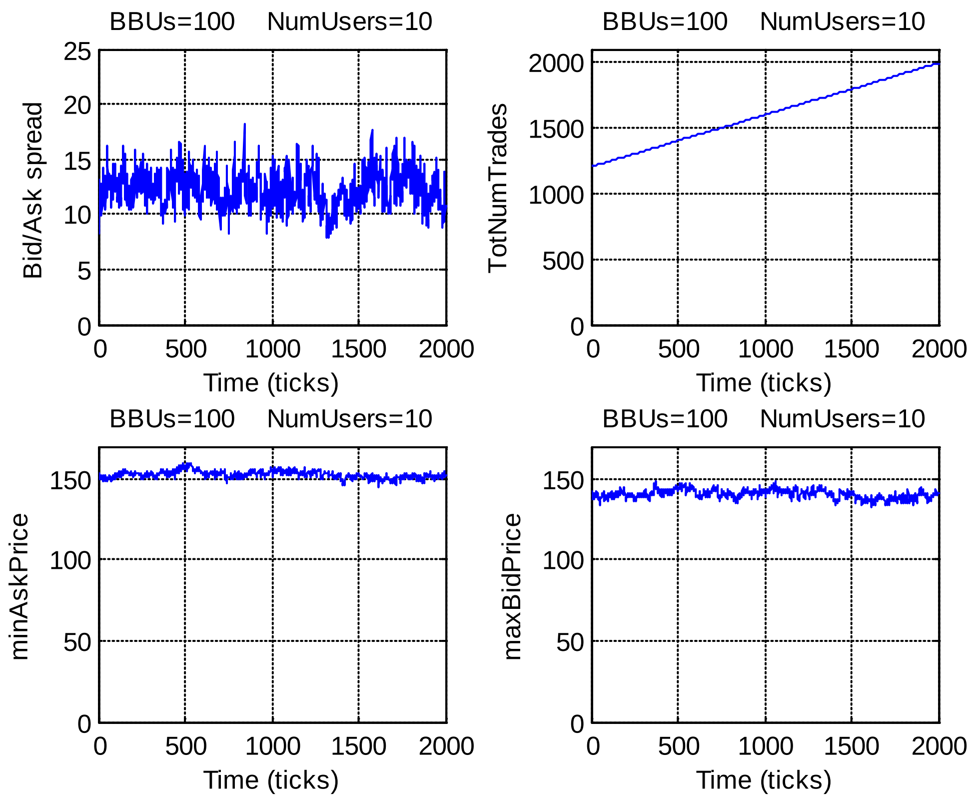


Figure 22. Price and trade activity measurements

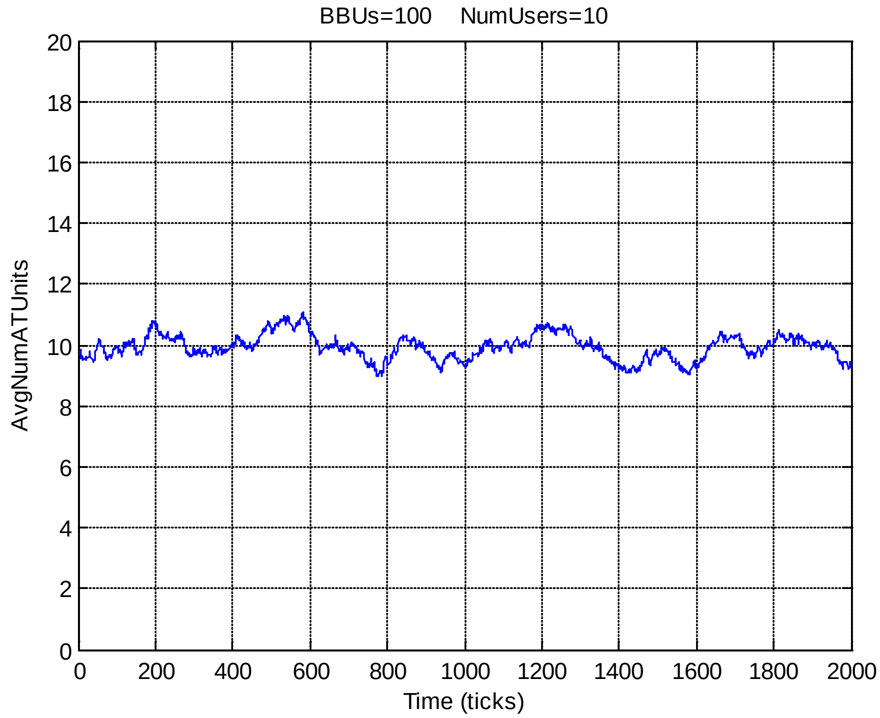


Figure 23. Average number of ATs

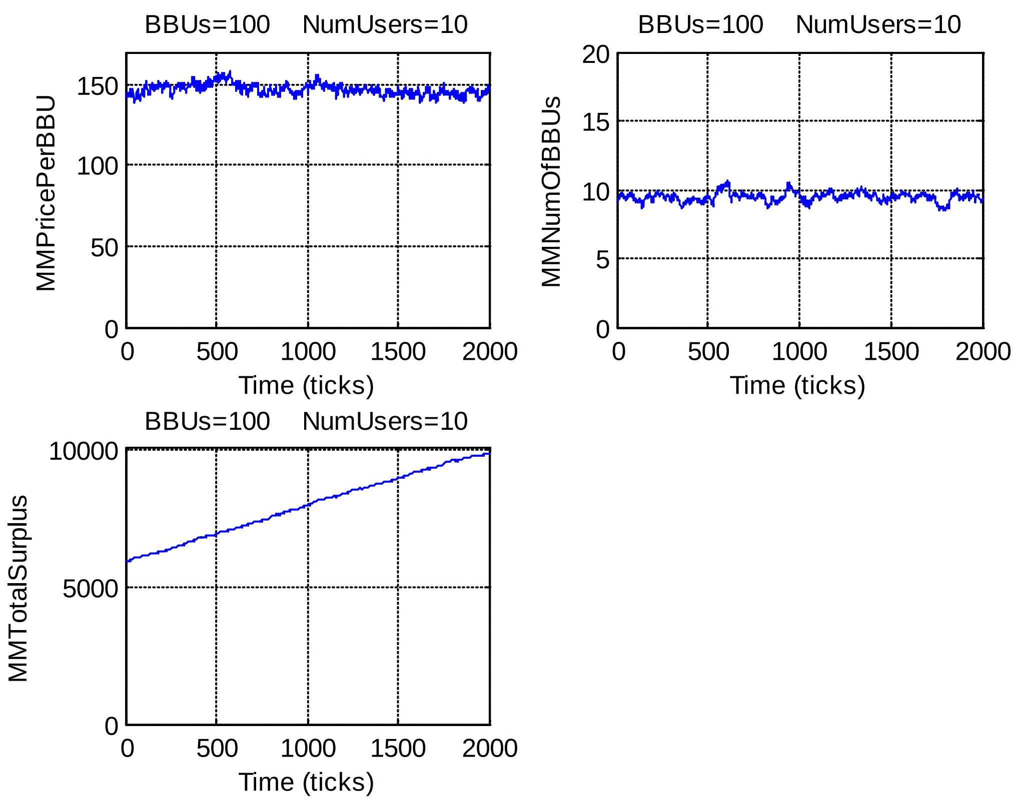


Figure 24. Market maker behavior measurements

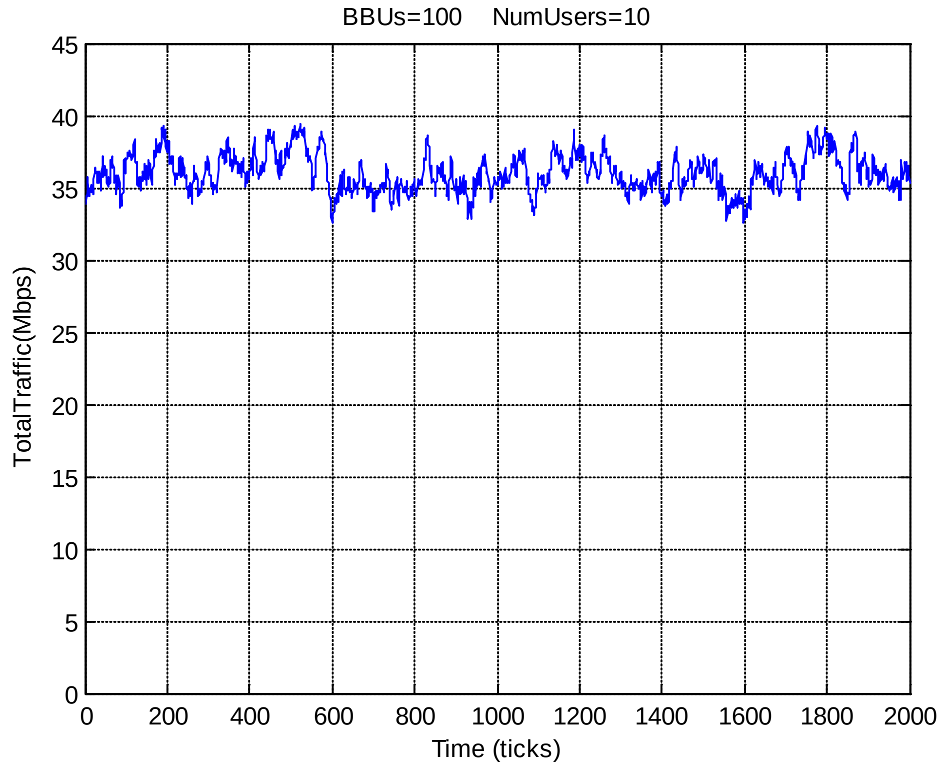


Figure 25. Total traffic being served

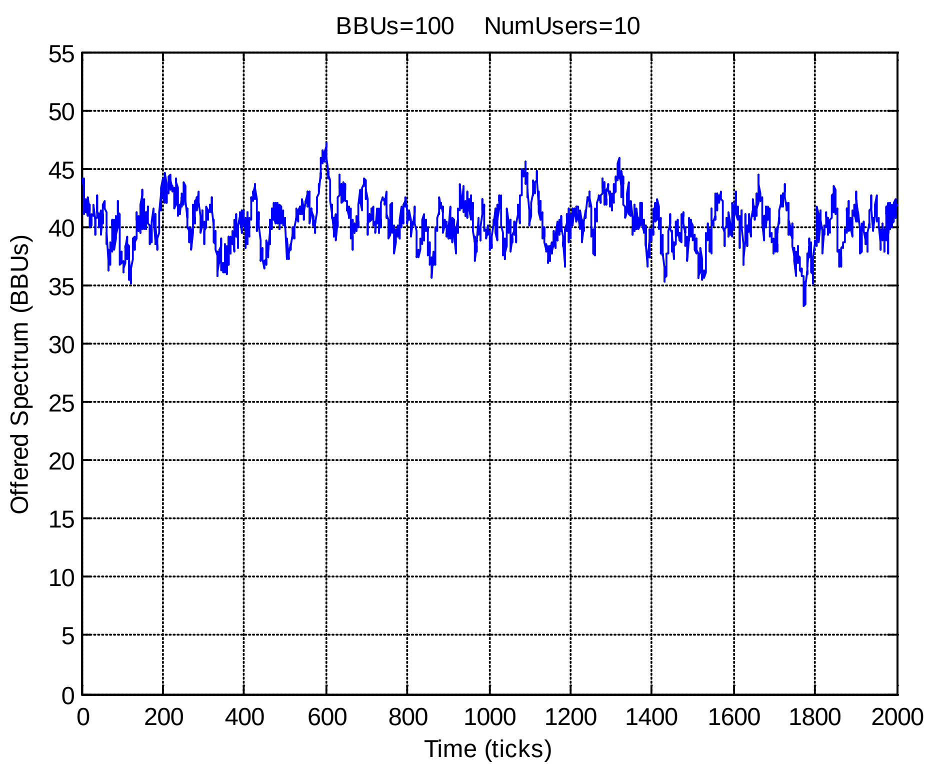


Figure 26. Amount of offered spectrum

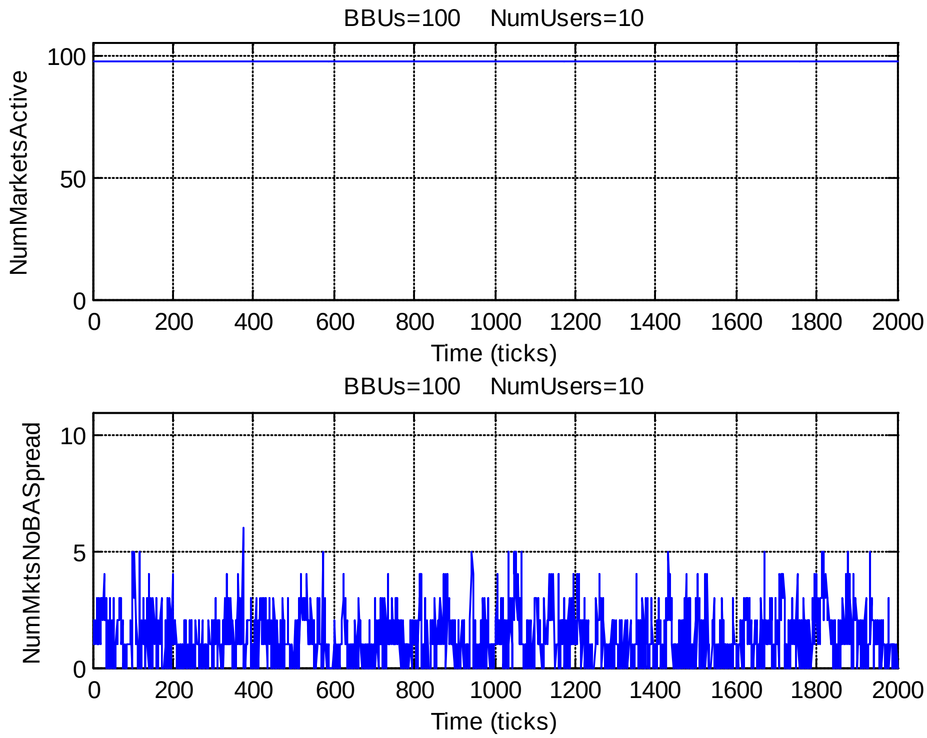


Figure 27. Running market count and number of markets with no bid-ask spread

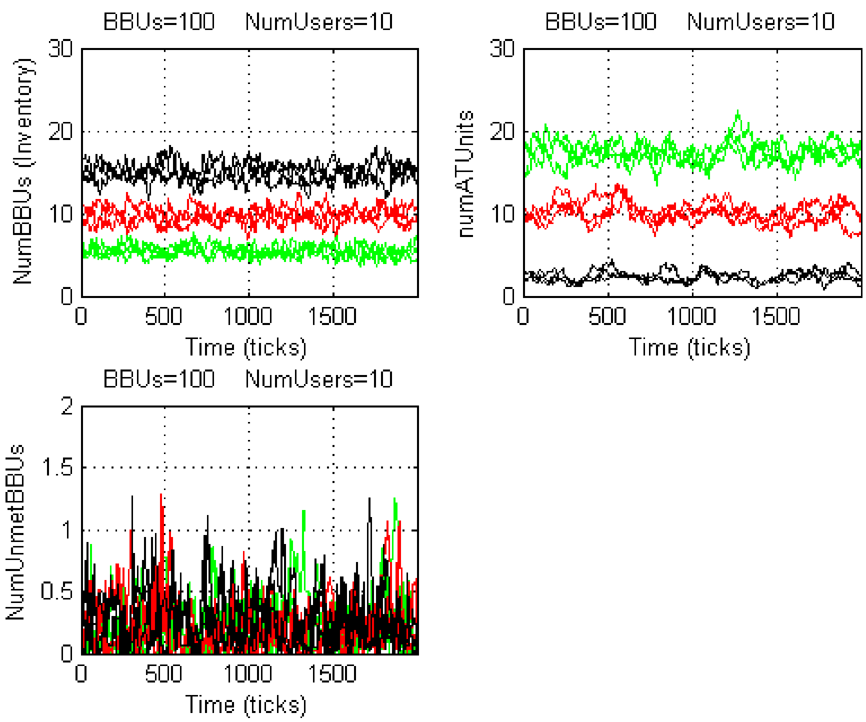


Figure 28. Detailed SU inventory behavior

(Green=low level SUs, Red=medium level SUs, Black=high level SUs)

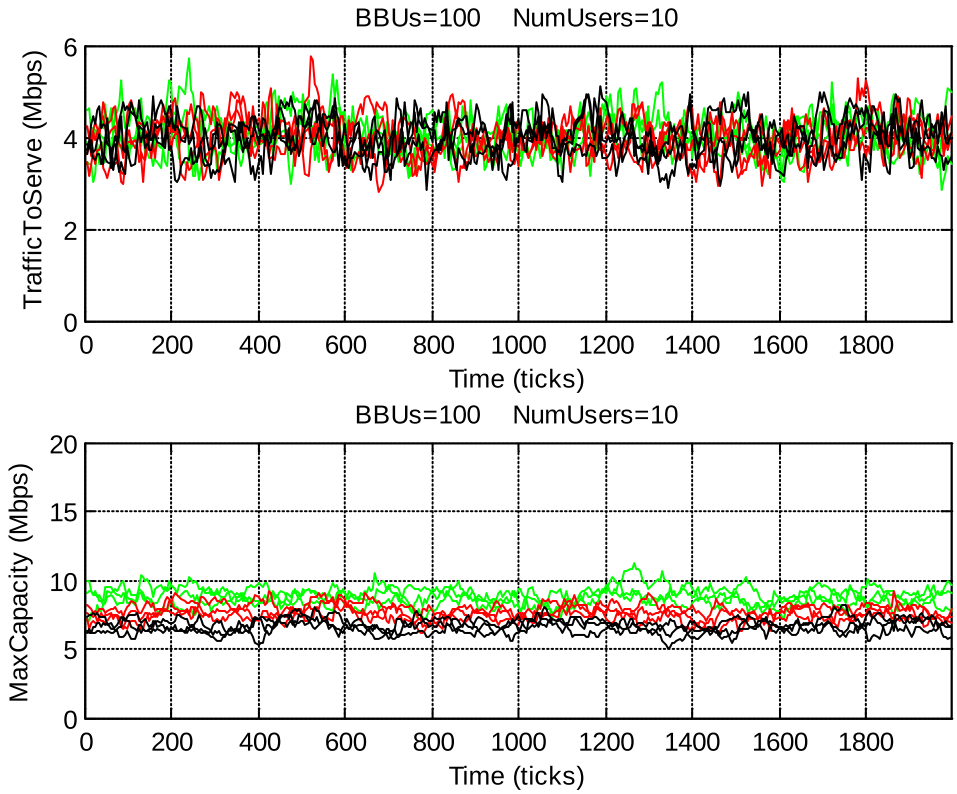


Figure 29. Behavior of total traffic to serve and maximum capacity for each SU.

(Green=low level SUs, Red=medium level SUs, Black=high level SUs)

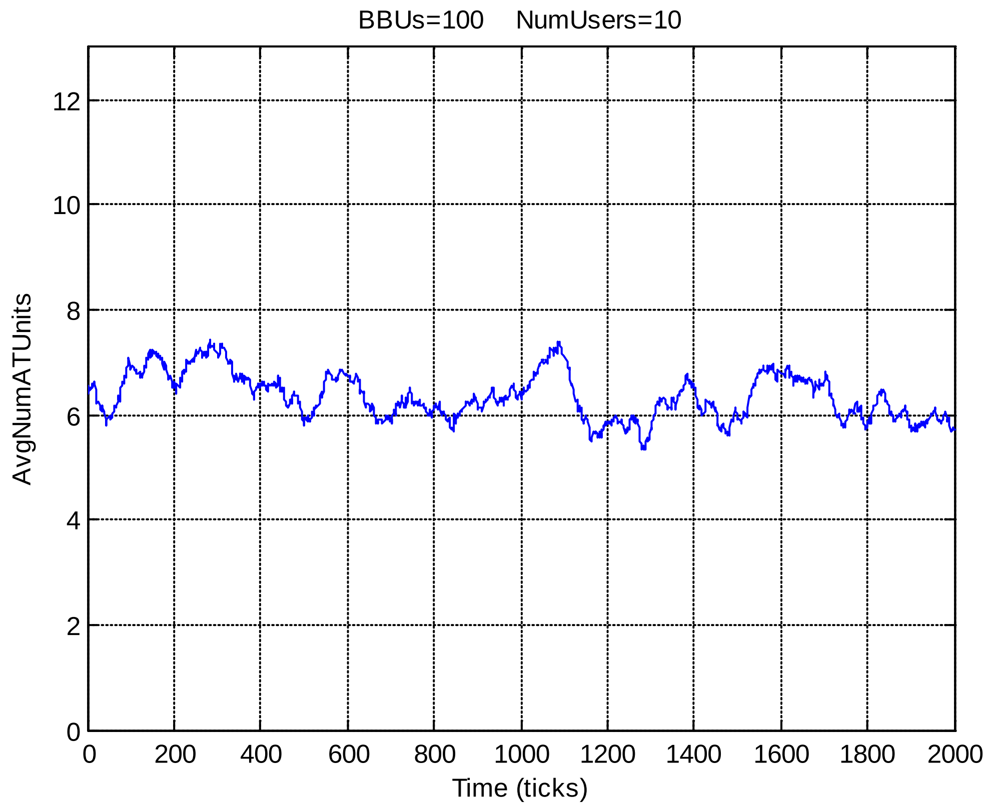


Figure 30. Average number of ATs

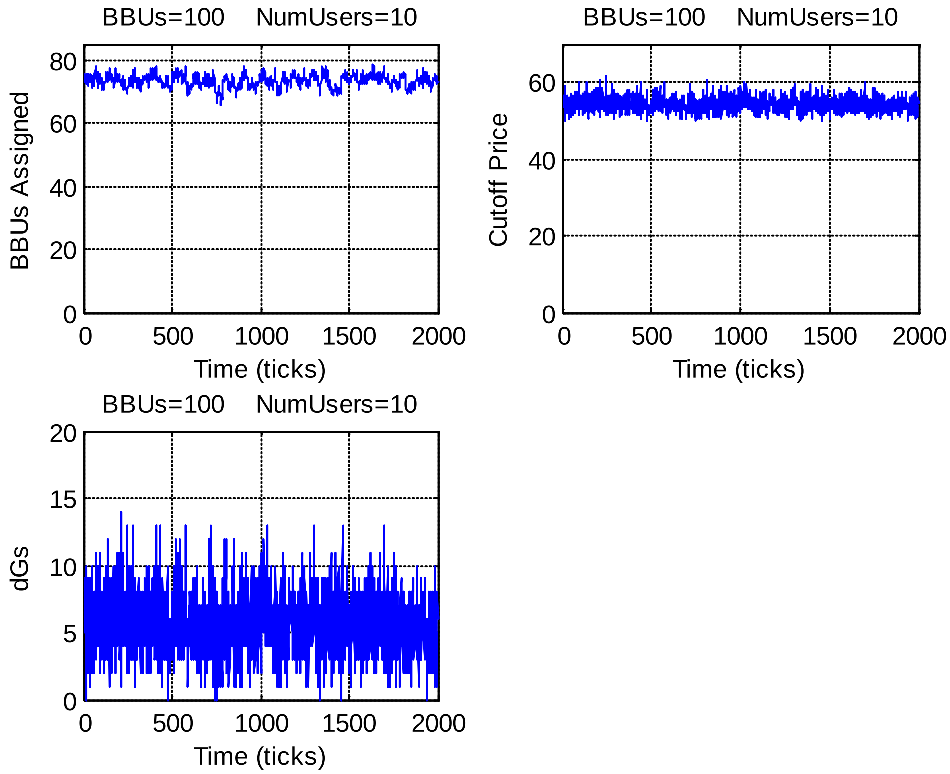


Figure 31. Spectrum assignment, price and demand behavior of the band manager

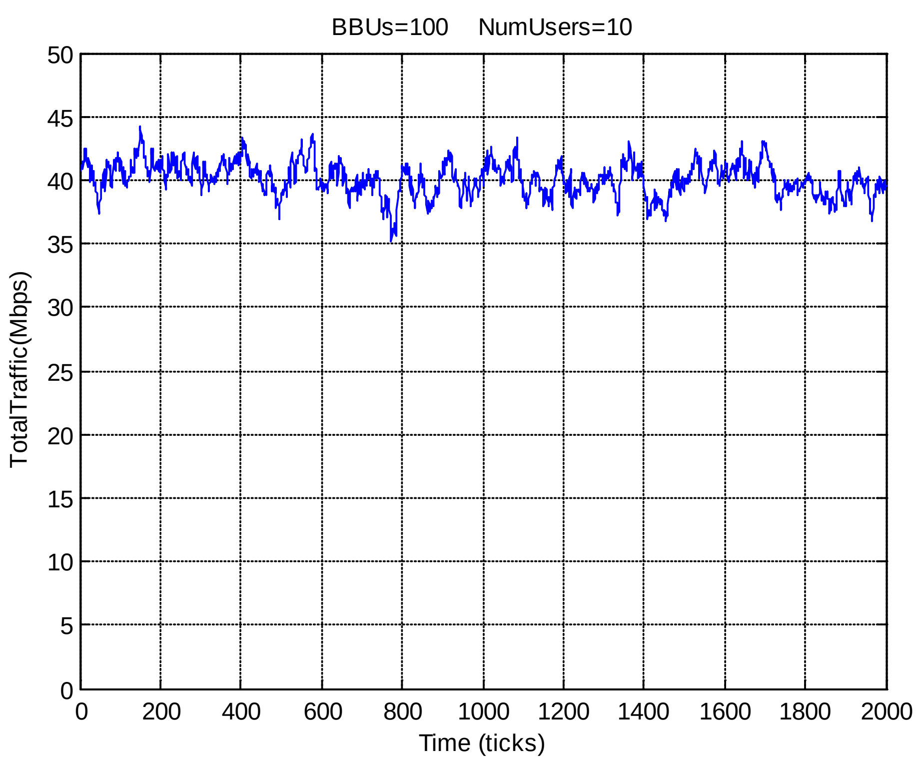


Figure 32. Total traffic served

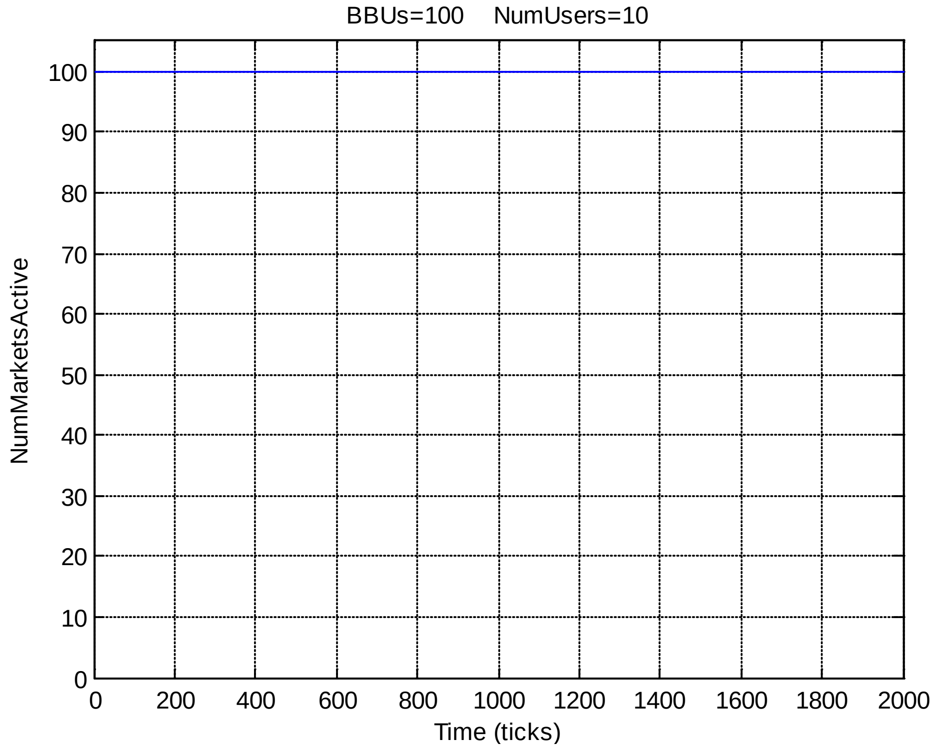


Figure 33. Number of active markets

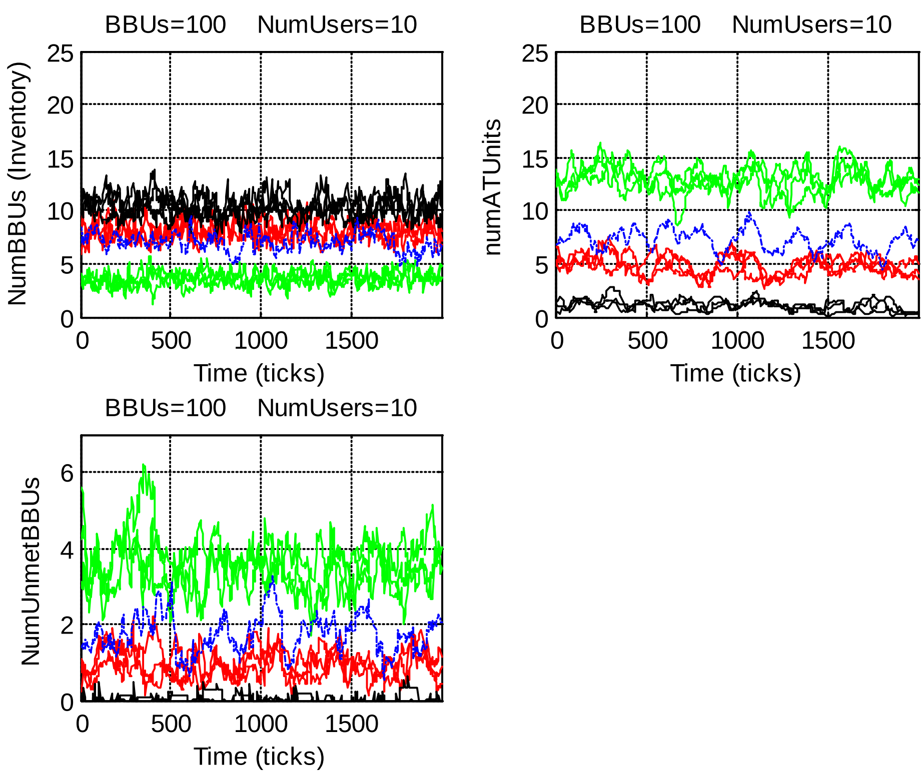


Figure 34. Detailed BBU and AT inventory behavior per SU

APPENDIX D

NOBM SCENARIO SCORES

The tables in this appendix show the scores obtained by each spectrum trading scenario based on the criteria mentioned on Table 24.

Scenario Descriptors				Criteria					
nsuids	nbbus	User Distrib	R	C1	C2	C3	C4	C5	Total score
6	150	3	25	-2	-1	-1	-1	0	-5
10	250	1	25	-2	-1	-1	-1	0	-5
10	250	2	25	-2	-1	-1	-1	0	-5
10	250	3	25	-2	-1	-1	-1	0	-5
4	100	2	25	-2	-1	-1	0	0	-4
4	100	3	25	-2	-1	-1	0	0	-4
5	125	2	25	-2	-1	-1	0	0	-4
5	125	3	25	-2	-1	-1	0	0	-4
6	150	1	25	-2	-1	-1	0	0	-4
6	150	2	25	-2	-1	-1	0	0	-4
4	100	1	25	-2	-1	-1	1	0	-3
5	125	1	25	-2	0	-1	0	0	-3
20	500	1	25	0	-1	-1	-1	0	-3
20	500	3	25	0	-1	-1	-1	0	-3
6	120	1	20	-2	-1	0	1	0	-2
6	120	3	20	-2	-1	0	1	0	-2
10	200	1	20	0	-1	-1	0	0	-2
10	200	2	20	0	-1	-1	0	0	-2
10	200	3	20	0	-1	-1	0	0	-2
4	20	2	5	-2	0	1	0	0	-1
4	20	3	5	-2	0	1	1	-1	-1
4	80	1	20	-2	0	0	1	0	-1
4	80	2	20	-2	0	0	1	0	-1
4	80	3	20	-2	0	0	1	0	-1
5	100	1	20	-2	0	0	1	0	-1
5	100	2	20	-2	0	0	1	0	-1
5	100	3	20	-2	0	0	1	0	-1
6	120	2	20	-2	0	0	1	0	-1
20	400	1	20	2	-1	-1	-1	0	-1
20	400	2	20	2	-1	-1	-1	0	-1
20	400	3	20	2	-1	-1	-1	0	-1
20	500	2	25	2	-1	-1	-1	0	-1
50	750	1	15	2	-1	-1	-1	0	-1
50	750	2	15	2	-1	-1	-1	0	-1
50	750	3	15	2	-1	-1	-1	0	-1
50	1000	1	20	2	-1	-1	-1	0	-1
50	1000	2	20	2	-1	-1	-1	0	-1
50	1000	3	20	2	-1	-1	-1	0	-1

Scenario Descriptors				Criteria					
nsuids	nbbus	User Distrib	R	C1	C2	C3	C4	C5	Total score
4	20	1	5	-2	0	1	1	0	0
4	40	1	10	-2	1	1	1	-1	0
4	40	2	10	-2	1	1	1	-1	0
4	40	3	10	-2	1	1	1	-1	0
4	60	1	15	-2	1	1	1	-1	0
4	60	2	15	-2	1	1	1	-1	0
4	60	3	15	-2	1	1	1	-1	0
5	25	1	5	-2	1	1	1	-1	0
5	25	2	5	-2	1	1	1	-1	0
5	25	3	5	-2	1	1	1	-1	0
5	75	1	15	-2	1	1	1	-1	0
5	75	2	15	-2	1	1	1	-1	0
5	75	3	15	-2	1	1	1	-1	0
6	90	2	15	-2	1	1	1	-1	0
6	90	3	15	-2	1	1	1	-1	0
50	1250	1	25	2	0	-1	-1	0	0
50	1250	2	25	2	0	-1	-1	0	0
50	1250	3	25	2	0	-1	-1	0	0
5	50	2	10	0	1	1	1	-1	2
5	50	3	10	0	1	1	1	-1	2
6	30	1	5	0	1	1	1	-1	2
6	30	2	5	0	1	1	1	-1	2
6	30	3	5	0	1	1	1	-1	2
6	90	1	15	0	1	1	1	-1	2
20	300	1	15	2	0	0	1	0	3
20	300	2	15	2	0	0	1	0	3
20	300	3	15	2	0	0	1	0	3
5	50	1	10	2	1	1	1	-1	4
6	60	1	10	2	1	1	1	-1	4
6	60	2	10	2	1	1	1	-1	4
6	60	3	10	2	1	1	1	-1	4
10	50	1	5	2	1	1	1	-1	4
10	50	3	5	2	1	1	1	-1	4
10	100	1	10	2	1	1	1	-1	4
10	100	2	10	2	1	1	1	-1	4
10	100	3	10	2	1	1	1	-1	4
10	150	2	15	2	1	0	1	0	4

Scenario Descriptors				Criteria					
nsuids	**nbbus**	**User Distrib**	**R**	**C1**	**C2**	**C3**	**C4**	**C5**	**Total score**
10	50	2	5	2	1	1	1	0	5
10	150	1	15	2	1	1	1	0	5
10	150	3	15	2	1	1	1	0	5
20	100	1	5	2	1	1	1	0	5
20	100	2	5	2	1	1	1	0	5
20	100	3	5	2	1	1	1	0	5
20	200	1	10	2	1	1	1	0	5
20	200	2	10	2	1	1	1	0	5
20	200	3	10	2	1	1	1	0	5
50	250	1	5	2	1	1	1	0	5
50	250	2	5	2	1	1	1	0	5
50	250	3	5	2	1	1	1	0	5
50	500	1	10	2	1	1	1	0	5
50	500	2	10	2	1	1	1	0	5
50	500	3	10	2	1	1	1	0	5

APPENDIX E

BM SCENARIO SCORES

The tables in this appendix show the scores obtained by each spectrum trading scenario based on the criteria mentioned on Table 28.

Scenario Descriptors				Criteria					
nsuids	nbbus	User Distrib	R	C1	C2	C3	C4	C5	Total Score
4	80	1	20	0	-1	-1	-1	0	-3
5	125	2	25	0	-1	-1	-1	0	-3
4	40	1	10	-1	0	0	-1	0	-2
4	40	2	10	-1	0	0	-1	0	-2
4	40	3	10	-1	0	0	-1	0	-2
4	80	2	20	1	-1	-1	-1	0	-2
4	100	1	25	1	-1	-1	-1	0	-2
4	100	2	25	1	-1	-1	-1	0	-2
4	100	3	25	1	-1	-1	-1	0	-2
5	100	1	20	1	-1	-1	-1	0	-2
5	100	2	20	1	-1	-1	-1	0	-2
5	100	3	20	1	-1	-1	-1	0	-2
5	125	1	25	1	-1	-1	-1	0	-2
5	125	3	25	1	-1	-1	-1	0	-2
6	120	1	20	1	-1	-1	-1	0	-2
6	120	2	20	1	-1	-1	-1	0	-2
6	120	3	20	1	-1	-1	-1	0	-2
6	150	1	25	1	-1	-1	-1	0	-2
6	150	2	25	1	-1	-1	-1	0	-2
6	150	3	25	1	-1	-1	-1	0	-2
10	200	1	20	1	-1	-1	-1	0	-2
10	200	2	20	1	-1	-1	-1	0	-2
10	200	3	20	1	-1	-1	-1	0	-2
10	250	1	25	1	-1	-1	-1	0	-2
10	250	2	25	1	-1	-1	-1	0	-2
10	250	3	25	1	-1	-1	-1	0	-2
20	400	1	20	1	-1	-1	-1	0	-2
20	400	2	20	1	-1	-1	-1	0	-2
20	400	3	20	1	-1	-1	-1	0	-2
20	500	1	25	1	-1	-1	-1	0	-2
20	500	2	25	1	-1	-1	-1	0	-2
20	500	3	25	1	-1	-1	-1	0	-2
50	1000	1	20	1	-1	-1	-1	0	-2
50	1000	2	20	1	-1	-1	-1	0	-2
50	1000	3	20	1	-1	-1	-1	0	-2
50	1250	1	25	1	-1	-1	-1	0	-2
50	1250	2	25	1	-1	-1	-1	0	-2
50	1250	3	25	1	-1	-1	-1	0	-2

Scenario Descriptors				Criteria					
nsuids	nbbus	User Distrib	R	C1	C2	C3	C4	C5	Total Score
4	20	1	5	-1	0	0	1	-1	-1
4	20	2	5	-1	0	0	1	-1	-1
4	20	3	5	-1	0	0	1	-1	-1
4	60	1	15	0	0	0	-1	0	-1
4	60	2	15	0	0	0	-1	0	-1
4	60	3	15	0	0	0	-1	0	-1
4	80	3	20	1	-1	0	-1	0	-1
5	25	1	5	-1	0	0	1	-1	-1
5	25	2	5	-1	0	0	1	-1	-1
5	25	3	5	-1	0	0	1	-1	-1
5	75	1	15	0	0	0	-1	0	-1
5	75	2	15	0	0	0	-1	0	-1
5	75	3	15	0	0	0	-1	0	-1
6	30	1	5	-1	0	0	1	-1	-1
6	30	2	5	-1	0	0	1	-1	-1
6	30	3	5	-1	0	0	1	-1	-1
6	90	1	15	0	0	0	-1	0	-1
6	90	3	15	0	0	0	-1	0	-1
6	90	2	15	1	0	0	-1	0	0
50	750	1	15	1	-1	-1	1	0	0
50	750	2	15	1	-1	-1	1	0	0
50	750	3	15	1	-1	-1	1	0	0
5	50	1	10	0	0	0	1	0	1
5	50	2	10	0	0	0	1	0	1
5	50	3	10	0	0	0	1	0	1
6	60	1	10	0	0	0	1	0	1
6	60	2	10	0	0	0	1	0	1
6	60	3	10	0	0	0	1	0	1
10	50	1	5	0	1	0	1	-1	1
10	50	2	5	0	1	0	1	-1	1
10	50	3	5	0	1	0	1	-1	1
10	100	2	10	0	0	0	1	0	1

Scenario Descriptors				Criteria					
nsuids	**nbbus**	**User Distrib**	**R**	**C1**	**C2**	**C3**	**C4**	**C5**	**Total Score**
10	100	1	10	1	0	0	1	0	2
10	100	3	10	1	0	0	1	0	2
10	150	1	15	1	0	0	1	0	2
10	150	2	15	1	0	0	1	0	2
10	150	3	15	1	0	0	1	0	2
20	100	1	5	1	1	0	1	-1	2
20	100	2	5	1	1	0	1	-1	2
20	100	3	5	1	1	0	1	-1	2
20	200	1	10	1	0	0	1	0	2
20	200	2	10	1	0	0	1	0	2
20	200	3	10	1	0	0	1	0	2
20	300	1	15	1	0	0	1	0	2
20	300	2	15	1	0	0	1	0	2
20	300	3	15	1	0	0	1	0	2
50	250	1	5	1	1	0	1	-1	2
50	250	2	5	1	1	0	1	-1	2
50	250	3	5	1	1	0	1	-1	2
50	500	1	10	1	1	0	1	0	3
50	500	2	10	1	1	0	1	0	3
50	500	3	10	1	1	0	1	0	3

APPENDIX F

SENSITIVITY ANALYSIS

This appendix presents an analysis of the effect of changing the values of some of the parameters set in the initial conditions of the market scenarios studied in this work. However only scenarios with user distribution 1 (as defined in Table 23) where considered since the general behavior across market scenarios has been found to be independent of the user distribution. The 90% confidence intervals for all measured parameters are used to establish differences or equivalence between the reference scenarios and the alternate scenarios used for sensitivity analysis.

Sensitivity analysis for NOBM scenarios

Sensitivity analysis for NOBM scenarios will be performed over the parameters listed in Table 30. The table lists the reference values used in the scenarios studied in this work (reference scenarios) and the low (50% lower than reference) and high values (50% higher than reference) which will be considered in this analysis.

Parameter	**Reference Value**	**Low**	**High**
AT lifetime	Uniformly distributed between (90, 110) time units	Uniformly distributed between (40, 60) time units	Uniformly distributed between (140, 160) time units
Average traffic per spectrum user (SU)	4 Mbps	2 Mbps	6 Mbps
Market maker quote spread	10 monetary units	5 monetary units	15 monetary units

Table 30. Parameters for sensitivity analysis (NOBM)

Effect of changing the AT lifetime: The changes in the AT lifetime did not affect the relative bid-ask spread in a statistical significant way. Additionally, the number of running markets was not affected for the scenarios that were determined viable with the reference values.

When using the low AT lifetime values, the midpoint price increased and the AT inventory decreased when compared to the reference case. When using the high AT lifetime values, the midpoint price decreased and the AT inventory increased. These behaviors were expected but they did not influence the overall behavior of the scenarios significantly.

Using the same criteria and scoring procedure for NOBM scenarios mentioned in section 9.2.3 the score values shown in Figure 35 are obtained. The viable scenarios are those with scores greater than 0. It can be concluded that the NOBM scenarios analyzed are not sensible to changes in the AT lifetime over the range of AT lifetimes value considered in this analysis.

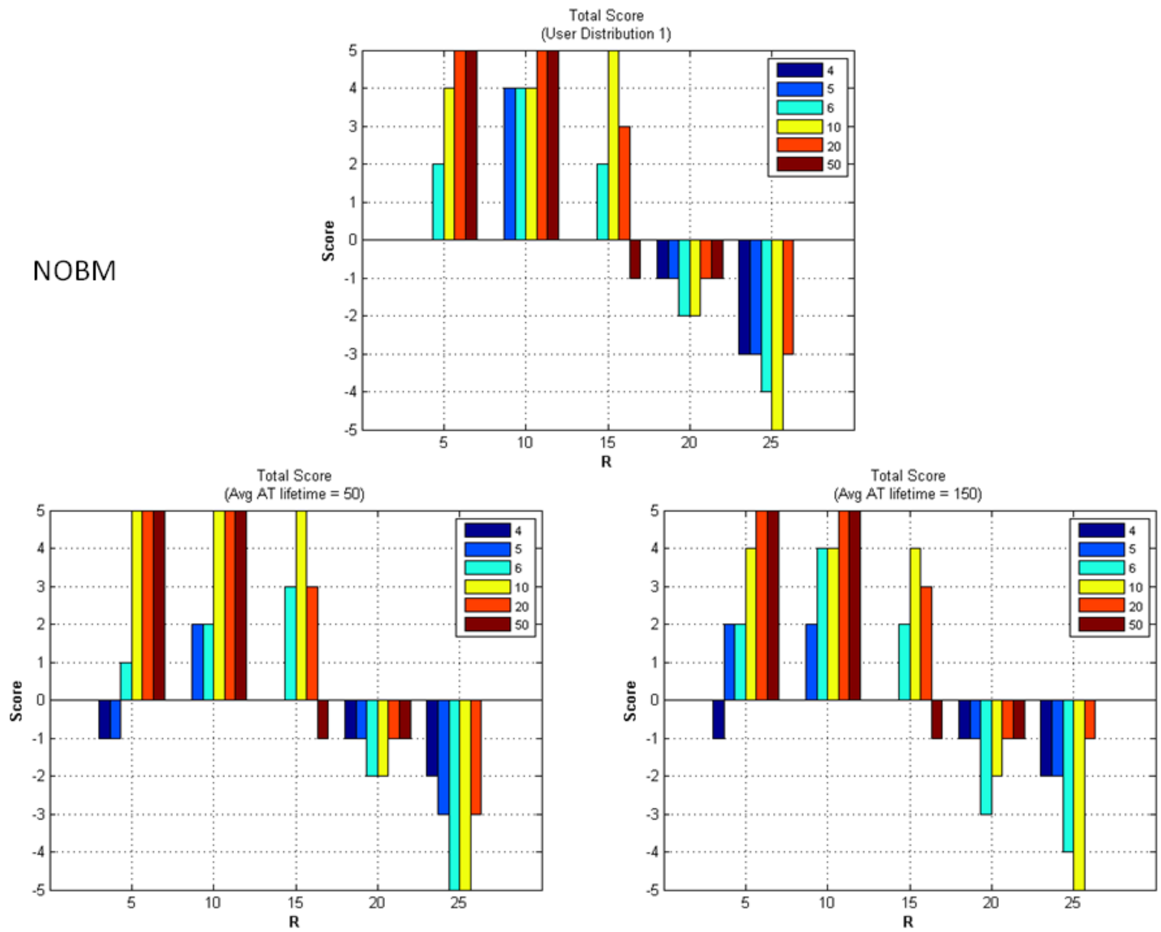


Figure 35. Comparing NOBM scenarios with different AT lifetimes
(upper graph is the reference case)

Effect of the Market Maker's spread value: The market maker's spread is the average difference between its bid (buy) price and its ask (sell) price for spectrum BBUs. The changes in this value (to low and high values as mentioned in Table 30) produced improvements in the relative bid ask spread for a few NOBM scenarios. Mid-point prices changed as expected being lower for a low spread value and higher for a high spread value. However, all the changes in behavior were not significant enough to change the selection of viable scenarios as shown in Figure 36. Viable scenarios are those with scores greater than 0.

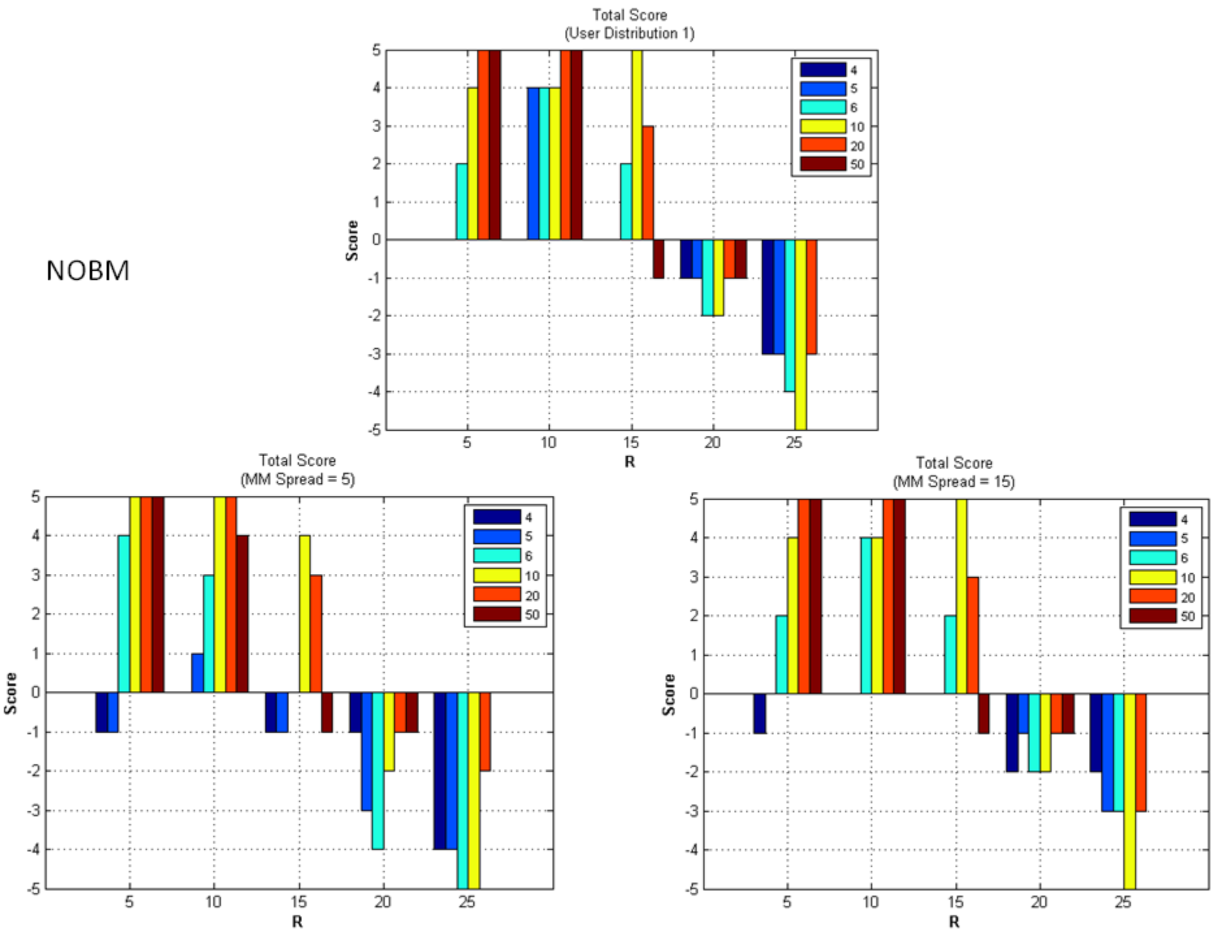


Figure 36. Comparing NOBM scenarios with different MM spreads
(upper graph is the reference case)

<u>*Effect of changing the average traffic per SU*</u>: The average traffic per SU determines the average amount of spectrum BBUs or AT units (or a combination of both) which the SU will have to hold to serve traffic requests. For the scenarios studied in this work the average value

was 4 Mbps which means that at R=10, the SUs should on average have enough spectrum to closely meet their traffic request needs. R=10 becomes the “average” R value.

When changing the average traffic per SU to 2 Mbps, the “average” R value is 5 and when setting it at 6 Mbps it’s 15.

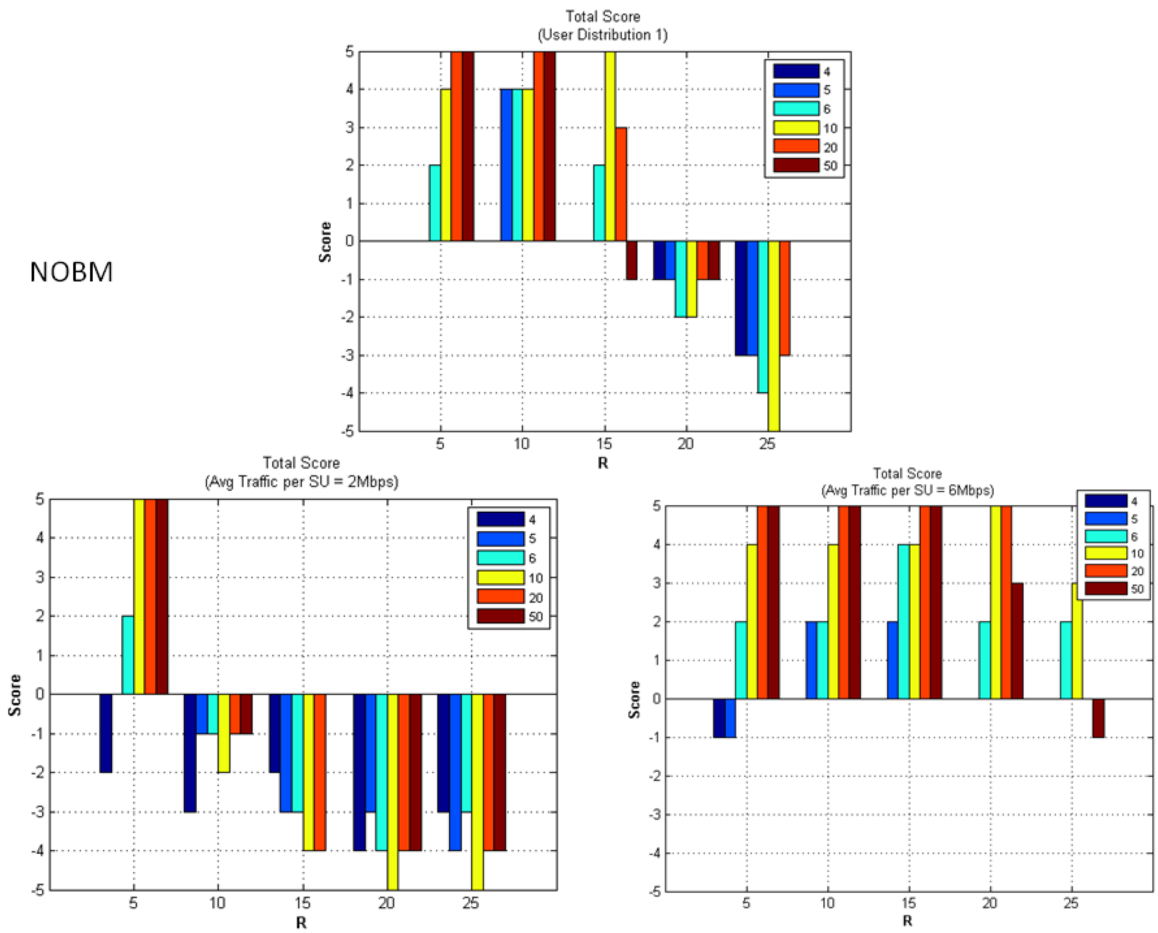


Figure 37. Comparing NOBM scenarios with different average traffic per SU values
(upper graph is the reference case)

Changing the average traffic per SU does affect the viability and behavior of the scenarios analyzed but in such a way that the viable scenarios are *centered* over the average R value. The viable scenarios as well as the behavior of some of the parameters of the scenarios *shifts* to the new average R value. This implies that knowing what is the average traffic per SU and determining from it the average R value for serving that traffic (average amount of BBUs that a SU should have to serve the traffic) and comparing that value with the average amount of BBUs actually being given to the SUs should provide a good indication of market viability.

Sensitivity analysis for BM scenarios:

Sensitivity analysis for BM scenarios will be performed over the parameters listed in Table 31. The table lists the reference values used in the scenarios studied in this work and the low (50% lower than reference) and high values (50% higher than reference) which will be considered in this analysis.

Parameter	Reference Value	Low	High
AT lifetime	Uniformly distributed between (90, 110) time units	Uniformly distributed between (40, 60) time units	Uniformly distributed between (140, 160) time units
Average traffic per spectrum user (SU)	4 Mbps	2 Mbps	6 Mbps

Table 31. Parameters for sensitivity analysis (BM)

Effect of changing the AT lifetime: The changes in the AT lifetime did not affect the relative bid-ask spread for BM scenarios in a statistical significant way. For the low AT lifetime value, the cutoff price and the probability that demand is greater than supply were slightly affected, while no significant change with respect to the reference case was present when the high AT lifetime value was used.

The sets of scores determined by applying the viability criteria for BM scenarios to the scenarios with the low and high AT values are shown in Figure 38. The viable scenarios are those with scores greater than 0. From the figure it can be seen that BM scenarios are sensible to the choice of the AT lifetime value.

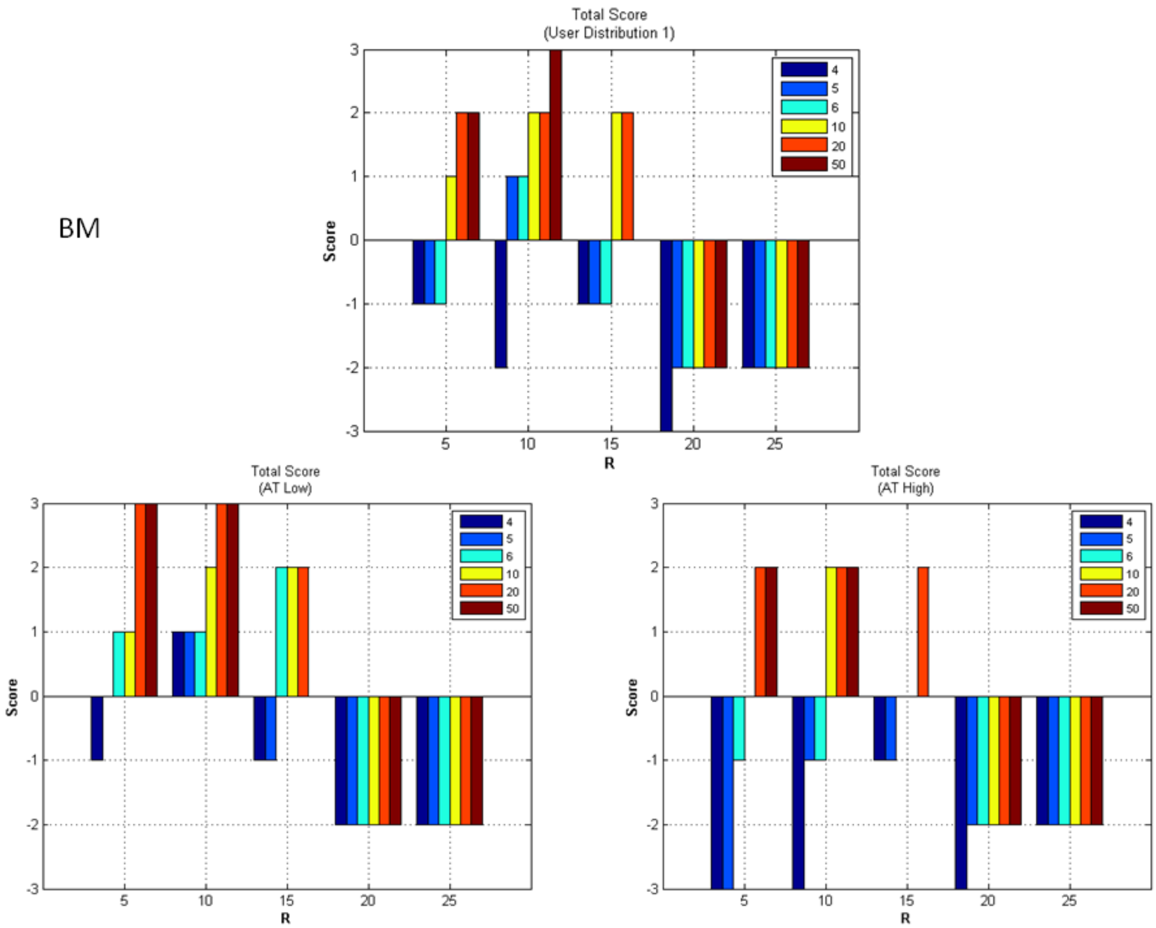


Figure 38. Comparing BM scenarios with different AT lifetime values
(upper graph is the reference case)

<u>Effect of changing the average traffic per SU</u>: Changing the average traffic per SU does affect the viability and behavior of the scenarios analyzed but in such a way that the viable scenarios are *centered* over the average R value. This means that the viability behavior as well as the behavior of some of the parameters of the scenarios *shifts* to the new average R value. This characteristic of BM scenarios is similar to the one found for NOBM scenarios. However, scenarios with low number of users (*numSU* < *10)* are not viable when using the high value for the average traffic per SU. Figure 39 shows the scores obtained for all the scenarios analyzed.

In general it can be concluded that BM scenarios are sensible to changes in their operation parameters.

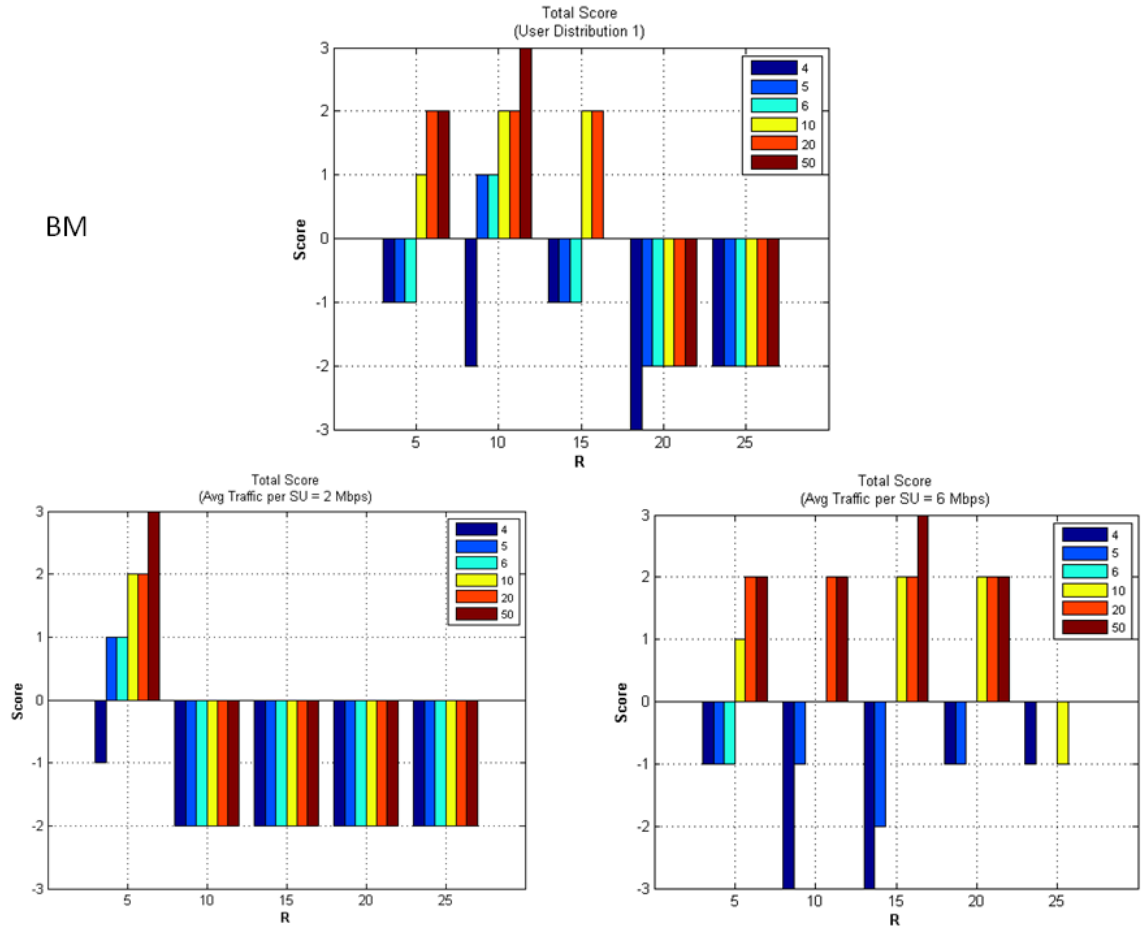


Figure 39. Comparing BM scenarios with different average traffic per SU values
(upper graph is the reference case)

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