Characterization and Modeling of Spectrum Trading Markets

Carlos E. Caicedo, *Member, IEEE*, Martin B. H. Weiss

***Abstract*— Telecommunication regulators are facing increasing pressure to make spectrum resources more widely available to new wireless services and providers. In spectrum trading markets, buyers and sellers determine the assignments of spectrum and, possibly, its uses. These markets are being considered or implemented by the regulatory bodies of many countries as a way to provide increasing efficiency in the use of spectrum and attend the demand for this resource. This work describes a classification for the implementation of spectrum trading markets and a way to model them and identify the conditions for their viability. Specifically, we make use of Agent-Based Computational Economics (ACE) to model the participants in these markets, analyze the behaviors that emerge from the interactions of its participants and determine the conditions for viable markets. Our results, provide guidelines that can be used by regulators and wireless service providers for the design and implementation of these markets.**

***Index Terms*— Spectrum trading, secondary spectrum markets, agent-based computational economics, dynamic spectrum assignment, spectrum management.**

I. Introduction

THE radio frequency spectrum is a highly regulated resource whose management is usually deferred to a government agency in most countries. The tasks related to spectrum management encompass all the activities related to regulating this resource including spectrum allocation and assignment of spectrum as well as regulation enforcement activities. For our purposes, 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).

Currently, most of the spectrum is used sub-optimally most of the time with low average occupancy values (less than 6% as reported in [1]). A main cause for this is that 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. In addition to seeking mechanisms that improve spectrum efficiency, the tasks related to managing spectrum have 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.

In order to address these issues, flexible spectrum assignment mechanisms have to be put in place to adjust to the evolving wireless landscape while still achieving the best usage of spectrum possible under economic or social welfare considerations. In particular, market based mechanisms are being used by many spectrum management agencies in order to reduce their emphasis on command and control methods. Spectrum trading (ST) is a market based mechanism where buyers and sellers determine the assignments of spectrum and, possibly, its uses. 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 [2]. ST provides a mechanism for regulators to address the allocation and assignment aspects of spectrum use. It is also a mechanism of interest to wireless service providers since ST can help them in:

- Providing new revenue generating services
- Serving geographical regions where spectrum resources are needed
- Having mechanisms to handle peak loads of traffic
- 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).
- Obtain economic gains from spectrum that is unused (i.e. speculation)

For economically-driven spectrum assignment 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 [3]. We use Agent-Based Computational Economics (ACE) to analyze these markets and the behaviors of their participants which would be difficult to realize with conventional statistical and analytical tools due to the range of scenario parameters that can be changed [4],[5]. ACE has been previously used to study secondary spectrum use in [6]. A Spectrum Trading market modeling tool (SPECTRAD) has been developed as part of our research work and makes use of ACE methods and concepts [7]. With this tool, we model the participants in a ST market over a set of different scenarios. Our objective was to

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Carlos E. Caicedo is with the School of Information Studies, Syracuse University, Syracuse, NY 13244 (e-mail: ccaicedo@syr.edu)

Martin B.H. Weiss is with the Telecommunications Program, School of Information Sciences, University of Pittsburgh, Pittsburgh PA 15260 (email: mbw@pitt.edu).

find the conditions that lead to viable ST markets based on their liquidity and sustainability characteristics.

This paper is structured as follows. Section II describes the entities that participate in a ST market. Section III provides a classification for exchange based ST markets. Section IV describes how we modeled ST markets and the behaviors of the different agents considered in our modeling. Section V describes the results obtained from the modeled scenarios. Section VI provides conclusions and recommendations based on the results of this work.

II. Participants in a spectrum trading market

In [3] we classified the market structures that support ST. This classification considered two main types of market structures for spectrum trading: over-the-counter markets and exchange-based market operation. We will focus on the exchange-based markets as they offer a richer set of market behaviors. The entities that that participate in these markets are described below.

Spectrum license holders (SLH): Entity that owns a spectrum license and that offers it for trading in exchange of financial compensation. This entity can be a wireless service provider, a market maker, or a spectrum exchange which has been assigned a spectrum trading band by a regulatory agency. In general, SLHs hold spectrum for speculation or for their own use.

Spectrum license requestors (SLR): Entity that submits bids for spectrum licenses to the ST market with the intent of acquiring the license. SLRs obtain spectrum for speculation or their own use. An entity that acts as a SLR can be: a wireless service provider, a market maker or a company/enterprise that acquires spectrum on behalf of another.

Spectrum regulator: Government entity that oversees the ST market and defines the regulations for its operation. It is also responsible for providing and maintaining a spectrum availability and assignment database which is updated every time a spectrum trade is completed.

Market makers: A market maker facilitates trading; it does not provide services with its inventory. It acts as a dealer that holds an inventory of spectrum and stands ready to trade when a SLR (buyer) or SLH (seller) desires. It gets revenue through the spread between the sell and buy prices for spectrum, and holds a spectrum inventory for negotiating and speculating.

Spectrum exchange: An entity 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.

III. Characterization of spectrum trading markets

A. Implementation architecture

A spectrum trading market can be implemented in many ways. We have characterized the technical architectures for ST based in four dimensions (infrastructure, configuration method, activation and flexibility) described below [8].

Infrastructure: Traded spectrum can be used by the buyer through a shared infrastructure (pooling point) where several market participants can make use of their awarded spectrum for transmissions. When infrastructure is not shared a licensee utilizes its own equipment to make use of his spectrum.

Configuration method: Configuration of traded spectrum over a region can be done in a centralized or distributed manner. In a centralized architecture a central entity is in charge of configuring and controlling the infrastructure required for the use of spectrum. In a distributed architecture, the central entity gives permission over a specific area to a service provider to use the spectrum that has been traded which then configures its equipment.

Activation: The requests to acquire spectrum can be provider initiated 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. 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.

Flexibility: Flexibility refers to the number of wireless standards that can be used to support services over the traded spectrum. When a set of a few wireless standards can be used, we refer to a multi-protocol architecture. When only one standard is allowed, we have a single standard architecture.

Figure 1 summarizes the characterization of spectrum trading implementation architectures.

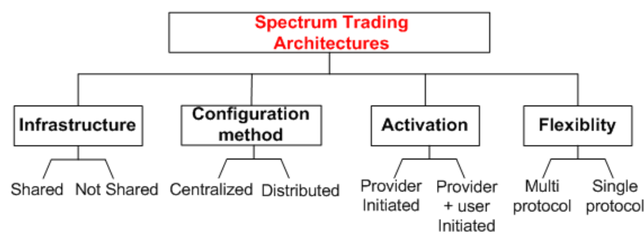

Fig 1. Spectrum trading implementation architectures

B. Market structure

We define a spectrum exchange as an organization made up of entities whether incorporated or unincorporated, that provide and maintain a marketplace 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 [9]. 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, the devices required to make use of traded spectrum do not need to be co-located in the exchange so the exchange might not be involved in the active delivery of wireless services.

In [3] we presented a characterization for exchange based ST markets based on their technical structure and market functionality. From the point of view of technical structure we considered that a spectrum exchange acts as a pooling point

(POOL) if its facilities house the equipment that enable the delivery of wireless services through spectrum acquired by a buyer in the exchange. In contrast, a non-pooling point exchange (NOPOOL) only delivers the authorization for use of spectrum to the buying party in a 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 acting as a band manager supports spectrum leasing transactions. A NOBM exchange will only facilitate the trading of spectrum among entities in the market without holding any spectrum inventory itself.

Unless a basic amount of bandwidth has been defined 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.

The proposed characterization generates four types of spectrum exchanges which can be used to implement a ST market. These are listed in table 1 as mentioned in [3]. By studying the trading, information overhead and infrastructure costs of different combinations of ST market implementation architectures with the set of ST exchange types and since we are interested in the running behavior (sustainability) of the market once its operating infrastructure has been put in place we find that the only differentiating factor between the different combinations was whether the exchange is organized to work as a band manager (BM) or not (NOBM) [7].

Thus, under the following assumptions/restrictions:

- One wireless standard is being used in the market
- Interference conditions do not impact the services provided over a unit of traded spectrum.
- Trading takes place over an exchange entity.

when modeling the running behavior ST 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) and markets with no band manager duties – a NOBM exchange.

TABLE I
TYPES OF EXCHANGES

Exchange type	Characteristics
POOL_BM *(Pooling point + band manager functionality)*	- Use of traded spectrum is enabled and configured through equipment and/or infrastructure owned 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 and/or 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 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

IV. Agent Based Modeling of ST Markets

We use Agent-Based Computational Economics (ACE) to study the behaviors that emerge in ST markets from the interactions among market participants. Our objective is to determine the conditions that lead to viable spectrum trading markets, where viability is determined by the liquidity and sustainability of the market. 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. Once initial conditions have been specified, the evolution of an ACE model is only dependent on the interactions among agents.

A Spectrum Trading market modeling tool (SPECTRAD) has been developed as part of our research work and makes use of ACE concepts. The tool works on top of the REPAST (Recursive Porous Agent Simulation Toolkit) platform developed by the Argonne National Laboratory for the development of agent based models [10,11]. The list of agents used in our models is shown in table 2. The different market scenarios studied in this work were generated by varying the market type, the number of market participants, the distribution of valuation levels for spectrum users and the amount of available spectrum in the market.

A. 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. The spectrum users (SUs) can obtain resources to serve their traffic demands 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 are generic and can resemble investing in equipment to make better use of

TABLE II
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.

spectrum already owned by the SU or in wireline technology, thus avoiding the purchase of additional 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. In our models, each SU has a fixed price for its choice of AT unit that does not change during the life of the market. Thus, if a SU is acting as a SLR (i.e. buyer) when the market price for a BBU is higher than the AT unit price, the SU will buy ATs and when BBU prices are lower or equal to the AT price, the SU will buy BBUs.

In order to make the behavior of a scenario more realistic, 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 traffic demand is too high for the SU to incur. Thus, a SU will 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 (sell) the BBUs for which it "overpaid". AT units have a finite lifetime, after which they become unusable. At this time, the SU must again decide whether to purchase spectrum BBUs or ATs.

B. Spectrum User behavior

For our analysis we model the aggregate traffic demand for each SU within the ST service area and the interval between changes of traffic demand with exponential distributions. In this model, we assume that the traffic demands faced by SUs are independent. As the traffic to serve changes in time, if a SU's inventory of BBUs and AT units is more than enough to service the traffic, the SU can sell part of its spectrum inventory, thus becoming a SLH and prepare to post an offer to sell 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.

1) SU behavior in a NOBM exchange based market

In a NOBM exchange based market, each SU submits requests to buy or sell to the exchange. The exchange collects these requests and tries to find the best match between requests to establish a trade. SUs can query the spectrum exchange for its current market quote, which contains the minimum ask (minAsk) and the maximum bid (maxBid) price posted in the market. SUs use this information in their market decisions (price setting). Additionally, a SU can post limit orders to buy/sell 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 market 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.

2) SU behavior in a BM exchange based 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 all the SUs, the exchange determines a cutoff price. A SU with a bid above the cutoff price gets assigned spectrum via a spectrum lease for a time period T_{lease} after which it 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. 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 recalculates its bidding price and announces 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 tick). Over the course of the activation delay, the SUs that did not get spectrum will not be able to satisfy their traffic requirements.

C. Exchange behavior

1) NOBM exchange

In NOBM exchange based market scenarios, the market initialization is done via a call market trading session (all trades take place when the market is "called") 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 [12]. 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 the initialization phase, the SU agents may trade at anytime they choose by posting 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.

After each update to the order book, the exchange announces the *market quote* informing market participants of the current market ask price (best price at which spectrum is being sold) and the current market bid price (price of the best offer to buy spectrum). This way, market participants can adapt their price behavior to make competitive bids or asks in the future. Figure 2 shows the general behavior of a NOBM exchange.

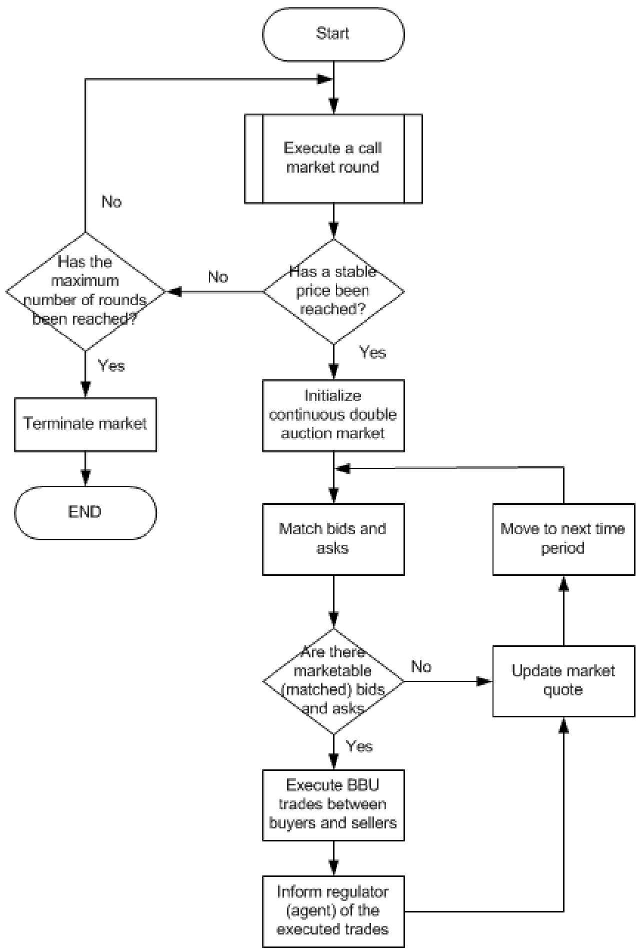

Fig 2. NOBM exchange behavior

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. 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 the cutoff 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. Figure 3 illustrates the behavior of a BM exchange.

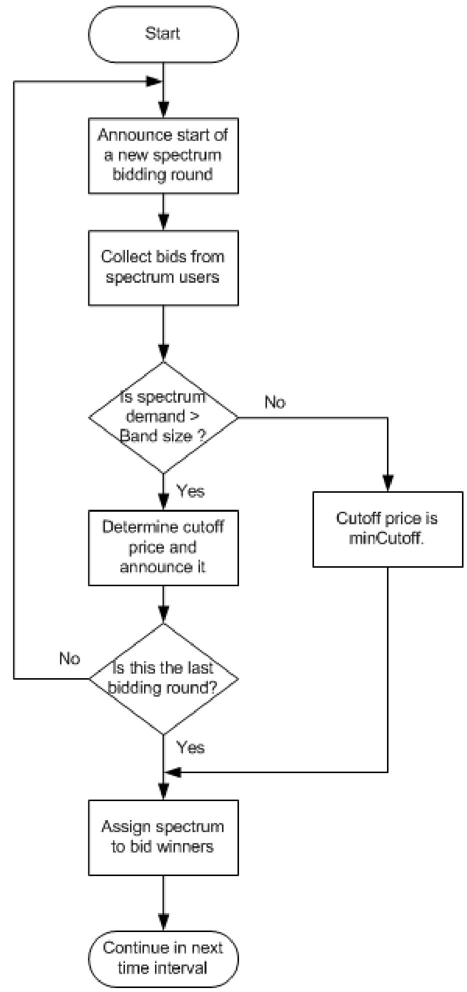

Fig 3. BM exchange behavior

D. *Market maker behavior*

The market maker provides liquidity to the market and corrects market imbalances. Following [13], we considered a reactive market maker that only intervenes when there are no entities in the buying side or on the selling side of the market with the objective of keeping the market alive and more liquid. The market maker (MM) has an initial inventory of BBUs assigned to it, and it uses that inventory to ensure that a bid-ask spread exists at all times in the market. When its inventory is exhausted, it stops making the market. When the market maker cannot act in the market, there will be unattended traffic capacity for at least one SU 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.

E. Regulator agent

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.

Further details on the behavior of these agents and their implementation in the SPECTRAD tool developed for this work are available in [7].

V. Experimental design and results

We make use of SPECTRAD and the agent behaviors specified in Section IV to simulate several market scenarios and determine the conditions for viable spectrum trading markets. Different market scenarios were simulated by varying the values of the amount of tradable spectrum in the market (*S*), the number of spectrum users present in the market ($numSU$), the type of market exchange used (NOBM or BM) and the distribution of spectrum users' valuations of spectrum (users with low valuations can only pay low prices for spectrum, those with high valuations can pay higher prices). The variation of the amount of tradable spectrum (in BBU) 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]. For all scenarios, when ***R*** is equal to 10, on average every spectrum user has enough spectrum to serve its average traffic requirement value. 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 3 lists the characteristics of the full-factorial experimental design for the market scenarios that were simulated. 100 runs for each scenario were performed in order to get statistically meaningful data. Each run was executed for 5000 time ticks of which 3000 were used for the warmup period. Data was collected on the last 2000 time ticks.

TABLE III
Parameters for modeled market scenarios

<table>
<tr><th>Parameter</th><th>Values</th></tr>
<tr><td>Number of spectrum users (numSU)</td><td>4, 5, 6, 10, 20, 50
(For NOBM scenarios, this number includes one market maker)</td></tr>
<tr><td>Distribution of spectrum users' valuation level (L) The table indicates proportion of spectrum users at a given valuation level</td><td><table>
<tr><th>User Dist</th><th>Low</th><th>Med.</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) Values indicate the number of BBUs available for trading</td><td>5*numSU, 10*numSU, 15*numSU, 20*numSU, 25*numSU.
The amounts of spectrum where chosen for each value of numSU in order to have
R=$\left(\frac{S}{numSU}\right)$ 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>

A. Results for NOBM scenarios

In order to determine the viable NOBM markets, we developed decision criteria to classify the behavior of a particular factor in a market as desirable/acceptable (positive) or undesirable/unacceptable (negative). Additionally, in order to keep track of the aggregate behavior characteristics of a market we associated a score value to each factor. It is positive when the market complies with the desired behavior characteristic or negative when it complies with the undesirable behavior. Based on the total scores for a market's characteristics, a final list of viable markets was determined. Most of the threshold values that determine whether a market's factor value should be considered acceptable or unacceptable were derived from the simulation data. Table 4 summarizes the criteria to be used to evaluate and give scores to the different NOBM scenarios studied in this work. Factors such as the percentage of completed market runs were given more weight than other factors given their relative importance in the determination of viability characteristics (sustainability in this case).

The scores for the simulated scenarios based on the viability criteria are summarized in figure 4. Only scores for user valuation distribution 1 are shown since the scores for the scenarios with other distributions are very similar. The NOBM markets that can be considered viable are those with scores

TABLE IV
Criteria for NOBM scenario evaluation

ID	Factor	Pass (P)	Fail (F)	Score P/F
C1	Percentage of completed market runs	≥70%	≤50%	2/-2
C2	Relative bid-ask spread (this is an indicator of liquidity in the market [9])	≤20%	≥50%	1/-1
C3	Mid-point BBU price (price at the mid-point between *minAsk* and *maxBid*)	≥100	≤25	1/-1
C4	Relative difference of the MM's inventory to its reference level	≤25%	≥100%	1/-1
C5	Percentage of spectrum being offered for sale	N/A	≥38%	0/-1

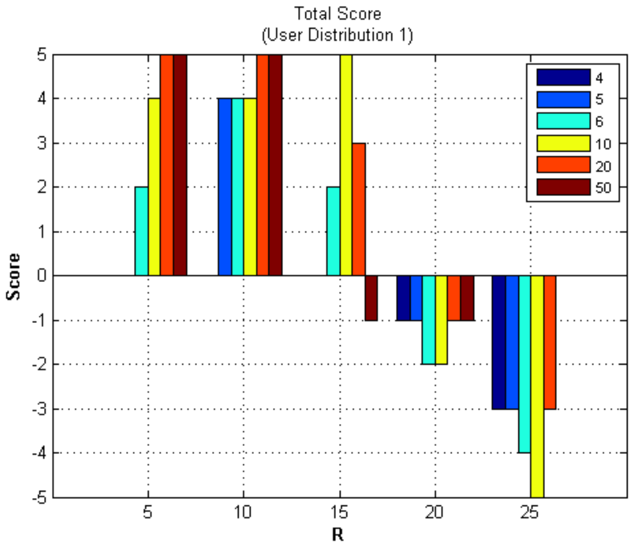

Fig. 4. Scores for NOBM market scenarios

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

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" value 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 greater than or equal to 6, most NOBM spectrum trading markets will be viable.

B. *Results for BM scenarios*

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. In a similar manner to the development of viability criteria for NOBM markets, we developed decision criteria and a scoring scheme to determine the viability of BM markets. Most of the threshold values that determine whether market factor values should be considered acceptable or unacceptable were derived from the simulation data. Table 5 summarizes the criteria to be used to evaluate and give scores to the different BM scenarios studied in this work.

Using the viability criteria, the scores for the simulated scenarios are summarized in figure 5.The viable BM markets can be considered those with scores greater or than 0 since

TABLE V
CRITERIA FOR BM SCENARIO EVALUATION

ID	Factor	Pass (P)	Fail (F)	Score P/F
C1	Probability of empty bid list	= 0	> 0	1/-1
C2	Probability that demand is greater than supply	≥10%	< 1%	1/-1
C3	Average cutoff price	N/A	< 51	0/-1
C4	Percentage of assigned spectrum	≥62%	≤62%	1/-1
C5	Average number of AT's per SU	N/A	≥10	0/-1

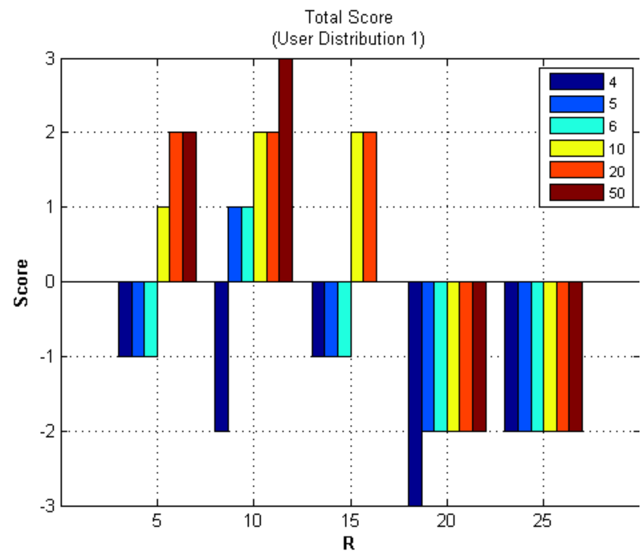

Fig 5. Scores for BM market scenarios

these scenarios do not meet many of the undesirable criteria, additionally all viable scenarios have a percentage of assigned spectrum > 62%.

The largest grouping of viable scenarios satisfy the conditions that $5 \leq \boldsymbol{R} \leq 10$ and have a number of users 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 $5 \leq numSU \leq 50$.

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.

C. *Viability implications from NOBM and BM scenarios*

From the viability conditions identified for NOBM and BM scenarios we can make the following observations:

Number of market participants for NOBM scenarios: NOBM scenarios require more than 6 market participants (SUs) and no excessive spectrum oversupply in order to be viable. Regulators that want to implement ST markets should be aware of this critical level of required market participation. As the barriers to obtain spectrum are lowered, it should be expected that new wireless services providers will appear and become potential participants in ST markets. Thus having more than 6 SUs in a given geographic area could be feasible.

Characteristics of the market maker: When defining the rules for the operation of market makers, regulators should understand that even simple market makers can provide adequate liquidity in a ST market. Since a market maker does not make use of its spectrum holdings to provide communication services, 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.

Viability in BM scenarios: 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.

Behavior trends are independent of user's valuation distribution: Behavior trends for all markets analyzed are the same independently of the distribution of user's valuation levels. 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 distributions used in this work, we can say that market behavior was not affected by them.

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 only when n*umSU* is less than 5.

Spectrum efficiency analysis: Figure 6, illustrates the spectrum efficiency for NOBM and BM scenarios. 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

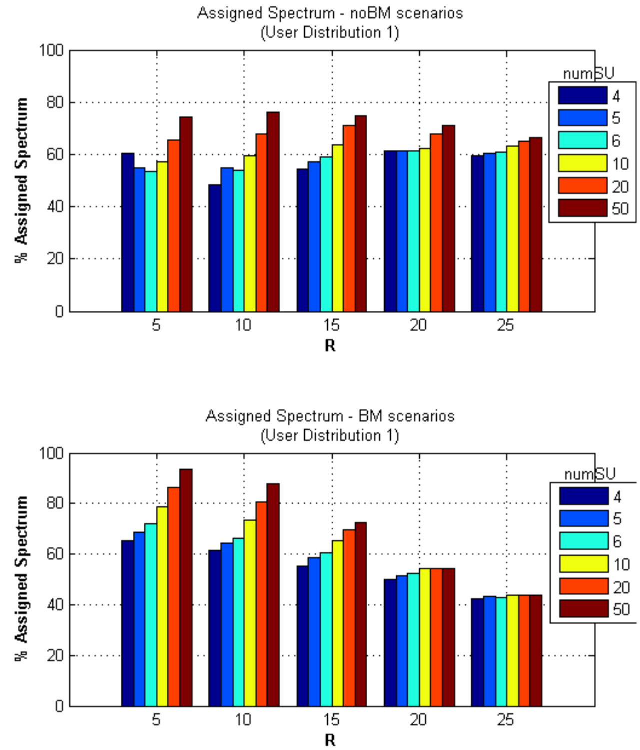

Fig. 6. Spectrum efficiency for NOBM and BM scenarios

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.

Number of users in a viable ST market: 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 $5 \leq \boldsymbol{R} \leq 10$. 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 spectrum undersupply conditions better than BM markets. In general, BM markets are more sensible to spectrum oversupply and undersupply conditions than NOBM markets.

VI. Conclusions

Spectrum trading can be used to move the current wireless market structure to support further flexibility in spectrum allocation and assignment. Our results can help policy makers and wireless service providers (future and current) to understand the required conditions for implementing spectrum trading markets so that they are economically viable.

We have shown that these markets can be viable in a service area if sufficient numbers of market participants exist and the amount of tradable spectrum is balanced to the demand. The dynamics of spectrum trading market could interest entities not traditionally involved in the use of 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 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. In general, unless barriers to the acquisition of spectrum are lowered enough to obtain sufficient market participants (6 or more) in a service area spectrum trading will not be viable.

Identifying an appropriate frequency band to promote spectrum trading or to facilitate the entry of new market participants will be a key challenge for regulators and researchers. Additionally, determining an adequate balance of tradable spectrum to demand will also be challenging and could be approached by developing useful (and observable) proxies that enable regulators to estimate how well markets are behaving.

An important byproduct of our research is demonstrating how ACE can be applied to the study of telecommunication markets. The methods and tools we have employed can be extended to the study of other telecommunications markets or scenarios where policy and regulatory frameworks determine the limits of the adaptive behaviors of the participants in a market.

References

[1] M. A. McHenry, "NSF Spectrum Occupancy Measurements Project Summary," Shared Spectrum Company, 2005.

[2] J. Scott Marcus, L. Nett, Mark Scanlan, Ulrich Stumpf, Martin Cave, and G. Pogorel, "Towards More Flexible Spectrum Regulation," in http://www.bundesnetzagentur.de/media/archive/4745.pdf., 2005.

[3] C. Caicedo and M. Weiss, "An Analysis of Market Structures and Implementation Architectures for Spectrum Trading Markets," in Telecommunications Policy Research Conference (TPRC 2008) George Mason University, 2008.

[4] L. Tesfatsion, "Agent-Based Computational Economics: A Constructive Approach to Economic Theory," Handbook of Computational Economics, vol. 2, pp. 831-880, 2006.

[5] K. Boer-Sorban, De Bruin, Arie and Kaymak, U., "On the Design of Artificial Stock markets," in ERIM Report Series No. ERS-2005-001-LIS, 2005.

[6] A. Tonmukayakul and M. Weiss, "A study of seconday spectrum use using agent-based computational economics," Netnomics, vol. 2008, pp. 125-151, 2008.

[7] C. E. Caicedo, "Technical Architectures and Economic Conditions for the Viability of Spectrum Trading Markets," in School of Information Sciences: Dissertation - Ph.D. in Information Science, University of Pittsburgh, 2009.

[8] C. Caicedo and M. Weiss, "Spectrum Trading: An Analysis of Implementation Issues," IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN 2007), 2007.

[9] L. Harris, Trading and Exchanges: Market Microstructure for Practitioners: Oxford University Press, USA, 2003.

[10] M. J. North, E. Tatara, N.T. Collier, and J. Ozik, "Visual Agent-based Model Development with Repast Simphony," in Agent 2007 Conference on Complex Interaction and Social Emergence Argonne National Laboratory, Argonne, IL (USA), 2007.

[11] M. J. North, T.R. Howe, N.T. Collier, and J.R. Vos, "Repast Simphony Runtime System," in Agent 2005 Conference on Generative Social Processes, Models and Mechanisms Chicago, IL, 2005.

[12] C. Preist, "Commodity trading using an agent-based iterated double auction," in International Conference on Autonomous Agents, 1999, pp. 131-138.

[13] M. B. Garman, "Market Microstructure," Journal of Financial Economics, vol. 3, pp. 257-275, 1976.

[14] Federal Communications Commission, "Report and Order - Facilitating Opportunities for Flexible, Efficient and Reliable Spectrum Use Employing Cognitive Radio Technologies." vol. ET Docket No. 03-108, 2005.

[15] Ofcom, "Spectrum Trading Consultation," available at http://www.ofcom.org.uk/consult/condocs/spec_trad/spectrum_trading/, 2003.

[16] Federal Communications Commission, "Promoting Efficient Use of Spectrum Through Elimination of Barriers to the Development of Secondary Markets (Report and Order and Further Notice of Proposed Rulemaking)." vol. WT Docket 00-230, 2003.