Spectrum Markets and Sharing via Spectrum Consumption Models

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I. Introduction

Wireless communication services and associated applications rely on the use of radio frequency resources for their operation. Due to the growth in the use of these services, spectrum management agencies and wireless service providers are determining ways to establish flexible spectrum assignment mechanisms as a means to respond in the near future to the demand for spectrum resources. The regulatory, technological and economic changes that are now driving the wireless services industry will spawn new technical and business models in wireless service provision and spectrum management practices, many of which will rely on Dynamic Spectrum Access (DSA) methods to enable efficient use of spectrum resources. However, the use of DSA methods also requires using policy-based mechanisms in radio devices to facilitate and control the assignment of spectrum given the wide range of communication scenarios in which there may be conflicting goals for the use of this resource (e.g. public safety vs. profit-based services).

Spectrum consumption modeling (SCM) attempts to capture spectral, spatial, and temporal consumption of spectrum of any specific transmitter, receiver, system, or collection of systems (Stine and Schmitz 2011). The information contained in the models enable better spectrum management practices and allows for the identification of spectrum reuse opportunities. The characteristics and structure of spectrum consumption models are being standardized within the newly formed IEEE P1900.5.2 group in which the authors participate.

This paper presents and discusses how SCM can be used to enable spectrum sharing and our initial research in establishing the techno-economic basis for the use of SCM in spectrum trading markets. We focus on exchange based spectrum trading markets where the entities wanting to use spectrum resources (e.g. wireless service providers) make use of SCMs to express the characteristics of the spectrum they desire to use. Then, based on these SCM, a spectrum exchange entity can determine the range of frequencies within the service area that can satisfy a particular requesting entity's demand and the charge that it should pay. We hope that the results and insights of this paper are of use to regulators and policy makers and that it provides them an initial exposure to the potential uses of Spectrum Consumption Models and policy-based spectrum management.

The paper is structured as follows: Section II describes the operation and structure of spectrum trading markets, section III explains the main concepts related to the structure of spectrum

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consumption models and their practical use. In section IV we provide a description of the use of SCMs for spectrum sharing and its integration with Policy-based spectrum management which in section V is extended to describe the use of SCMs in spectrum trading. Section VI mentions the conclusions and future perspectives for this work.

II. Spectrum Trading Markets

The radio frequency spectrum is a highly regulated resource whose management in most countries is usually deferred to a government agency. Currently, a large part of the usable spectrum is not used efficiently and has low average occupancy values (McHenry et al. 2006). 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 socio-economic benefits. Thus, rigid spectrum management policies are in part to blame for creating an artificial spectrum scarcity and new mechanisms to improve spectrum use efficiency need to be found. (McHenry 2005; Qing and Sadler 2007, 79-89).

In addition, the growth in demand for existing services and the emergence of new technologies and uses for spectrum place increasing demands on this resource, which make the management of spectrum increasingly difficult for regulatory agencies. In particular, the traditional command and control model for managing spectrum makes it difficult for entities that use spectrum (i.e. wireless service providers) to share or trade spectrum. This is especially problematic when sharing can increase the use of a band of frequencies (Bazelon 2008). Likewise it impedes quick reaction to variations in traffic demand (Burgkhardt et al. 2009, 363-367). Thus, mechanisms that enable dynamic spectrum assignment have to be put in place to adjust to a wireless landscape that requires more flexibility and to achieve the best usage of spectrum possible under economic or social objectives (NSF 2010).

Models and methods to provide flexible spectrum assignment make use at some degree of software defined radio (SDR) or cognitive radio (CR) concepts and range from opportunistic spectrum access based on Dynamic Spectrum Access (DSA) mechanisms to license-based access through the use of spectrum markets (Qing and Sadler 2007, 79-89; Buddhikot 2007; Maharjan, Zhang, and Gjessing 2011, 33-51; Yoon, Hwang, and Weiss 2010). Opportunistic access relies on DSA methods to identify spectrum opportunities and to exploit spectrum availability. However, it also needs adequate regulatory policy to support its operations. The purpose of well-designed opportunistic access mechanisms is to provide sufficient benefit to secondary users while protecting spectrum licensees (primary users) from interference (Qing and Sadler 2007, 79-89). In contrast, market-based spectrum assignment mechanisms rely on license transfers or leases which can be established through many different market structures (Caicedo and Weiss 2009; Caicedo Bastidas 2009).

Spectrum markets would promote a more competitive communications environment lowering barriers of entry to service provision for new companies/enterprises and facilitating the introduction of new services (Berry, Honig, and Vohra 2010, 146-155; Bae et al. 2008). A spectrum market would allow efficient and flexible allocation of spectrum according to demand

and create incentives for the development of new types of radio systems (Berry, Honig, and Vohra 2010, 146-155; Bae et al. 2008). Due to their benefits, regulatory policy efforts to facilitate spectrum markets are being implemented in several countries (Mayo and Wallsten 2010, 61-72; Ofcom 2011; Webb 2005, 32-35; Olafsson, Glover, and Nekovee 2007, 52-63; Marcus 2010, 7-7). However, these efforts still impose regulations that limit the types of trades allowed in the market and the use given to traded frequencies. The development of spectrum markets for wireless service provision will require a well-integrated regulatory and market operation framework. This framework should be adequately supported on a technological infrastructure which must include mechanisms to prevent anti-competitive behavior, avoid burdening market operations with high transaction costs, promote spectrum use efficiency, and guarantee a sustainable market that can provide benefits to its participants (Cave and Webb 2011; Cave, Doyle, and Webb 2007; Caicedo and Weiss 2007, 579-584; Ofcom 2003).

Spectrum trading (ST) is a market-based mechanism where buyers and sellers determine the assignments of spectrum and its uses. Trading transactions are initiated by an entity that holds spectrum and that wants to sell some of it. Once a buyer is found, and the financial transaction is completed, the new owner gains the spectrum usage rights. ST provides a mechanism whereby regulators can address the allocation and assignment aspects of spectrum management. This mechanism is also of interest to wireless service providers as the flexibility in spectrum resource management/acquisition offered by ST can provide economic benefits to them (Caicedo and Weiss 2007, 579-584; Caicedo Bastidas 2009; Olafsson, Glover, and Nekovee 2007, 52-63).

Figure 1 shows a basic spectrum trading scenario based on the use of a spectrum exchange. The exchange collects the offers to sell and offers to buy (bids) for spectrum, determines the winning bid (through a continuous double-auction mechanism for example), and transfers the right of use from the seller to the new owner of the right (Harris 2003; Caicedo and Weiss 2007, 579-584). Other spectrum trading scenarios can have the exchange acting as a band manager just allowing trades in the form of leases on the set of frequencies it manages (Caicedo Bastidas 2009). In general, the rules and behaviors governing the market structure along with any regulatory policy limitations will influence the technical and economic benefits achievable in a market-based spectrum management environment (Caicedo and Weiss 2011, 46-52).

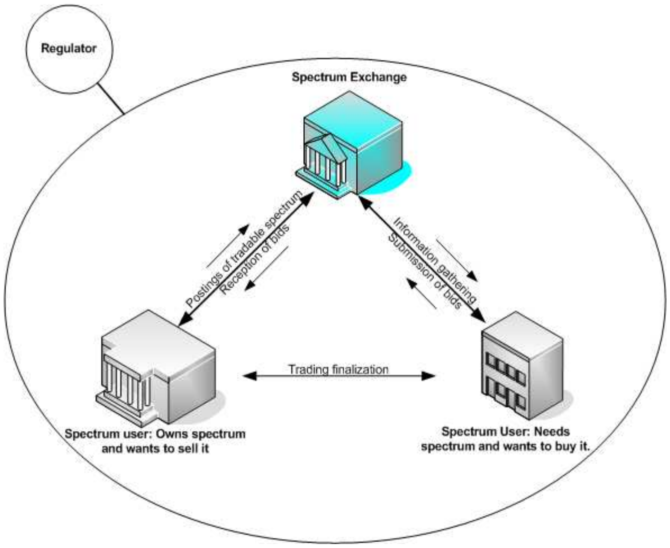


Figure 1. Spectrum Trading Scenario

Spectrum as a traded item is different than the trading of traditional commodities since spectrum use has a geographical area specificity which allows for its reuse in other areas. Spectrum cannot be stored in a traditional way (box, container, etc.) and interference from other radio frequency sources/users can diminish its value. In general, the objective of any market-based spectrum assignment mechanism like spectrum trading is to maximize the revenue of the entities participating in a trade while enhancing the use and delivery of services in the traded spectrum.

For economically-driven dynamic 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 (Caicedo and Weiss 2008). To understand the organization of and interactions in a ST market we need to know what entities participate in such a market. We will focus on the exchange-based spectrum trading markets. A description of the entities that participate in these markets and some of their functions is provided below:

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 to obtain financial compensation.
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 their own use or for speculation.
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 while keeping trading entities anonymous.
Spectrum regulator: Government entity that oversees the ST market and defines the regulations for its operation.
Market makers: A market maker is an entity that facilitates trading. It does not provide services with its inventory. It obtains revenue through the spread between ask (sell) and bid (buy) prices for spectrum, and holds a spectrum inventory for negotiating and speculating.

Spectrum exchanges can be categorized based on their technical structure and market functionality as mentioned in (Caicedo and Weiss 2011, 46-52). This spectrum exchange classification generates four types of spectrum exchanges which can be used to implement a ST market. Their characteristics are listed in Table 1. From a technical perspective, a spectrum exchange acts as a pooling point (POOL) if it is capable of acting as the point from where the delivery of wireless services in the spectrum acquired by a buyer is configured and managed. In contrast, a non-pooling point exchange (NOPOOL) only awards an authorization for use of spectrum to the buyer that is participating in a spectrum trade. The new owner of spectrum can then proceed to use the spectrum through its own wireless transmission/reception devices.

In terms of market functionality, a spectrum exchange can be a band manager (BM) for a given segment of spectrum over a geographical region or have no band manager functionality (NOBM). When the exchange operates as a BM, the exchange assigns timed leases for spectrum within the band of frequencies it manages. A NOBM exchange will establish trades of spectrum units (channels, or sub-carriers, etc.) among entities in the market without holding any spectrum itself. The traded units could come from non-contiguous segments of spectrum depending on

Table 1. Spectrum exchange classification

Exchange type	Characteristics
Type I (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 and it assigns/leases it to potential users. • All tradable spectrum returns to the exchange after the end of the assignment/lease period.
Type II (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
Type III (NOPOOL_BM)	*Non-pooling point + band manager functionality* • All tradable spectrum is held by the exchange and it assigns/leases it to potential users. • All tradable spectrum returns to the exchange after the end of the assignment/lease period. • Exchange grants authorizations for use of spectrum (no equipment configuration is done by the exchange)
Type IV (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

when and from where they are put into the market by prospective sellers. In either type of exchange, the spectrum assignment decisions are based on the objectives of the policies governing the technical and economic operation of the exchange which can affect the number of participants in the market and the level of trading activity.

III. Spectrum consumption models (SCM)

SCMs capture the boundaries of radio frequency (RF) spectrum use by devices and systems of devices. These models enable Model-Based Spectrum Management (MBSM), which is spectrum management executed through the creation and exchange of SCMs. MBSM allows distribution of the spectrum management problem where spectrum users can model their use of spectrum independent of other users and place those models in a MBSM system where common algorithms arbitrate compatibility. These models are machine readable and so serve as a means to convey RF spectrum use policy to devices. SCMs could be a core technology of any future national Spectrum Access System (SAS) such as the one recommended in (PCAST 2012). With such a system, SCM will allow spectrum segments to be combined, subdivided, shared or traded. Spectrum market interactions would use SCM to capture the characteristics of the quanta of spectrum that are traded. The market coordinating entities (i.e. exchanges) would also use the methods of MBSM to communicate spectrum availability and requests and to arbitrate the compatibility of proposed uses.

SCMs were conceived to be a loose coupler in spectrum management. Loose coupling refers to an element that exists at the intersection of a large set of systems that allow them to interoperate and to be integrated. When identified and placed between the layers of complex systems, a loose coupler has a nearly boundless ability to support innovation. A couple of well-known systems serve as examples. The first is the electrical power system. The loose coupler is the specification for power distribution at the user end: frequency, voltage, and interface definition. This standardized coupler then allows innovation at two ends, power generation and electrical appliances and tools. There is no constraint to development of means of generating power so long as it can be converted into the frequency and voltage necessary at the end of the distribution. There is no constraint to the development of appliances and tools so long as they can accept power at the specified voltage and frequency. The second example is the Internet. The IP protocol serves as a loose coupler with the two layers being the means of data transport and the services of the internet. There can be innovation in the means to enable transport so long as the systems can accept and route IP packets and there can be innovation in the services and applications that ride the network and use the transport so long as they conform their communications to the standards of IP.

Figure 1 illustrates the loose coupling role of SCM. SCM are placed at the center of what appears as a bow tie turned on its side. At each end of the bow tie are different layers of the spectrum management system. At the top are the management systems and at the bottom are the RF devices and systems. In its loose coupling role, the SCMs capture the minimum amount of information that allows multiple management systems to communicate with each other about spectrum, for the management systems to communicate spectrum use guidance to RF devices and systems, for RF devices and systems to communicate and collaborate in the sharing of spectrum, and to communicate their decisions on the spectrum they use to management systems. To be a truly effective, loose couplers are standardized so that the developers of systems at each of the layers have confidence that external factors will not change and render their system designs and innovation irrelevant. Currently, the methods and data structures to model spectrum consumption are being standardized through the IEEE Dynamic Spectrum Access Networks Standards Committee (DySPAN-SC) Work Group 1900.5 in the project P1900.5.2.

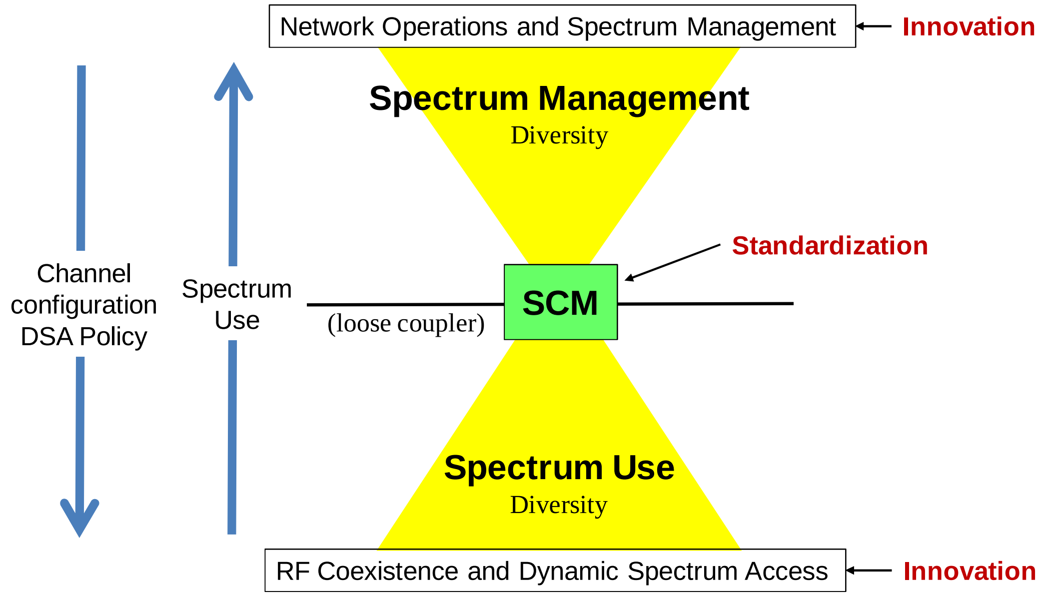


Figure 2. Bowtie diagram with SCM as the loose coupler revealing the layers of innovation and the central role of SCM

There are two key objectives in standardizing spectrum consumption modeling: capturing the boundaries of spectrum use in all of its dimensions and defining how to arbitrate the compatibility of SCMs. It is necessary that their development occur simultaneously. The methods of modeling must support tractable and efficient algorithms for arbitrating compatibility.

SCMs consist of several construct elements that collectively capture spectrum use boundaries. The current methods of modeling use the 12 construct elements listed below.

1. Total Power: The power at the transceiver to which values of the spectrum mask, underlay mask, and power map reference. It is typically modeled as the total power that drives the antenna of a transmitter or a reference for the total power received after the antenna at a receiver.
2. Spectrum mask: A variable sized data structure that defines the relative spectral power density of emissions by frequency. Figure 3 illustrates an example of this construct element.
3. Underlay mask: A variable sized data structure that defines the relative spectral power density of allowed interference by frequency. Figure 4 illustrates an example of this construct element.
4. Power map: A variable sized data structure that defines a relative power flux density per solid angle. Power maps capture antenna effects and some environmental effects.
5. Propagation map: A variable sized data structure that defines a path loss model per solid angle.
6. Intermodulation mask: A variable sized structure that defines the propensity of co-located signals to combine in nonlinear components of an RF system and be emitted by a transmitter or be received in the later stages of a receiver.
7. Platform Name: A list of names of platforms that a particular system is located. These names are used to identify when multiple systems are co-located and could suffer IM and out-of-band interference issues.
8. Start time: The time when the model takes effect.

9. End time: The time when the model no longer applies.
10. Location: The location where a component may be used. A location may be a point, a volume, a trajectory or orbit.
11. Minimum power spectral flux density: A power spectral flux density that when used as part of a transmitter model implies the geographical extent in which receivers in the system are protected.
12. Policy or protocol: A named protocol or policy with parameters that define behaviors of systems that allows different systems to be co-located and to coexist in the same spectrum.

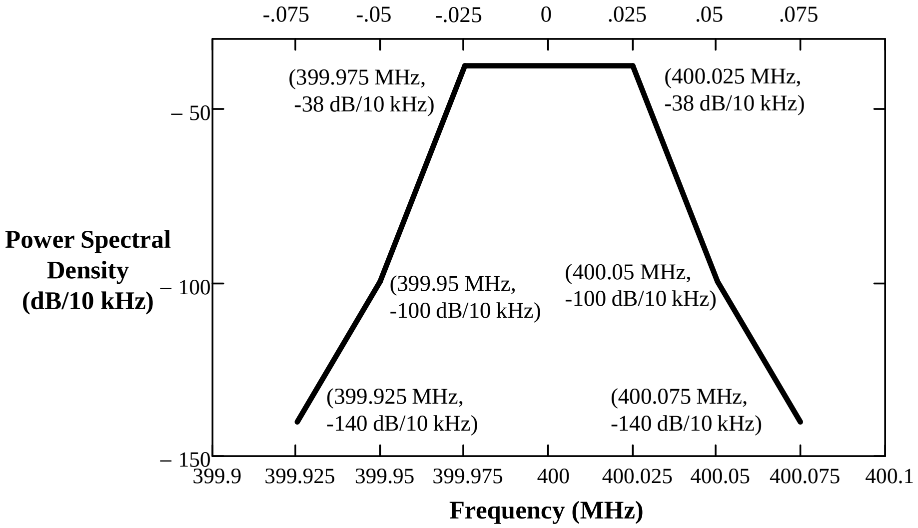


Figure 3. Spectrum masks such as this one convey the power spectral density of a signal as a function of frequency

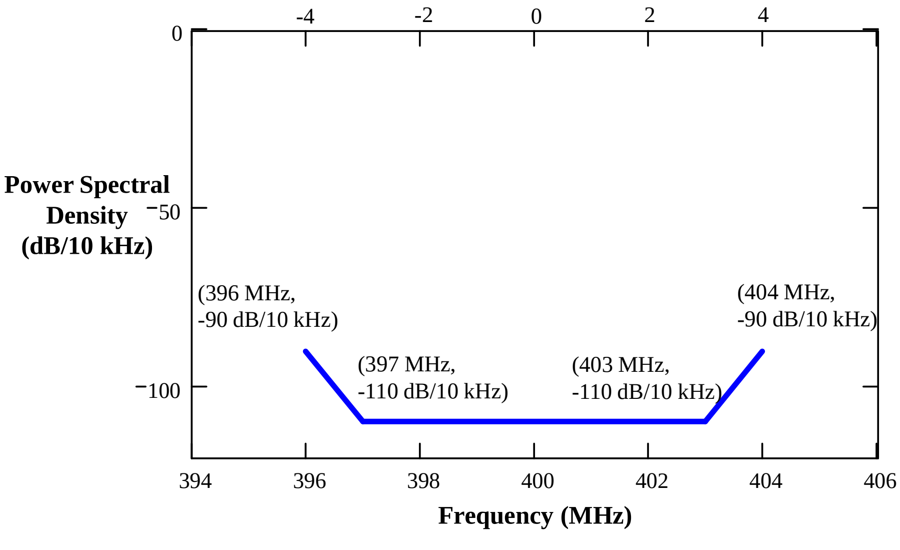


Figure 4. Underlay masks such as this one convey the power spectral density of signals that a receiver can tolerate

SCMs consist of component models of transmitters and of receivers. Transmitter models attempt to convey the extent and strength of RF emissions. The essential construct elements that must be part of a transmitter model are a total power, a spectrum mask, a power map, a propagation map, and a location. Radio frequency emissions can come from anywhere in the space identified by the location construct element. From those locations, the total power, spectrum mask, and power map define the strength of the emission at the source (see Figure 5). The propagation map defines the rate of attenuation of those signals as they propagate away from the transmitters. Figure 6 illustrates an example of a propagation map.

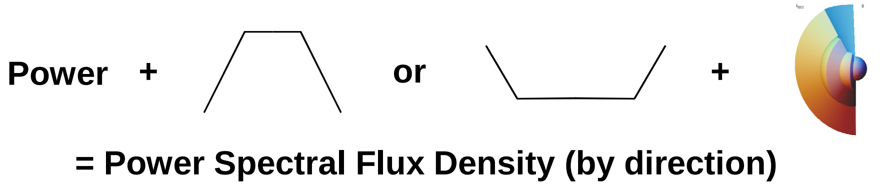
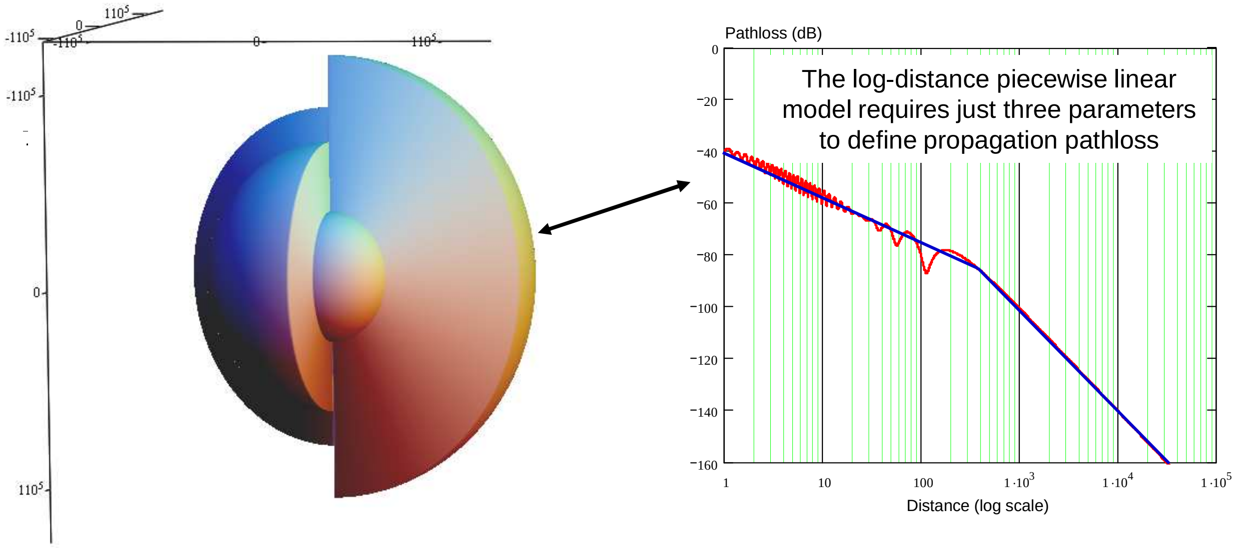


Figure 5. The total power, spectrum mask and power map of a transmitter model convey the power spectral flux density after the antenna of a transmitter and the total power, underlay mask, and power map of a receiver model convey the power spectral flux density of the allowed interference before entering the receiver's antenna

Receiver models attempt to convey what is harmful interference. The essential construct elements that must be part of a receiver model are a total power, an underlay mask, a power map, a propagation map, and a location. A receiver can be anywhere in the space defined by the location construct element. There are three differences in receiver models as compared to a transmitter model. It requires an underlay mask rather than a spectrum mask, the construct elements define the allowed strength of an interfering signal at the receiver rather than the strength of transmission, and the propagation model parameters of the propagation map define the rate of attenuation to be used in computing the attenuation of a potentially interfering signal.



The log-distance piecewise linear model requires just three parameters to define propagation pathloss

Figure 6. The propagation map conveys a concise propagation model for all directions chosen by the modeler

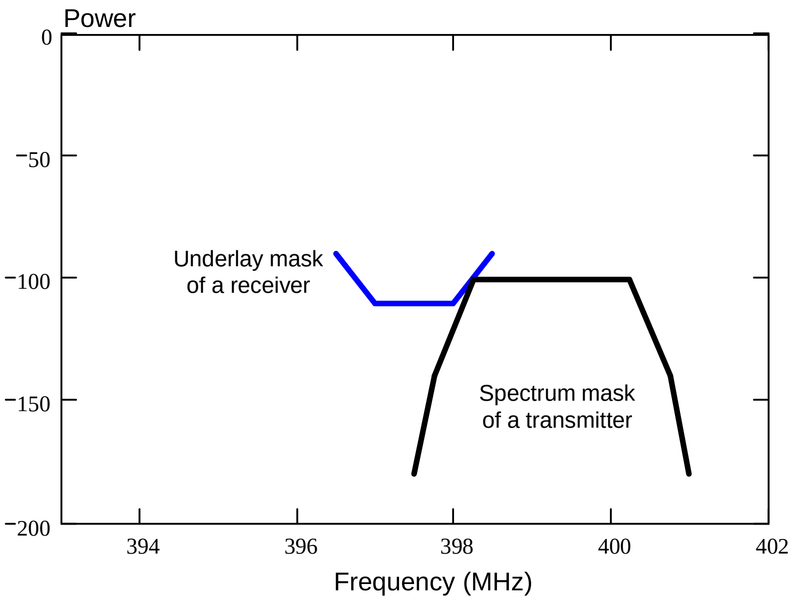


Figure 7. Compatibility between a transmitter and a receiver occurs when the propagation pathloss attenuates the transmitter power spectral flux density so that the interference it causes is beneath that specified by the receiver model

These multidimensional models establish boundaries of spectrum use between systems through the interaction of the transmitter model of one and the receiver model of the other and vice versa. Models capture the contribution of the particular characteristics of transmitters and receivers in defining spectrum consumption. Spectrum is consumed by both transmitters and receivers. Spectrum is consumed by the systems of an entity to the extent that its transmitter model(s) precludes the modeled receivers of another entity from operating and to the extent that its receiver model(s) precludes the modeled transmitters of other entities from operating. The spatial extent of consumption is determined by identifying the boundary of compatibility beyond which the secondary must operate. Thus, spectrum consumption is as dependent on the modeled characteristics of the secondary as it is on the primary.

Modeling is artful and so it is feasible to model the same boundaries in multiple ways thus modelers can model in ways that obfuscate sensitive classified or proprietary aspects of spectrum use. This ability removes one of the more significant barriers to spectrum sharing.

The details of modeling have been described in (Stine and Schmitz 2011) which includes the definition of an Extensible Markup Language (XML) for spectrum consumption modeling called Spectrum Consumption Modeling Markup Language (SCMML). The SCMML supports the modeling of transmitters and receivers individually, the combining of multiple transmitter and receiver models into a system model, and then the combining of multiple system, transmitter, and receiver models into a collection. Collections are used to convey spectrum use, availability, policy, and authorizations. The SCMML schema can be combined with other schema for the creation of trading transaction documents. The additional schema would define the contractual data elements required for trading.

SCMs may be used to convey spectrum availability and proposed use. An owner of spectrum can convey the availability of a portion of spectrum it controls in two ways. It can create a model of a spectrum use where any new use that can be contained within the model is permitted. It is assumed that the owner creates this model to preclude interference with itself and to be compliant with their own spectrum license. This same owner may also provide a model of permissible use together with a list of constraining models. In this case, a secondary user may operate within the bounds of the authorizing model so long as its use does not interfere with any of the provided constraining models.

Thus, SCM and the systems that are built around SCM would provide sufficient information to enable spectrum sharing and spectrum trading interactions. Further, the very definition of SCM creates the means to make spectrum a resource with characteristics close to those of a commodity that can be efficiently managed and traded. The current most comprehensive description of spectrum consumption modeling can be found in (Stine and Schmitz 2011). When completed, the standard of DySPAN-SC Project 1900.5.2 will be the definition for SCMs.

IV. Spectrum Sharing with SCM

As previously stated, MBSM is spectrum management based on the creation and exchange of SCM. SCM were developed so that tools can automatically assess the compatibility of any two models. Preliminary computations for compatibility determine whether the models overlap in time and in spectrum. If so, then the models are checked to determine if they interfere with each other. Given the location of a victim receiver and an interfering transmitter the computation of compatibility follows the procedures described in Figures 5, 6, and 7.

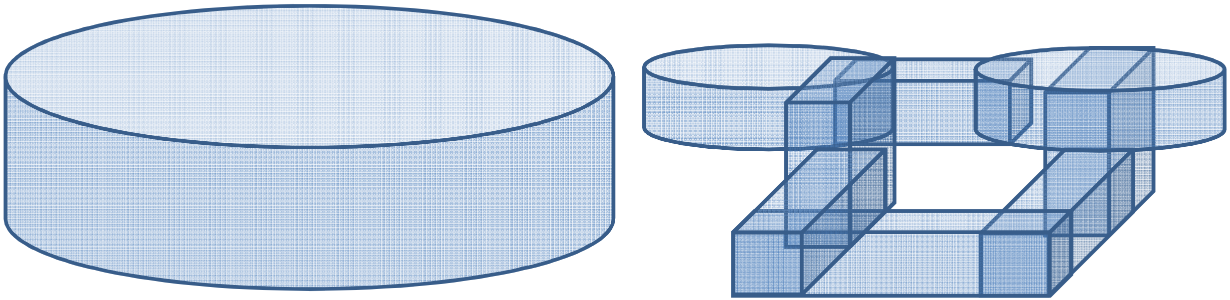
Although seemingly simple, actual computations are more complex. Rather than single points for a victim receiver and interfering transmitter, there are geographical areas within which they may be located and so it is necessary to determine the worst case placement of these two in their operational areas before computing whether they are compatible or not. Determining the worst case placement is made more complex if there are directional differences in transmission power and path loss. Additionally, rather than there being just two systems there may be multiple systems competing for the same spectrum and so a series of pairwise assessments may be necessary.

Given the ability to compute compatibility between models, other functions may be added to the management system. For example, in cases where there are channel assignment options, such as would be the case for assigning channels from a pool to a collection of networks, algorithms may be built on top of the compatibility computations to assign channels to minimize the potential for interference among users. Given a collection of models with assigned channels, algorithms can search through these models and available channels to find the best channel to assign to a new user.

SCM provide the additional value of greater resolution in spectrum use. This resolution follows from the ability to subdivide spectrum use in time and space. Figure 8 illustrates an example. In Figure 8a, a large volume is used to capture a persistent assignment of a system's use of spectrum that is typical of today's spectrum management. It captures the whole volume of where the system may be used in all operations over a long period of time up until an assignment is changed. Spectrum reuse opportunities can be created by subdividing that volume based on actual use of the spectrum. Figure 8b illustrates the idea. Several volumes are presented. Each of these volumes would correspond to a separate period of the system's use of spectrum and would be conveyed in separate models with different start and end times. The anticipated benefit is that these smaller volumes offer opportunities for other systems to use the same spectrum that the system being modeled uses. In general, MBSM enhances the management of spectrum sharing. The ability to capture the spatial, the spectral, and the temporal dimensions of spectrum use also offers the ability to use spectrum consumption models to compute where spectrum reuse is possible. Thus, tools can use the models as a means to optimize reuse.

Spectrum sharing is also achieved through DSA. DSA refers to a collection of different technologies that allow RF systems and devices to autonomously determine which spectrum to use at the time of use rather than as a preset configuration. There are many different approaches to DSA including requesting a channel from a broker, coordinating a use with a database of existing users, selecting from a set of channels based on location, or selecting a channel based on policy that is informed by spectrum sensing. All of these techniques are guided by processes or policies that are created by humans based on their judgment of what will allow effective spectrum sharing. It is this dependence on judgment that makes MBSM well suited to support the DSA vision. Models are a means to capture the judgment aspects of spectrum consumption: where devices will be, how they will emit RF radiation, and what would constitute interference. They enable Policy-Based Spectrum Management (PBSM)

SCMs provide a bound to spectrum consumption and as such they are readily used to convey limits for spectrum use. As is, spectrum consumption modeling can be used to provide a restrictive location based policy. The models of existing users convey restrictions to new users and so a collection of models of existing users are a policy. Assuming radios are cognizant of how they use spectrum, these models provide sufficient information for a DSA system to determine the locations where they can use specific channels and the limits to their transmit power at those locations. Many of the developers of DSA systems seek more aggressive sharing



a. A large volume that captures a persistent assignment of spectrum to a system

b. The subdivision of spectrum use into smaller volumes to capture segments of a systems use in a mission

Figure 8. Using the spatial and temporal dimensions of spectrum to subdivide use into smaller volumes

where behaviors are chosen that allow compatible reuse within the very spaces of existing use. The "protocol or policy" construct element of spectrum consumption models allows SCM to provide behavioral guidance that allows finer coexistence mechanisms, e.g. using sensing and timing, in addition to location as means to achieve reuse.

Policies typically have two parts, a permissive part identifying what the DSA system may do and a restrictive part that constrains what the DSA system may do. In the case of using SCM models for DSA policy definitions, the models of incumbent users would be the restrictive part. Additional models can be used to convey the permissive part. Policies written using SCM have the advantage that their compatibility with existing spectrum users can be verified using the algorithms of MBSM.

V. Spectrum Trading and SCM

A key benefit of SCMs is that they allow spectrum trading based on the characteristics of the transmissions of the entity that wishes to use the spectrum in a given service area and the characteristics of the intended receivers within that area. These can be expressed via transmitter and receiver models using SCM constructs as mentioned in section III. Spectrum Trading with SCMs thus takes into account the interference and propagation characteristics related to the use of spectrum and allows for the use of assignment policies that take this information into account such as those mentioned in (Caicedo Bastidas et al. 2013). This capability provided by SCMs is important since not all segments of spectrum are the same due to noise, fading, and other phenomena that can affect a range of frequencies at a given moment in time and location in space. Thus, a segment of spectrum may look different to one potential user than to another.

SCMs can be used by the spectrum exchange to convey spectrum availability and proposed use. Adequate use of the SCMs would preclude interference with other users that are active in the service area. Potential spectrum buyers would then convey their requests to the exchange by providing a model of their use which would be validated by the exchange to fall within the boundaries of the SCM(s) used to convey availability. Trades would be completed by defining the SCM that establishes the boundary of allowed secondary use.

SCMs allow for a fine grained management of spectrum resources in a spectrum market. For example, instead of having spectrum assignments made to an entity where the frequencies assigned to it are not available at all for any other user entity within the service area, the details of the SCM could allow a spectrum exchange to award the same frequencies to more than one entity if the SCMs specify non-overlapping use in time and/or space within the service area. SCMs also offer a way to express and conduct spectrum trades by “pairing” the spectrum required to do transmissions from base station equipment to mobile nodes in a service area with that of the transmissions that the mobile nodes will make to the base stations (assuming full-duplex communication).

In more detail, spectrum trades using SCM would differ in their procedures depending on the type of exchange entity present in the market. For BM exchanges, the entities wanting to use spectrum resources (spectrum users) could use SCMs to express the characteristics of the way they will use spectrum and based on them the exchange can determine the range of frequencies within the service area that can satisfy the user and the charge that it should pay. However, due to the control the BM exchange has over the spectrum band in which trades can take place, it can define the transmission model or models (a discrete set of them) that buyers must agree to and specify when submitting bids for spectrum. The same rationale applies to the receiver models defined by the BM.

In a ST market based on a Non-Band Manager (NOBM) exchange, setting up a continuous-double auction environment in which the exchange can match the requests to buy spectrum with the offers to sell spectrum would be very complicated unless the sets of values for construct elements in the SCMs that are used to express the characteristics of the spectrum to buy or sell are reduced to discrete sets. The exchange could also act as an intermediary to "negotiate" the best fitting SCM parameters that can be used by a buyer of spectrum within the service area at a specific moment in time.

For NOBM and BM exchange based interactions, the requests to buy spectrum (bids) would be expressed to the exchange by the entity wishing to buy spectrum by including the following information:

- Transmission model parameters: Total power, spectrum mask, power map, propagation map, a location, start time and end time
- Reception model parameters: Total power, underlay mask, power map, propagation map, expected service area location, start time and end time
- Bid parameters: Buying price, time window over which the bid is valid

In a NOBM scenario, an ask (offer to sell), would be expressed by the entity wishing to sell spectrum to the exchange using the following information:

- SCM transmission model describing the amount of spectrum being sold, range of frequencies this amount covers and the characteristics of allowed transmissions.
- Selling price and time window over which the offer to sell is valid. The seller might have transmissions in segments of spectrum adjacent to the one he is selling so he could specify that no interference be present at the boundaries of the band and express this with an underlay mask that should be satisfied by any potential buyer of the spectrum. A SCM receiver model can convey this information.

As mentioned previously, in a BM scenario, the offers to sell would be expressed by the exchange using the following information:

- Transmission model parameters: Total power, spectrum mask, power map, propagation map, a location, a start time and an end time. One specific transmission model or a limited set of them to which spectrum buyers must agree simplifies the trade matching tasks of the exchange.
- Reception model parameters: Total power, underlay mask, power map, propagation map, expected service area location, start time and end time. One specific reception model or a limited set of them to which spectrum buyers must agree helps the exchange in limiting interference effects and making assignments.

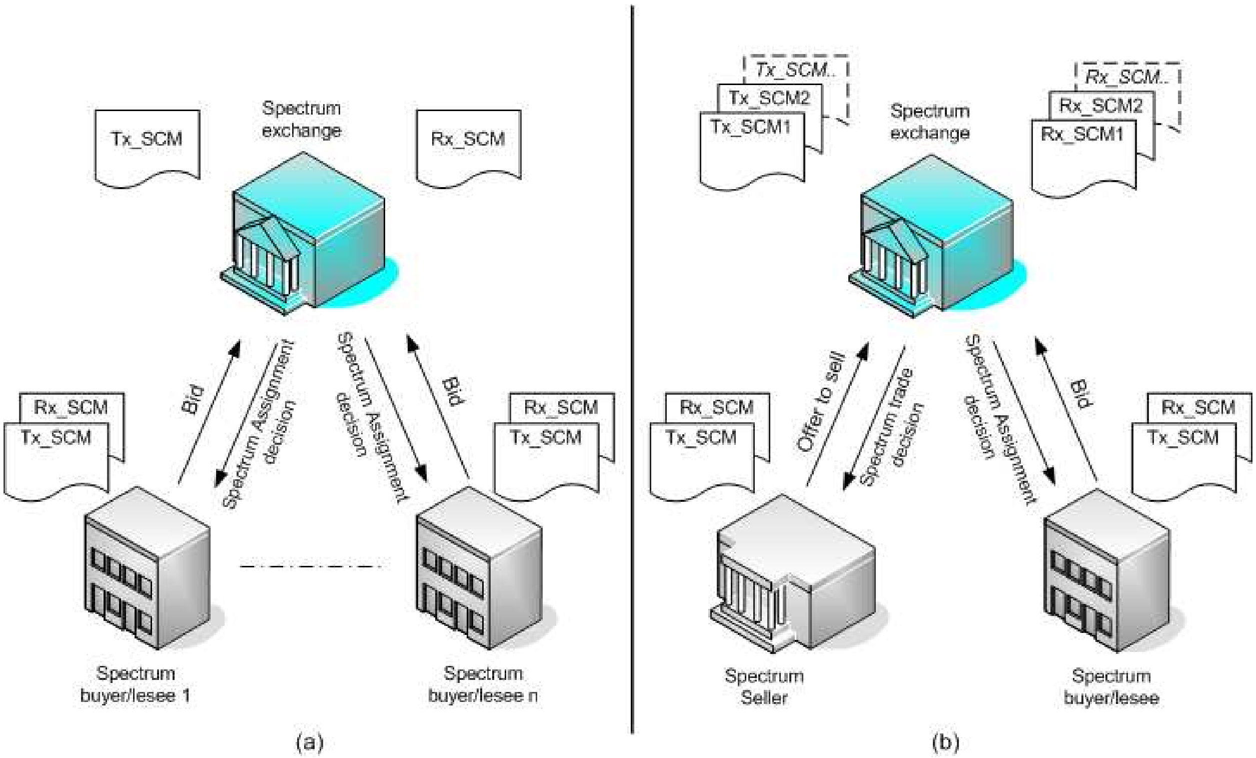


Figure 9. Spectrum trading with SCMs. (a) BM exchange scenario (b) NO_BM exchange scenario

Figure 9 illustrates some of the main interactions and information elements required for spectrum trading with SCMs. In practice, we envision that spectrum management and spectrum trading using SCM would be complemented with spectrum use sensing. While management and the establishment of trades could be based on the use of SCM and the attendant compatibility computations alone, in practice, modelers use their judgment in much of the creation of SCMs. There is sufficient unpredictability in environmental effects and in user behaviors that actual use may deviate from the SCM boundaries with no malicious intent. A system of sensors would serve to assist in the creation of SCM, to verify users of spectrum keep their use within the boundaries of their models, and to arbitrate solutions to interference when it occurs. A combination of a spectrum trading system and spectrum sensors for interference aware spectrum market environments is described in (Caicedo Bastidas et al. 2013).

VI. Conclusions and future perspectives

Spectrum markets can lower the barriers of entry to acquire spectrum, which means that with an adequate regulatory regime, business entities other than traditional wireless service providers could acquire and sell spectrum for private purposes and small time scales (i.e. a concert organizer, a shopping mall launching an event, a neighborhood association hosting a festival, etc.). This would potentially lead to new types of businesses and interactions in the wireless services area.

Entrepreneurs who develop new products or services that use spectrum would be able to enter the wireless services market and test the commercial viability of their ideas by purchasing spectrum on the spectrum trading market. Regulatory roles in this vision would change from one of admission of the new technology through regulation to one of certifying the critical constructs of the SCM that define how to compute the compatibility of the systems. This would allow new businesses to avoid the very expensive legal maneuvering of the current spectrum management system.

Although SCMs convey aspects of spectrum use that can be used in spectrum trading market interactions, the study of the economic behavior of these markets merits more research. Future work will make use of agent-based modeling techniques and economic tools to evaluate the viability and economic characteristics of spectrum trading markets that can exploit the fine-grained spectrum management/assignment capabilities offered by the use of SCMs in spectrum trading.

The standardization efforts led by the IEEE Dynamic Spectrum Access Networks Standardization Committee (DySPAN-SC) and the work of entities like the Wireless Innovation Forum are providing a common technical framework for describing policies and automating processes that will enable dynamic spectrum access interactions in future wireless service provision environments. These efforts should be complemented by developments in spectrum management regulations and policies in order to establish spectrum management frameworks that can support the requirements for spectrum resources of the near future.

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