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MITRE TECHNICAL REPORT

MITRE

Model-Based Spectrum Management

Part 1: Modeling and Computation Manual (Request for Comments)

John A. Stine and Samuel Schmitz
April 2011

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Request for Comments

This paper is being distributed as a request for comments. It is our intent to collect comments and then to update this manual by October 2011. Please send comments to jstine@mitre.org. Responding by 15 August 2011 should ensure their consideration in the next version. It is our intent that the next version will serve as a foundational document for a subsequent standardization of spectrum consumption modeling.

Abstract

Radio frequency (RF) spectrum is a finite resource that is essential to many enterprises to include those of governments, militaries, businesses, and citizens. The broad utility of RF spectrum guarantees that demand for access will not wane and is likely to increase continuously. Obtaining greater utility from spectrum is universally beneficial. However, current trends to achieve greater utility have focused on prioritizing uses to those argued to be most beneficial or most effective, getting the most out of a particular use of spectrum, as opposed to developing the means to use spectrum most efficiently, i.e. use the least amount of spectrum for a particular task. Currently, there is a concerted effort to convert over 14% of the most useful spectrum, spectrum less than 3.5 GHz, to enable greater commercial broadband access.

An alternative means to obtain more utility from spectrum to that of converting spectrum between uses is to more agilely manage spectrum and to build systems that can respond to that agile management so that uses can more effectively share spectrum. This approach can also enable greater broadband access but without compromising the various government operational, security, and public safety functions that currently occupy much of the spectrum targeted for conversion. Further, this type of technology would also mitigate many of the challenges confronted by the large users of spectrum such as the defense and intelligence communities.

This manual describes a new spectrum management approach based on spectrum consumption modeling that can enable both the agile management envisioned and the systems that can respond to that agile management. The concept is to define an approach to model spectrum consumption and then to use these models to compute opportunities to reuse spectrum, to communicate spectrum consumption among systems and to convey spectrum authorizations and policy to RF systems. Models capture the aspects of spectrum consumption that are human judgment, the knowledge not present in mere datasets of system characteristics. The vision is that a well standardized approach to modeling spectrum consumption can be used as a loose coupler among the systems that manage and use spectrum. This type of loose coupler would encourage innovation in spectrum management and innovation in RF systems to dynamically access spectrum which combined could enable the agile management and use that is sought.

Spectrum consumption modeling attempts to capture spectral, spatial, and temporal consumption of spectrum of any specific transmitter, receiver, system, or collection of systems. The details in the models of the spectral, spatial and temporal consumption provide an immediate opportunity for better management by enabling the identification of reuse opportunities. An effective spectrum consumption modeling approach achieves three objectives:

1. Provides constructs for capturing the many facets of spectrum use within models
2. Provides well defined tractable and efficient methods for computing compatibility of modeled uses.
3. Provides a means to use the models to convey both the consumption and the availability of spectrum

This manual defines a modeling approach that can achieve these three objectives. It defines a set of 12 constructs, describes how they are used to capture spectrum consumption, and describes how compatibility among models is computed. It describes how models are combined to convey system and enterprise use of spectrum, how models are used to convey spectrum availability, and how models may be used to convey policy to dynamic spectrum access systems.

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1 Introduction

Radio frequency (RF) spectrum is a finite resource that enables services that people, commercial enterprises, and governments across the world rely for safety, operations, routine communications, and entertainment. It is a necessary resource for products and services that a large portion of the technology community builds and sells. Thus, spectrum has value and there is demand and there is no indication that this demand will do anything but increase.

Unfortunately, spectrum is fully assigned to uses, primarily by a static, reservation-based methodology; and so, satisfying any particular demand requires making room either by displacing current users or by shifting or more finely managing assignments to create or find space for new uses. Current policy trends are to do the former, they seek to change assignments based on the relative value of the use. Several factors cause this preference with one being the absence of the technical means to do the latter. Model-Based Spectrum Management (MBSM) is intended to overcome this shortcoming and to provide the technical means to manage spectrum more agilely and so allow spectrum to satisfy the needs of more users and to enable users to share spectrum, effectively.[1]

Here we describe why current spectrum management (SM) approaches lack this agility and how MBSM does something different. Our story starts with a brief description of spectrum management and its mindset to find persistent and broadly applying assignments following what usually amounts to be a prolonged study. Spectrum consumption modeling is designed to reduce and in most cases eliminate the need to do these types of studies by capturing the salient features of spectrum consumption in models so that generic algorithms can compute whether uses are compatible. This in turn allows more agile management. The adoption of this modeling approach in spectrum management can further solve other technical challenges in spectrum management such as articulating and managing policy for future dynamic spectrum access (DSA) systems. This manual is written to serve as a guide to the methods of spectrum consumption modeling. This chapter concludes with an overview of the guide.

1.1 Spectrum Management Processes

Traditionally, spectrum management has been performed globally through international agreements and nationally by government administrations. Bands of spectrum are divided into allocations that are designated to support particular services. The allocations are subdivided into allotments that may be used by administrations in specified geographic areas. National administrations may further allot the spectrum into channels, specify the conditions of their use, and assign (a.k.a. license) them to users. Enterprises that have collections of assigned spectrum may further manage that spectrum internally. Most notable is spectrum used by governments and in particular within agencies of governments like defense.

Current spectrum management methods are based on persistent assignments. Persistent assignments are made accounting for the entire area of potential deployment of a system and follow from extensive review and study of spectrum compatibility with other systems. The methods of spectrum management have encouraged this deliberative approach to spectrum assignment as it is necessary to arbitrate the many competing demands for spectrum most specifically in the international arena. The scientific study of alternatives creates objectivity that

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[1] Concepts of MBSM have been presented earlier in a paper [1] and in a book chapter [2]. This presentation is an evolution of the concept of modeling spectrum consumption and so there are more constructs and in many cases the constructs in this manual differ from similar constructs described in these foundational documents.

mitigates the risk of allocations, allotments, and assignments being distributed based solely on political considerations, and can contribute to more objectively determining the potential value of spectrum. Thus, the organization of the International Telecommunications Union – Radiocommunications Sector is based on study groups. International allocations are established and changed through World Radiocommunication Conferences (WRC). Each WRC prepares an agenda for the next WRC containing proposals for changes and each of these proposals are assigned to work groups or task groups formed from the study groups. National contingents that participate in the WRC mirror this organization and administrations within nations, such as the Federal Communications Commission (FCC) and the National Telecommunications and Information Agency (NTIA) in the United States help feed the contingents with the technical information to support their national position. The deliberateness of this process permeates all organizations and the techniques and tools used to perform spectrum management worldwide. Tools and methods attempt to achieve precision in arbitrating compatibility of spectrum use.

Some effects of this deliberateness and precision in spectrum management are the loss of temporal agility in spectrum assignment and the dependence of spectrum management on data sets and computational methods that are impractical to consolidate. A case study of the problem is seen in the U.S. Department of Defense (DoD). A recent survey of spectrum management tools used in DoD identified that there were at least 46.[2] The cause of this large number of management systems is that there are a large number of RF systems that need to be managed and many involve unique tasks either because of the technical aspects of the systems, the propagation characteristics of the frequencies they use, or the operational aspects of their use. A common characteristic of these tools is that they are all designed to support making a decision: identifying spectrum assignments, namely the frequencies and transmit powers RF systems may use. The shortcomings of this approach is the absence of information in assignment decisions to inform other spectrum management tools what these assignments truly mean for other RF systems that may operate in the same RF spectrum bands. Figure 1-1 illustrates the problem. Managers use system specific data and models, models of terrain and environmental effects, and their

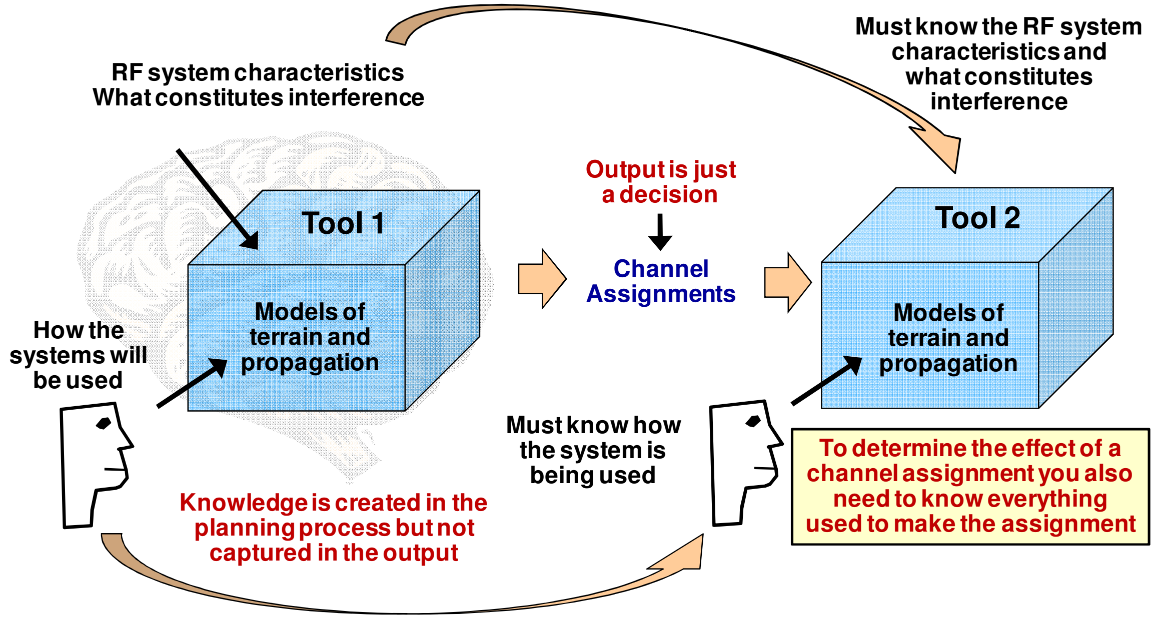

Figure 1-1. The Problem with Spectrum Management Outputs

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[2] This survey was conducted internal to MITRE and was coordinated among those supporting the spectrum management community and also various programs of record.

knowledge of the operational use of the system and other systems operating in the same bands and make a decision on what channels to assign. The knowledge created by managers in this process is lost in the output. In order for a second manager to fully understand the decision and its impact on other spectrum users there must be a transfer of data between tools, a common set of models used within the tools, and transfer of the knowledge on the RF system's use between the managers. In most cases, this is not practical either because of the sensitivity of system or use information, the challenges of integrating different computational models within the tools, or the difficulty in explaining the intricacies of the operational use of systems between users. The result is that spectrum management in the operational setting remains an activity of study and deliberate consideration where the analysis and decisions seek as persistent a solution as possible.

There are two deficiencies in the current spectrum management processes that, if fixed, can result in more agile spectrum management and consequently, more spectrum reuse. First, spectrum management seeks persistent solutions. So long as spectrum management uses persistent assignments based on prolonged study, it will be inefficient and forfeit many opportunities for spectrum reuse. Spectrum management should be a system that continuously seeks and exploits reuse opportunities. Ideally it should capture and manage the spectrum used per mission rather than just the use of spectrum by systems in general. Second, achieving this outcome requires that the decisions of spectrum management be more than channel assignments and convey the knowledge of the analysis revealing the extent of the use of the spectrum in time, frequency and space and revealing what constitutes acceptable reuse.

1.2 Objectives of Spectrum Consumption Modeling (SCM)

The objective of spectrum consumption modeling is to provide a solution to the second deficiency listed above, to capture spectrum use in a model that conveys the extent of use in time, frequency, and space and reveals what constitutes acceptable reuse. The difference in using models of spectrum consumption as opposed to data sets of system and component characteristics is the significant advancement. Given data sets of the characteristics of RF systems and components it is up to the spectrum managers to assess whether the systems are compatible. Their assessments will be based on their knowledge of the use of the systems, their judgment of what constitutes interference to a system, and the terrain, propagation, and interference models that the tools they use provide. But, in the end, the output is the same data set with the only addition being the new channel assignments. The knowledge of use, the judgment used, and the criteria for assessing compatibility is not part of the data set. This leaves the next manager the task of doing it all over again when needing to make an assessment of the same system. In contrast, spectrum consumption models attempt to capture the relevant aspects of a systems use of spectrum by modeling it. These models provide an unambiguous definition of the extent to which a system will emit radiation and what would constitute harmful interference to that system's operation. These models capture specific uses of spectrum as opposed to being general characteristics of systems as is the case with system data. They provide a means to capture and use the judgment of mission planners and spectrum managers.

Figure 1-2 illustrates the advantage of using this approach in conveying decisions of spectrum management as compared to the use of simple channel assignments as illustrated in Figure 1-1. A spectrum consumption model of spectrum use created by one system provides sufficient information to allow other management tools to compute compatible reuse. The details of the RF components of systems and of the specific missions of systems do not need to be shared across management tools and spectrum managers. These details are captured abstractly within

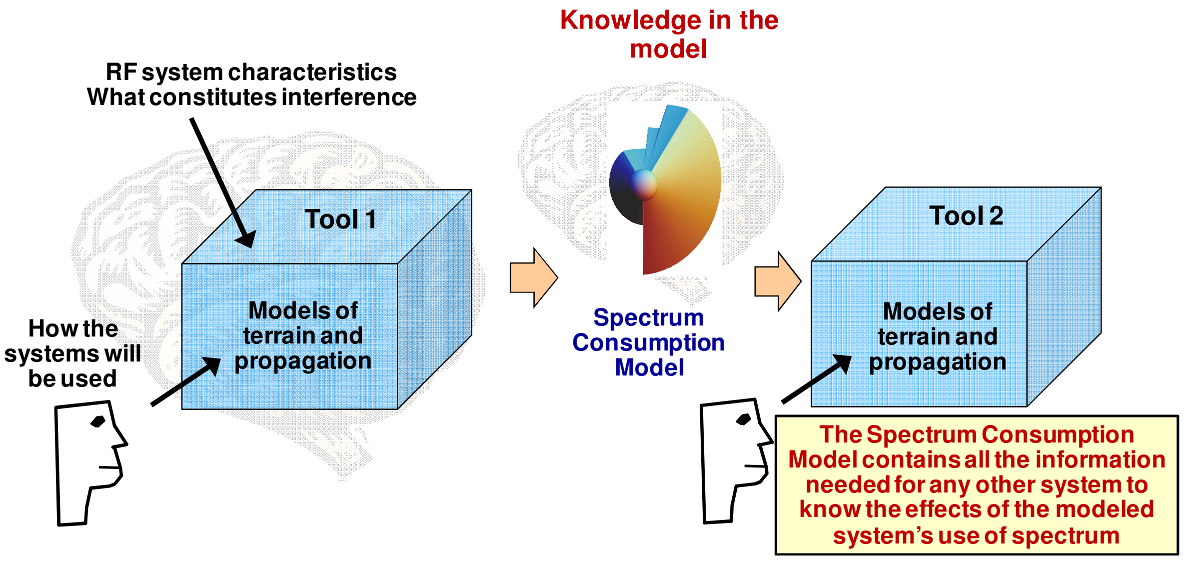

Figure 1-2. The Effect of Spectrum Consumption Models on Spectrum Management

the model. Decision about where the next use can begin can be made much more rapidly without any requirement for the manager making the decision to understand what the incumbent system is doing in the spectrum it uses. Thus, using SCMs as the core interface of spectrum management systems provides a solution to the first deficiency, the lack of agility in management. Further, they can serve as loose couplers between and among spectrum management systems and the RF systems that use spectrum. The significance of loose coupling is that it can greatly enhance innovation in spectrum management and use that will result in ever more agile use of spectrum. The next section provides a brief introduction to loose couplers and is followed by a section comparing the coupling characteristics of SCM to those of existing spectrum management systems.

1.2.1 Loose Coupling

Loose coupling refers to a thing 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 then something nearly magical occurs where the larger system becomes boundless in its 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 Internet Protocol (IP) serves as a loose coupler with the two layers being the means of 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.

Loose coupling also works within the layers. In the power distribution example, loose coupling allows multiple means of power generation to be combined within a power distribution system.

It allows multiple sets of appliances and tools to be integrated into a system, e.g. think of a home and its appliances. In the Internet, the IP protocol enables multiple transport technologies to interoperate to support the larger transport function and allows multiple services and applications to be integrated within the same network.

As seen in these examples, an effective loose coupler standardizes a smaller portion of a system at the intersection of what must be shared between the layers and across the layers. An effective loose coupler then allows innovation among a large collection of systems so long as they conform to this standard.

The spectrum consumption modeling approach serves as a loose coupler among spectrum management systems and RF systems since it provides a means to share the data that is necessary at their intersection. The shared data are models of spectrum consumption and the attendant computations that are used with these models to arbitrate compatibility. Figure 1-3 is a bowtie diagram that illustrates the loose coupler role of the spectrum consumption model. At the top layer it provides a means for systems that collectively perform spectrum management to convey to each other their vision of spectrum consumption. At the bottom layer it allows RF systems that use the spectrum to coexist. Spectrum consumption models provide a means for spectrum management systems to convey[3] to RF systems what spectrum they can use. This includes means to convey machine readable protocols and policies to DSA systems and a means for RF systems to convey the actual spectrum they are using to spectrum management systems. The path to this vision is the creation of a standardized approach to modeling spectrum consumption. This manual is a first attempt to create such a standard. An effective SCM standard will allow innovation to occur in both the spectrum management and RF system domains while enabling integration and interoperability because of their use of the common SCM standard.

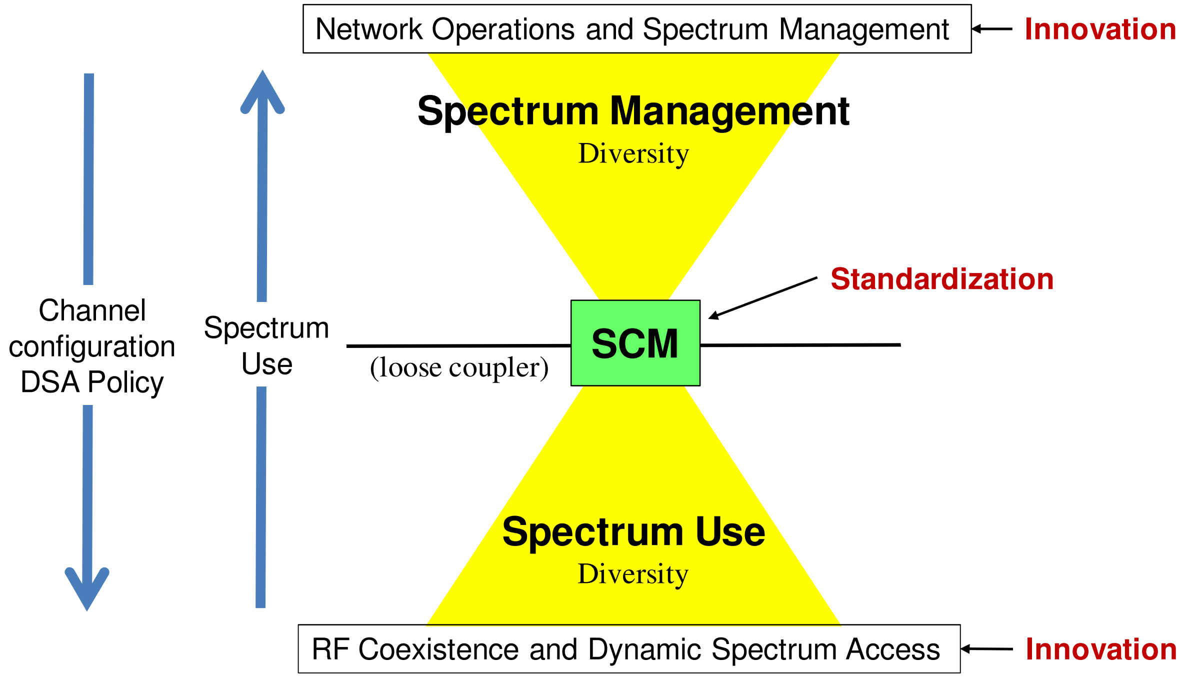

Figure 1-3. Bowtie diagram of the SCM loose coupler

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[3] The word "convey" refers to the collection of data in a model to indicate a policy for using spectrum or a definition of a use of spectrum as opposed to the means to transmit such guidance or information.

1.2.2 Comparison of Coupling Characteristics

Existing management approaches use systems that are tightly coupled. Tightly coupled systems are characterized by the necessity to change multiple modules of a system to accommodate the change or addition of one. The addition of new RF systems that must be managed requires the addition of algorithms within the spectrum management tools to capture the unique aspects of its consumption of spectrum and additional algorithms to assess its compatibility with systems that compete for the same spectrum. Further, the operators of the tools must be trained to use these new models. And still further, in operational use, the operational changes in spectrum use by a particular system must be conveyed in an explanation of that use among spectrum managers. In contrast, in a system based on the use of spectrum consumption models, so long as a new type of use can be conveyed in a spectrum consumption model there is no need to modify the spectrum management system. All details of operational use of spectrum are conveyed in models and so this eliminates any need to exchange information among SM tool operators on the operational use of the systems. Table 1-1 compares the coupling differences of the two approaches.

Table 1-1. Comparison of Coupling Characteristics of Spectrum Management Systems

Condition	Coupling Characteristics of Existing Spectrum Management Systems	Anticipated Coupling Characteristics of Using Spectrum Consumption Models in Spectrum Management Systems
A new RF system is developed and must be managed	Requires the addition of algorithms accounting for the use of spectrum by those systems in all spectrum management systems that manage the spectrum they use.	Management systems of the new RF systems will need methods to capture their spectrum consumption in models which are then input into spectrum management systems but MBSM tools will not need modification.
	Has a development ripple effect. Analytical approaches must be developed and implemented in spectrum management tools for determining the pairwise compatibility of all existing systems that compete for the same spectrum as the new system	Has no development ripple effect. Compatibility in MBSM systems use generic algorithms with the models to compute compatible reuse and so no changes are required.
	The addition of spectrum management models and analytical methods to SM tools requires operators to be trained in their use.	MBSM tool operators would require no additional training
Creation of new spectrum management capabilities (e.g. Dynamic Spectrum Access)	Integration of new capabilities requires broad revisions of spectrum management tools and sister systems. For example, although DSA has been proposed for a while there are only very crude methods of spectrum management developed to accommodate DSA.	New capabilities are easily developed so long as the spectrum consumption model remains the point of integration.
An operational use of an RF system changes	Spectrum management decisions must either be very broad so that the changes have no effect on the spectrum management solution or the details of the operational use must be conveyed to the spectrum manager. The spectrum manager then needs to study the spectrum management solution to determine if it is still valid	So long at the operational use is modeled by some system those models can be conveyed to a spectrum manager and used to determine the ramifications in a SM tool, e.g. compatibility issues, reuse opportunities, and requirements to change spectrum management plans.

1.3 Model-Based Spectrum Management (MBSM)

Model-Based Spectrum Management, as the name implies, is a system of spectrum management that is based on the use of spectrum consumption models. It is characterized by two features: First, spectrum management decisions are conveyed in spectrum consumption models. Second, the arbitration of where reuse of spectrum among systems is compatible is determined using their spectrum consumption models and specified computational methods based on the models. The processes of spectrum management then use the creation and exchange of models as the means to achieve more agile management. Spectrum management activities become easier to execute and more effective through using algorithms and methods made tractable because they are designed specifically to operate on the models.

The next subsection describes the impact of MBSM on existing spectrum management. This is followed by sections introducing the constructs of modeling and the use of models to arbitrate compatibility.

1.3.1 Spectrum Management

MBSM is not intended to be a wholesale replacement of existing spectrum management approaches and business processes. Data will still be collect on the characteristics of systems and exchanged with host nations and allies. Managers will use tools with state of the art terrain and propagation models to visualize and understand the effects of RF system deployment. Managers will perform the same tasks: assess spectrum supportability, request and provide frequency allotments and assignments, and report and resolve interference. Modeling is intended to simplify these tasks and then to enable additional processes that are anticipated to improve the effectiveness of spectrum management. Spectrum consumption models are outputs of a first step of analysis and are used to perform subsequent activities of spectrum management more effectively.

The entry point of using spectrum consumption models for spectrum management is the construction of a model of a particular operational use of spectrum. This model may be created initially without considering any other competing uses of spectrum. Assuming that there are competing uses of spectrum and that those uses are also modeled then tools, with the collection of models, can quickly assess whether there are compatibility issues. Tools may also be developed to do even more sophisticated analysis such as given a set of models determining how to best distribute frequency assignments among them, identify where there are opportunities to reuse spectrum, and when spectrum is congested, suggest modifications to spectrum assignments or modifications to models and so the operational use of systems to enable full support.

A benefit of modeling is that those most familiar with the operational aspects of systems can build the models of their use and communicate those models to a centralized activity where assignments are made. Thus, the activities of spectrum management can be distributed to the individuals best capable of performing them and the spectrum manager is relieved of some of the harder tasks that tend to encourage pursuing persistent assignments. An expected outcome of the new efficiency is a change in mindset from one where spectrum users attempt to stake claim to what they need and to prevent intrusion to one where the collective participants attempt to minimize their spectrum consumption, to mine the collections of models for opportunities to reuse spectrum and then to find ways to exploit those opportunities. It is also feasible that RF systems themselves can mine a set of models and make autonomous decisions on which spectrum to use based on the system's deployment and the incumbent uses.

1.3.2 Modeling

An unfortunate characteristic of spectrum consumption is that it has a complex relation with how RF systems are designed, how they are deployed, and the environment where they are deployed. This complexity makes the use of datasets of RF system characteristics insufficient to drive spectrum management activities on their own. Some level of human judgment is necessary to understand how systems will be used, where interference might occur and its severity, and to conceive of ways to overcome it. This deficiency is what makes spectrum management processes slow, based on study, and focused on persistent solutions. The purpose of modeling is to expose the critical parts of human judgment so that they may be reused in subsequent management activities. Further, effective modeling can make automated processes feasible to accomplish tasks that otherwise would require long thoughtful manual efforts.

A modeling methodology needs to capture multiple phenomena and activities and so a full spectrum consumption model consists of multiple sub-models. These sub-models capture phenomena such as pathloss and intermodulation, system characteristics such as spectral occupancy, what constitutes interference and possibly how the system manages it access to spectrum, and deployment characteristics such as location and time of operation and antenna directivity. Further, modeling needs to capture the differences in how transmitters, receivers, and systems consume spectrum. And finally, models should support Policy-Based Spectrum Management (PBSM) and allow models to be used to authorize and to specify policy on the use of spectrum. It is the purpose of this manual to define a method for doing this type of modeling. It proposes twelve constructs to capture the spatial, spectral, and temporal characteristics of spectrum use:

1. Maximum power density: The power density at the component to which values of the spectrum mask, underlay mask, and power map reference. It is typically the maximum power density among the directions and among the frequencies emitted.
2. Spectrum mask: A variable sized data structure that defines the relative power density of emissions by frequency.
3. Underlay mask: A variable sized data structure that defines the relative power density of allowed interference. Together with the spectrum mask, it defines a margin of protection required to prevent interference.
4. Power map: A variable sized data structure that defines a relative power density per solid angle.
5. Propagation map: A variable sized data structure that defines a pathloss exponent per solid angle.
6. Intermodulation mask: A variable sized data 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 on which a particular system is located. These names are used to identify when multiple systems are co-located and could suffer intermodulation and adjacent frequency 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 component may be used. A location may be a point, a volume, or a trajectory or orbit.

11. Minimum power density: A power 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 place to account for behaviors of systems that allow different systems to be co-located and to coexist in the same spectrum, e.g. a definition of a radar chirping frequency that allows intertwined packet transmission during the silent intervals.

Use of these constructs to define spectrum consumption is described throughout the remainder of the manual. It should be understood that the selection of these constructs was done mindfully of the attendant computations necessary for computing compatibility. The choices of modeling abstractions were made to simplify and to keep these computations tractable.

1.3.3 Using SCM to Perform Spectrum Management Tasks

The fundamental computation of spectrum management is the determination of compatibility. Two systems are compatible if they do not cause harmful interference at the other. The basic computation is to determine the strength of a transmitted signal by one system on a receiver of the second. If the strength exceeds what is considered acceptable then the systems are incompatible.

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 the other. Given the location of a victim receiver and an interfering transmitter the computation of compatibility requires two computations before the check can be made. The first is to determine the strength of the interfering signal at the victim receiver. This computation begins at the interfering transmitter where the maximum power density, spectrum mask, and the power mask model components are used to determine the strength of the signal from this transmitter in the direction of the victim receiver. Then that signal is attenuated based on the directional rate defined by the propagation map of either the transmitter model or the victim receiver model, the worst case of the two is used, and the distance of their separation. The second step is to determine what is considered acceptable interference. This is computed using the maximum power density, the power map, and the interference mask of the victim receiver for the direction toward the interfering transmitter. Given the power level of the interfering signal and the power level of acceptable interference, compatibility is determined using a simple comparison.

Although seemingly simple, actual computations are more complex. Rather than single points for a victim receiver and interfering transmitter there are spaces within which they may be located and so it is necessary to determine the worst case placement of these two in their operational spaces before computing whether they are compatible. Determining the worst case placement is made more complex if there are directional differences in transmission power and pathloss. 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. There are multiple other considerations for assessing compatibility that are described later in this document in Chapter 3 after the reader has had the opportunity to study the nuances of the modeling constructs described in Chapter 2.

Given the ability to compute compatibility between models other functions may follow. In cases where options are available for channel assignment such as would be the case for assigning channels from a pool for a collection of networks using the same technology, 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, all based on its model of consumption.

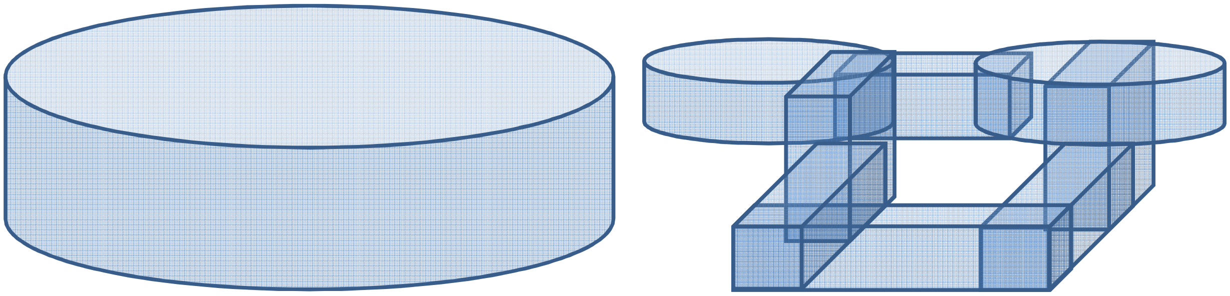
1.4 Anticipated Benefits of MBSM

MBSM promises two fundamental improvements to spectrum management from which many other improvements can evolve. First, the models can capture all dimensions of spectrum use enabling additional resolution in spectrum management. Second, spectrum consumption models, as described in Section 1.2, allow loose coupling in spectrum management systems. The ability to communicate spectrum consumption in models and then to compute reuse opportunities using these models makes modeling a common method for disparate systems to convey and resolve spectrum demands. So long as systems can capture their use of spectrum into models, they can play. In the following subsections we show how MBSM can enable a much more effective spectrum management capability and the creation of systems to use spectrum more dynamically. These subsections incrementally build the story that spectrum consumption models are not only good for spectrum management tasks but for enabling dynamic spectrum access systems as well.

1.4.1 Greater Resolution in Spectrum Management

Greater resolution in spectrum use comes from the ability to subdivide spectrum use in time and space. Figure 1-4 illustrates an example. In Figure 1-4a, 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 mission use of the spectrum. Figure 1-4b 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.

The ability to capture the spatial, the spectral, and the temporal dimensions of spectrum use also offer the ability to use spectrum consumption models to compute where spectrum reuse is possible. Thus, there is a reason to use the models as a means to optimize use. This is as true within systems as among spectrum users. An example of using this concept in planning aerial unmanned autonomous system (UAS) missions follows.



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 1-4. Using the spatial and temporal dimensions of spectrum to subdivide use into smaller volumes

Example: Using Spectrum Consumption Models to Plan UAS Missions

A typical UAS may use three sets of channels: one for the command and control of the aerial platform, one for the downlink of flight video, and one for the downlink of sensor data. The transmitting and receiving components of the system are on the aircraft and at a ground control station (GCS). The ground control station is likely to remain stationary while the aircraft is quite mobile. If the aircraft can be bounded in space for some period of time then the service volume where a second UAS may be flown using the same spectrum controlled by another GCS may be identified. Figure 1-5 illustrates an example scenario. Two GCSs are separated by half the range of the unmanned aerial vehicles (UAV) they control. The blue GCS at the top of the illustration is the primary GCS and it controls a UAV in the illustrated box. We want to determine where the second green GCS may operate a UAV using the same spectrum. The service volume for the second mission controlled from the green GCS must prevent harmful interference to the blue mission and avoid receiving harmful interference from the blue UAV transmitters. It is possible to protect the downlink to the blue GCS by keeping the green UAV at a distance where it will not interfere. This volume is illustrated in the first panel. It is possible to prevent harmful interference at the green GCS by keeping the green UAV sufficiently close to the green GCS to maintain an appropriate signal to interference and noise ratio (SINR). This volume is illustrated in the second panel. It is possible to protect uplink channels by ensuring the green UAV is sufficiently close to the green GCS with respect to the blue GCS such that it receives the green GCS's transmissions with adequate SINR over the interfering blue GCS transmission. This volume is illustrated in the third panel. The intersection of these three volumes is the service volume in which a second mission may be flown and it is illustrated in the fourth panel.

In this scenario, it is interesting that the green UAV may not operate in the region near the green GCS because of the need to protect the downlink reception at the blue GCS. Thus, to launch the green UAV may require synchronizing its launch with that of the blue UAV assuming the launch site is co-located with the GCS.

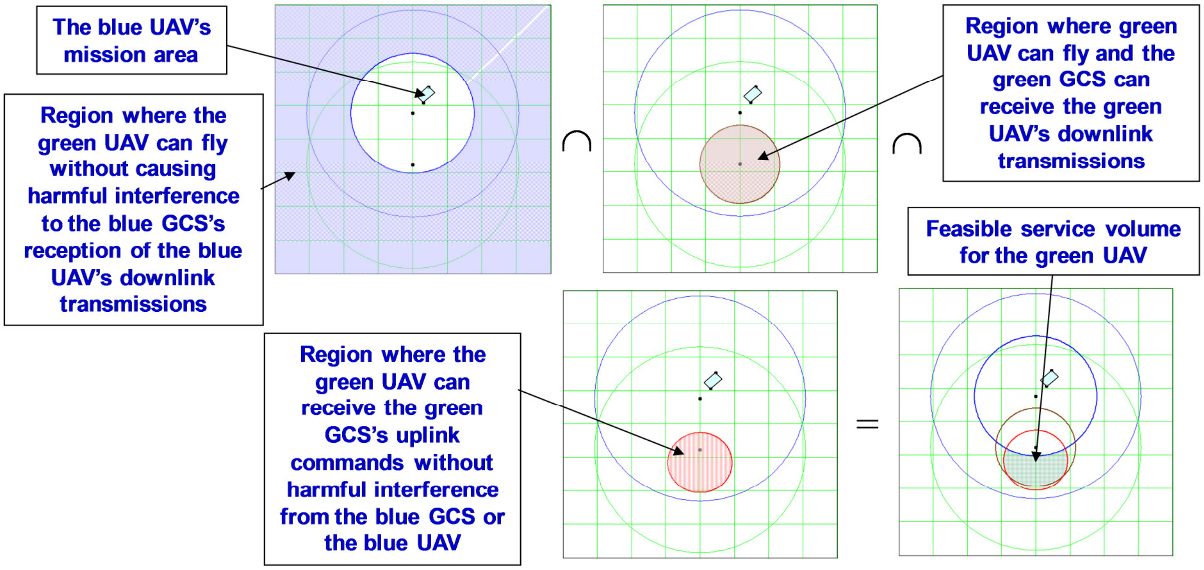


Figure 1-5. A scenario where spectrum consumption models are used to determine a service volume for a secondary UAS mission that is flown using the same spectrum

1.4.2 Integration of Spectrum Management Systems

A point that has been made several times and will be remade throughout is that SCM are built with the intent of capturing the judgment of planners and managers on the salient aspects of RF system use that determine spectrum consumption. Modeling is inherently a distributed activity since knowledge of the details of these salient aspects is distributed among the planners and managers who handle the systems. Who is best to distribute channels among networked radios, the network manager or the spectrum manager? Who is best to specify the model of the deployment of a UAS, the mission planner or a spectrum manager? And, in both these cases, would be giving the spectrum manager the role of resolving the use of these systems so that they could modeled be appropriate. It is impractical to consolidate all these types of planning into an overarching spectrum management tool since the planning will involve using RF system specific algorithms and methodologies that are best applied by those trained in each RF system's use as opposed to generic spectrum managers. Further, if consolidated into a single tool, the tool would likely become a bottleneck in planning and reduce the agility of spectrum management. Thus, spectrum management is best made a distributed process across multiple planning systems and their users. Herein is the next great benefit of MBSM, the spectrum consumption models enable the integration of these disparate planning systems into a single integrated spectrum planning system of systems where the judgments of multiple parties can be arbitrated to arrive at the best distribution of spectrum. Mission planners and system managers of RF systems can receive their general authorization for spectrum from spectrum managers using the SCM format. The general authorization would be a larger piece of spectrum within which an RF system's use of spectrum is expected to fit. The mission planners and system managers would then plan their missions within the constraints of the general authorization while simultaneously trying to minimize their own spectrum consumption. Their final plan would be captured in a revised set of models. The collection of these revised models would provide all the information needed to determine whether neighboring systems' use of spectrum will conflict with each other.

An additional benefit of using MBSM is that the models convey spectrum consumption with minimal detail about what the spectrum is being used to do. This vagueness about the mission of spectrum use is likely to encourage cooperation of spectrum users with highly sensitive equipment and missions. The consumption of spectrum by such systems can be conveyed to spectrum managers without revealing the sensitive details of equipment capabilities and missions. Spectrum managers can analyze the collective spectrum use and identify conflicts without violating this secrecy.

Creating this type of distributed and cooperative spectrum management capability will require the creation of new processes to govern the distributed planning, the sharing of plans, and the arbitration of the priority of use. These new processes would take advantage of this ability to distribute spectrum management. First, the distribution of spectrum planning ensures the most capable individuals model the operational and technical aspects of a system's use. Second, the arbitration of conflicts may be accomplished between the competitors for the same spectrum since they will be able to share their models of their use of spectrum and will know best what compromises are practical, especially if the conflict is just the result of overly conservative modeling. The centralized part of management will involve governing this process and resolving conflicts that parties cannot resolve themselves.

1.4.3 Easy Policy for Dynamic Spectrum Access (DSA)

Dynamic spectrum access 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 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. As already described, 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 are an obvious complement to PBSM.

Spectrum consumption models provide a bound to spectrum consumption and as such they are readily used to convey limits for spectrum use. As is, SCM 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 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 where behaviors are chosen that allow compatible reuse within the very spaces of existing use. The "protocol or policy" construct of spectrum consumption models was added to the modeling constructs specifically to allow 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.

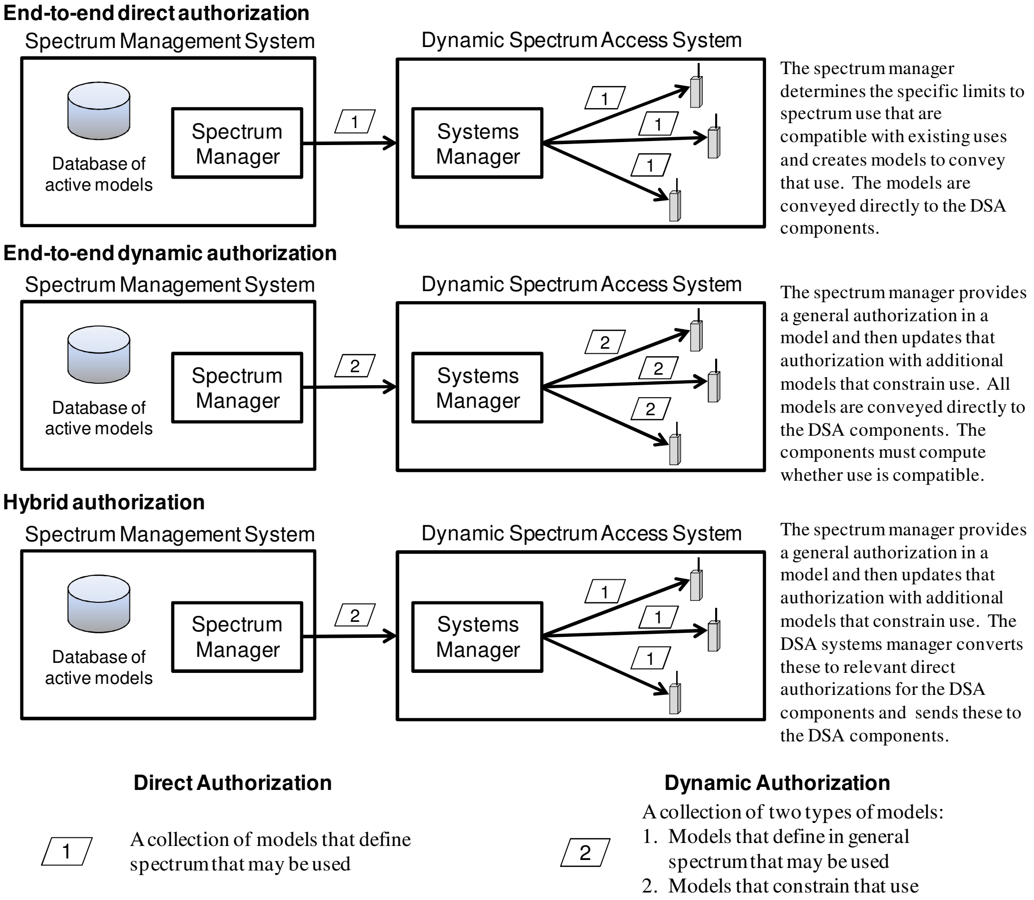
Policies typically have two parts, a permissive part identifying what the DSA system may do and a restrictive part that constrains what the DSA system may do. In the case of using SCM models for DSA policy, the models of incumbent users would be the restrictive part. Additional models can be used to convey the permissive part. Section 2.3.4 describes the methods for conveying restrictions and Section 2.3.3 describes the method for conveying permissions using SCM. Policies written using SCM have the advantage that their compatibility with existing spectrum users can be verified using the algorithms of MBSM.

Further policy can be conveyed to DSA systems in two ways, either as a direct or a dynamic authorization. They differ in the computations expected at the DSA system.

Direct Authorization: The spectrum manager determines the requirements for compatible reuse and creates a set of permissive models of that compatible reuse. These models are given as policy to the DSA systems. Components of the DSA system would simply determine where they are and lookup which models apply and so which channels can be used. If there are choices, they can use other criteria of their own to select which of the choices to use.

Dynamic Authorization: Policy is conveyed using two types of models, permissive models which are broad in scope that describe the spectrum that might be considered and then restrictive models which are the spectrum consumption models of spectrum use of other incumbent systems which have precedence in spectrum use. The expectation is that the DSA system would make the computations that ensure that a use within the broader permissive model also respects the restrictions of the restrictive models. This approach can provide many more opportunities for reuse. From the spectrum manager's view, creating the models of the incumbent use is equivalent to writing restrictive policies for DSA use. A long term permissive model can be augmented over time with short term restrictive models as they are created for new uses.

There are three methods of DSA policy management. These are illustrated in Figure 1-6. The first is simply an application of the direct authorization. The second is an application of dynamic



The spectrum manager determines the specific limits to spectrum use that are compatible with existing uses and creates models to convey that use. The models are conveyed directly to the DSA components.

The spectrum manager provides a general authorization in a model and then updates that authorization with additional models that constrain use. All models are conveyed directly to the DSA components. The components must compute whether use is compatible.

The spectrum manager provides a general authorization in a model and then updates that authorization with additional models that constrain use. The DSA systems manager converts these to relevant direct authorizations for the DSA components and sends these to the DSA components.

A collection of models that define spectrum that may be used

A collection of two types of models:
1. Models that define in general spectrum that may be used
2. Models that constrain that use

Figure 1-6. DSA management methods

authorization where both the permissive and constraining models are distributed to the components of a system with an expectation that the components will all independently use the two types of models to compute reuse opportunities. A possible concern of using end-to-end dynamic authorization is that individual radios may not be able to compute compatible reuse fast enough. The third method of DSA policy management attempts to mitigate this concern. A system management function accepts the dynamic authorization from a spectrum manager and translates them into the purely permissive policy of a direct authorization for the components of the systems to use.

DSA policy created using spectrum consumption models at the very least will identify the channels a system may use based on location.

1.4.4 Dynamic Spectrum Management

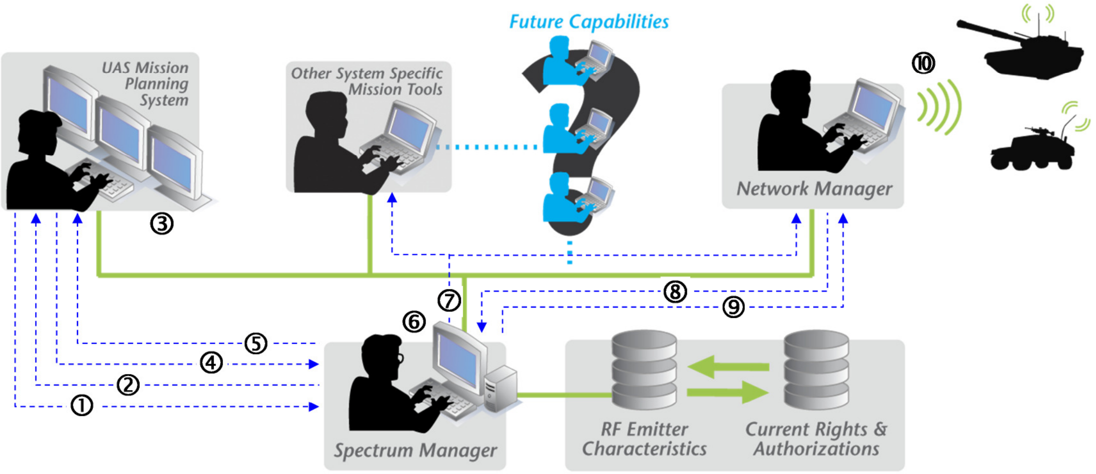
A dynamic spectrum management system combines all the previous benefits we have defined for MBSM. The spectrum consumption models enable a higher resolution management of spectrum with temporal resolution that requires more active interaction among systems. The resulting spectrum management distributes the spectrum management problem across multiple systems with mission planners, spectrum managers, and system managers working as part of a larger spectrum management process. Collectively, they form a system that attempts to get the most use out of a pool of spectrum. An example scenario of dynamic spectrum management in action follows.

Example: A Dynamic Spectrum Management Scenario

Figure 1-7 illustrates a dynamic spectrum management scenario. It begins with the mission planning system requesting spectrum from a spectrum manager (SM). The spectrum manager responds with authorizations for the UAS systems together with relevant restrictions to spectrum use. The mission planner considers the available spectrum in planning and defining missions. Once the mission planner resolves upon the set of missions, she requests authorization for the required spectrum from the spectrum manager. If the requests have no errors, then the spectrum manager loads the spectrum consumption models into the database of active models and confirms the request. The spectrum manager can then search for reuse opportunities and convey these opportunities to secondary users that may also be able to use the spectrum in a compatible way. In this case the network manager identifies ways that it can use a portion of the available spectrum and responds to the spectrum manager with a request. The spectrum manager grants this request. It happens in this case that the network manager was requesting spectrum for cognitive radios and so those radios are informed of the spectrum that they may try to use.

In this example, spectrum may be set aside for a system. So maybe all of some set of channels are available for a UAS system at any time and the UAS planning system works autonomously to find opportunities for reuse within its own domain. At the completion of planning when it requests authorizations, Step 4 below, it is not really receiving the opportunity to use spectrum since it already has authorization but is actually freeing spectrum for other users.

This type of system can be integrated with additional capabilities such as a network of sensors that allow the spectrum manager to assess the use of spectrum spatially and to identify additional opportunities for spectrum reuse.



1. Request potential rights
2. Spectrum manager (SM) sends relevant rights
3. Mission planner creates plan and the appropriate spectrum rights
4. Mission level spectrum rights request
5. Mission level spectrum rights granted
6. SM identifies reuse opportunities
7. Potential users of spectrum notified of opportunities
8. Network manager (NM) identifies reuse and requests rights
9. SM reviews NM's request and grants rights
10. NM informs cognitive radios of rights

Figure 1-7. A dynamic spectrum management scenario where spectrum consumption models are used to convey spectrum authorizations and uses

1.5 Transitioning

The vision for MBSM is the use of spectrum consumption models as the primary means to share information on the operational use of spectrum among spectrum management systems and as the primary means to provide guidance and policy to RF systems that are designed to react to directives or designed to dynamically access spectrum based on policy guidance. The motivation for such a vision is that it promises more effective spectrum management and more efficient spectrum use. Reaching that vision will likely be incremental. Transition has six distinct activities which are described in the next subsections

1.5.1 Standardizing the Modeling Methods

As shown in Figure 1-3, a loose coupler attempts to capture the part of a system that is broadly shared. As such, it is necessary that this shared part be defined and stable so that the other parts of the system that use the loose coupler can be developed. Thus, the first step in pursuing this MBSM vision is the development of the standard that defines how spectrum consumption may be modeled. This manual is a first attempt to create this type of standard. The next step is to move this effort forward into a formalized standardization effort. A most appropriate venue would be within the auspices of the IEEE DySPAN Standards Committee.

1.5.2 Development of Spectrum Management Algorithms using Models

The value of a model is contingent on the ability to use the model to automate spectrum management and dynamic spectrum access activities. It is appropriate that concurrent to the development of the modeling methods that algorithms that use the models be developed. This development activity should inform the standardization efforts and ensure that only modeling methods that result in efficient and tractable algorithms be standardized. The research project that developed this manual is also developing a set of algorithms that use these models. These algorithms will be published separately later after some further development. This work will be rudimentary and should be continued throughout the effort to standardize the modeling methods. It is appropriate to make the algorithms open so that others can use them and even better, improve them. Algorithm development is one of the areas where there is likely to be continuous innovation.

1.5.3 Incorporating MBSM into Existing SM and RF System Management Tools

Given a modeling approach and a set of algorithms that use the models to perform spectrum management activities it is then time to use the models in spectrum management processes. The next step is to add the modeling to existing spectrum management and RF system management tools with the intent of exploiting the attendant algorithms to make spectrum management activities more effective. With use will come the experience and the development of modeling best practices where particular modeling approaches are identified for particular RF systems. Functions within the spectrum management tools may be developed to simplify SCM creation based on these practices. Further, using SCM in spectrum management processes will reveal further algorithms to develop to support spectrum management. In this step, we would also see the beginning of the distribution of spectrum management activities most specifically through the development of tools for use within management systems of particular RF systems and the means to exchange models among them. This development is most obvious for the management systems of networked radios but also the management systems of UAS, sensors, Electronic Warfare (EW), and radars. With this development would come the creation of business processes and technical means for requesting and granting spectrum for RF systems.

1.5.4 Development of Policy Based Spectrum Management Technologies

An objective of the first task is to make SCMs suitable for conveying spectrum authorization and policies to other managers and directly to RF systems and radios. These models are intended to be machine readable and capable of informing the algorithms of dynamic spectrum access systems. Given a standard of modeling, it is anticipated that RF system vendors would develop RF systems that can respond and comply with the guidance implied by the models. This activity is likely to begin when modeling reaches maturity and is standardized. An important feature of the modeling approach proposed in this manual is the twelfth construct, protocol and policy. It allows further development and definition of policy and protocol methods for sharing spectrum. Here too, innovation can continue well beyond the definition of the modeling standard.

1.5.5 Development of Analytics to Assess the Compatibility Among Policy-Based RF Systems and Other Modeled Uses

The objective of using PBSM to drive dynamic spectrum access systems is to make spectrum access autonomous at the RF devices and so more agile. It is important that these policies protect incumbent systems. Over time experience will be gained as to which policies and protocols are compatible with particular systems and which policies and protocols particular DSA systems can implement effectively. With this experience, RF systems and types of policies can be rated for their ability to coexist with other systems. Models of spectrum consumption can use the protocol and policy construct of modeling to convey the critical characteristics that would inform managers which protocols or policies they can implement or with which they can be compatible.

1.5.6 Development of Dynamic Spectrum Management Processes

The culmination of incorporating MBSM into spectrum management is the creation of very dynamic processes where individual users and the system work collectively to release unused spectrum and find ways to exploit it. Given the adoption of using SCM as the core of spectrum management and technologies that can respond to directives and policies provided using the models, dynamic spectrum access processes would be developed by users to meet their needs. These processes could be developed to uniquely support different enterprise activities such as commercial markets for spectrum exchange among spectrum users and in defense procedures for ranking spectrum missions and for tracking spectrum use, revealing spectrum availability, and then identifying systems that can exploit it.

1.6 Conclusion

As described in this chapter, MBSM and the use of spectrum consumption models enables a very dynamic form of spectrum management. The spectrum consumption models enable managers and users to capture their judgment on how spectrum will be used and what would constitute interference in a format that allows algorithmic assistance in spectrum management. Characteristics of this management include greater spectral, spatial, and temporal resolution, distribution of the management across systems including management by systems as part of the mission planning of those systems, easy policy generation for DSA systems, and the integration of these capabilities into a dynamic spectrum management system. Further, spectrum consumption modeling is a loose coupler in this larger system enabling innovation in the design of systems that use RF spectrum and those that manage RF spectrum while ensuring they can be integrated together.

This introduction to MBSM provides the motivation for wanting to model RF spectrum consumption and to build spectrum management around those models. It describes how spectrum consumption models may be used. The remainder of this manual describes how to model spectrum use. The next chapter starts this discussion by describing a proposed set of constructs for spectrum consumption models and the methods to combine these constructs to build models. The third chapter describes how to use these models to assess compatibility of different modeled uses. Since modeling is based on judgment it will be artful. The fourth chapter is a first attempt to discuss the art of modeling and how various types of RF systems might be modeled using the specified constructs. The final chapter discusses follow-on activities and issues for implementing a MBSM system.

2 Spectrum Consumption Models

The purpose of spectrum consumption modeling is to capture the extent of spectrum use in a manner that allows arbitration of compatibility. Although the spectrum consumption of a system is a function of the location of the transmitters and the receivers of that system, the boundaries of use are less easy to define. Consumption depends on the signal space, the transmission power, the antennas used, the attenuation that occurs in propagation, and the susceptibility of the modulation to interference. Most of these cannot be modeled exactly. Variations in location and antenna orientation, variation of propagation effects that result from changes in the environment, and the imperfections in RF components make the consumption stochastic. Therefore, modeling consumption does not attempt to precisely capture these effects but attempts to create a bound on these effects, one that ultimately protects the users that need protecting.

This chapter describes the constructs of spectrum consumption models, the model types, and the conventions for combining the constructs into models. As the constructs of spectrum consumption modeling are described, the reader should be attuned to the interaction of the constructs and how they are used collectively to capture consumption. Ultimately, we want the models to make the computation of compatible reuse unambiguous and tractable and for the uncertainty in what actually happens in spectrum use to be bounded.

2.1 Constructs of Spectrum Consumption Modeling

The constructs of spectrum modeling should be viewed in much the same way as construction materials. Each construct has a purpose but it is how the multiple constructs are combined and assembled that ultimately makes the final product, in this case a spectrum consumption model. Some constructs may be found in every model such as the maximum power density while other constructs are likely to be used infrequently such as the protocol or policy construct. Some constructs may appear multiple times in the same model. There are twelve constructs:

Table 2-1. The spectrum modeling constructs

Construct	Description
Maximum Power Density	The power density at the component to which values of the spectrum mask, underlay mask, and power map reference.
Spectrum Mask	A variable sized data structure that defines the relative power density of emissions by frequency.
Underlay Mask	A variable sized data structure that defines the relative power density of allowed interference by frequency.
Propagation Map	A variable sized data structure that defines a pathloss exponent per solid angle.
Power Map	A variable sized data structure that defines a relative power density per solid angle.
Intermodulation Mask	A variable sized data 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.
Platform Name	A list of names of platforms on which a particular system is located.
Location	The location where system components may be used.
Start Time	The time when the model takes effect.
End Time	The time when the model no longer applies.
Minimum Power Density	A power density that when used as part of a transmitter model implies the geographical extent in which receivers in the system are protected.
Protocol or Policy	A place to account for behaviors of systems that allow different systems to be co-located and to coexist in the same spectrum

The description of each of the constructs starts with a brief overview of the construct and is followed by a discussion of its rationale, the data structure(s) that are used, the units for the elements in the data structures, and then a discussion on its interaction with other constructs and their collective use in computing compatibility. Specific conventions for combining the data structures of the constructs and the combining of the constructs to form models are found in Appendix C which describes the eXtensible Markup Language (XML) schema for spectrum consumption modeling.

2.1.1 Maximum Power Density

The maximum power density specifies the maximum power density at some designated distance toward any direction from a transmitting antenna for a transmitter model or at a receiving antenna from any direction for a receiver model.

Spectrum consumption models use a variant of the log-distance pathloss model, $RP(d) = RP(1m) - 10n\log(d)$, that captures the distance based strength of a received signal. This model is described in Section 2.1.4.1. The maximum power density of a transmitter maps to the constant term in the log-distance pathloss model, $RP(1m)$. It is the power density at one-meter for a far field propagation result. The maximum power density of a receiver maps to the distance attenuated power, $RP(d)$, and is the power received at the antenna of the receiver.

2.1.1.1 Rationale

The intent of the spectrum consumption model is to capture the geospatial limit of a use of spectrum. For such a system to work, the model must be decoupled from the antenna technology. So transmit power is defined as the effective power density at a specified distance away from the antenna. Transmitters with high gain antennas must still conform to these limits in the models. The maximum power density specifies that maximum power density of any frequency in the model toward any direction from a transmitting antenna for a transmitter model or at a receiving antenna from any direction for a receiver model.

2.1.1.2 Data Structure

A single real number.

2.1.1.3 Units

$\mathrm{dBW}/\mathrm{m}^2$

2.1.1.4 Dependencies

All other transmitter power constraints in models are relative to this maximum power density so changing this value changes all power constraints in a model. Specific components that are referenced to this value are the spectrum mask, the underlay mask, the power map, and the intermodulation mask.

2.1.2 Spectrum Mask

The spectrum mask specifies the spectral power density relative to the maximum power density for all frequencies. It is presented as a piecewise linear graph of power density versus frequency. In the case of frequency hopping systems, a generic mask, i.e. one without a specific frequency reference, is used to show the spectral content of signals and then additional data is provided to specify the frequency hopping characteristics. pairs of masks are used to convey spectrum occupancy, one to show the range of frequency traversed in hopping and one to show the spectral content of the signals. Additional data structures in the construct convey the dwell and average period between revisits, and in some cases, specifics on the particular channels that are used.

2.1.2.1 Rationale

The purpose of the spectrum mask construct is to convey the spectral content of RF emissions. RF signals occupy a band of spectrum and may extend beyond the nominal bounds of their channel or fit well within the channel. The spectrum mask attempts to convey the bounds to the spectral content of the signal. This sort of model provides the ability to identify when adjacent band interference will occur.

In a frequency hop system, transmissions are not persistently on a single channel and so offer an opportunity for other systems operating in the same frequency bands of the hopping to coexist. In this case, the spectrum mask captures not only the spectral content of a signal at an instant but also the statistical characteristics of its hopping. Varying amounts of detail about the hopping can be provided. Subsequent determination of harmful interference on coexisting systems will depend on the modeling of the receiver's susceptibility to this interference in its underlay mask. The frequency hopping spectrum mask serves only to capture the nature of the frequency hopping. The basic content is the generic spectral content of a signal, the channels or frequency bands through which these signals hop, the dwell time of a signal at a hop, and then the average period between revisits. In cases where the signal space varies at individual hops or when the dwell time varies, modelers have the choice to use multiple spectrum mask data structures to capture the variation in these characteristics.

2.1.2.2 Data Structure

Spectrum masks are specified using a variable length (1 × n) array of real values alternating between frequency and power density of the form, $(f_0, p_0, f_1, p_1, \cdots f_x, p_x)$, with each sequential pair specifying an inflection point in the mask. Odd numbered terms in the array are frequencies and even number terms are powers. The power for all frequencies outside the mask are considered to be less than or equal to those at the closest end of the mask. Figure 2-1 is an example of a spectrum mask providing the data structure of the mask and it illustration.

Frequency hopping systems require the modeling of the signals that are transmitted and also the characteristics of the frequency hopping. The mask used to capture the spectral content of a signal is generic where frequency terms are reference to the center frequency of the signal. In the case of a signal with the same bandwidth and shape as illustrated in Figure 2-1, the generic spectrum mask is $(-0.075, -100, -0.05, -60, -0.025, 0, 0.025, 0, 0.05, -60, 0.075, -100)$. This mask together with a 400 MHz center frequency reference would be identical to that in Figure 2-1. This type of spectrum mask must be complemented with details on the frequency hopping, specifically, the channels used, the dwell time, and the average period between revisits. There are two options for specifying the frequencies used: a listing of the specific center frequencies such as $(f_0, f_1, f_2, \cdots f_x)$ or a listing of the end frequencies of the bands that are used. In the second case, the tuple (f_{b1}, f_{e1}) define the beginning frequency and ending frequency of a band. A collection of disjoint bands can be specified through a series of frequency pairs such as $(f_{b1}, f_{e1}, f_{b2}, f_{e2}, \cdots f_{bx}, f_{ex})$. The generic spectrum mask and the frequency specifications are

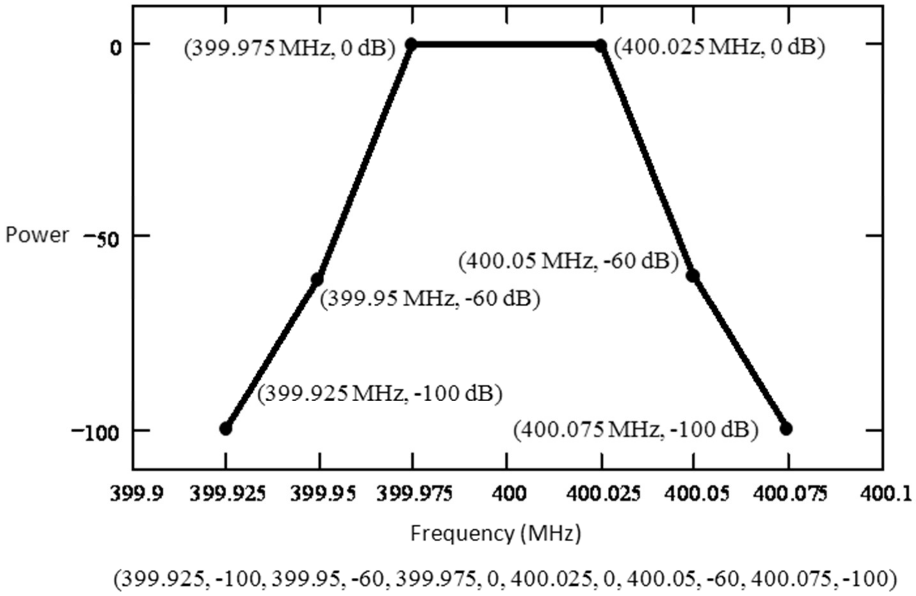


Figure 2-1. Example spectrum mask with its corresponding spectrum mask vector

paired with two additional data elements that define the frequency hopping. The first is the dwell time and the second is the average revisit period. In the case of using specific center frequencies the dwell time refers to the duration of time that a signal dwells on one of the center frequencies before the next hop. The average revisit period specifies the average time between occurrences of a signal on the same channel. In the case where bands are specified for the hopping frequencies, the dwell time also specifies the dwell time of a signal as specified by the generic mask at a particular frequency. In this second case, the average revisit period, however, accounts for the fact that individual signals may overlap in spectrum. The revisit period is a function of the relative bandwidth of generic signal as compared to the bandwidth of the hopping frequency band and the duty cycle for that band. As an example, if the ratio of the generic signal bandwidth to the bandwidth for the signal occupancy (the bandwidth of the center frequency plus the bandwidth of the generic signal) is 1 to 50 and the duty cycle is 50 %, then the revisit period would be

$$T_{revisit} = \frac{1}{50} \cdot 0.5 = 0.01 \text{ seconds} .$$

This type of computation exaggerates the signal occupancy at the edges of the frequency bands while underestimating the occupancy in the center but these discrepancies are small if the ratio is small.

2.1.2.3 Units

Frequency terms are in kHz, MHz, or GHz and power terms are in dB. Dwell times and revisit periods are specified in units of either µsec or msec.

2.1.2.4 Dependencies

The power terms in the spectrum mask are relative to the power density of the model at a particular location. Starting with the maximum power density the power density at a location is determined using the accompanying power map and propagation map in the model. A description of these computations is described later. The highest power in a spectrum mask is 0 dB and never larger. Computation of compatibility depends on the extent of spectrum modeled by the spectrum mask. Ideally, the power density of the signal less the power at the end points of the power mask should be beneath the ambient noise floor, -140 $\mathrm{dBW}/\mathrm{m}^2$, at the locations they are considered for compatibility.

The models of frequency hopping signals are used together with the underlay mask of a receiver model to produce a measure of interference. The computation of this measure and a description of how it is used to assess compatibility are provided in the next section.

2.1.3 Underlay Mask

The underlay mask specifies the spectral power density relative to a maximum power density at a receiving antenna of the maximum allowed interference by a remote interfering transmission. Like the spectrum mask, it is presented as a piecewise linear graph of power density versus frequency. A single underlay mask may apply to any signal of any bandwidth or a model may provide multiple underlay masks each for different bandwidths of interference or for different time spectral occupancies as is typical of interference from frequency hop systems. The masks may be defined relative to the power density of a transmitter and so the reference power density varies by location or be uniformly applied to all potential locations of receivers all referenced to a single power density.

2.1.3.1 Rationale

Underlay masks are the constructs of spectrum consumption modeling that define what is considered harmful interference. They are selected to provide an interference margin that will protect reception in a system. The mask may be defined relative to a spectrum mask of a transmitter or be absolutely applied to all potential locations of receivers. The former method is used when there is a single transmitter and so the reference power density of the underlay mask is the same as that used for the spectrum mask and so adjusts with propagation. The latter method is used in systems with multiple transmitters or mobile transmitters and receivers. The reference power density for these masks is the maximum power density of the model.

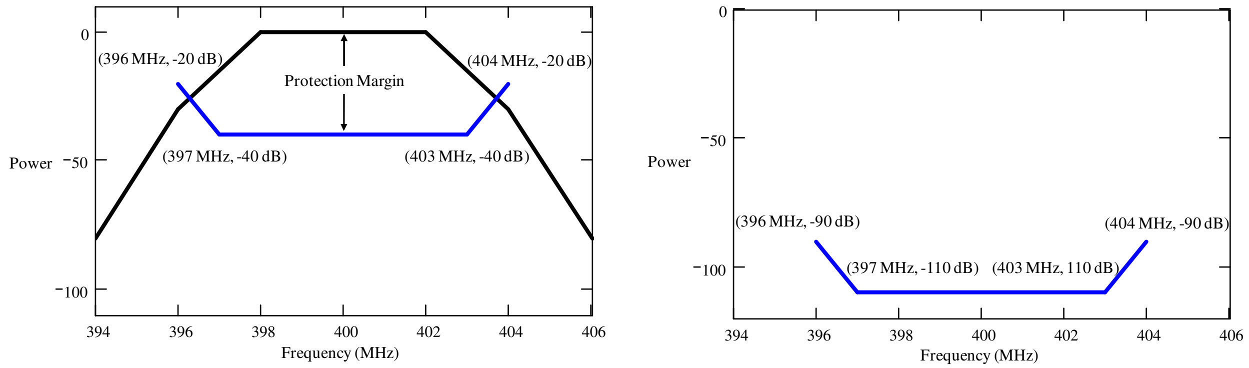
Underlay masks may differ based on the signal spaces of the protected signal and the interfering signals. A broadband signal can withstand interference from a signal with greater power density if the interfering signal is narrowband. Multiple sets of underlay masks can be used to account for different scenarios of narrowband interference. These collections of masks are used to enable more reuse opportunities. The rules for applying these masks to interference scenarios are described below in Section 2.1.3.4.

Underlay masks may differ further based on the duration of interference and its bandwidth as caused by frequency hop systems operating in the same band. RF systems may be able to coexist in the presence of frequency hopping systems operating in the same bands if the frequency hop systems occupancy in the band is infrequent, brief, or weak. Underlay masks with bandwidth-time product ratings allow modelers to convey the resilience of receivers to this type of interference.

2.1.3.2 Data Structure

Underlay masks are specified using a variable length ($1 \times n$) array of real values alternating between frequency and power density of the form, $\left(f_0, p_0, f_1, p_1, \cdots f_x, p_x\right)$, with each sequential pair specifying an inflection point in the mask. Odd numbered terms in the array are frequencies and even number terms are powers. Unlike a spectrum mask, there are no restrictions or assumptions made about the power at frequencies outside the mask. When multiple underlay masks are used to indicate allowed interference for different bandwidth signals, the maximum bandwidth, BW, of the interfering signal considered by the mask is provided. When multiple masks are used for different narrowband interference scenarios and the basic shape of the underlay mask is the same, then a single underlay mask may be provided followed by an offset data structure of bandwidth and relative power pairs of the form $\left(BW_0, p_0, BW_1, p_1, \cdots BW_x, p_x\right)$. Underlay masks rated for frequency hop interference use a format similar to this latter type for narrowband interference. A single mask is given several ratings associating a bandwidth-time product with a power level of the form $\left((BW\cdot T)_0, p_0, (BW\cdot T)_1, p_1, \cdots (BW\cdot T)_x, p_x\right)$. The bandwidth-time product is a product of the bandwidth and duration of occupancy of a single signal on average per second within the spectrum covered by the underlay mask. When multiple signals arrive within the spectrum covered by the underlay mask then the effective bandwidth-time product is the sum of the individual bandwidth time products.

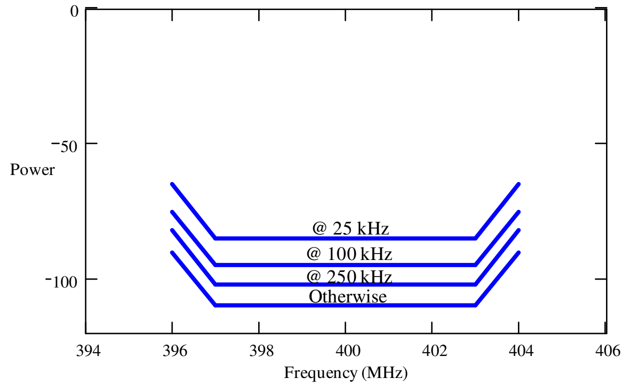
Figure 2-2 provides a comparison between underlay masks referenced to a transmitter and an underlay mask referenced to a location. The constraints of the first provide a margin relative to the spectrum mask and the constraints of the second are fixed for all locations. The frequency



a. An underlay mask referenced to a spectrum mask $(396,-20,397,-40,403,-40,404,-20)$

b. A similar underlay mask that might be referenced to a location $(396,-90,397,-110,403,-110,404,-90)$

Figure 2-2. Comparison of underlay masks with alternative references, spectrum mask and location



Multiple Mask Structure

$(396,-65,397,-85,403,-85,404,-65)$ @ 25 kHz

$(396,-75,397,-95,403,-95,404,-75)$ @ 100 kHz

$(396,-82,397,-102,403,-102,404,-82)$ @ 250 kHz

$(396,-90,397,-110,403,-100,404,-90)$

Single Mask with Offset Data Structure

$(396,-90,397,-110,403,-100,404,-90)$

$(25,25,100,15,250,8)$

Figure 2-3. Using multiple masks to specify different interference constraints for different interference bandwidths and a comparison of data structures specifying these masks

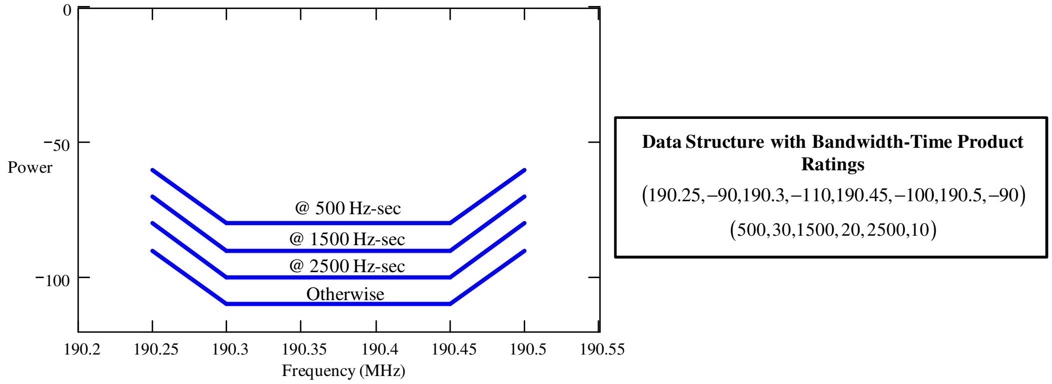


Figure 2-4. Using underlay masks to specify ratings for frequency hopping interference

terms of the two are the same but power terms of the mask referenced to a location are much smaller. Figure 2-3 provides an example using multiple masks to account for different signal spaces of interfering signals and compares the two approaches used to specifying the values. When the same mask shape can be used for all underlay masks as shown in the example the single underlay mask with offset data structure is the more efficient way to specify the masks. Figure 2-4 illustrates the use of these data structures to convey the allowed interference from frequency hopping systems.

2.1.3.3 Units

Frequency terms in the underlay mask are in kHz, MHz, or GHz and power terms are in dB. The bandwidth terms are in kHz or MHz. The time-spectral ratings are a product of time and bandwidth and so have units of Hz-sec.

2.1.3.4 Dependencies

The dependencies of underlay mask modeling are of three kinds. Those associated with determining the reference power density, those associated with identifying the applicable interfering bandwidth scenario for narrowband interference of broadband signals, and those associated with identifying the bandwidth-time product for interference from frequency hopping systems.

The reference power density may be either the spectrum mask power density at a location when the underlay mask is relative to the spectrum mask or may be the maximum power density when the underlay mask applies to a location. The former is used when the underlay model is part of a transmitter model and the latter is used when the underlay mask is part of a receiver model. In the case of the former, when the mask is part of a transmitter model, the reference power density is determined using maximum power density and the accompanying power map and propagation map of the model. A description of these computations is provided later in Section 3.2.7.

The objective in assessing acceptable interference with BW scenarios is to allow stronger interfering signals if the interfering signals are relatively narrowband and small in number. For the purposes of applying this model the bandwidth of an interfering signal is determined from its spectrum mask and is the bandwidth between the -20 dB points[4]. Figure 2-5 illustrates an example of this bandwidth determination for a signal. When computing compatibility of

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[4] This value was arbitrarily selected and may change as we gain experience in modeling.

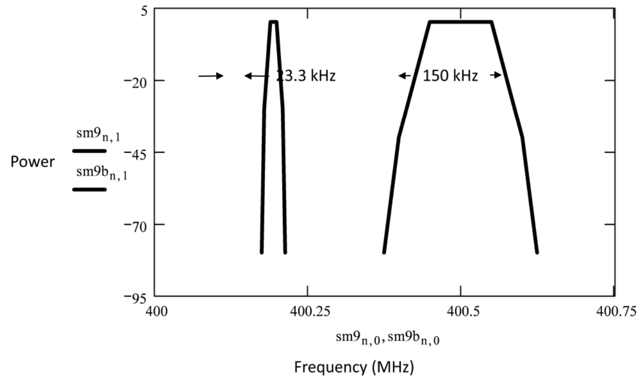

Figure 2-5. Example measurements of narrowband signal bandwidth

multiple narrowband signals, any signal beneath the full bandwidth underlay mask may be ignored. When there are multiple signals, the effective bandwidth is the sum of their bandwidths. The effective maximum power density, EPD, is a normalized power density of the collection of signals determined by the following equation.

$$EPD = 10 \cdot \log_{10}\left(\frac{\sum_x \left(BW_x \cdot 10^{\frac{\max p_x}{10}} \right)}{\sum_x BW_x} \right)$$

If both the effective bandwidth and the effective power density is less than the bandwidth rating and the power density of one of the bandwidth rated underlay masks then the combination is compliant and the computations can stop. Otherwise, these should then be adjusted to the bandwidth of the next highest bandwidth underlay and a bandwidth adjusted effective power density, BAEPD, is computed for use with this underlay mask spreading the power density to that of the bandwidth of the underlay mask.

$$BAEPD = 10 \cdot \log_{10}\left(10^{\frac{EPD}{10}} \cdot \frac{\sum_x BW_x}{BW_{mask}} \right)$$

A use is acceptable if the bandwidth adjusted effective power density is less than the restriction of an underlay mask with a reference bandwidth larger than the effective bandwidth. Note that when an underlay mask is multilevel, the power of a signal that falls in the range of a less restrictive segment of the mask is reduced to a level equally displaced from the most restrictive segment. Example computations follow.

The goals of using multiple bandwidth specific underlay masks are to provide a means to compute differences in allowed interference based on the bandwidths of signals in a method that makes compatibility computations simple. At present, there is no theory on how to create these underlay masks and doing so would likely require experiments with the modeled equipment.

Example: Determining effective power density and effective bandwidth of combinations of narrowband signals and checking for compatibility with narrowband underlay masks

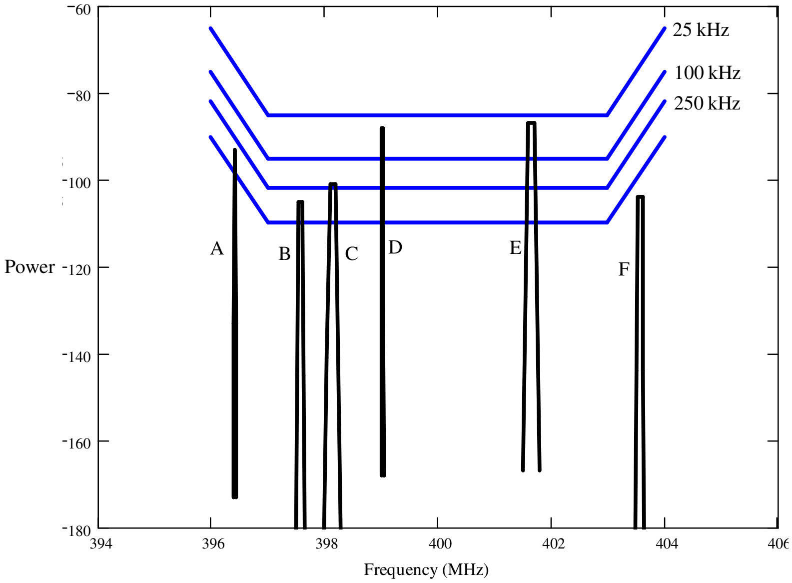

Figure 2-6. A dynamic spectrum management scenario where spectrum consumption models are used to convey spectrum authorizations and uses

Figure 2-6 illustrates the same multi-bandwidth underlay mask illustrated in Figure 2-3 and then several signals that might occur at some point in the space it applies. Table 2-2 lists the maximum power density and bandwidth of these signals.

Table 2-2. Underlay mask scenario signal characteristics

Signal	Bandwidth	Max Power Density	Signal	Bandwidth	Max Power Density
A	25 kHz	-93 dB	D	25 kHz	-88 dB
B	100 kHz	-105 dB	E	150 kHz	-87 dB
C	150 kHz	-101 dB	F	100 kHz	-104 dB

The objective is to determine which signals can coexist and be compliant with the underlay masks. We can start off by noting that signal F is beneath the base underlay mask so it is always acceptable. The signals A, B, C, and D all can exist individually since they have bandwidth and power densities beneath one of the underlay masks. Signal E has greater bandwidth and power density than the 100 kHz mask and so is not compatible. So only combinations of A, B, C, and D are considered.

Prior to computing the combined effects the effective power of signal A must be referenced to the most restrictive part of a mask. The signal A is 2 dB beneath the closest mask and the adjusted power density that is 2 dB beneath the most restrictive part of the same mask is -104 dB.

Table 2-3 lists the effective bandwidth and effective power of combinations of the signals A, B, C, and D and for those combinations that are compliant, identifies the bandwidth mask with which the compliance check was made.

Example: Determining effective power density and effective bandwidth of combinations of narrowband signals and checking for compatibility with narrowband underlay masks

Table 2-3. Assessment of underlay mask compliance of narrowband signal combinations

Signals	Effective Bandwidth	Effective Power Density	Mask Bandwidth	Bandwidth Adjusted Effective Power Density	Mask Power Density Criterion	Compliance
A, B	125 kHz	-104.8 dB	250 kHz	-107.8 dB	-102 dB	Yes
A, C	175 kHz	-101.3 dB	250 kHz	-102.9 dB	-102 dB	Yes
A, D	50 kHz	-90.9 dB	100 kHz	-93.9 dB	-95 dB	No
B, C	250 kHz	-102.2 dB	250 kHz	-102.2 dB	-102 dB	Yes
B, D	125 kHz	-94.7 dB	250 kHz	-97.7 dB	-102 dB	No
C, D	175 kHz	-95.3 dB	250 kHz	-96.9 dB	-102 dB	No
A, B, C	275 kHz	-102.3 dB	NA			No
A, B, D	150 kHz	-95.3 dB	250 kHz	-97.6 dB	-102 dB	No
A, C, D	200 kHz	-95.8 dB	250 kHz	-96.8 dB	-102 dB	No
B, C, D	275 kHz	-97 dB	NA			No

These computations show that the only signal combinations that are compatible are signals A and B, or A and C, or B and C. The signal combinations of A, B, and C and B, C, and D have effective bandwidths that exceed those of any bandwidth underlay mask and so are not feasible. The remainder have bandwidth adjusted effective power densities that exceed the criterion of the mask.

The bandwidth-time product of interference from frequency hop systems is a measure that is used together with an underlay mask to assess the harmfulness of interference from signals that interfere very briefly. A bandwidth-time product is computed using the frequency hop rated spectrum masks of interfering systems.

Let f_L and f_H be the lowest and highest frequency of an underlay mask and $\left[f_L, f_H\right]$ define the range between those frequencies. Let *S* be the set of signals that are contained within or partially extend into that range. Then the overall bandwidth time product of a system is computed as

$$BTP = \sum_{s \in S} bw_s \cdot td_s \cdot \frac{1}{tr_s},$$

where bw_s is the portion of the bandwidth of a signal that is in the underlay mask frequency range, td_s is its dwell time, and tr_s is its average revisit time. The bandwidth of a signal is the bandwidth where the mask is 20 dB below peak. When a frequency list is used, this bandwidth is applied for every signal within the range. When a signal is partially in the range then only the portion of the bandwidth that is within the range is summed. When a frequency band list is used to specify the frequency hop signal, then there is one bandwidth that is prorated by the portion of the total frequency range of the frequency band list that is also in the underlay mask frequency range.

The bandwidth time product of a collection of frequency hop signals is the sum of their bandwidth time products. In the case of multiple frequency hop signals, there is no effective bandwidth power computed. The bandwidth time product of a collection of frequency hop signals determines the mask to use and each of the signals must have a power density less than that specified by the underlay mask. An example computation follows.

Example: Determining Compatibility of Frequency Hop Systems

This example scenario considers the interference of two frequency hopping systems with the following spectrum masks on a third system with the underlay masks illustrated in Figure 2-4.

System 1

Spectrum mask: (-0.0125, -20, -0.0075, 0, 0.00750, 0, 0.0125, -20)
Frequency list: (190.0125, 190.0375, 190.0525, … , 194.9875) (i.e. signals spaced every 25 kHz starting at 190.0125 MHz and ending at 194.9875 MHz)
Dwell time: 100 µsec
Revisit time: 20 msec

System 2

Spectrum mask: (-0.025, -20, -0.020, 0, 0.020, 0, 0.025, -20)
Frequency band list: (190.0,193.5, 196.5,205.5, 211.0, 218.5)
Dwell time: 200 µsec
Revisit time: 1.0 msec

Figure 2-7 illustrates the power scenario of the interference at a location where the compatibility computation is made. The relevant individual signals of System 1 are all illustrated. Since System 2 uses a band list, the power level of the band across the illustration is shown. The signals of each system are assumed to have the same power level.

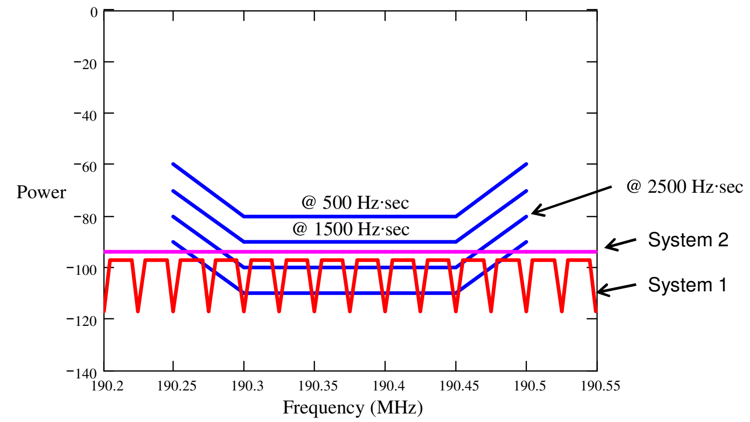

Figure 2-7. A scenario where multiple frequency hop signals are present

System 1 is compatible if its bandwidth time product is less than 1500 Hz·sec. System 2 is compatible if its bandwidth time product is less than 1500 Hz-sec. The combination is compatible if their combined bandwidth time product is less than 1500 Hz·sec. Ten signals of System 1 are within the underlay mask frequency range, so its bandwidth time product is

$$BTP = 10 \cdot 25 \text{ kHz} \cdot 100 \text{ µsec} \cdot \frac{1 \text{ sec}}{20 \text{ msec}} = 1250 \text{ Hz} \cdot \text{sec}.$$

1250 Hz·sec falls within the constraints of the 1500 Hz·sec underlay mask. In the case of System 2, the underlay mask covers 250 kHz of the 20 MHz specified in the band list. Thus the prorated bandwidth time product of frequency hop signal of System 2 is

$$BTP = \frac{250 \text{ kHz}}{20{,}000 \text{ kHz}} \cdot 50 \text{ kHz} \cdot 200 \text{ µsec} \cdot \frac{1 \text{ sec}}{1 \text{ msec}} = 125 \text{ Hz} \cdot \text{sec}.$$

125 Hz·sec easily falls within the constraints of the 500 Hz·sec mask. The sum of the bandwidth time products of these two systems is 1375 Hz·sec and since this product and the power levels of all the signals are within the constraints of the 1500 Hz·sec underlay mask, the combination of System 1 and System 2 is also compatible.

Despite the level of emphasis in this discussion about using multiple bandwidth specific underlay masks, most modeling of RF systems, however, will use a single underlay mask with no bandwidth specific underlay masks. Any signal that is beneath this underlay mask would be compatible. That is the only computation that would need to be made.

2.1.4 Propagation Map

The propagation map specifies a rate of attenuation by direction. This rate is specified using a single parameter, the exponent of the log-distance pathloss model. Discussion of the log-distance pathloss model follows in the next section. The map data structure that enables the specification of values by direction is described later in Section 2.1.4.2.

2.1.4.1 Rationale

The goal of including a propagation model in a spectrum consumption model is to account for the attenuation of RF emissions and so the location based differences in signal strength of a signal being generated by the same source. RF emissions attenuate as they propagate away from their source. The quantity of attenuation is a function of frequency, distance, and the environment. On account of the rich diversity of environmental effects, there is no shortage of propagation models in the literature since no single model can do it all. Precise prediction of attenuation is usually untenable since total attenuation can vary significantly by slight movements and subtle changes in the environment. The model chosen in engineering is typically that which best supports the specific task. In spectrum consumption modeling the propagation model needs to capture attenuation trends but result in tractable computations for spectrum reuse. The model chosen for this purpose is the log-distance pathloss model [3]. The log-distance pathloss model decreases monotonically at a rate specified by a single parameter. It is compact and allows tractable computations.

The log-distance pathloss model is a linear model in which pathloss is a function of distance related by $PL(d) = PL(1m) + 10n\log(d)$ on a logarithmic scale and is related by $PL = PL_{1m}d^n$ on a linear scale, where the parameters of the model are the pathloss PL_{1m} of the first meter and the pathloss exponent *n*. The PL_{1m} term accounts for the frequency effects on attenuation, the distance term accounts for the effect of distance, and the pathloss exponent, *n*, accounts for the environment. In the log-distance pathloss model, a pathloss exponent of 2 corresponds to the freespace pathloss model, i.e., Friis equation, and larger exponents are used in terrestrial models where reflected signals are likely to result in destructive interference and where other environmental effects contribute to further signal attenuation.

The use of the log-distance pathloss model is a significant feature of modeling. Typically, spectrum management tools use propagation models that depend on having an accompanying terrain database, for example the Terrain Integrated Rough Earth Model (TIREM) uses Digital Terrain Elevation Data (DTED). These models consider the locations between transmitter and receiver and the terrain in between. Other models, say for urban propagation effects, may consider the surface effects of manmade structures. Using these models require having a current database of the structures. A goal in modeling is to remove this dependence on external databases and so simplify propagation computations and enable interoperability of tools and systems. The pathloss exponent of the log-distance pathloss model is typically determined empirically. Thus propagation models that use environmental data such as terrain and structure

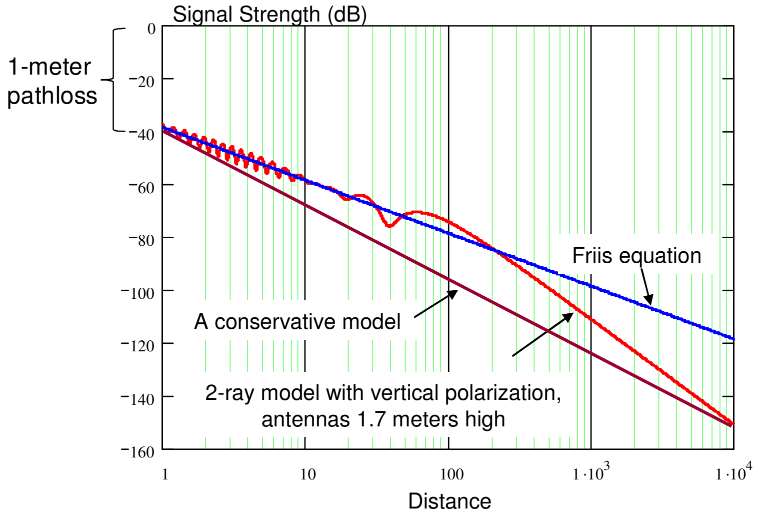

Figure 2-8. Examples of propagation model predictions graphed on a log-log plot.

databases might be part of the tool sets that a modeler uses to select appropriate pathloss exponents for the propagation map.

Figure 2-8 illustrates several propagation models on a dB versus the log of distance plot. Free space attenuation is captured by Friis equation which is linear on this plot. The 2-ray model demonstrates some oscillations but still has linear trends. The conservative model demonstrates a log-distance pathloss model that provides a bound to the 2-ray model. This illustration demonstrates that attenuation has a linear trend on these scales and, where attenuation is a little more complex, a linear model can still be used to provide a bound on the effects.

2.1.4.2 Data Structure

The data structures that are used to specify parameters by direction are referred to generally as maps. A map is a vector that lists azimuths, elevations, and the model parameters in a prescribed order so there is no ambiguity as to which elements in the vector represent what type of value. A complete map will specify a model parameter toward all directions. The vector of values starts with elevations (ϕ) from the vertical down direction 0° and reaching to the vertical up direction 180°, and azimuths (θ) reaching about the node on the horizon. The first and last azimuths point in the same direction, i.e. 0° and 360°. The vector uses two elevations to define a spherical annulus about a node and then a series of parameters and azimuths that specify different parameters on that annulus by sector. One or multiple annuluses are defined ultimately to define parameters for all directions. The number and spacing of elevations and azimuths that are listed in the vector is arbitrary and used as necessary to provide resolution. The form of the vector is $\left(0°,0°,n_{0,0},\theta_{0,1},n_{0,1},\theta_{0,2},\ldots,360°,\phi_1,0°,n_{1,0},\theta_{1,1},\ldots,360°,\phi_2,0°,n_{2,0}\ldots,n_{last},360°,180°\right)$. Figure 2-9 illustrates an interpretation of this vector. The vector starts in the 0° elevation and the 0° azimuth, and an annulus is specified for each pair of elevations and so from 0° to ϕ_1 and from ϕ_1 to ϕ_2 and so on. These elevations bound a series of values alternating between model parameters and azimuths. Each model parameter $n_{x,y}$ applies to the sector that reaches from elevation ϕ_x to ϕ_{x+1} and from azimuth $\theta_{x,y}$ to $\theta_{x,(y+1)}$. For example, in Figure 2-9, the model parameter $n_{1,0}$ applies from elevation ϕ_1 to ϕ_2 and from azimuth 0° to $\theta_{1,1}$.

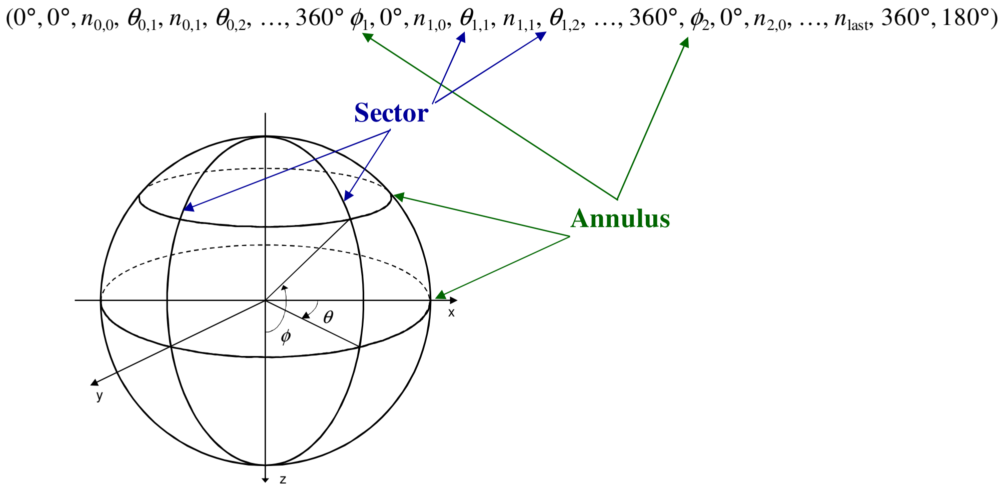

Figure 2-9. Example of the map vector used in propagation map and power map modeling.

Since $\theta = 0°$, $\theta = 360°$, $\phi = 0°$, and $\phi = 180°$ appear predictably in the map vector, most can be dropped. The convention for writing these vectors is to drop the leading zeroes and then to use zero to represent the $360°, 180°$ sequence and terminate the vector. The only zero angle value in the reduce vector format is the last value and so indicates the end of the vector. The general form of the reduced vector is $\left(n_{0,0}, \theta_{0,1}, n_{0,1}, \theta_{0,2}, \ldots, 360°, \phi_1, n_{1,0}, \theta_{1,1}, \ldots, 360°, \phi_2, n_{2,0} \ldots, n_{last}, 0°\right)$. The map vectors are variable in length depending on the resolution desired. When there is just one value specified for all directions the reduced vector has only two values, $\left(n_{0,0}, 0°\right)$.

Using maps in spectrum consumption models require that they have a reference location and an orientation to the physical environment. Propagation maps are oriented based on the geographic location of its center. The horizon of the map is considered parallel to the plane tangent to the earth's surface with the 0° azimuth pointing north and the 90° azimuth pointing east. Azimuths progress clockwise. So this is similar to measuring directional azimuths in land navigation. The elevations, however, are different. Typically, elevations are measured from the horizon rather than from the nadir as is done with the maps. The conversion between the two is very simple,

$$\phi_{map} = \phi_{nav} + 90°$$

where ϕ_{map} is the elevation used in the map and ϕ_{nav} is the elevation used in navigation. The coordinate systems and the methods for computing directions and distances are described in Section 2.1.8.2. The transformations between coordinates systems are described in Appendices F and G.

Pathloss modeling usually does not attempt to capture the nuances that differentiate propagation as transmitters or receivers move. Rather, the propagation map is made more conservative using smaller exponents and using less differentiation by direction. The intent is to accept a worse case that ensures compatibility. If location differences can be exploited to enable more reuse, the modeler has the choice of subdividing the model into multiple parts, each with different locations so that different propagation models may be used.

2.1.4.3 Units

The angles in the propagation map all have units of degrees and are presented in a decimal format as opposed to a <degrees, minutes, seconds> format. The exponents are dimensionless and typically have values between 2 and 10, however, there is no restriction on the values.

2.1.4.4 Dependencies

The determination of a pathloss exponent is a simple lookup in the propagation map. The example below demonstrates a possible search algorithm.

The computation of location specific signal strengths using the models requires the coordinated use of the propagation map, the maximum power density, the power map, and the spectrum mask. The log-distance model is generally considered to be an unreliable predictor of pathloss due to the wide variance in pathloss that occurs due to shadowing and multipath fading. Nevertheless, in spectrum consumption modeling, the log-distance pathloss model possess advantages over comparable models, including the simplicity of the model and because the model provides a monotonic trend it leads to tractable computations of compatible reuse. The variance in signal strength caused by fading and shadowing is accommodated by the protection margin of the spectrum consumption model created by choosing a larger one meter pathloss term, a smaller exponent, or increasing the relative difference of the power levels in the underlay masks of the model.

An example computation of a location specific power density follows the discussion of the power map.

Example: Determining the pathloss exponent for a direction

Determining the directional pathloss exponent involves a simple search through the propagation map. The meanings of the numbers in the propagation map are implied by their location in the map and by their values. The pseudo code algorithm that follows is an example. Here the algorithm first finds the elevations that bound the direction and then the azimuths and returns the value between the azimuths or the last value if the end of the vector is reached.

Let c be the length of the power map P.
Define ϕs to be the index to a start elevation, ϕe to be the index to an end elevation and θs to be an index to an azimuth

```
$\phi s = -1, \phi e = c, i = 1$
while $i < (c-1)$
    if $P_i == 360$
        if $P_{i+1} \le \phi, \phi s = i+1, i = i+1$
        else $\phi$e=i+1, break
    $i = i+2$
$\theta s = \phi s + 2$
while $\theta s < \phi e$
    if $P_{\theta s} > \theta$, return $P_{\theta s-1}$
    else $\theta s = \theta s + 2$
return $P_{\theta s-3}$
```

Example: Find the pathloss exponent in the direction $\theta = 38°$, $\phi = 95°$, given the propagation map (4, 360, 85, 2.2, 30, 2.1, 270, 2.2, 360, 110, 2.3, 0).

So in this example this algorithm would find the propagation map elevations of 85° and 110° to bind the elevation of 95° and the power map azimuths of 30° and 270° to bind the azimuth of 38° and would then return the value of 2.1.

2.1.5 Power Map

The power map specifies the directional values of the transmitted power density relative to the maximum power density of the model. It uses the same map data structure as used for the propagation map but the directional values are powers rather than pathloss exponents These values, together with the maximum power density, indicate the signal strength one meter from an antenna, $RP(1m)$, for a far field computation of signal strength using the following version of the log-distance pathloss model:

$$RP(d) = RP(1m) - 10n\log(d)$$

In this model, $RP(d)$ is the signal strength at distance d and n is the pathloss exponent for the same direction obtained from the propagation map.

2.1.5.1 Rationale

Power maps attempt to capture the directional transmission characteristic of a system. Transmit power may vary directionally because of directional antenna effects or because of local obstruction. Local obstruction includes the effects of platform mounting (e.g. an antenna mounted on the belly of an aircraft may have less gain in a direction above the aircraft) and proximate independent structures (e.g. a building that is close to the antenna).

2.1.5.2 Data Structure

The power map data structure is similar to that of the propagation map but with the directional value being a power level. It is most desirable for a power map to have the same orientation as that of the propagation map of the model since this simplifies computations. These power map orientations are platform independent. *This orientation should be used in most modeling.* However, there are specific scenarios where the orientation is best referenced to that of a platform. In this case, we assume that the starting reference matches that coordinate system of the platform and then coordinate rotations are used to reorient the antenna from that reference. Figure 2-10 illustrate the standard platform coordinate system where the x axis is coincident with the normal direction of travel of a platform (e.g. coincident to the fuselage of an aircraft) that the y axis is perpendicular to and to the right of that direction and generally parallel to the horizon (e.g. parallel to the wings of an aircraft) and that the z axis points towards the earth. The antenna may then be displaced from this orientation by rotating the axis first about the z axis by an angle of rotation α, then the y axis by an angle of rotation β, and finally the x axis by an angle of rotation γ. Thus the orientation of the power map is conveyed in the 3-tuple $<\alpha, \beta, \gamma>$. Details about how to compute rotations of coordinate systems and to convert directions between coordinate systems are described in Appendix E. An additional feature that is available for power map modeling is to define a point towards which the vertical axis of a power map points

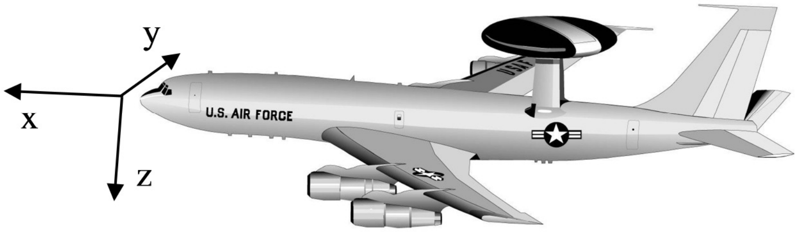

Figure 2-10. Example platform coordinate systems

as it moves. The purpose of this modeling approach is to account for the benefits of using directional antennas that can point to a specified stationary transmitter or receiver even while the system moves.

2.1.5.3 Units

The angles in the power map all have units of degrees and are presented in a decimal format as opposed to a <degrees, minutes, seconds> format. The power terms are relative to the maximum power density and have units of dB. The angles in the 3-tuple <α, β, γ> all have units of degrees. The point location used in this model is described in Section 2.1.8.1.1

2.1.5.4 Dependencies

The determination of the transmit power density by direction uses both the maximum power density and the power map. The following example demonstrates searching for a value in a map and computing the power density in that direction at some distance.

Example: Determining the power density from a transmitter

Given a maximum power density, 10 dBw, a spectrum mask (400,-30,401,-10,402,-10,403,-30), a propagation map (7,360,85,2.3,360,110,2,0), and a power map (-20,360,70,0,360,110,-20,0) determine the power specified by the model at a point at a distance of 6500 meters at an azimuth of $\theta = 100°$ and an elevation of $\phi = 10°$.

The 1-meter power density at the transmitter is 0 dBW. This power is the sum of the maximum power density of the model and the maximum gain of the spectrum mask, 10 dBW + (-10 dB). The power map specifies 0 dB at the specified azimuth and elevation and the pathloss exponent is 2.3. The distance based power is easily determine as

$$RP(6500) = 0 \text{ dBW} - 10 \cdot 2.3 \cdot \log_{10}(6500) \text{ dB} = -87.7 \text{ dBW}$$

Figure 2-11 illustrates a surface plot of the range of the combined power and propagation map to the threshold power of -110 dBW.

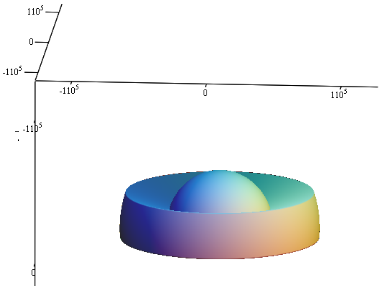

Figure 2-11. Surface plot of the range to a -110 dBW threshold for the example scenario

2.1.6 Intermodulation (IM) Masks

Intermodulation masks convey the susceptibility of transmitters or of receivers to generating IM products from externally received signals.[5] The IM products of transmitters are transmitted and cause interference at distant receivers on adjacent channels to that of the transmitter. The IM products of receivers result in interference within the receiver. IM masks are optional

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[5] Intermodulation distortion that occurs within a radio from the signals the radio is generating should be captured in the spectrum masks of these systems. The IM masks model intermodulation involving externally generated signals.

components of spectrum consumption models and are used when radios are known to generate harmful IM products. As all constructs, they are designed to provide a bound to a spectrum effect, in this case the ill effects of IM.

The IM masks identify the frequencies of signals that are likely to be combined into IM products and how they would be amplified in that process. Transmitters have two types of masks. The first specifies the frequencies of signals that are likely to combine. Incoming signals may be reshaped by this mask. The second identifies the frequency dependent amplification at the transmitter of the IM output. This mask may also shape the output. Receivers only use one IM mask which identifies both the frequencies of signals likely to create IM and also their likely amplification. These masks may also shape the inputs. Analysis of receiver IM is only concerned with those IM products that would interfere with a signal it tries to receive. In addition to using separate masks for receivers and transmitters, separate sets of masks are also used for different order IM products when different order IM is possible.

2.1.6.1 Rationale

Intermodulation products are created in the non-linear components of systems. Signals combine in these components and generate new signals at frequencies that are sums and differences of the fundamental and harmonic frequencies of the inputs. For example, say the frequencies of the signals that combine are f_1 and f_2, $f_1 > f_2$, then the possible second order IM products are $2f_1$, $2f_2$, $f_1 + f_2$, and $f_1 - f_2$. The possible third order products are $3f_1$, $3f_2$, $2f_1 + f_2$, $f_1 + 2f_2$, $2f_1 - f_2$ and $2f_2 - f_1$.[6] The IM products that are of most interest are those that are close to the passband of the radios which typically are those that are odd order. Second order IM products may be of interest in cases of passive IM at transmitters such as IM that may occur in the non-linear components of high power antennas. In the case of passive IM, one of the frequencies is that of the transmitter carrier. At receivers, the combining signals are external to the receiver.

The output power of IM products is an attenuated product of the inputs. The relevance of this observation is that the output power is proportional to the sum of the dB powers of the combining signals. If the power of each of the input signals of a third order IM product were to increase 10 dB then the power of the output IM product would increase 30 dB.

The bandwidth of an IM product can be as broad as the combined bandwidths of the signals that intermodulate together. Thus the assumption of the model is that the bandwidth is this sum unless reduced as shaped by the IM masks.

Typically, the signals that will combine in the non-linear components of radios are strong and close to the operating frequencies of the transmitters and receivers within which they combine. The motivation for modeling IM is to identify the systems that are susceptible to IM so that spectrum assignments can be made to avoid IM generation that is harmful. IM occurs most frequently when transmitters and receivers come close to each other.

The primary scenarios that IM modeling attempts to address are:

Co-location of susceptible radios on the same platform,
Co-location of susceptible radios in the same device, and
High power transmitters that are prone to generating IM in passive components.

The platform name modeling construct is used to identify when different systems are co-located on a platform or in a device. IM modeling is not so concerned about mobile systems that by

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[6] If $f_1 > 2f_2$, then the third order product $f_1 - 2f_2$ would be possible and $2f_2 - f_1$ would not be.

happenstance come in proximity to each other. Although some factor of risk might be associated with this event, this type of occurrence of IM is likely rare and when it does occur is short lived as systems eventually move apart from each other. Spectrum managers may use spectrum consumption models to mitigate this risk but a risk value is not an inherent aspect of spectrum consumption but of operational use. As such, spectrum planning tools may want to provide a means for spectrum managers to assess the ramifications of this risk.

2.1.6.2 Data Structure

Intermodulation masks are specified using a variable length vector of real values alternating between frequency and power density of the form, $\left(f_0, p_0, f_1, p_1, \cdots f_x, p_x\right)$, with each sequential pair specifying an inflection point in the mask. Odd numbered terms in the vector are frequencies and even number terms are powers. There are two types of IM masks input IM masks and output IM masks. Input masks shape incoming signals and convey how the signals combine with each other providing an IM product power that is a function of the input signal powers. This value is used directly in receivers as the IM product power at the receiver. Output masks are used with transmitters to convey how the combined signal, the IM product, is amplified in transmission.

Developing IM masks for a radio involves testing systems for IM distortion and measuring the effect. A possible concern in modeling is that susceptibility to IM occurring among co-located radios is a function of the platform on which they are mounted as the platforms provide some shielding. It may be necessary in models to associate IM masks with specific radios of a system rather than to the radios in general. The following platform name construct attempts to identify platforms where radios are located and so in turn identifies specific radios where IM is most likely because of their co-location with systems that may use similar spectrum. If multiple types of radios are employed in the same subnet and have different IM characteristics, it may be necessary to create multiple transmitter and receiver models, one for each type of radio, each with their own IM masks and platform names.

2.1.6.3 Units

Frequency terms in the underlay mask are in MHz and power terms are in dB. The dB level is applied to the sum of powers of the intermodulating signals.

2.1.6.4 Dependencies

The computation of IM products depends on all previously mentioned spectrum consumption modeling constructs, the platform name, and location. The computation starts by determining the signals of interest that arrive at the device that creates IM products. The strength of these signals are computed using the model constructs of the sources including the maximum power density, the spectrum mask, the propagation map, and the power map. The strength and shape of the signal arriving at the intermodulating device has the shape of the spectrum mask and a power level that accounts for the effects of the maximum power density, the power map and the attenuation that occurs in propagation according to the dominant propagation map.[7] When IM products are formed from the signal of a co-located transmitter then the one meter amplitude is the power of the arriving signal. At transmitters, the arriving signal is then shaped and

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[7] When propagation can be computed using the propagation map of two different systems the worst case propagation is chosen. Since we are concerned with the generation of interference, the values that result in the worst interference are worst case and so smaller pathloss exponent value of the two system is the dominant pathloss.

attenuated by the input IM mask, the IM products are computed, and then the product is amplified by the output IM mask. This signal is an input to the power map of the transmitter model and the distant interference is computed as one would a signal strength using the power map and propagation map of the IM source transmitter. At receivers, the arriving signals are shaped and attenuated by the input IM mask and the in-band IM products are computed. If the strength of the IM product exceeds that of the underlay mask as adjusted by the receiver power map, then the IM product is harmful.

An approximation of the shape of the IM product is created from the shaped inputs. They are combined by placing the relatively flat portions of the shaped input masks end-to-end to create a broader bandwidth IM product. The trail off is a combination of the trail off at the edges of the input signals and is extended to 40 dB below the flat portion. The amplitude of the flat portion is the sum of the dB amplitudes of the inputs adjusted by the input IM mask level. When a transmitter's signal is one of the signals combined in the intermodulation, the amplitude used is that at the one meter point distance just prior to propagation.

Examples of determining the IM products and assessing whether they cause harmful interference for both a transmitter and a receiver follow.

Example: Determining passive IM interference caused by a transmitter

Given a transmitter IM input mask (35, -20, 65, 0, 120, 0, 130, -20) and IM output mask (30, -120, 60, -100, 180, -100, 200, -120) for second order passive IM at a transmitter, determine the shape and strength of the transmitted IM product at the transmitter prior to propagation.

The following are the characteristics of the transmitter signals.

Transmitter at the IM source
Maximum power density: 60 dBW
Spectrum mask: (88.4, -60, 88.42, 0, 88.58, 0, 88.6, -60)
Propagation map: (2, 0)
Power map: (0, 0)

Neighboring Transmitter
Maximum power density: 10 dBW
Spectrum mask:(87, -60, 87.02, 0, 87.18, 0, 87.2, -60)
Propagation map: (2.1,0)
Power map: (-20, 360, 50, 0, 360, 130, -20, 0)

The neighboring transmitter is displaced 10 meters from the IM source.

There are four steps to determining the passive IM output.

Step 1. Determine the strength of the signals at the source of intermodulation

In this case the signal of the IM transmitter has the same power that it uses for transmission so is specified by the combination of the maximum power density and the spectrum mask. The power of the neighboring transmitter signal is determined by the separation distance and the

Example: Determining passive IM interference caused by a transmitter (continued)

propagation and power map effects. The distance is 10 meters, the maximum power density is 10 dBW, the pathloss exponent is 2.1, and the power map power is 0 dB. The maximum power density of the arriving signal at the IM source is computed as

$$RP(10) = 10 \text{ dBW} - 10 \cdot 2.1 \cdot \log_{10}(10) \text{ dB} = -11 \text{ dBW}$$

Step 2. Shape the intermodulating signals

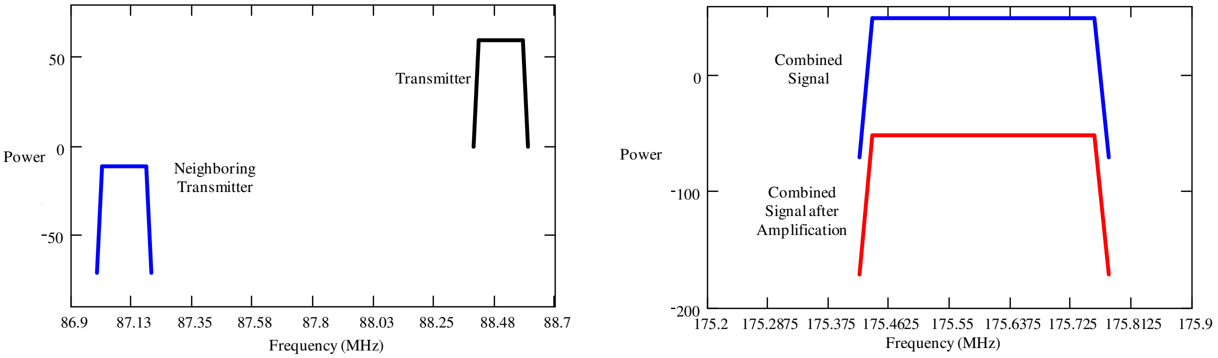
The input IM mask shapes both the transmitter signal and the signal from the adjacent transmitter. In this case the shaping has no effect on the power levels of the signals. The resulting masks of the shaped signals are:
Spectrum mask S1: (88.4, 0, 88.42, 60, 88.58, 60, 88.6, 0)
Spectrum mask S2: (87, -71, 87.02, -11, 87.18, -11, 87.2, -71)
These shaped signals are illustrated in Figure 2-12a.

Step 3. Combine the intermodulating signals in an IM product

The IM product has the combined bandwidth of the IM signals and a combined trail-off at the ends. The spectrum mask of the intermodulated signal before amplification is (175.42, -71, 175.44, 49, 175.56, 49,175.58, -71) and is illustrated in Figure 2-12b.

Step 4. Amplify the IM product by the output IM mask

The output IM mask operates on the combined signal. Here, the IM product is beyond the linear portion of amplification and so the combined signal is slightly distorted. Its spectrum mask is (175.42, -171.34, 175.44, -51.35, 175.56, -51.61,175.58, -171.62) and is illustrated in Figure 2-12b.



a. The input signal prior to intermodulation

b. The intermodulation product before and after amplification

Figure 2-12. Inputs and outputs of the second order passive IM example

Example: Determining IM interference created within a receiver

Given an IM input mask (79, -45, 80, -25, 81, -25, 82, -45) for third order IM at a receiver and a receiver underlay of (80.5, -80, 80.505, -100, 80.52, -100, 80.525 -80), determine the shape and strength of the IM product at the receiver.

Example: Determining IM interference created within a receiver (continued)

The following are the characteristics of two transmitter signals of transmitters co-located with the receiver of the given IM input mask.

Co-located Transmitter1
Maximum power density: 6 dBW
Spectrum mask: (80.225, -20, 80.23, 0, 80.245, 0, 80.25, -20)
Propagation map: (2.1, 0)
Power map: (-20, 360, 50, 0, 360, 130, -20, 0)

Co-located Transmitter 2
Maximum power density: 6 dBW
Spectrum mask: (79.95, -20, 79.955, 0, 79.970, 0, 79.975, -20)
Propagation map: (2.1,0)
Power map: (-20, 360, 50, 0, 360, 130, -20, 0)

Since the radios are co-located the maximum power density of the signals that are intermodulated is that of their 1 meter power level.

There are then two more steps to determining the IM output to the receiver.

Step 1. Shape the intermodulating signals

The input IM mask shapes both transmitter signals and attenuates them. The resulting masks of the shaped signals are:
Spectrum mask S1: (80.225, -39, 80.23, -19, 80.245, -19, 80.25, --39)
Spectrum mask S2: (79.95, -40, 79.955, -19.9, 79.970, -19.9, 79.975, -39)
These shaped signals are illustrated in Figure 2-13

Step 2. Combine the intermodulating signals in an IM product

The IM product has the combined bandwidth of the IM signals and a combined trail-off at the ends. The intermodulation products of interest are $2f_1 - f_2$ and $2f_2 - f_1$. The mask of these two IM products are (80.5, -118, 80.505, -57.9, 80.55, -57.6, 80.555, -117.5) and (79.675, -119, 79.68, -58.8, 79.725, -58.2,79.73, -118). They are illustrated in Figure 2-13.

The results show that the IM product $2f_1 - f_2$ is above the underlay mask of the victim receiver and would cause interference.

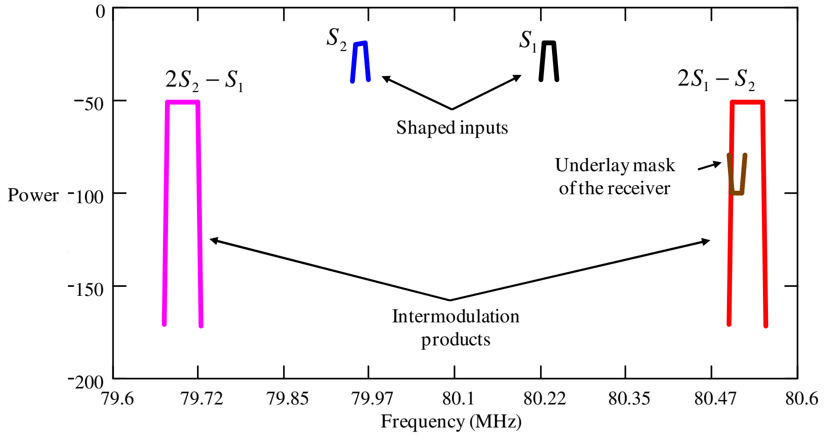


Figure 2-13. Inputs and outputs of the third order receiver IM example

2.1.7 Platform Name

The platform name construct is used to identify devices or platforms that individual transceivers or receivers of a system are placed. It may be used to identify a particular platform or device or a particular class of platform or device. As an example, Vehicle #27 would be a particular platform and "2-41 Company Command Vehicle" would be a class of platforms.

2.1.7.1 Rationale

Transceivers of systems are often combined on the same platform or in the same device, in which case they are more susceptible of interfering with each other either through adjacent frequency or IM interference. This construct is used to tag when different systems are co-located so these occurrences of interference can be considered and mitigated. Checking for receiver IM is restricted to systems that are co-located.

2.1.7.2 Data Structure

The data structure for the platform name is a string. The requirement is that the platform or device name be unique.

2.1.7.3 Units

Not applicable.

2.1.7.4 Dependencies

Systems that have common platform names are given greater scrutiny for IM and adjacent frequency interference. It is assumed that these systems are so close to each other physically that signals between systems do not attenuate on account of propagation and so are more likely to be issues in processes that search for and assign channels. The typical processing will identify systems or collections of transmitters and receivers that are on common platforms or in common devices. Systems that are on common platforms or devices will undergo this scrutiny.

2.1.8 Location

The location construct of a spectrum consumption model conveys where the components of the RF system being modeled may be used. Locations may be specified as points, areas, volumes, or tracks. When non-point locations are used it indicates that the RF components are mobile and may be located anywhere on the area or in the volume specified. All locations are referenced to a geospatial datum with coordinates given as a longitude, latitude, and altitude.

2.1.8.1 Rationale

The purpose of location modeling is to specify the limits of the space in which the components of an RF system may be located so that compatibility of uses may be computed. Generally, modeling seeks to define a location that best reduces the uncertainty in the locations of the RF components. Location is a required component of all models.

The common datum for spectrum consumption models is the World Geodetic System – 1984 (WGS 84). WGS-84 defines an earth-centric ellipsoid datum that can be used for locations across the world. Details of this datum are described in Appendix D. Spectrum consumption models do not model terrain and where appropriate terrain effects should be captured in the propagation maps and power maps of spectrum consumption models. The assumption in modeling is that the strength of interfering signals at distant receivers can be computed using the models alone. The purpose of this assumption is to remove the need for detailed terrain and propagation models and the complexity they incur from the process of computing compatibility. Models of terrain and propagation may be used in the development of spectrum consumption models but what is learned by using these tools must be captured in the constructs of the spectrum consumption model. Since models of terrain are not used in spectrum consumption model compatibility computations, conveying locations referenced to the WGS-84 coordinate system is sufficient for computing compatibility. Guidance on converting between coordinate systems of different datum is described in Appendix G.

A small set of methods have been chosen to specify locations that provide sufficient versatility to capture typical types of RF component locations. They are defined in the following subsections.

2.1.8.1.1 Point

The point location is the most restrictive of the location models specifying an unmovable location for a component for the duration of the model.

2.1.8.1.2 Terrestrial Surface Area

A terrestrial surface area may be specified in one of two ways, either as a point and a radius or as a series of points that together form a convex polygon on the surface of the earth. When a point and radius is used it is assumed that all points on the locus have the same altitude as the center. When a series of points are used, the altitude of the points on the edge of the area are interpolated based on the altitudes and separation distance of the end points. When computations involve points in the interior of the convex polygon, the altitude is the average of the points specified in forming the model. Most computations of compatibility will use points on the edges. When the area of use can be confined to a space that is inefficient to specify in a single polygon it is possible to subdivide an area of use into multiple polygons.

2.1.8.1.3 Cylinder

A cylinder is specified using three components, a point location, a radius, and a height. The point location is at the base of the cylinder closest to the earth. It is assumed that the planar surfaces of the cylinder are planes parallel to the tangent plane to the ellipsoid at the reference point of the cylinder.

2.1.8.1.4 Polyhedron

A polyhedron is a volume created by specifying a height with a convex polygon. The points of the polygon are assumed to be on the surface of the earth. This technique is used when the volumes are small enough to allow a flat earth approximation. In the flat earth approximation the base and top of the polyhedron is assumed to be flat. The approximation assumes the base's altitude is the lowest altitude of the vertex points of the polygon and the top surface's altitude is the highest altitude of the vertex points plus the height of the polyhedron.

2.1.8.1.5 Track

A track may be used for mobile and stationary objects. A track consists of a point location, a heading, and a velocity. The platform on the track is located at the point at the start time of the model and at a time into the future the location is computed using the heading, velocity, and time of travel. The heading gives explicit information on direction of the platform. Tracks with no speed can be used as a method to specify the pointing of antennas from a stationary object although the preferred method is to use a platform independent power map.

2.1.8.2 Data Structure

Points are specified with the 3-tuple of longitude, latitude, and altitude, $\langle \lambda, \varphi, a \rangle$. Altitude is referenced to the surface of the datum ellipsoid and is measured on the prime vertical. Figure 2-14 illustrates an Earth ellipsoid, the reference for these values, and the directions for positive rotation and altitude. The altitude value of "a" is different than the value of the major axis of an ellipsoid also labeled as "*a*" in this illustration. A circular surface area is specified with four values of longitude, latitude, altitude, and radius, $\langle \lambda, \varphi, a, r \rangle$, and a polygon surface area is specified as a series of points in a vector, each point specified with three values, $(\lambda_0, \varphi_0, a_0, \lambda_1, \varphi_1, a_1, \ldots, \lambda_{n-1}, \varphi_{n-1}, a_{n-1})$. The assumption is that these points are listed in the order that they are connected and that the last point connects to the first. The cylinder is specified as the circle surface area but with one additional value for height, $\langle \lambda, \varphi, a, r, h \rangle$. The polyhedron is specified as a polygon surface area but with the addition of a height value, $\langle (\lambda_0, \varphi_0, a_0, \lambda_1, \varphi_1, a_1, \ldots, \lambda_{n-1}, \varphi_{n-1}, a_{n-1}), h \rangle$. Tracks are specified by giving a point location, a heading, and a velocity. Headings are specified by an azimuth and elevation referenced to the earth's surface coordinates that apply to the point. (See Appendix E for the description of the different coordinate systems.) The complete data structure of a track is $\langle \lambda, \varphi, a, \theta, \phi, v \rangle$.

2.1.8.3 Units

The units of longitude and latitude are degrees decimal. The <degrees, minutes, seconds> 3-tuple is not used. Altitudes, heights, and radii are all specified in meters. The velocity of platforms used in tracks is given in kilometers per hour.

2.1.8.4 Dependencies

Computations depending on location are the most important in determining compatibility since

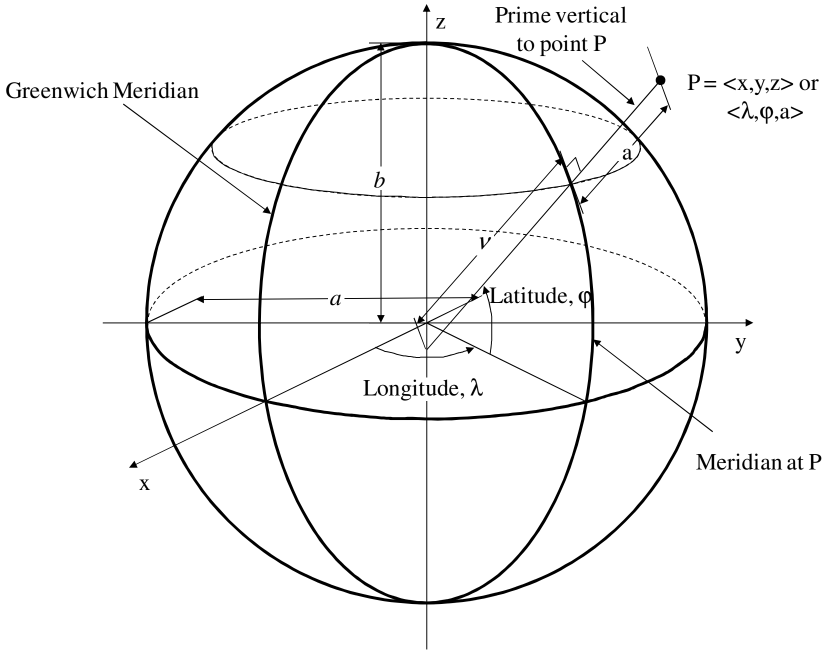


Figure 2-14. An Earth ellipsoid datum and the references for point locations

signal strength in these computations depends on distance-based attenuation. Given two points, the separation distance is Euclidean, the line of sight distance between them. Remember that terrain effects should be captured within the models and there is no need to consider terrain when using the models to compute compatibility. Computing Euclidean distance between two location coordinates involves a coordinate conversion from the WGS-84 ellipsoid coordinates to Earth centered Cartesian coordinates and then using a Euclidean distance computation:

$$d = \sqrt{\left(x_2 - x_1\right)^2 + \left(y_2 - y_1\right)^2 + \left(z_2 - z_1\right)^2}$$

The method for converting WGS-84 coordinates to Cartesian coordinate is described in Appendix G.

The harder set of computations that are at the heart of using spectrum consumption modeling is determining which points in the spaces defined by a pair of models offer the greatest constraint between modeled uses. The specific points are dependent on direction and the parameters for pathloss and power in the propagation and power maps for the directions between them. Searching for and identifying these points can be quite complex. Section 3.2 describes compatibility computations and the role of searching for the constraining points. Algorithms for identifying constraining points between models are described in (*Research in this area is ongoing and will be documented in a separate report which we will identify in the final edition of this manual.*).

2.1.9 Start Time

The start time is the time that a model begins to apply. The start time may also be used to define a periodic use of spectrum that begins with the start time.

2.1.9.1 Rationale

Increasing the reuse of spectrum requires subdividing the use of spectrum in time and so specifying the duration that a swath of spectrum is used. The start time in a spectrum consumption model is the beginning of the period that the model applies. Included in the start time is a description of any periodic use of a model. The periodic use is defined by a period that a model is on and then a period that it is off. It is assumed that these on-off periods alternate until the end time of model. This definition provides support easy specification of spectrum uses that are periodic and persist such as models that might be associated with orbiting satellites or radio stations that have different models based on the time of day.

2.1.9.2 Data Structure

Start times include year, month, day, hour, minute, and second with an hour and minute displacement from the Coordinate Universal Time (UTC). The format for start time is $\left\langle YYYY, MM, DD, hh, mm, ss.s, \pm hh_o, mm_o \right\rangle$. In addition to a time of day, the start time data structure may optionally specify a cyclical period of on-off events for the spectrum use. This data structure specifies three sets of durations $\left\langle duration_d, duration_{on}, duration_{off} \right\rangle$ where $duration_d$ identifies the time displacement from the models start time that the first on period begins, $duration_{on}$ specifies the duration of on periods and $duration_{off}$ specifies the duration of off periods. The on and off periods alternate until the end time of the model.

2.1.9.3 Units

YYYY is the Gregorian year, *MM* is the integer number of the month in the year, *DD* is the day of the month, *hh* and hh_o are integer numbers of hours on a 24 hour clock, *mm* and mm_o are an integer number of minutes less than 60, and *ss.s* is a decimal number of seconds less than 60. The combination $\langle hh, mm, ss.s \rangle$ indicates the time of day and the combination $\langle \pm hh_o, mm_o \rangle$ indicates the timezone. The duration elements use the ISO 8601 extended format of P*n*Y*n*M*n*DT*n*H*n*M*n*S where *n*Y is the number of years, *n*M is the number of months, *n*D is the number of days, *n*H is the number of hours, *n*M after the T value is the number of minutes, and *n*S is the number of seconds. The P designator is always present. The T designator is only used when one of the time elements of hours, minutes, or seconds is present. The duration of one day would be written P1D. The duration of one hour would be written PT1H. The duration of one month and one minute would be written P1MT1M. Durations are assumed positive unless preceded by a negative sign before the P designator in which case there is a negative duration.

2.1.9.4 Dependencies

The computations of whether two uses of the same spectrum are compatible are required when their models overlap in time. This is true if the start time of one model falls within the start and end time of the second or their start times coincide.

2.1.10 End Time

The end time is the time that a model stops applying.

2.1.10.1 Rationale

The end time is the second half of a duration model and identifies when the model ceases to apply.

2.1.10.2 Data Structure

End times provide year, month, day, hour, minute, and second with an hour and minute displacement from the Coordinate Universal Time (UTC). The format for the end time is $\langle YYYY, MM, DD, hh, mm, ss.s, \pm hh_o, mm_o \rangle$.

2.1.10.3 Units

YYYY is the Gregorian year, *MM* is the integer number of the month in the year, *DD* is the day of the month, *hh* and hh_o are an integer number of hours on a 24 hour clock, *mm* and mm_o are an integer number of minutes less than 60, and *ss.s* is a decimal number of seconds less than 60.

2.1.10.4 Dependencies

The computations of whether two uses of the same spectrum are compatible are required when their models overlap in time. The check described for the start time is sufficient for this assessment.

2.1.11 Minimum Power Density

The minimum power density specifies the attenuation level where transmitted signals are no longer protected. It is used as part of a transmitter model, usually when modeling a broadcasting service where reception is based only on the range of the transmission. These sorts of transmitter models also use referenced underlay masks. With these constructs, a transmitter model can stand alone without a receiver model and specify the protection of transmitters.

2.1.11.1 Rationale

The purpose of the minimum power density is to allow a transmitter model such as would be used for a commercial radio or television station to also imply a receiver model. Receivers are protected to the spatial extent that the transmission model predicts the signal will reach before attenuating beneath this threshold.

2.1.11.2 Data Structure

A single real number.

2.1.11.3 Units

$\mathrm{dBW}/\mathrm{m}^2$

2.1.11.4 Dependencies

The minimum power density is used together with a maximum power density, a spectrum mask, a propagation map, and a power map of a transmitter as part of an alternative method to define the spatial volume of use of the spectrum. It is intended to be used with broadcaster rights to define the space where receivers should receive protection making that protection contingent on the ability of the broadcaster to deliver a reasonably strong signal identified by the minimum power density. The surface of this volume is computed by identifying the range at which a signal attenuates to the minimum power density using the transmission power specified by the maximum power density, the spectrum mask, and the power map and then the attenuation specified by the propagation map. The following example demonstrates the use of the minimum power density and the computation that follow.

Example: Determining the range of receiver protection given a minimum power density and a reference receiver underlay mask

Given a transmitter model with the following constructs:

Maximum power density: 30 $\mathrm{dBW}/\mathrm{m}^2$

Propagation map (2.2, 0)

Power map (0, 0)

Minimum power density: -80 $\mathrm{dBW}/\mathrm{m}^2$

Underlay mask: (107.4, 0, 107.41, -40, 107.59, -40, 107.6, 0) relative

Determine the distance to the boundary of the receiver right and the corresponding maximum allowed power of an interfering signal at that boundary.

The use of spherical propagation and power maps results in the range being the same in all directions from the transmitter. The range is determine using the log-distance pathloss equation, $PL(d) = PL(1m) - 10n\log(d)$. Using the values we are provided by the transmitter model we have: $-90\ \mathrm{dBW/m^2} = 30\ \mathrm{dBW/m^2} - 22\log(d)$. Note that the starting power is $30\ \mathrm{dBW/m^2}$ and the power at the boundary is $-90\ \mathrm{dBW/m^2}$ and we need to solve for *d*. In this case, the range, *d*, is 285 km. The maximum interference level at the boundary is computed using the minimum power density and the lowest power of the underlay mask: $-90\ \mathrm{dBW/m^2} - 40\ \mathrm{dB} = -130\ \mathrm{dBW/m^2}$. The level of protection interior to the boundary will be less and will depend on the level of attenuation at the location being considered.

2.1.12 Protocol or Policy

The protocol or policy component specifies additional information on how a system is using spectrum or what a system must do to share spectrum. The distinction used to separate what is a protocol versus what is a policy concerns their scope and influence on the behaviors of a radio system. Guidelines given to radios that specify the conditions that must be assessed by those radios to be present to consider spectrum available for those radios to use are policy. The detailed procedures used by radios to share information in order to assess spectrum availability and then to collaborate to use the spectrum are protocols. Thus, policy specifies the conditions for spectrum use while protocols define the procedures that a radio or radio system follows to abide by the policy and to accomplish the radio system's purpose.

The protocol or policy component can be used both to specify the conditions for spectrum use when models are used to provide policy or to specify how a system is using the spectrum.

2.1.12.1 Rationale

The protocol and policy component provides the means to specify behavioral guidance for spectrum reuse. This component is provided to offer two benefits;

1. It provides a means to specify how spectrum sensing may be used to inform spectrum use decisions. Thus, it adds greater flexibility in the management of cognitive RF systems, radios and radars.
2. It provides a means to exploit reuse opportunities that come from knowing the specific behaviors of incumbents.

An additional way to distinguish between policy and protocol is to understand how the two would differ in the cognizance of the cognitive system. Policy provides guidance to the reasoning components of a cognitive system. The cognitive system would observe the use of spectrum and use the policies to determine its alternative courses of action. The cognitive systems have many degrees of freedom in how they choose spectrum to use and which protocols they use for their own access. Meanwhile protocols specify the mechanics and timing of spectrum access. Given a protocol, a cognitive system would simply operate using the protocol. There is only one course of action. Compliance with the protocol ensures compatibility. The advantage of protocols is that spectrum sharing can occur at a much finer time resolution and so enable a more efficient reuse.

2.1.12.2 Data Structure

The basic data structure of a protocol or policy is a name followed by a set of parameters. The assumption made is that the name implies to the target system the general behavior and the parameters fill in the details of timing, structures, and counts. Each policy and protocol name would have an expected number of parameters associated with it that need to be provided for the policy or protocol to be complete.

2.1.12.3 Units

Policies and protocols are named and so have no units. The units of the parameters are specified for each named policy and protocol as they are defined.

2.1.12.4 Dependencies

The policy and protocol component only applies to the spectrum defined in the rest of the spectrum model. Other than this, there are no further computational dependencies with the other components of the model.

Example: Sensing Policy

Policies are designed to specify behaviors that prevent harmful interference to an incumbent user. Policies can enable the use of sensing strategies such as sensing threshold, sensing period, abandonment time, and disuse time. A possible sensing policy could require a cognitive system to sense a channel for a particular power threshold for some duration and once true allow that spectrum to be used. It would then require the cognitive system to continue sensing the channel periodically and if another user is detected in this sensing, require the cognitive system to abandon the channel for some minimum period. For example, if the spectrum specified in the model is sensed below a power threshold of -120 dBW for 5 minutes then the cognitive system may use the spectrum within the constraints of the model so long as it senses the channel every 1 millisecond and abandons the channel if the power threshold is violated during that sensing. It must abandon the channel for 5 minutes before trying to use the spectrum again. This policy would have a name, say in this case "simple sensing," and then four parameters, power threshold, p_{th}, free period, t_f, sensing period, t_s, and abandonment time, t_a. Since the meaning of the parameters are associated with the policy name, the complete policy can be conveyed concisely as $\langle name, p_{th}, t_f, t_s, t_a \rangle$ or specifically as $\langle \text{Simple Sensing}, -120, 300, 0.001, 300 \rangle$ where it is understood that the power term has units of dBW and all timing parameters have units of seconds.

Example: Protocol - 1

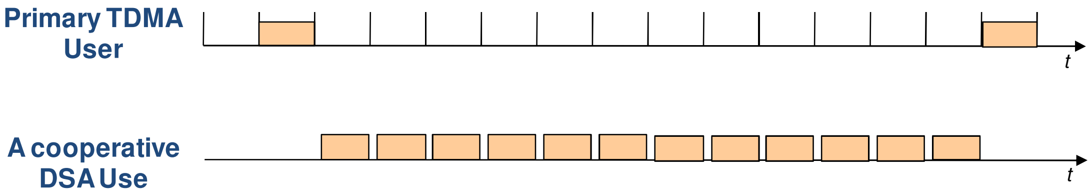


Figure 2-15. TDMA sharing example

Figure 2-15 illustrates both a primary user and a cooperative dynamic spectrum access user of a simple implementation of time division multiple access (TDMA) medium access control (MAC) protocol. Here, different protocols are being implemented by the primary user and the cooperative user. The primary user would likely identify that it is using TDMA and the size of the slots. Say the slots are 2.5 milliseconds long and the protocol is named "Simple TDMA." The primary user could completely define its use of the spectrum as $\langle \text{Simple TDMA}, 2.5 \rangle$. Remember that the rest of the model provides the details of the channel. The spectrum manager may then recognize that there is a cognitive system that can operate compatibly with this protocol by sensing the channel free for some duration of the slot, say 1 millisecond and transmitting in the remainder of the slot only if it is sensed free, say no signal above -120 dBW. Such a sharing protocol might be named "Simple TDMA Sharing." The policy specification for use could then be $\langle \text{Simple TDMA Sharing}, 2.5, -120, 0.1 \rangle$. It would be expected that the cognitive radio sharing this spectrum would first synchronize with the primary user. Additional parameters could be used to specify that these protocols are synchronized to some absolute time standard. The former requires a primary to be observed before sharing while the latter would allow sharing without this prerequisite.

Example: Protocol - 2

A variant of the Synchronous Collision Resolution (SCR) MAC protocol has been designed to arbitrate primary and secondary access [8]. SCR is a slotted protocol that uses signaling at the front of each transmission slot to arbitrate access. It is unique in that it orchestrates spatial reuse. This variant that arbitrates primary and secondary use gives access precedence to primary users and then fills the spaces among primary users with secondary users. Figure 2-16 illustrates the protocol.

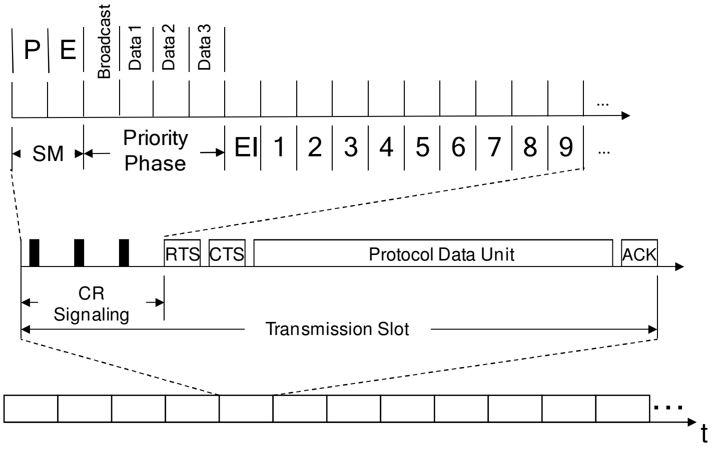


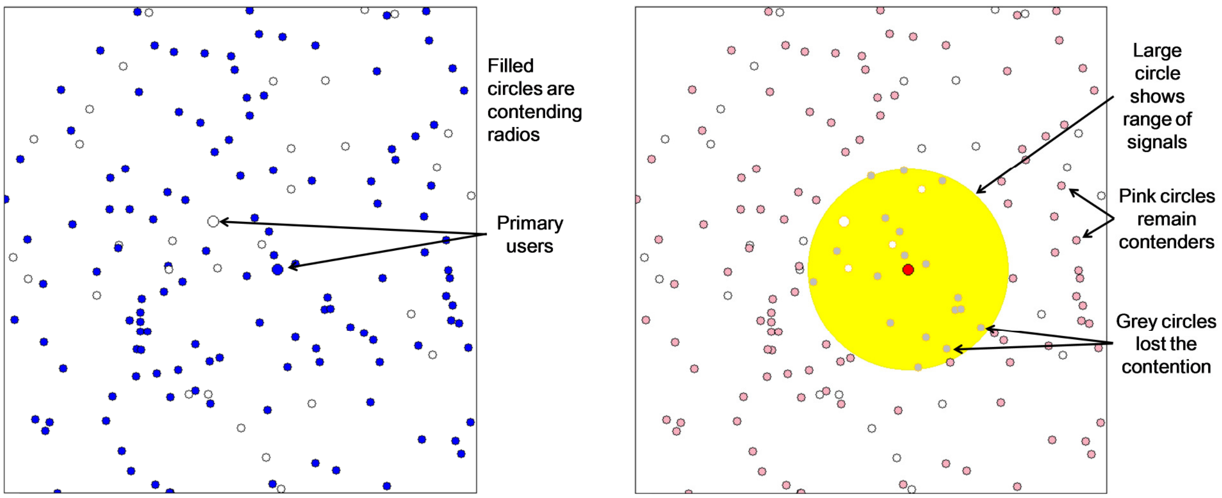
Figure 2-16. SCR design for arbitrating primary and secondary spectrum access

Generally, in the collision resolution signaling, the radio that signals first gains access over its contending neighbors. In this design, there is a special spectrum management (SM) phase of signaling at the beginning that all primary contenders signal to assert their precedence and then the remainder of the signaling is collectively used to arbitrate access among peers.

Figure 2-17 illustrates an example of arbitrating primary and secondary access. At the start, as illustrated Figure 2-17a, all blue nodes are contending and the primary users are illustrated with larger circles. In the SM phase, all the primary contenders signal in the P slot of the SM phase, Figure 2-17b. Any radio that did not signal and heard these signals knows they can no longer contend for the slot. They also extend the effect of this contention by echoing the signal in the E slot of the phase, Figure 2-17c. All nodes that did not signal in the P slot of the SM phase that hear this signal no longer contend. The surviving nodes then signal as normally done in SCR for the remainder of the contention resolution signaling. A possible result is illustrated in Figure 2-17d and shows that multiple secondary users fill the spaces around the primary users.

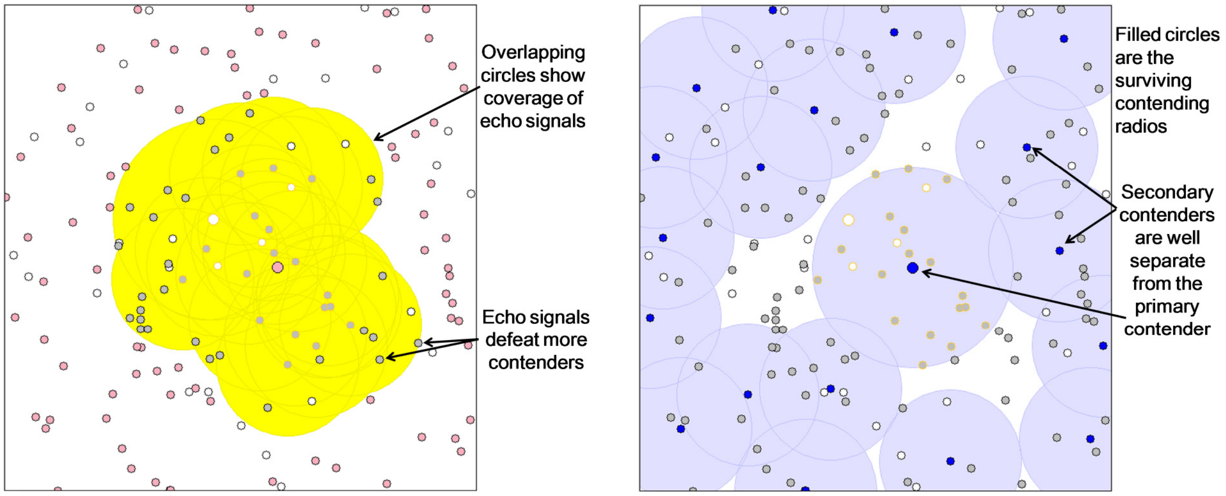
Say "SCR PS" is the specific name that is associated with this protocol design. The SCR signaling is understood but the timing may vary. Possible parameters would specify the duration of signaling slots, say 50 microseconds, the duration of signals, say 35 microseconds, and the duration of transmission slots, say 2 milliseconds. In this case the protocol could be specified as $\langle \text{SCR PS}, 0.05, 0.035, 2 \rangle$ where all timing units are in milliseconds. The primary user and the secondary user would use the same definition since they are using the same protocol. However, notice in the example that the primary has greater range. In this case, the maximum power density of the two models of use would be different between the primary and the secondary users. The purpose of this example is to demonstrate a protocol specifically designed for sharing. Additional information on the details of the SCR protocol and its many other capabilities can be found in [9, 10, 11, and 12].

Example: Protocol 2 (continued)



a. Starting condition where blue nodes are contenders

b. The primary contender signals first



c. All nodes that receive the primary's signal echo it

d. Secondary users fill the spaces around the secondary user

Figure 2-17. Example of signaling giving a primary priority in access and filling spaces with secondary users

2.2 Model Types

Spectrum is consumed both by transmitting and by receiving. Transmitters emit radiation and may cause harmful interference to other users. Receivers do not emit radiation but can suffer interference and so must be protected. Thus, models for transmitters and receivers will be different and will have different effects in spectrum consumption. These models must be distinguished from each other since the meaning of the maximum power density, power maps and propagation maps are opposite, specifying the propagation of radiation away from transmitters but toward receivers. Most systems consist of both transmitting and receiving functions. Thus, system models will consist of some number of transmitter and receiver models that combine to convey the spectrum consumption of the system.

2.2.1 Transmitter Models

Transmitter models attempt to convey the extent and strength of RF emissions. The essential components that must be part of a transmitter model are a maximum power density, a spectrum mask, a power map, a propagation map, and a location. Emissions can come from anywhere in the space identified by the location component. From those locations, the maximum power density, spectrum mask, and power map define the strength of the emission at the source. The propagation map defines the rate of attenuation of those signals as they propagate away from the transmitters. Figure 2-18 illustrates this attenuation.

2.2.2 Receiver Models

Receiver models attempt to convey what is harmful interference. The essential components that must be part of a receiver model are a maximum power density, an underlay mask, a power map, a propagation map, and a location. A receiver can be anywhere in the space defined by the location component. There are three differences in receiver models as compared to a transmitter model. It requires an underlay mask rather than a spectrum mask, the components define the allowed strength of an interfering signal at the receiver rather than the strength of transmission, and the pathloss exponents of the propagation map define the rate of attenuation to be used in computing the attenuation of a potentially interfering signal. Figure 2-19 illustrates the attenuation of a receiver model and clearly shows it is the opposite of a transmitter model.

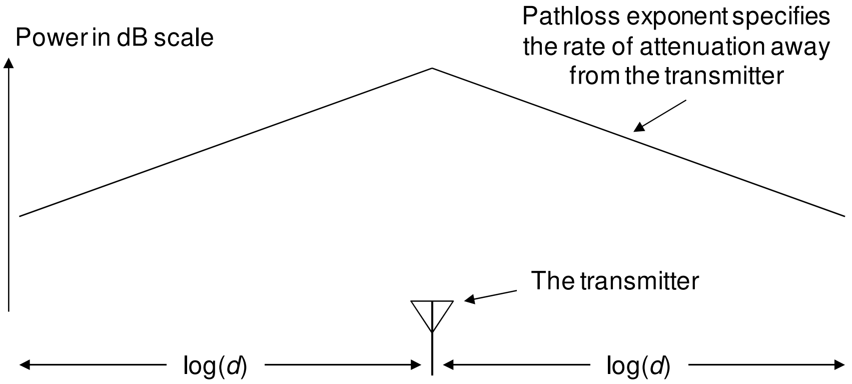


Figure 2-18. A transmitter model defines the emitted signal at the transmitter and its rate of attenuation

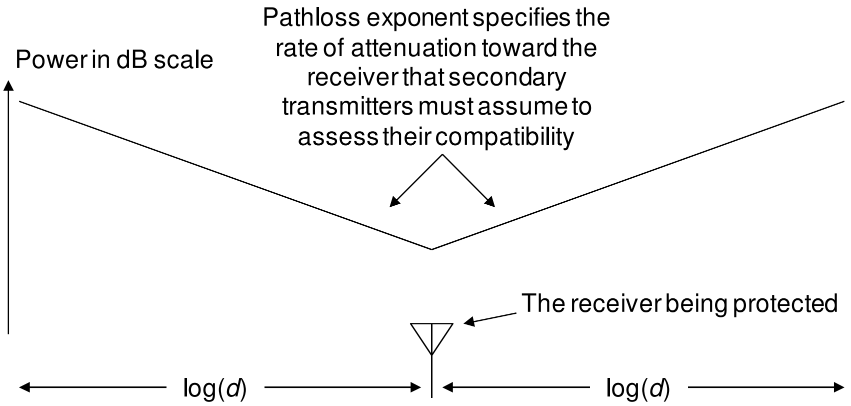


Figure 2-19. A receiver model defines the maximum allowed interference at a receiving antenna and the rate of attenuation to be used in determining interference by distant transmitters

2.2.3 System Models

Most systems consist of both transmitters and receivers and so spectrum consumption modeling of systems will contain a collection of both types of models. In addition to there being different types of components, other reasons for using multiple transmitter and receiver models in a system model include:

Attempts to capture different propagation behaviors associated with different spaces
Attempts to build complex spaces of operation that are not feasible with a single location primitive.
Attempts to distinguish between specific transmitters and receivers that have different component features, usually their power maps.

Although few, there are some examples where a single transmitter or receive model is used in a system model. Surveillance systems, such as radio telescopes and signal intelligence devices, are examples of systems that would just use a receiver model. Jammers are examples of systems that just use a transmitter model.

2.3 Conventions for Combining Components into Models and Collections

Spectrum consumption models may be used:

To define spectrum consumption of a system,
To define the spectrum consumption of a collection of systems,
To define the permitted use of spectrum by a system, or
To define the constraints to the spectrum used by a system or systems.

There are four types of standalone model data sets: transmitter models, receiver models, system models, and model collections. System models are used for the first function above and collections are use for the latter three. Figure 2-20 illustrates their relationship showing that transmitter and receiver models are possible components of the system models, and all three of these are possible components of model collections. Each, however, has their own set of modeling components. The components that are associated with the data sets have different roles based on their function. The subsequent subsection describes the role of the heading model components in systems and collections for the different functions above.

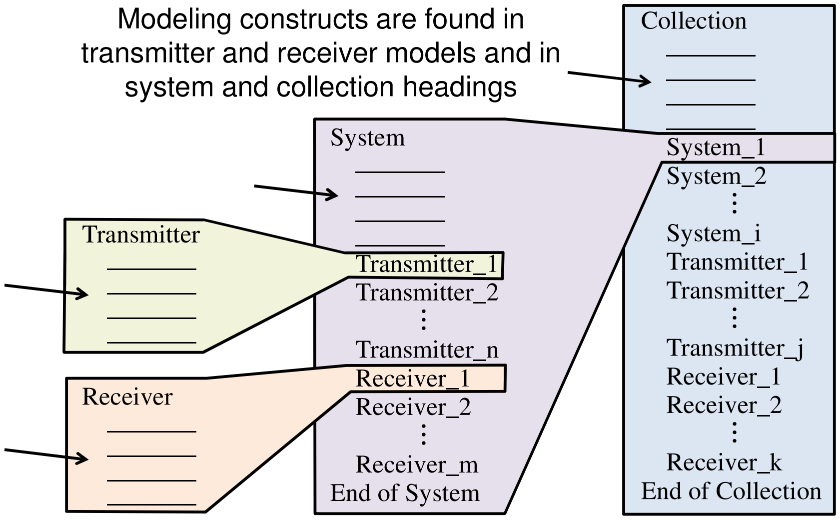


Figure 2-20. The relationship between transmitter models, receiver models, systems models and collections

Although the collection data sets may include systems models, in practice it may be more useful to decompose the system models into separate transmitter and receiver models and to only use transmitter and receiver models in the collections.

Appendix C provides an Extended Markup Language (XML) definition for conveying spectrum models and collections and should be referenced for precise formats and organization of transmitter models, receiver models, systems models, and model collections.

2.3.1 System Models

The convention for conveying a model of a system is to specify the system model with a list of modeling constructs that apply to the system as a whole, and then provide a list of transmitter and receiver models. Each of the transmitter and receiver models has their own list of modeling constructs. When a type of modeling construct is not provided in a system's transmitter or receiver models but is provided as part of the system heading, then these transmitter and receiver models adopt the construct found in the system heading. For example, if a location is provided for a system but not within one of its transmitter models then the location of the system is considered the location of the transmitter being modeled. On the contrary, if its transmitter has a different model construct for location then that location has precedence and is used in computations involving the use of the transmitter model of a system. In the case where locations and time limits appear both in the system heading and in the individual transmitter and receiver models, the values in the transmitter and receiver models have precedence so long as they are contained within the bounds (within the space and within the time limits) of the constructs of the system heading. In cases where they do not, the actual values of the constructs in the model are the intersection of their location and time values and those of the system model. This feature may be exploited for systems that dynamically access spectrum where models conveying spectrum availability have different bounds than the model identifying where a system is located.

The combination of constructs in the system model and in the individual transmitter and receiver models should collectively allow the construction of standalone transmitter and receiver models with a complete set of the necessary constructs. These standalone models would likely be conveyed in collections and be used in compatibility computations.

2.3.2 Collective Consumption Lists

Collective consumption lists use model collections to convey spectrum consumption among spectrum management systems. The convention for conveying a collection of consumption models is to specify the constructs that apply to the application of the collection of models as part of the collection heading and then a collection of system, transmitter and receiver models. The collection heading defines the scope of the collection. The typical components included in a collection heading are spectrum masks, locations, and the start and end times. The purpose of these components is to specify the extent to which the models in the collection are comprehensive from the perspective of the source of the list. The models within the collection may extend beyond the bounds of the collection components but are included since they affect the use of spectrum within the specified bounds. Unlike system models, constructs in the collection heading are not components to be used in the subsequent system, transmitter or receiver models. Each of the system, transmitter and receiver models is intended to stand on its own.

The spectrum mask in the heading of a collective consumption listing will be just two points specifying the start and end of the band of spectrum that the collection applies. If there are multiple disjoint bands being specified by the collection then it should use multiple spectrum masks of this type.

2.3.3 Spectrum Authorization Lists

Spectrum authorization lists use model collections to convey which spectrum a system may use. It can be used to convey spectrum that is available for a system to use with the expectation that the system chooses from the list and requests the channels that are appropriate. It may also be used to provide a permissive policy to a DSA system. The listing is given to a DSA system with the expectation that the DSA system will dynamically choose channels within the constraints of the models within the list.

The convention for conveying spectrum authorizations is to specify the components that apply to the overall application of the collection of models as part of the collection heading. This heading indicates the limits in spectrum, space, and time to which the subsequent listing of authorizations apply. The models that follow in the collection are likely derived from other sources and may imply a larger authorization. The limits specified in the spectrum authorization heading have precedence and limit the subsequent authorizations in the listing when they imply something broader.

Spectrum authorizations are conveyed in transmitter models and in systems models. Systems models are used for systems that have combinations of transmitters and where only certain channel combinations may be used. These system models will consist of only transmitter models. The components of the transmitter models define the limits to spectrum use. The location component defines where transmitters may emit, the combination of spectrum masks, maximum power density, and power map components provide the constraints to spectral power density of the transmission, the start and end time components provide the period of authorization, and the policy and protocol components specify behaviors that are necessary for using the spectrum.

Spectrum authorization listings may be complemented with a spectrum constraint listing. When this is the case, the authorizations extend only to the additional limits provided by these constraints.

2.3.4 Spectrum Constraint Lists

Spectrum constraint lists use model collections to convey incumbent spectrum uses that may limit the use of spectrum in an authorization. The lists convey a restrictive policy. These listings are sent in conjunction with sending spectrum authorization listings. The convention for conveying a collection of constraining models is to specify the constructs that apply to the application of the collection of these models as part of the collection heading and then a collection of system, transmitter and receiver models. The typical components included in the constraint listing heading are spectrum masks, locations, and the start and end times. The purpose of these constructs is to specify the extent to which the models in the collection provide a comprehensive set of constraints. The limits of the constraint listing heading does not limit the constraints of the models in the listing. The models that extend in time, frequency, or space beyond the limits in the heading are still valid representation of uses.

System, transmitter and receiver models may appear in the constraint listings. It is preferable if the system models are decomposed into transmitter and receiver models and not used in their native form. Although there are both transmitter and receiver models in the lists, the receiver models are the only true constraints. The transmitter models convey how other users are using spectrum and only serve as constraints if that use will interfere with a user considering using the same spectrum. The receiver models constrain use of spectrum by specifying what use would be harmful to an incumbent.

2.4 Summary

This chapter has described the eleven components of spectrum modeling including their rationale, the data structures they use, the units for those data structures, the basic computations that are used with the components and their dependency on other components in those calculations. The chapter concludes describing how these components are combined into models of transmitters, receivers, and systems and how these models are combined into collections that are used for conveying spectrum consumption, for authorizing use of spectrum, and for conveying constraints to the use of spectrum.

3 Assessing Compatible Spectrum Use

The purpose of modeling spectrum consumption is to allow a common set of rules and algorithms to be applied to determine the compatibility of spectrum uses or whether spectrum uses can coexist. In this chapter we provide the general rules for the interaction of models and the requirements for computing compatibility. Specific algorithms for computing compatibility are much more involved and will be presented in subsequent reports.

Computing spectrum compatibility requires determining the precedence of models and then assessing whether the model of a new use of spectrum is compatible with those models of existing or planned uses that have higher precedence. Reasons for not being compatible include causing harmful interference to one of these systems and being susceptible to harmful interference from one of these systems.

This chapter specifies the precedence of models and describes the necessary computations that must be performed to assess compatibility. It describes the general conditions for compatibility and then some special cases of compatibility that can be enabled by modeling.

3.1 Model Precedence

The precedence of models is established by spectrum managers. If the guidance from managers gives permission to systems to use spectrum using an authorization listing without any accompanying constraint listing then these models are sufficient for determining what spectrum to use. When guidance includes a constraint listing then the use of spectrum must fall within the permissive constraints of the authorization listing and also avoid causing interference to any of the receivers modeled in the constraint listing. The transmitters in the constraint listings define a worst case interference that new uses must accept. In cases where explicit guidance is not available, it is assumed that incumbent uses have precedence over new uses.

When computations of interference are being made there will be two pathloss exponents available, one for each model. The pathloss exponent that provides the greatest restriction to reuse should be used, i.e. the smaller pathloss exponent.

3.2 Assessment Processes

Compliance to an authorization listing requires that:

- The transmitted signal be within the spectrum mask.
- The power of emission at the transmitter complies with the combined guidance of the maximum power density and the power map.
- The transmitter only transmits when it is in a location where it is authorized to use the spectrum
- The transmissions are within the time limits of the authorization.

Compliance to a constraint listing requires that:

- Spectrum identified in authorization listings not be used if the use causes interference to a receiver modeled in the constraint listing.
- Secondary spectrum users to adjust their use of spectrum in space, spectrum, power, or time to avoid interfering with receivers modeled in the constraint listing.

A system seeking spectrum to use may employ two strategies for making the choice:

1. It may start by reducing the authorization and constraint listings to a smaller authorization listing that is fully compliant with the constraint listing and then use this new listing to find a suitable channel.
2. It may select a set of candidate channels from the authorization listing, assess the restrictions placed by the constraint listing on the use of those channels and then use the channel with least restrictions.

Of these two approaches, the second offers the greater number of opportunities of finding spectrum to use and greater visibility on its suitability since potential transmitter interference from incumbents conveyed in the constraint listings may be used to assess if interference to the proposed secondary use would be unacceptable. The first approach is likely to be used in systems employing the hybrid authorization process illustrated in Figure 1-6. Although, the interference from incumbent models would not be considered in assessing suitability, these systems might be complimented with spectrum sensors and so suitability may be assessed by the systems themselves in real time using their sensors.

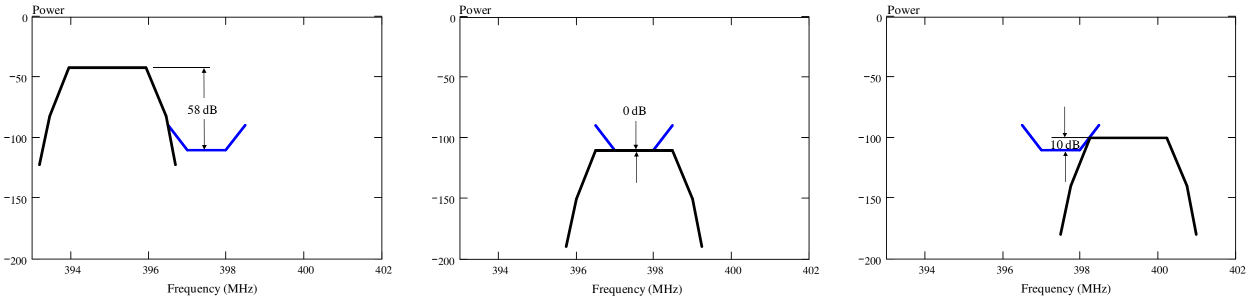
The process of assessing whether the use conveyed in a transmitter model is compliant with the use conveyed in a receiver model requires multiple of the computations that are described in the next seven subsections.

3.2.1 Determining Time Overlap

The first computation that should be made is to determine if two models overlap in time. It is the simplest assessment to make and if the models do not overlap then no further computations are necessary. Models overlap in time if the start time of one of the models falls within the period defined by the start and end time of the second model. It does not make a difference which of the two models falls within the other.

3.2.2 Determining Mask Power Margin

An underlay mask constrains a second user if the second user's spectrum mask and the underlay mask overlap in spectrum, i.e. the end point of one mask falls within the endpoints of the second. The power margin is the difference between the maximum power that can be used by the secondary user relative to the minimum power of the underlay mask. Figure 3-1 illustrates three scenarios using similar spectrum masks that differ in their frequency band showing that how a spectrum masks overlaps an underlay mask will affect the power margin. The ultimate



a. Power match at the first underlay inflection point determines power margin

b. Power match at the second underlay inflection point determines power margin

b. Power match at the third spectrum mask inflection point determines power margin

Figure 3-1. Effect of inflections points and the overlap of spectrum masks with underlay masks on the computation of the mask power margin

constraint to this power margin will occur where the power of an inflection point in one mask matches the power at the same frequency in the second masks. An algorithm for determining the power margin has two steps. First, determine the maximum power of the spectrum mask at each of the overlapping inflection points of the masks where the spectrum mask's maximum power is set such that the spectrum mask power matches the underlay power at those points. Second, select the minimum of the maximum powers of those determined in the first step and compute the power margin as the difference between that maximum power and the minimum power of the underlay mask.

3.2.3 Determining Power Margin Specified by the Power Maps

Given two points, one for the transmitter and one for the receiver, the direction between the two are used at each to look up a directional power value from the power map. The power margin specified by the power maps is the sum of these two values.

3.2.4 Determining Power Margin Specified by Propagation

Given two points, the power margin specified by propagation is the total attenuation that occurs in the computation pathloss that occurs because of distance of propagation. This computation requires determining the applicable pathloss exponent. The direction between the points is computed and the pathloss exponents are looked-up in the maps of both the transmitter and receiver models. If they differ, then the smaller of the exponents, the exponent that will predict the least margin, is used in the computation. The propagation power margin is determined by

$$PM_{prop}\left(d\right)=10\cdot n\cdot \log\left(d\right)$$

where d is the distance between the points and n is the smaller of the two pathloss exponents looked-up in the propagation maps of the transmitter and the receiver.

3.2.5 Determining Maximum Secondary Transmit Power

The maximum secondary transmit power as allowed by a receiver constraint that results from a secondary transmitter and a constraining receiver at two specific points is the sum of the receiver maximum power density, the underlay power margin at the location of the receiver, and the power margins of the spectrum masks, the power maps, and of propagation.

$$P_t = P_{\max} + PM_{underlay} + PM_{masks} + PM_{power\_maps} + PM_{prop}(d)$$

3.2.6 Determining Constraining Points among Models

In most cases the models of spectrum consumption will not use points to define the locations of the systems but rather areas or volumes. Given either an area or a volume for a transmitter and a constraining receiver, computing a maximum secondary transmit power requires identifying the pair of locations of the transmitter and the receiver that are most constraining within those volumes or areas. This can be a non-trivial computation and the development of algorithms to find these points is the primary objective of ongoing research. A brute force method for determining the constraining points has two steps.

1. For both the transmitter and the receiver combine the effects of the power map and the propagation map creating a new map vector where the values associated with solid angles are the pathloss exponent and power pairs.

2. Execute a pairwise comparison or each combination of a transmitter and a receiver sector of the new vectors. For each identify the two points in the transmitter and receiver areas that are closest to each other where the two sectors apply and compute the permitted transmit power.
3. Select the smallest power from the collection in step 2. This is the constraining power and the points used to compute that power are the constraining points between the two models.

Step two is the most complex of the computations and invites the creation of multiple heuristics. Many of the pairwise computations can be eliminated by simple tests that assure they cannot generate the constraining points, e.g. a determination that the two sectors can never point towards each other. The algorithms manual that accompanies this manual provides suggestions on methods to reduce the pairs checked and to find the constraining points most efficiently.

3.2.7 Determine Power Margin for a Receiver Underlay Mask Referenced to a Spectrum Mask

A spectrum mask may be referenced to the space defined in the location component of the model such that it's constraint is the same everywhere in the volume or area specified by the primary location. It may also be referenced to the spectrum mask and so have a constraint that changes based on the model's estimate of pathloss from the primary transmitter to the receiver that constrains the secondary user. Given the constraining point, the computation of the permitted power is not that more complex than that for a point with a spectrum mask referenced to all locations. Figure 3-2illustrates an example of how to determine the permitted power. Here we show a scenario with primary transmitter, ①, with an underlay mask referenced to a spectrum

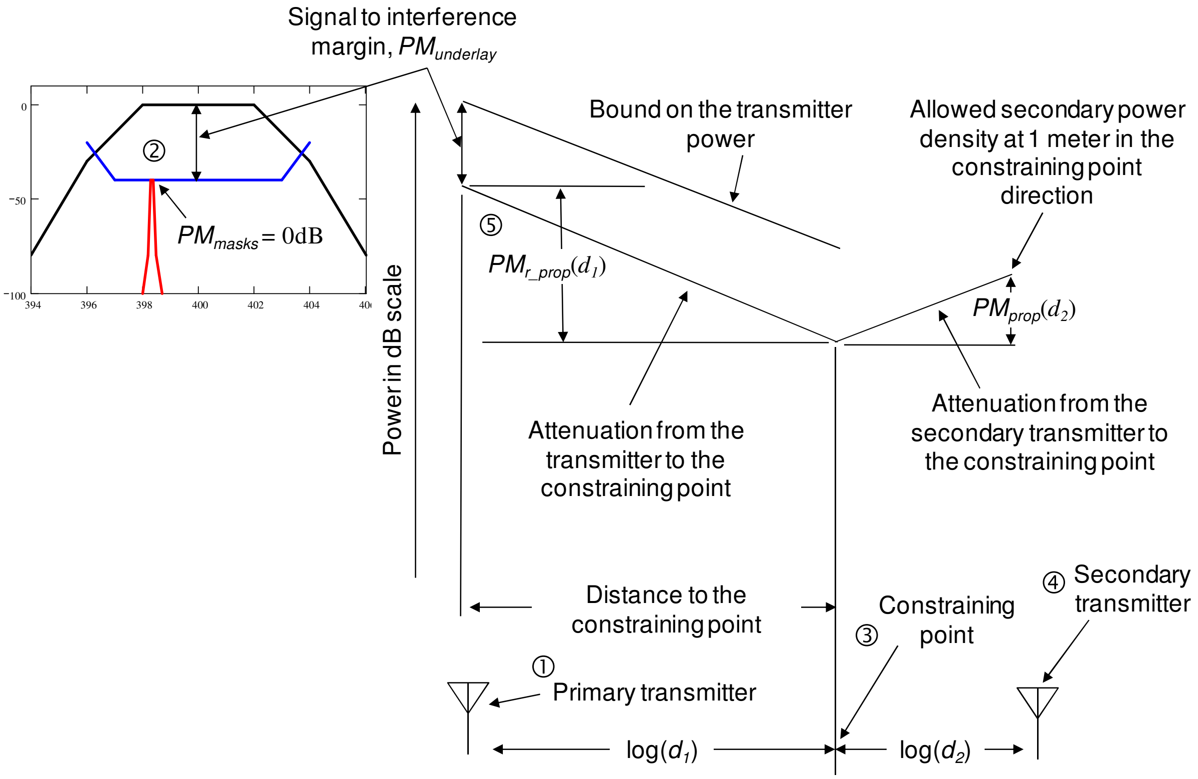


Figure 3-2. Example scenario of the determination of transmit power of a secondary user with a broadcaster using an underlay mask referenced to the transmit power density.

mask, ②. The constraining point of the scenario, ③, is locate is located a distance of d_1 from the primary transmitter and a distance of d_2 from the secondary transmitter, ④. The permitted transmit power can be computed as before with the additional terms for attenuation from the primary transmitter to the constraining point, ⑤, and the power margin from the power map at the primary transmitter.

$$P_t = P_{\max} + PM_{underlay} + PM_{masks} + PM_{power\_maps} + PM_{prop}(d_2) - PM_{r\_prop}(d_1)$$

Although the maximum transmit power computation shown here is straight forward, the determination of the constraining points can be more complex since spectrum masks referenced underlays add additional degrees of freedom in that determination, i.e. the range to the constraining point, the power towards the constraining point, and the rate of attenuation towards the constraining point. There would then be three combinations of sectors to consider in the search for constraining points, the sector from the primary transmitter into the volume of the model and then the receiver and secondary transmitter sectors as considered before.

3.2.8 Avoiding Interference from Intermodulation

When a spectrum mask is within the bands specified by an intermodulation mask of a neighboring transmitter, then intermodulation could be an issue. Typically, some screening mechanism is applied first. For example, checks may be limited between transmitters and receivers co-located on the same platform. Intermodulation computations for compliance will be of two types, IM interference within receivers and interference caused by IM products.

3.2.8.1 Avoiding IM Interference within Receivers

Given a receiver with an IM mask, the first step is to apply the screening process defined for this mask to determine if the conditions exist for considering IM. Usually, the conditions will be that there are a sufficient number of co-located transmitters with the receiver. The second step is to determine whether the channels used by these transmitters are within the IM mask of the receiver. The third step is to determine whether the channels used by these transmitters that are within the IM mask can combine into an IM product that overlaps the spectrum of the underlay mask of the receiver. This requires assessing all possible IM products of the specified order of the mask. Given that the IM product can potentially interfere, then the computation of the specific interference is determined using the methods described in Section 2.1.6.4. If the constraint of the receiver's underlay is violated then there needs to be some remedial action. It is likely these computations will be part of spectrum assignment where power requirements are specified for the transmissions and so the only practical remedy would be to consider other spectrum assignments for the combination of networks these transmitters and receivers belong. If the situation allows for mitigation by reducing the transmit power of one or multiple of the neighboring transmitter, the level of reduction can be computed from the results of the determination of interference and then applied across the contributing transmitters that can have their powers adjusted.

3.2.8.2 Avoiding Interference from Transmitted IM Products

Given a transmitter with an IM mask, the first step is to apply the screening process for the mask. Depending on the IM transmitter[8], the screening may be similar to that described above for receivers and only consider co-located transmitters or the screening could, in the case of an IM mask for large high power transmitters, consider whether locations of operation of other transmitters come within some specified range of this high power IM transmitter. In this second case, the range may be a function of the maximum power density of a potential source transmitter and the subsequent computations would require identifying the specific location that would cause the largest power at the IM transmitter. Given this location and the specific signal that arrives at the IM transmitter, the IM products would be computed and each of these products would be considered as potential interference sources and so treated as a virtual transmitter in determining if the products cause interference. This virtual transmitter would use the power density and the spectrum mask of the IM product, and the power map and propagation map of the IM transmitter. Computations would proceed as though each IM product were a transmitter. If the IM products are found to cause interference at a distant receiver, remedies are to adjust the powers of the source transmitters, adjust the operating location of the source transmitters, or assign new channels that avoid creating the IM products that result in harmful interference.

3.3 Model-Based Reuse

An advantage of using spectrum consumption modeling as the basis of spectrum management is that it enables additional coexistent uses that would be impossible using spectrum sensing alone. There are many cases where a secondary transmitter can use spectrum without interfering with a primary use and allow the reception of the second transmission without harmful interference from the primary which with a sensing requirement would not be tried because one end or another of a transmission would sense the spectrum occupied. Here we describe two general ways where models convey reuse opportunities unavailable to sensor-based technologies.

3.3.1 Scenario-Based Reuse

In scenario-based reuse specific details of the scenarios and of the modeling of the primary use of spectrum result in reuse opportunities. Figure 3-3 is an example. The primary use in this

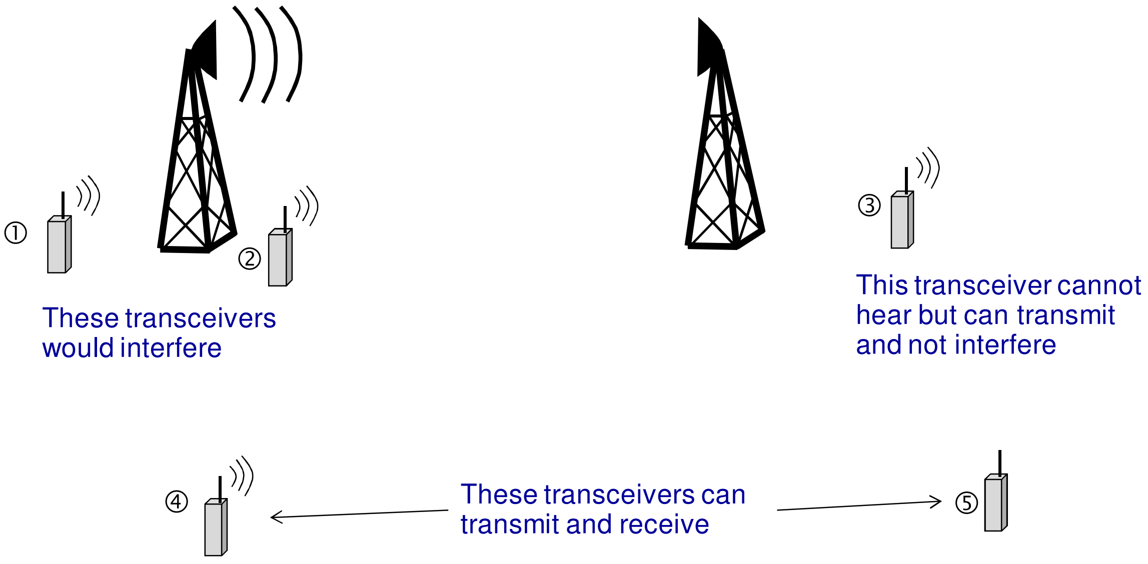


Figure 3-3. Example of a reuse scenario enabled by MBSM

scenario is the direct link between two towers where one is always transmitting and the other is always receiving and they both have highly directional antennas. About these two RF terminals are a number of transceivers of a mobile network that may use the same spectrum if they do not cause interference. The system model of spectrum consumption for the primary use would be modeled with one transmitter model and one receiver model and both would have point locations. In this illustrated scenario Transceivers 1, 2, 4, and 5 would be unable to hear the primary and so would not detect the spectrum in use. Transceiver 3 would detect the primary. If transceiver 1 and 2 made the decision to use the spectrum based on their failure to sense its use then they might interfere with the reception at the receiving tower. So if pairs of radios in the mobile network were to base their transmission on what they sensed it is possible that transceiver 1 might transmit to Transceiver 4 since both fail to sense the primary. Clearly, this would result in interference. Thus, a DSA policy based on sensing would either have to exclude consideration of this spectrum or require consideration of the sensing of all nodes in order to avoid causing interference. Some scenarios can be conceived where sensing by all nodes would not solve the problem either, in the example of Figure 3-3 consider the case if Transceiver 3 were not in the scenario. No node would detect the use but half the nodes, if they were transmit, would cause interference.

There are many similar uses of spectrum were high gain directional antennas are used to receive remote transmissions that are unlikely to by sensed by any general sensing protocol of a DSA technology. If the DSA technology were to use this spectrum based on its failure to sense the spectrum's use, it could generate harmful interference that disrupts the sensitive receiver's reception of the transmissions. Satellite terminals are the obvious example. DSA based solely on sensing would need to receive policy to prevent considering using this spectrum.

Assuming individual nodes have the resources to assess their compliance with the constraints of the primary models, each could determine the availability of the primary channel and whether they can transmit and/or receive on it. Assuming that this information can be shared across the network, then the pairs of nodes that can exchange transmission over the channel can identify themselves and do so. The computations for these assessments at nodes are no different than those described above. The mechanisms for coordination and selection of nodes to use the channels would need to be built into the protocols of the mobile network.

3.3.2 Channel Puncturing

Figure 3-4 illustrates the idea of channel puncturing where a short range use of spectrum can be exploited in the same space through which a long range transmission in the same spectrum propagates. This is possible because of the power law nature of pathloss. In the area close to the secondary user the signal power can be larger than that of a primary yet the transmitted signal may still attenuate sufficiently to avoid interference at the distant receiver. Figure 3-4 illustrates the relative signal strength of a primary transmission and a secondary transmission. The primary transmission is transmitted at a 50 dB greater power than the secondary but the secondary can still obtain a SINR advantage in close proximity to itself and then provide a wide interference margin at a distant receiver.

The spectrum model that would enable this spectrum puncturing reuse would isolate the receiving function and the transmitter function in separate models. The secondary user would compute the allowed transmit power that preserves an adequate SINR at the primary receiver and then use the transmitter model and perhaps the sensing as well to assess the power that may be used by the secondary transmitter.

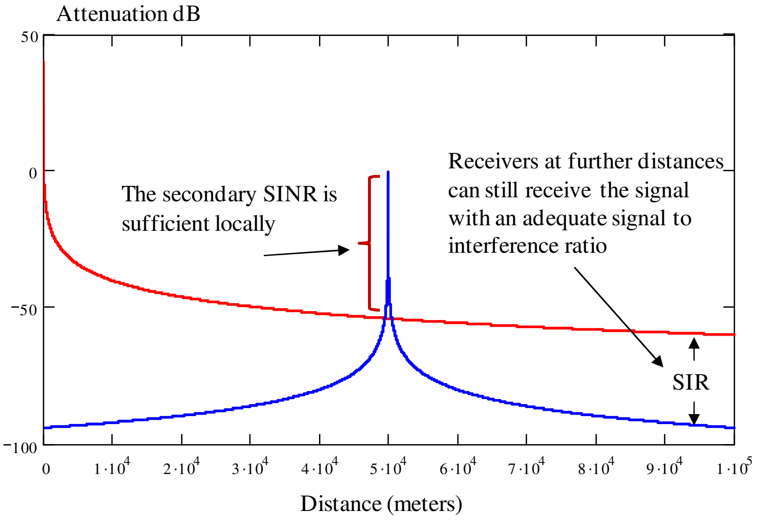


Figure 3-4. A channel puncturing scenario

3.4 Planar Approximations

The various computations above can be quite complex for locations on a spherical earth. Fortunately, most reuse opportunities will involve reusing spectrum in close proximity to an incumbent. Appendix E demonstrates that at distances of 200 kilometers or less the effect of a curved surface as opposed to a planar approximation is insignificant. However, it is far easier to build algorithms and to do the computations in a planar approximation than in the actual elliptical representation and so the planar approximation is the preferred representation. So it is suggested that when the distance between primary user's location and that of a second user's location is 200 km or less that a linear approximation be used. In this section we define how to convert model locations and directions to a planar approximation.

The conversion of a pair of models to a planar approximation for analysis of compatibility involves four steps: 1) Find the centroid of the location of each of the models as projected onto the surface of the earth, 2) Compute the great circle distance between these centroids, 3) Place these centroids on a planar surface separated by the great circle distance and minimize an equal error in the relative azimuths between the two centroids, and 4) rotate the points used to define the location volume to maintain the same azimuth and distance from the centroid as in the ellipsoidal coordinates. Assume the directions in power and propagation maps remain unchanged.

3.5 Summary

This chapter has described the fundamental computations that are used to assess compatibility and to support assessing spectrum reuse.

4 The Art of Spectrum Consumption Modeling

Spectrum modeling is artful with many degrees of freedom. The goal is to model spectrum consumption so that it bounds a system's RF emissions and specifies constraints that would protect the system from harmful interference. In the collective sense, the goal is to create models that achieve these objectives but consume the least amount of spectrum so that there are more opportunities to reuse spectrum. This chapter describes approaches to capture spectrum consumption of specific types of systems in models, methods within those approaches to ensure system performance is bounded within the models, and then approaches to divide or to aggregate models to support efficient management and spectrum reuse.

4.1 System Modeling

System modeling involves choosing combinations of transmitter and receiver models and components within those models to capture a system's use of spectrum. Here we present several common systems and describe their typical spectrum use case and present potential modeling methods for each. This section attempts to provide a part of the story of modeling, the modeling of system use of spectrum. However, the modeling approaches listed here are suggestions only as specific details and operational use of systems may afford other approaches that may provide better resolution of the spectrum that is consumed.

4.1.1 Broadcasters

Broadcasters are single transmitters that transmit signals to a number of surrounding receivers. These communications are continuous and are only a downlink. Exemplary users of broadcasting include, but are not limited to, commercial television stations, commercial radio stations, and broadcast satellite as used for both radio and television. Currently, broadcasters are regulated by placing limits on the amount of power they may use in their broadcasts and controlling where that broadcast might originate. The benefit of using a spectrum consumption model to define a broadcaster’s use of spectrum is that the model would define the geospatial limit on the broadcaster’s use and would reveal the conditions required for reusing the spectrum.

There are several methods available to model broadcaster spectrum consumption. In the first, the transmitter of the broadcaster is modeled with a transmitter model that provides the location of the transmitter, a maximum power density, a power map, a propagation map, and a spectrum mask. Then a receiver model is developed for the typical receiver with a location that covers the area where these receivers are anticipated to be. The receiver model would use a maximum power density with a fixed underlay mask to specify the protection necessary for the weakest receivable signal from interference. It would provide a power map and a propagation map to specify the attenuation that should be used in computing power levels of interfering signals. A secondary user with authorization could use the spectrum so long as it would not interfere with any receiver at any point in the location modeled in the broadcaster's receiver model. An additional consideration in a secondary's use of the broadcaster's spectrum is whether it can tolerate the interference that the broadcast transmitter model predicts.

In the second approach to modeling a broadcast, the transmitter model has an underlay mask that is referenced to the transmitter spectrum mask in addition to a maximum power density, a power map, a propagation map, and a minimum power density. The components of the transmitter model specify the location of the receiver model. It is the volume subsumed by the surface defined by where the transmit power attenuates to the minimum power density as predicted by the model. The receiver model has a power map and a propagation map to be used in computing interference. The interesting dynamic is that the power level of the underlay mask will vary with location providing more reuse options, potentially even within the receiver volume area.

Broadcasting radios frequently use high power for transmission and may be susceptible to generating IM. If this is the case, an IM masks may be added to the transmitter model. Table 4-1 and Table 4-2 list the different components and constructs that are found in the two different modeling approaches.

Table 4-1. Components used in a broadcaster model with an explicit location for receivers

Model Constructs	System Heading	Transmitter	Receiver
Maximum Power Density		R	R
Spectrum Mask		R	
Underlay Mask			R
Propagation Map		R	R
Power Map		R	R
Intermodulation Mask		O	
Platform Name		O	
Location		R - Point	R - Surface or Volume
Start Time	R		
End Time	R		
Minimum Power Density			
Protocol or Policy	O		

R - Required, O - Optional, T - Typical (To provide a refined definition)

Table 4-2. Components used in a broadcaster model with a relative underlay mask

Model Constructs	System Heading	Transmitter	Receiver
Maximum Power Density		R	
Spectrum Mask		R	
Underlay Mask		R	
Propagation Map		R	R
Power Map		R	
Intermodulation Mask		O	
Platform Name		O	
Location		R - Point	
Start Time	R		
End Time	R		
Minimum Power Density			
Protocol or Policy	O		

R - Required, O - Optional, T - Typical (To provide a refined definition)

Example: Broadcaster Models

This example demonstrates the options for modeling the spectrum consumption of a broadcast system. Figure 4-1 illustrates an asymmetric broadcaster scenario where the location of the antenna, labeled as A in the illustration, is at the edge of an area where the receivers are anticipated to be. The first modeling approach would use separate transmitter and receiver models. The receiver model would attempt to capture the area where receivers are to be protected and would use a maximum power density, an underlay mask, a power map, a propagation map, and the time constraints to complete the model. Figure 4-2 illustrates how a terrestrial polygonal surface defined by five points could enclose the receiver area.

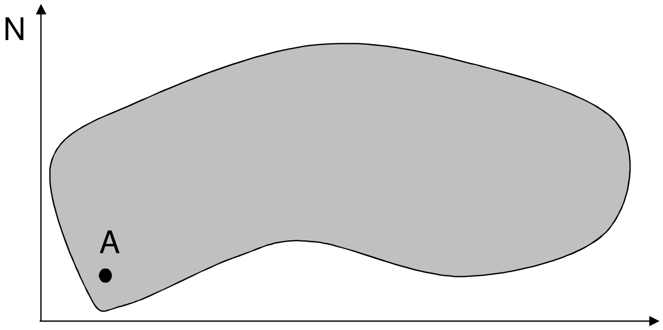


Figure 4-1. An asymmetric broadcast scenario

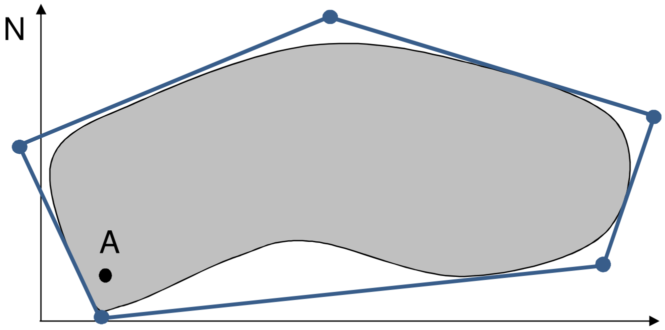


Figure 4-2. Capturing the receiver area with a convex polygon

The second approach to modeling the consumption is to combine both a spectrum mask and an underlay mask in the transmitter model where the underlay mask is relative to the spectrum mask and so its reference power level changes as the transmit power attenuates with propagation. The complete model would also include a maximum power density, a power map, a propagation map, a minimum power density, and the time limits of the consumption. The location of the transmitter model would be the location of the broadcast antenna. The asymmetric shape of the receiver location could make this model overly pessimistic but in this example the antenna is directional. Figure 4-3 illustrates the directionality of the antenna and the surface of the receiver location volume predicted by the model's maximum power density, power map, propagation map, and minimum power density. The surface of this volume is where the predicted transmit power reaches the threshold of the minimum power density. In this approach, the upper power of the spectrum mask attenuates with signal propagation with a matched reduction in the reference power level of the underlay mask. Reuse is feasible so long

Example: Broadcaster Models (cont.)

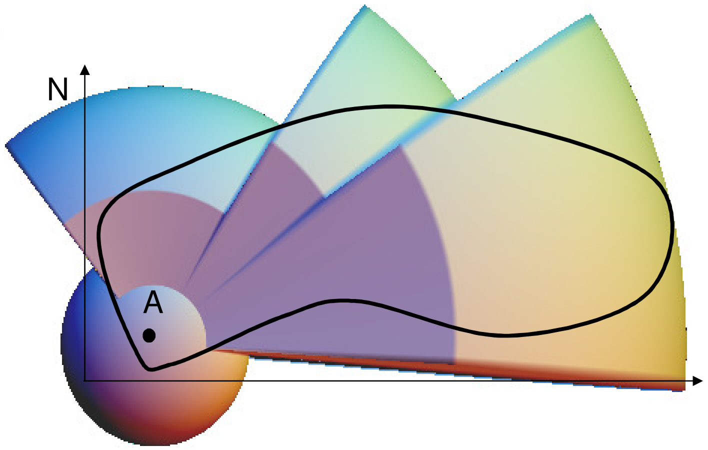
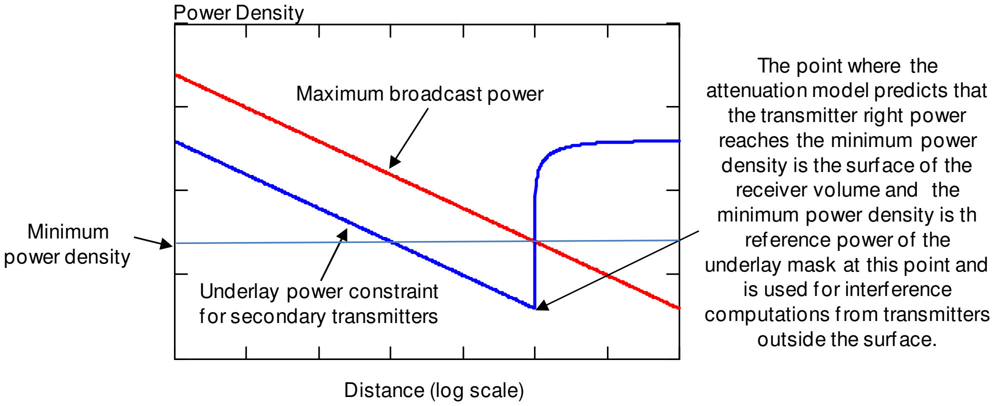


Figure 4-3. Determining the receiver area using the combination of the maximum power density, power map, propagation map, and minimum power density

as the interference is below this underlay reference at all locations within the volume. Figure 4-4 illustrates a generalized example of the distance varying power reference for the underlay mask and that at the point where the estimated transmit power reaches the minimum power density, the minimum power density is the power reference of the underlay mask. Secondary users beyond this surface would likely use a hypothetical receiver on this surface and so this underlay mask to determine the constraints to their use of the spectrum.



The point where the attenuation model predicts that the transmitter right power reaches the minimum power density is the surface of the receiver volume and the minimum power density is th reference power of the underlay mask at this point and is used for interference computations from transmitters outside the surface.

Figure 4-4. The distance varying power reference when using a transmitter referenced underlay mask

4.1.2 Radio Links

Radio links are transmitter-receiver pairs or transceiver pairs that are dedicated to the communications between the two ends. Such links could be simplex (a single transmitter at one end and a single receiver at the other), full duplex (a transmitter and a receiver at both ends each operating on separate channels), or half duplex (A transceiver at both ends alternating between transmitting and receiving). The ends of these links may be stationary or be mobile. An example of a stationary link would be wireless backhaul. Wireless backhaul could be a microwave link to a remote cell tower that is unable to connect to a wired backhaul. An example of a link that may have a mobile end is the command and control link of an autonomous system. The modeling of radio links is similar for all varieties. They simply consist of transmitter and receiver models for the end points for whatever those points have. So for a simplex link one end would have just a model of a transmitter while the distant end would have a receiver model. Full duplex and half duplex would have transmitter and receiver models for both ends of the link. When the ends of links are stationary, the locations for the models would be points. When an end of a link is mobile, then the location should attempt to specify the smallest feasible volume that contains the space that the end point will traverse. The transmitter and receiver models would have the typical components of maximum power density, spectrum mask (for the transmitter model), underlay mask (for the receiver model), power map, and propagation map. The time limits of the model are specified in the header portion of the system model since it applies to all the transmitters and receivers in the system. These models may provide a protocol component if the systems protocols provide a sharing opportunity. If the transmitters or receivers are susceptible to intermodulation, then the models may include an IM mask to convey that susceptibility. Table 4-3 and Table 4-4 list the typical components and constructs used in radio link system models.

Table 4-3. Components used to model a simplex radio link

Model Constructs	System Heading	Transmitter	Receiver
Maximum Power Density		R	R
Spectrum Mask		R	
Underlay Mask			R
Propagation Map		R	R
Power Map		R	R
Intermodulation Mask		O	O
Platform Name		O	O
Location		R - Point	
Start Time	R		
End Time	R		
Minimum Power Density			
Protocol or Policy	O		

R - Required, O - Optional, T - Typical (To provide a refined definition)

Table 4-4. Components used to model a duplex or half duplex radio link

Model Constructs	System Heading	Transmitter 1	Receiver 1	Transmitter 2	Receiver 2
Maximum Power Density		R	R	R	R
Spectrum Mask		R	R	R	R
Underlay Mask			R		R
Propagation Map		R		R	
Power Map		R	R	R	R
Intermodulation Mask		O	O	O	O
Platform Name		O	O	O	O
Location		R	R	R	R
Start Time	R				
End Time	R				
Minimum Power Density					
Protocol or Policy	O				

R - Required, O - Optional, T - Typical (To provide a refined definition)

4.1.3 Tactical Data Links

A tactical data links (TDL) is typically defined as a radio system with a set of accompanying messages that is used for some tactical purpose. It is the radio portion of these systems that consumes spectrum. Generally, the radios are intended to be mobile. The specification of the radio portion is usually of the physical layer and the system's medium access control (MAC) protocol. Routing is not normally included. In operation, radios are configured to participate in the MAC. A common approach is to use a TDMA MAC and allocate the slots of a TDMA epoch across the multiple users of the network. Radios in the system broadcast within their allocated slots. Radios are transceivers and both transmit and receive throughout the TDMA epoch. As such, the system model consists of both a transmitter and receiver model with most construct definitions being made in the system heading. Although there may be directional aspects to both propagation and power, most maps are likely to be spheres due to the anticipated mobility of the radios. The greater fidelity in the models will occur in the location and time components. Further, multiple models, differentiated in these constructs of location and time, may be used to capture changes in location that result from maneuver over time and so spectrum consumption over time. This subdivision of model location by time may be achieved by replicating a system model like that in Table 4-5 with a single transmitter and receiver or it can be accomplished using a single system model and then listing multiple transmitter and receiver models differentiated by their location definition and their time of applicability as shown in Table 4-7. Multiple transmitter and receiver models may also be used to collectively contain the operating region in a manner more efficient than an approach that uses just one location model.

Table 4-5. Components used to model a mobile tactical data links

Model Constructs	System Heading	Transmitter	Receiver
Maximum Power Density	R		
Spectrum Mask		R	
Underlay Mask			R
Propagation Map	R		
Power Map	R		
Intermodulation Mask		O	O
Platform Name		O	O
Location	R- Surface or Volume		
Start Time	R		
End Time	R		
Minimum Power Density			
Protocol or Policy	O		

R - Required, O - Optional, T - Typical (To provide a refined definition)

Table 4-6. Components used to model mobile tactical data links as a single system model with multiple time periods

Model Constructs	System Heading	Transmitter 1	Receiver 1	…	Transmitter n	Receiver n
Maximum Power Density	R					
Spectrum Mask	R					
Underlay Mask	R					
Propagation Map	R					
Power Map	R					
Intermodulation Mask		O	O		O	O
Platform Name		O	O		O	O
Location	R- Surface or Volume	T- Surface or Volume	T- Surface or Volume		T- Surface or Volume	T- Surface or Volume
Start Time	R	T	T		T	T
End Time	R	T	T		T	T
Minimum Power Density						
Protocol or Policy	O					

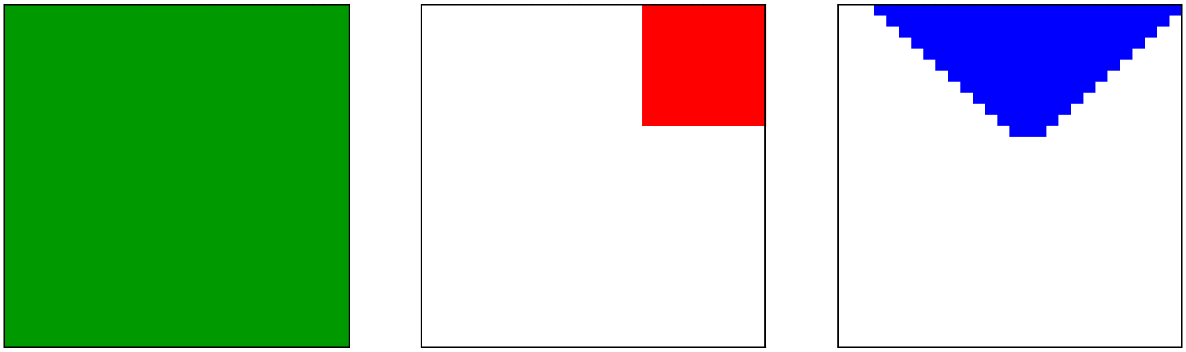
R - Required, O - Optional, T - Typical (To provide a refined definition)

4.1.4 Mobile Ad Hoc Networks (MANET)

Mobile ad hoc networks consist of multiple mobile nodes and may use multiple channels. Further, the radios within the networks may use advanced radio technologies and protocols to adapt to the environment and each other for best network performance. In the simplest case where there is a fixed assignment of spectrum to a MANET, the MANET can be modeled as described for the TDL. Each transceiver in the network would have similar characteristics and these characteristics would be modeled with a location or locations that contain the full operating region of the transceivers in the network.

In more advanced MANET systems where there is greater adaptability and cognizance of the environment, the use and modeling of spectrum may be much more interesting and involve dynamic spectrum access technologies. Consider the case shown in Figure 4-5. Portions of a square operating region have different channels available as illustrated in Figure 4-5 a-e. Collectively they provide regions with different numbers of channels available for a MANET to use depending on the location of the radios in the system. Figure 4-5f illustrates the number of channels that are available by location and by inspection of Figure 4-5 a-e it is possible to discern which specific channels are available in each region. A system model of spectrum consumption for this square region would define the limits of the region and then provide a transmitter and receiver model for each of the channels that are available. These would each have their own location construct. Table 4-7 lists the components that would be used to model this MANET's use of spectrum. Note that the availability of the region and the availability of the different channels may have different time limits and so the individual transmitter and receiver models aligned with the channel may have different time limits.

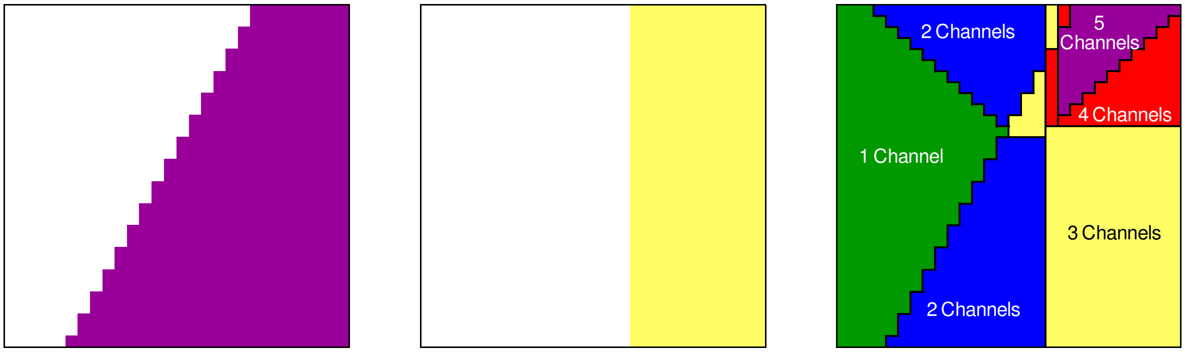
A MANET however, may not occupy the full space of this region but just a portion. A system model of the MANET in this portion would include a transmitter and receiver model for each channel that intersects the region and the location of these transmitter and receiver models would be either the boundary of where the channels may be used or the intersection of this boundary with the boundary of the system location. A feature of model precedence is that heading values



a. Channel 1 availability

b. Channel 2 availability

c. Channel 3 availability



d. Channel 4 availability

e. Channel 5 availability

f. Cumulative numbers of channels available by location

Figure 4-5. Example scenario of channel availability for a DSA MANET.

Table 4-7. Components used to model a multi-channel DSA MANET

Model Constructs	System Heading	Transmitter Channel 1	Receiver Channel 1	…	Transmitter Channel 5	Receiver Channel 5
Maximum Power Density	R					
Spectrum Mask		R			R	
Underlay Mask			R			R
Propagation Map	R					
Power Map	R					
Intermodulation Mask		O	O		O	O
Platform Name		O	O		O	O
Location	R- Surface or Volume	T- Surface or Volume	T- Surface or Volume		T- Surface or Volume	T- Surface or Volume
Start Time	R	O	O		O	O
End Time	R	O	O		O	O
Minimum Power Density						
Protocol or Policy	O					

R - Required, O - Optional, T - Typical (To provide a refined definition)

of location and time are boundaries for the individual transmitter and receiver model locations and times. This feature allows the direct transfer of the transmitter and receiver models of the original square region into system models that encompass smaller regions. The reduced size of the transmitter and receiver models is implied. This allows the subdivision of operational use over time by just modifying the system heading constructs of location and time. Generally, it is preferred that the transmitter and receiver models have explicit definitions of their locations and times of use as this will simplify the decomposition of system models into independent transmitter and receiver models. Using this latter approach to define transmitter and receiver models, it becomes possible to model the time varying locations of the system over time in a single system model. There may be multiple transmitter and receiver models for a channel which are differentiated by their location and time boundaries.

4.1.5 Cellular Systems

Our definition of cellular systems includes cellular telephony systems such as the Global System for Mobile Communications (GSM) and The Code Division Multiple Access 2000 (CDMA2000) technologies and cellular data systems such as Wireless Interoperability for Microwave Access (WiMAX) and Long Term Evolution (LTE) technologies. The fundamental concept of cellular systems is the spatial subdivision of wireless access into cells that reuse spectrum. Each cell provides the connectivity to the end host and its connectivity to the larger switched telephone network or the Internet is through a backhaul infrastructure that is typically wireline.

Cellular systems can be modeled as a collection of cells or as a collective region. In the first approach, each cell would be modeled with one or more transmitter and receiver models for the transceivers at the cell tower and then one or more transmitter and receiver models for the cell space covered by the tower accounting for the characteristics of the typical phone or data modem and the channels they might use. Table 4-8 identifies the possible components of this type of model for a single cell using a single channel. A cellular system would have multiple of these cell models, one set for each cell in the system. In the second approach, the cellular system is modeled as a collective region with a location that is the entire area of the cellular system. It would have a pair of transmitter and receiver models for each channel used by the system using the models of either the tower transceivers or of the telephone/modem transceivers depending on the role they play on the channel.

Table 4-8. Components used to model a cell of a cellular system

Model Constructs	System Heading	Tower Transmitter	Tower Receiver	Subscriber Transmitter	Subscriber Receiver
Maximum Power Density		R	R	R	R
Spectrum Mask		R		R	
Underlay Mask			R		R
Propagation Map		R	R	R	R
Power Map		R	R	R	R
Intermodulation Mask					
Platform Name					
Location		R- Point	R- Point	R- Surface or Volume	R- Surface or Volume
Start Time	R				
End Time	R				
Minimum Power Density					
Protocol or Policy	O				

R - Required, O - Optional, T - Typical (To provide a refined definition)

4.1.6 Radio Telescopes

Radio telescopes are merely receivers and can be modeled as such. A radio telescope system model could consist of one or multiple receiver models that specify the location of the telescope, provide an underlay mask of the spectrum where the telescope listens, provide a power map that captures the gain characteristics of the telescope antenna, and provide a propagation map to be used by potential interferers. Multiple receiver models would likely be used since the orientation of the telescope is affected by the rotation and orbit of the Earth causing time difference in use. Most components of these models would be the same with the differences being the time limits and the underlay masks. The models would specify different spectrum bands of interest in different blocks of time. Table 4-9 list the components and construct that might be found for a radio telescope operating on multiple bands.

Table 4-9. Components used to model a radio telescope

Model Constructs	System Heading	Receiver Band 1	…	Receiver Band n
Maximum Power Density	R			
Spectrum Mask				
Underlay Mask		R		R
Propagation Map	R	T		T
Power Map	R	T		T
Intermodulation Mask				
Platform Name				
Location	R- Point			
Start Time	R	T		T
End Time	R	T		T
Minimum Power Density				
Protocol or Policy				

R - Required, O - Optional, T - Typical (To provide a refined definition)

4.1.7 Radars

Radar is an acronym for radio ranging and detection. A radar transmits a signal and then waits for it to be reflected and returned to the radar where it is received. The detection of a reflected signal, the time of flight for this signal, the direction of the antenna when the returned signal was detected, and the characteristics of the received signal may all be used by the radar to reveal characteristics of the target. Radars typically transmit powerful signals and receive very faint reflected signals. Modeling of radars, in most cases, will consist of a transmitter model of the radar that will emit a relatively high power signal and a receiver model that reflects the sensitivity that a radar receiver must have. Radars are typically located at points. The spatial consumption of spectrum for the operational use of a radar will depend on the directionality of the radar's antenna and then its sweep in space. These components of the model require the greatest attention for a radar's efficient spectrum consumption modeling. The periodicity of radar signals may make it possible to create other systems that can coexist through the application of a protocol. If such a protocol exist it may be practical to specify the radar protocol for sending signals in the model, if the named protocol exists in the modeling lexicon. Table 4-10 Table 4-11provide a listing of the likely components in a radar spectrum consumption model.

Table 4-10. Components used to model a radar

Model Constructs	System Heading	Transmitter	Receiver
Maximum Power Density	R		
Spectrum Mask		R	
Underlay Mask			R
Propagation Map	R	T	T
Power Map	R	T	T
Intermodulation Mask			
Platform Name			
Location	R- Point		
Start Time	R	T	T
End Time	R	T	T
Minimum Power Density			
Protocol or Policy	O		

R - Required, O - Optional, T - Typical (To provide a refined definition)

4.1.8 Unmanned Aerial Systems

Unmanned aerial systems consist of multiple RF components that support both the control of the UAV and the transport of the information it senses. For example, it may provide a half duplex channel for its command and control, a downlink channel for its flight camera video, and a broadcast channel for its sensor data. Each of these three could be modeled differently. The flight video feed would be modeled as a simplex transmitter receiver pair with the transmitter at the aircraft. The sensor data transmitter would be modeled as a mobile broadcaster. The command and control channel would be modeled as a transceiver pair with a transmitter and receiver at both ends. Table 4-11 list the component models and constructs that would likely be used for the modeling of this type of UAS.

Table 4-11. Components used to model an unmanned aerial system

Model Constructs	System Heading	Ground C2 Tran	Ground C2 Rcvr	Airborne C2 Tran	Airborne C2 Rcvr	Airborne Video Tran	Ground Video Rcvr	Airborne Sensor Tran	Ground Sensor Rcvr
Maximum Power Density		R	R	R	R	R	R	R	R
Spectrum Mask		R		R		R		R	
Underlay Mask			R		R		R		R
Propagation Map		R	R	R	R	R	R	R	R
Power Map		R	R	R	R	R	R	R	R
Intermodulation Mask									
Platform Name									
Location		R- Point	R- Point	R- Volume	R- Volume	R- Volume	R- Point	R- Volume	R- Surface
Start Time	R								
End Time	R								
Minimum Power Density									
Protocol or Policy									

R - Required, O - Optional, T - Typical (To provide a refined definition)

4.2 Building Modeling Constructs for Better Spectrum Consumption

An objective of modeling is to enable more spectrum reuse. An important means of enabling spectrum reuse is to model in a manner that is efficient. An efficient model captures use of spectrum that provides protection from interference through compliance to its constraints but also consumes the least amount of spectrum to provide that protection. Spectrum consumption has five dimensions: RF bandwidth, time, and the three dimensions of space. Models need to be efficient in all these dimensions. Further, efficient models are designed to reduce the computational requirements to assess compatibility. In many cases there may be trades between better modeling of consumption and modeling for efficient computation.

4.2.1 Spectrum and Underlay Masks

The spectrum and underlay masks convey the RF bandwidth of spectrum consumption. The spectral envelopes of signals are the more predictable attributes of spectrum consumption. It is readily bounded with a spectrum mask. A spectrum mask is designed by selecting the points that define a piecewise linear bound on that envelope. Designing the mask with a small number of points reduces both the size of the model but also the complexity of compatibility computations.

Defining the underlay mask is less obvious. At the minimum it should place a bound on the interfering signal strength that would interfere with the ideal signal but the variations of propagation may require some additional margin. That margin is achieved by lowering the relative power levels with respect to the spectrum mask.

Figure 4-6 illustrates these concepts. The spectrum content of the transmitted signal is shown. There are two spectrum masks drawn to capture the envelope of this signal. The black mask uses six points and attempts to track the envelope more precisely. The red mask uses just four points. The red mask will reduce the computational complexity of compatibility computation but the black mask may identify reuse opportunities that the red would not. Regardless, both masks bound the envelope and so would protect this use of spectrum.

Note in Figure 4-6 that the underlay mask is not as wide in bandwidth as the spectrum mask. This indicates that the receiver filters the input of this signal and only needs to use the center band of the signal to recover the information in the signal. The underlay mask in this example is relative and potentially its power level can be raised or lowered. Shifting the power levels of the underlay mask changes the level of protection it affords but also changes the opportunities to reuse this spectrum.

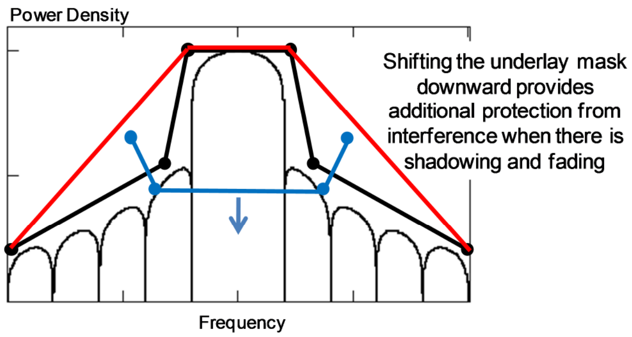


Figure 4-6. Example of creating a spectrum mask over a signal power envelope

4.2.2 Propagation Maps

Propagation maps capture the attenuation of signals that result from propagation and in so doing contribute to the spatial consumption conveyed by models. The modeling of propagation should not be viewed as an exercise to most accurately predict the strength of signals at a distance from a source but as a technique to establish the spatial boundary of a use on account of propagation. The more conservative model of propagation is one that predicts a lower rate of attenuation, i.e. a small pathloss exponent, as this will cause the greater separation between users. Square law attenuation in all directions can be a default when there is no knowledge of actual propagation conditions or when there is no evidence that a higher rate of attenuation will occur. Of course the modeler can attempt to build a model that more accurately predicts performance and this in turn will create boundaries that more accurately predict actual spectrum consumption.

Some phenomena of propagation cannot be modeled using a pathloss exponent. The monotonic nature of this attenuation model does not capture the non-monotonic effects of fading and shadowing where signal strength alternates between strong and weak as the observation point moves along a direction. Modeling in this case would attempt to capture the more optimistic attenuation of the furthest region where the signal is strong enough to be received. Similarly, the model cannot capture an abrupt change in propagation that might be caused by an obstacle or large terrain feature, for example a mountain. To benefit from the boundary that such a terrain feature provides requires using a pathloss exponent that overestimates attenuation to the obstacle so that the boundary of consumption matches the location of the obstacle. So the model that most accurately captures the boundary of consumption does not necessarily provide the best estimate of signal strength.

Figure 4-7 illustrates several options for choosing a pathloss exponent for a model. Each seeks a different goal or combination of goals. These goals include placing a bound on power transmitted, giving a best estimate of power transmitted, and predicting the maximum range. Generally, the lower pathloss exponent will result in the most conservative estimate of pathloss and results in the least reuse as smaller exponents result in greater propagation range. Placing an upper-bound on transmitted power is a means to ensure the modeled system does not interfere

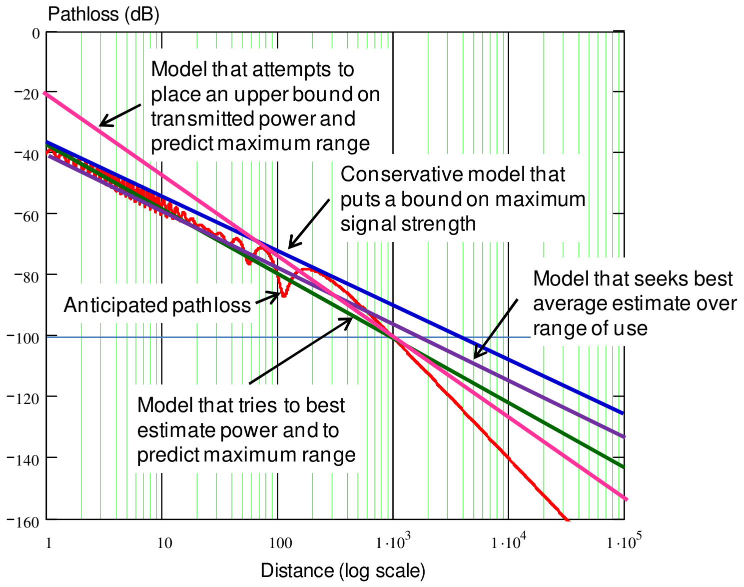


Figure 4-7. Options for selecting a pathloss exponent

with incumbent systems in the same spectrum. Using an exponent that best predicts the range of a system offers the best opportunities for reuse in adjacent areas. Adjusting the power at 1 meter combined with selecting an appropriate pathloss exponent, as demonstrated in the case that both bound the transmitter power (for the most part but not all in this example) and estimates the range, is a legitimate means to achieve multiple objectives.

Mobility contributes a special challenge to propagation modeling because propagation is so dependent on the environment and mobility continuously changes it. Mobility itself is accommodated by modeling a space that encompasses the range of movement and so a propagation model that accompanies such a space must account for the worst case in all of the space. Creating higher resolution models of propagation when there is mobility requires dividing the regions of mobility into smaller area so dividing the use up into spatial increments and then building separate propagation models for those increments.

Although the directional vector of propagation maps provide an unlimited ability to divide directions into different solid angles and so provides the ability to fit a model to observations, doing so is usually not helpful. Increasing the number of directions and exponents used in a model increases the complexity of the computations of compatible reuse and decreases the efficiency of communicating the model. Modeling needs to weigh the benefit of having a higher resolution model with these costs. It may also be reasonable for a model, say for a broadcaster, to be defined with a high resolution model but then for a system determining compatibility to reduce its resolution for more efficient computations and for less overhead.

4.2.3 Power Maps

Power modeling also affects spatial consumption and is intended to capture the effects of antenna directionality on the use of spectrum. Unlike in propagation modeling, power model values are not chosen to define a spatial boundary, rather they are chosen to bound the actual power that is emitted from an antenna. It is in their combined use with the propagation map that spatial consumption is determined. The more conservative power map models overestimates the power transmitted from an antenna. Power maps can conform to a known antenna's power pattern but in practice a lower resolution model will typically suffice. As with propagation maps, it is desirable to avoid complexity and overhead.

Mobility, both the maneuvering of the antenna direction and the mobility of the antenna platform contribute to the selection of a model. Angular displacement within the duration of a model is accommodated by a larger surface that captures the greatest gain that may be possible in a direction after an antenna is swept through its range of motion. Figure 4-8 illustrates an example. Here we show a directional antenna that may be used by a ground control station of an unmanned aerial vehicle (UAV) and a hypothetical power pattern for that antenna. We then show the power density surface of a power map that would contain the antenna power pattern. Next we illustrate a mission volume for the UAV that the antenna would need to sweep and then the corresponding power map that contains the highest gain of the sweep. A very simple vector with just a few values provides a map that bounds this operational use.

Power maps accommodate platform mobility in a manner similar to that shown for steering an antenna, capturing the range in orientations that follow from mobility. These changes might be caused by the changing directions that platforms move or be more unpredictable reorientations such as those caused by the undulation of ground vehicles that traverses rough terrain or an aircraft maneuvering. The sectors with the largest power values become larger as the variability in orientation becomes larger thus convey a greater consumption of spectrum. Dividing a use

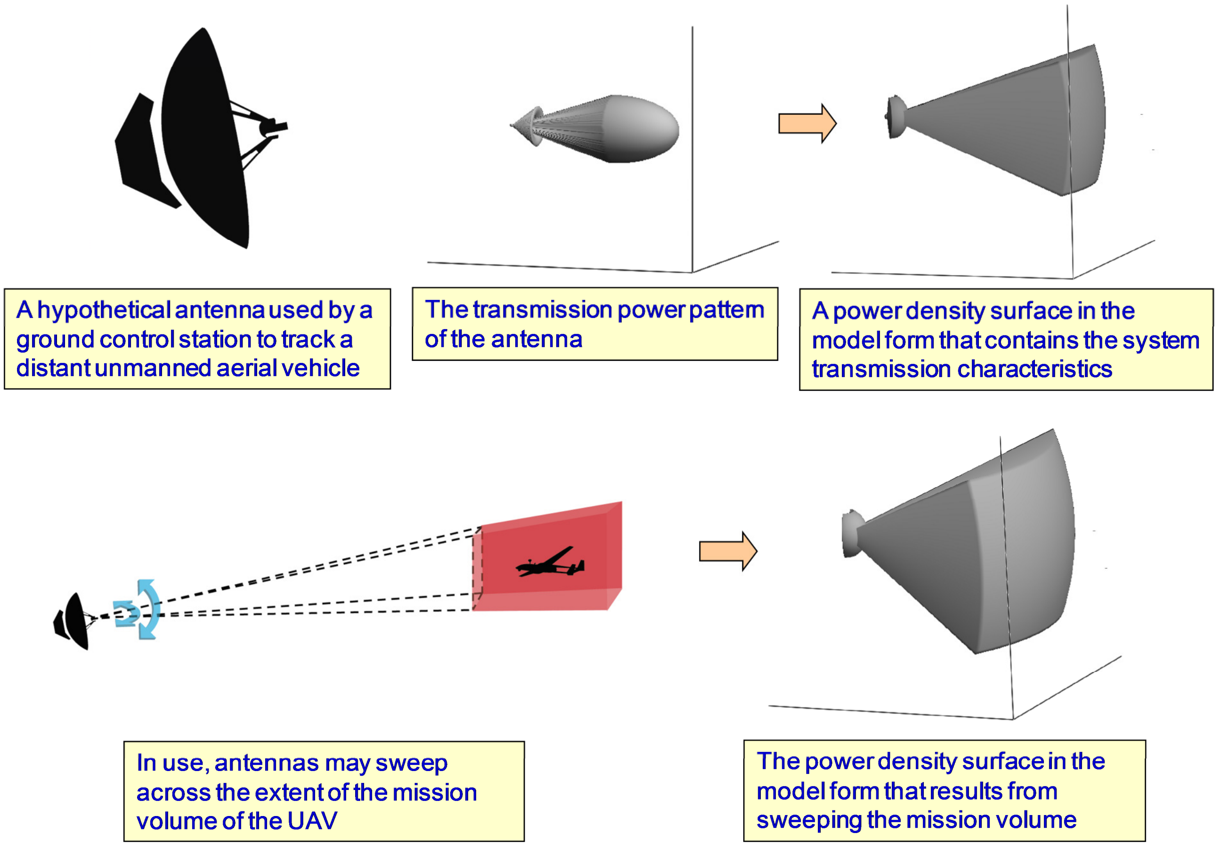


Figure 4-8. Example of creating power maps to contain the power patterns of antennas and the operational use of antennas

into temporal or spatial segments in which there is less variability helps reduce the consumption of the model.

4.2.4 Location and Time

The subdivision of models into smaller operational spaces differentiated by time offers the greatest opportunity to generate reuse opportunities. The vision is that spectrum consumption models can be a product of the operational planning of a system's use. If a system can be confined to a smaller space for the some part of a mission then the model of that smaller space for the time that the system operates in the space will result in less spectrum consumption than modeling the full space of operation for the full duration of a mission. Figure 1-4 illustrated an example of a subdivison of a space.

4.3 Aggregate and Decomposition Modeling

The aggregation and decomposition of models is a feature of modeling that allows further efficiencies in spectrum management. They both have meaning in terms of the listing of models and in the combining or subdivison of models. A collective listing of models is a collection of transmitter and receiver models that are each complete on their own. The purpose of collective listings can be found in Section 2.3. Listings may use transmitter and receiver models from multiple systems models. Listings may also include subsets of the transmitter and receiver models from various system models. Another possible aggregation of models is to combine several like types of models (e.g. several transmitter models or several receiver models) that are adjacent in spectrum or space into a single model with a larger space or a larger band of spectrum. Another possible decomposition of models is to divide a model into multiple smaller models either in terms of space or spectrum. This technique may be used with a spectrum use authorization to enable assignment of portions of the authorization to multiple independent users that can coexist.

5 Implementation

This manual has presented the motivation for creating a method for spectrum consumption modeling and has attempted to define an approach to build these types of models. An effective modeling approach accomplishes three objectives:

1. Provides constructs for capturing the many facets of spectrum use within models
2. Provides well defined tractable and efficient methods for computing compatibility of modeled uses.
3. Provides a means to use the models to convey both the consumption and the availability of spectrum

Proposing a modeling approach is just a beginning and validating that the three objectives are achieved comes in the evolution of the system. Spectrum consumption models only have value if they are used to increase spectrum uses. The greater benefit comes from the broad adoption of the technique as opposed to any targeted application as it is the sharing of spectrum among systems that is sought. As this approach to spectrum management and use is a significant change from what exists today, a successful implementation will evolve over time with no instantaneous benefit.

We anticipate that the path forward will see emphasis in two areas, the more academic exercises of defining a standard for modeling and the concurrent development of algorithms based on the models, and then the attempted implementation of the modeling into systems. This systems implementation would likely start by incorporating the models and algorithms into spectrum management systems and be followed by the development dynamic spectrum management and dynamic spectrum access systems that respond to this management. Here, in this manual, we have attempted to execute the very first step and define a modeling approach. In the remainder of this chapter we identify some objectives of the remaining tasks. We identify factors that should be considered before modifications are made to the modeling constructs this manual proposes.

5.1 Algorithms

Algorithms are a complementary component of developing a modeling approach. It is necessary that the modeling approach support a reasonably tractable and efficient set of algorithms to assess compatibility and to seek reuse opportunities. And so modeling options should be compared by their effects on efficient algorithm development. The modeling approach described in this manual made three significant choices to obtain efficiency. The most significant choice was to require that relevant terrain effects on propagation be part of the model, specified as a pathloss exponent in the model's propagation map, so that there would be no requirement to maintain and synchronize large databases of terrain data and complex propagation algorithms for computing propagation effects. The second significant choice was to require that the model define what is harmful interference removing the requirement for the spectrum management system to make this determination but only to determine if it is occurring. The third significant choice was to define consumption after the antenna and requiring that the model capture how a system generates radiation or is affected by radiation eliminating the requirement to assess how antennas convert a driving current into a spatial radiation pattern and vice versa. The result is the models and algorithms can stand alone without any databases of the environment or system specifications. The algorithms for assessing compatibility require no additional data other than that which is in the models.

There are three broad categories of algorithms required for a general spectrum management capability: assessing compatibility, quantifying consumption, and searching for reuse opportunities. The significance of these algorithms in spectrum management systems is described further in the subsequent subsections.

5.1.1 Assessing Compatibility

The primary task that must be completed using spectrum consumption models is determining whether one use of spectrum is compatible with another. Chapter 3 described this process for the spectrum consumption models described in this manual. Making a full assessment of compatibility is non-trivial. In most complex system uses, RF components can be located in a variety of locations and so compatibility among systems requires consideration of the many pairwise orientations of the systems. Algorithms for assessing compatibility would first search for the potential worst cases combinations of pairwise orientations of systems within the constraints of their models and then use these cases as those that constrain use.

Implementation of a model-based spectrum management system will depend on the effectiveness and efficiency of the algorithms used to assess compatibility. Modifications to the modeling approach described in this manual should also consider the concurrent effect those modifications may have on the development of these algorithms. Certain requirements in the models such as locations of use must be convex and propagation be monotonic are imposed to ensure the tractability of these future algorithms. More simply, trying to add resolution by adding more features to the models, e.g. dependence on terrain databases, could make compatibility computations intractable and should only be done after evaluating their effect on the efficiency of the algorithms.

5.1.2 Quantifying Consumption

A problem in current spectrum management is the definition of consumption. If consumption can be quantified then we can understand how much spectrum is being used, how much remains available for use, and how much spectrum a system requires. Consumption has spectral, temporal, and spatial dimensions and so is the product of time, RF bandwidth and volume of use. Spectrum consumption modeling provides a means to quantify consumption.

Quantifying consumption requires the definition of a nominal transmitter and receiver of a secondary user. The spatial consumption of a model is the union of the volumes that are formed by the boundary where these nominal transmitters and receivers can begin operation. Such integration can also capture spectral consumption by allowing the nominal transmitter and receiver to change in frequency and to then integrate across frequency as well. This four dimensional integration is then multiplied by the time of use to get the full measure of consumption.

Given a measure of available spectrum and then a measure of what spectrum is actually being used allows us to identify the opportunities for more uses. Quantifying consumption reveals the value of subdividing uses into operational segments and of employing technologies that reduce spectral consumption such as directional antennas. Over time, these measures reveal the improvements in both the modeling and management of spectrum and in the efficiency of systems.

5.1.3 Searching for and Managing Reuse Opportunities

Measuring consumption will likely reveal that a lot of spectrum is unused. Thus, a very important part of MBSM is to identify spectrum that is available to support additional operational uses. In general, given a requirement for spectrum in terms of space and bandwidth, such algorithms would search through existing uses and find spectrum that can be used.

Exploiting unused spectrum may not be so simple. It is likely that the boundaries of availability do not readily match the boundaries that are requested. Searching algorithms may then suggest adjustment to the boundaries of the requested use to those that available spectrum can come closest to supporting. Alternatively, the algorithms may also suggest shifts in existing uses to make room for the requested use.

There are likely many alternative algorithms of this nature that may be developed as systems and management processes allow adjustments.

5.2 Improving Spectrum Management

Spectrum management, in the near term, can be most improved in its resolution of the time and spatial differences in spectrum use. The spectrum consumption modeling approach described in this manual clearly makes these components important constructs of models. An initial spectrum management system would operate on databases populated with spectrum consumption models and so immediately could make these improvements to spectrum management.

The mindset of spectrum management is likely to change. Rather than waiting and then trying to fill requests, management will try to enable reuse opportunities. The process would start by encouraging users to model their use of spectrum as efficiently as they can, maybe using spectrum consumption measures described above as the measure of goodness. Assuming that users can create models that both protect their use of spectrum while consuming less of it, then there should be opportunities for some other system to use the spectrum that becomes available. Spectrum management will be about understanding which systems can exploit unused spectrum and informing them of the opportunity. As an example, consider the case where a UAS and a terrestrial ground system use the same spectrum. If the UAS system's use of spectrum is modeled on a mission basis, then when the system is idle there may be opportunity for the terrestrial communications system to use the spectrum for transport. Understanding of these cycles can allow the transport systems to store routine transmissions for periods where this additional spectrum is available and can support its transport.

5.3 Dynamic Spectrum Management and Access Systems

The ultimate evolution of spectrum management is the creation of a very dynamic system where operational planning and spectrum planning are integrated and distributed. Further, where planning systems can direct radio systems what spectrum to use and where radio systems can receive policy from the spectrum management systems and autonomously share spectrum with existing systems. The objective of spectrum consumption modeling is to create the conditions where such innovation can evolve without demanding any fundamental changes to the modeling approach.

5.4 Conclusion

Successful implementation of MBSM and achieving its full set of benefits requires broad adoption of the technique. The first step is to agree to a modeling approach. This manual attempts to define that modeling approach so that the idea can be shared and be used to seek agreement. Assuming that stake holders recognize the benefits of MBSM, then a modeling standardization effort will likely follow and this seminal work will serve as its foundation. A consideration that should be evaluated if changes are proposed to what is currently defined in this manual would be the subsequent effects those changes would have on the development of algorithms that are used in spectrum management and in the systems that could evolve from the use of MBSM. This last chapter has attempted to lay out some of those considerations.

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Appendix B Coding of Spectrum Consumption Model Components

It is desirable to make spectrum consumption models concise for those applications that rely on over-the-air communication of these models. Radio frequency systems are already constrained in their transport capacity and so it is beneficial to optimize the data structures within spectrum consumption models to avoid unnecessary overhead. Here we describe techniques that improve the efficiency of spectrum masks and the directional vectors used in propagation and power maps. The idea in each is to encode values into discrete digital values. The map methods also provide a means to shift resolution among the latitudes between the horizon and the axis. Further these techniques provide methods to delimit the ending of these variable length data structures.

B.1 Spectrum, Underlay, and Intermodulation Masks

Spectrum masks can be made more concise by encoding the vector into *m*-bit words, where *m* is an integer number greater than 1 but, for practical reasons, usually greater than or equal to 8. Each word corresponds to a unique frequency value or a unique power density value. The concise spectrum mask data structure also alternates between the frequencies of the inflection points and their power density levels, e.g. $\left(f_0, p_0, f_1, p_1, \ldots, f_x, p_x, 2^m - 1\right)$. Two values orient the mask, the center frequency of the mask f_c and the resolution of the frequency step f_i. There are 2^m frequency levels where each subsequent value is separated by the specified frequency step resolution. The frequency $2^{m-1}-1$ maps to the center frequency and the value $2^m - 1$ is only used to denote the end of the mask. There are 2^m power levels where 0 represents the maximum power density level of the mask, and each coded value maps directly to a decibel reduction in power from the maximum power. The reference transmission power also orients the mask and is conveyed through the combinations of the other components as described Chapter 2.

Thus, the conversions between the frequency coded values and their real values are

$$|f| = f_c + f_i\left(f - 2^{m-1} + 1\right)$$

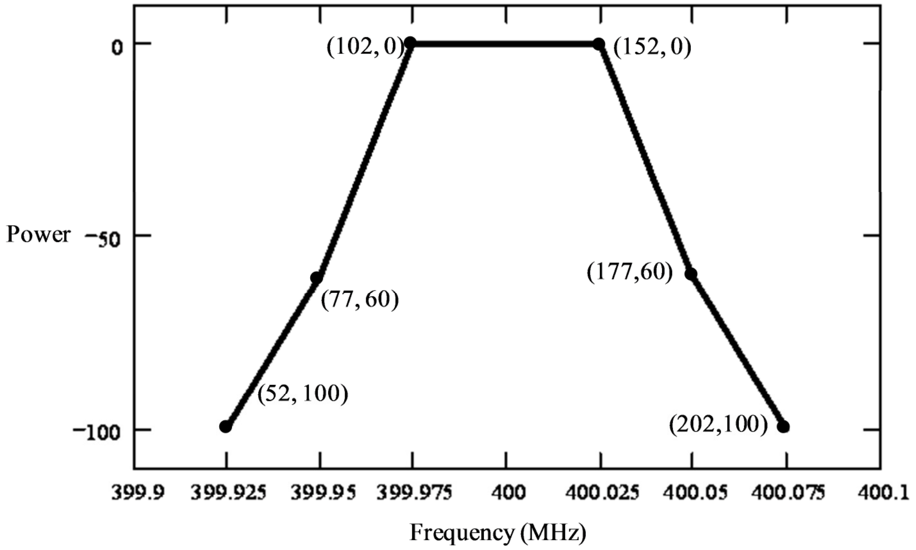
$$f = \frac{|f| - f_c}{f_i} + 2^{m-1} - 1$$

where f is the coded value and $|f|$ is the value that is coded. The conversions between the power values are

$$|p| = -p$$

where p is the coded value and $|p|$ is the real value that is coded.

Figure B-1 illustrates the concise vector approach of specifying the spectrum masks previously depicted in Figure 2-1. This spectrum mask uses 8 bit words with a center frequency of 400 MHz, and a frequency increment of 0.001 MHz. Note that the dummy value of $\left(2^8 - 1\right) = 255$ terminates the vector.



(52, 100, 77, 60, 102, 0, 152, 0, 177, 60, 202, 100, 255) $f_c = 400$ MHz, $f_i = 0.001$ MHz

Figure B-1. Encoded spectrum mask of Figure 2-1 using 8 bit values

B.2 Directional Vectors

The directional vectors used for maps may be made more concise by encoding the vector into *m*-bit words, where *m* is an integer number greater than 1 and, for practical reasons, usually greater than or equal to 8. A concise map is identical in form to a regular map, except it users a vector of m-bit words where each word is coded and supports specifying up to 2^m model parameters mapped to values from some minimum to some maximum value, $2^m - 2$ elevations (ϕ) starting from the vertical down direction and reaching to the vertical up direction (an odd number of latitudes so the middle latitude will point to the horizon), and $2^m - 1$ azimuths (θ) reaching about the node on the horizon (the first and last azimuths, 0 and $2^m - 1$ point in the same direction). As described in Section 2.1.4.2, direction vectors use the reduced form where the final angle about an annulus, $2^m - 1$ in a concise vector, also indicates that the next value is an elevation, that after an elevation that the first angle is implicitly 0, and that the end of a vector is indicated by the value 0 following an exponent value in a propagation map or a power value in a power map. A concise vector in reduced form would have the form

$$\left(n_{0,0}, \theta_{0,1}, n_{0,1}, \theta_{0,2}, \cdots, \left(2^m - 1\right), \phi_1, n_{1,0}, \theta_{1,1}, \cdots, \left(2^m - 1\right), \phi_2, n_{2,0}, \cdots, n_{last}, 0\right).$$

The discrete incremental values used to specify directions and exponents in propagation maps are mapped to values. Azimuth directions are evenly spaced about the map, with 0 and $2^m - 1$ values pointing in the same direction. The conversion from a map azimuth value to an angular direction is

$$|\theta| = \frac{\theta \cdot 360°}{2^m - 1},$$

where θ is the coded value and $|\theta|$ is the real azimuth that is coded. If an original vector azimuth direction is between the discrete values allowed by this encoding then the discrete value that is used should be the one that enlarges the sector with the most conservative values, the values that cause the greatest separation of users.

Frequently it is desirable to have greater elevation resolution near the horizon especially for terrestrial applications where topology, manmade structures, and foliage can greatly affect propagation at relatively low elevations. Alternatively, it may be desirable to have a greater resolution near the axial directions especially for airborne platforms with directional antennas oriented toward the earth. As a general method to provide the shifting of resolution, we incrementally scale subsequent elevation by some scaling factor moving from the axis to the horizon. Given a scaling factor of s, the relation of subsequent values are

$$\begin{aligned} \left(|\phi+2|-|\phi+1|\right) &= s\left(|\phi+1|-|\phi|\right) & \phi \le 2^{m-1}-1 \\ \left(|\phi+1|-|\phi|\right) &= s\left(|\phi+2|-|\phi+1|\right) & \phi > 2^{m-1}-1. \end{aligned}$$

where ϕ is the coded value and $|\phi|$ is the real elevation that is coded and where the elevation $\phi = \left(2^{m-1}-1\right)$ points to horizon. When the scaling achieves finer resolution at the horizon, s < 1, the conversion between values and coded values are

$$|\phi| = \left(1-s^{\phi}\right)\frac{90°}{\left(1-s^{2^{m-1}-1}\right)} \qquad 0 \le \phi \le 2^{m-1}-1$$

$$|\phi| = 180° - \left(1-s^{2^{m}-2-\phi}\right)\frac{90°}{\left(1-s^{2^{m-1}-1}\right)} \qquad 2^{m-1}-1 < \phi \le 2^{m}-2$$

$$\phi = \frac{\ln\left(1-\frac{|\phi|\left(1-s^{2^{m-1}-1}\right)}{90°}\right)}{\ln(s)} \qquad 0° \le |\phi| \le 90°$$

$$\phi = 2^{m}-2-\frac{\ln\left(1-\frac{\left(180°-|\phi|\right)\left(1-s^{2^{m-1}-1}\right)}{90°}\right)}{\ln(s)} \qquad 90° < \phi \le 180°$$

When there is no scaling, $s = 1$:

$$|\phi| = \frac{\phi}{2^{m}-2}180°$$

and when finer resolution is used at the axes, $s > 1$:

$$|\phi| = 90° - \left(1-\left(\frac{1}{s}\right)^{2^{m-1}-1-\phi}\right)\frac{90°}{\left(1-\left(\frac{1}{s}\right)^{2^{m-1}-1}\right)} \qquad 0 \le \phi \le 2^{m-1}-1$$

$$|\phi| = 90° + \left(1-\left(\frac{1}{s}\right)^{\phi-2^{m-1}-1}\right)\frac{90°}{\left(1-\left(\frac{1}{s}\right)^{2^{m-1}-1}\right)} \qquad 2^{m-1}-1 < \phi \le 2^{m}-2$$

$$\phi = 2^{m-1} - 1 - \frac{\ln\left(1 - \frac{\left(90° - |\phi|\right)\left(1 - \left(\frac{1}{s}\right)^{2^{m-1}-1}\right)}{90°}\right)}{\ln\left(\frac{1}{s}\right)} \qquad 0° \le |\phi| \le 90°$$

$$\phi = 2^{m-1} - 1 + \frac{\ln\left(1 - \frac{\left(|\phi| - 90°\right)\left(1 - \left(\frac{1}{s}\right)^{2^{m-1}-1}\right)}{90°}\right)}{\ln\left(\frac{1}{s}\right)} \qquad 90° < |\phi| \le 180°$$

B.3 Power and Propagation Values

The power density model parameters are coded in a concise power map vector in the same manner as that used for concise spectrum masks. The pathloss exponent model parameters in concise propagation map vectors are coded such that subsequent coded exponents estimate nearly equidistant change in propagation range from the largest to the smallest exponent value. Range is the distance to where attenuation causes a signal to go below a threshold, *RT*, according to the model, and the smallest exponent value estimates the furthest range. The conversion equation may be created from a nominal $RP(1m)$ and *RT* and selected values for $|n_{low}|$ and $|n_{high}|$. A process to create the conversion equation first determines a maximum and minimum range predicted by the nominal $RP(1m)$ and *RT* and the selected values for $|n_{low}|$ and $|n_{high}|$. Further, the incremental distance, d_{inc}, expressed by the exponents determined by:

$$d_{low} = 10^{\left(\frac{RP(1m)-RT}{10|n_{low}|}\right)},$$

$$d_{high} = 10^{\left(\frac{RP(1m)-RT}{10|n_{high}|}\right)},$$

$$d_{inc} = \frac{d_{low} - d_{high}}{2^m - 1}$$

The conversions between the coded exponents and the actual exponent values are

$$n = \frac{d_{low} - 10^{\left(\frac{RP(1m)-RT}{10|n|}\right)}}{d_{inc}}$$

$$|n| = \frac{RP(1m) - RT}{10\log\left(d_{low} - n \cdot d_{inc}\right)}$$

where n is the coded value and $|n|$ is the real elevation that is coded. As demonstrated, the interpretation of the concise propagation map is dependent on the method to code the exponents. In practice, the method may be explicitly defined by regulation or be arbitrary dependent on the decision of the map's creator. In the case of the latter, the map must be accompanied with the values used in the conversion, specifically $|n_{low}|$, $|n_{high}|$, $RP(1m)$, and RT.

B.4 Concise Vector Examples

Figures B-2 and B-3 illustrate the interpretation of concise propagation maps. The parameters in Table B-1 calibrate the maps, and the power density is assumed isotropic. The surface of these propagation maps identify the range from a transmitter where the signal strength threshold, *RT*, is reached.

Table B-1. Propagation Map Parameters

(General design parameters for propagation map definition)

Symbol	Description	Value
f_c	Center frequency	400 MHz
Maximum power density	Maximum 1-meter power density	0 $\mathrm{dB}W/m^2$
RT	Receive power threshold	-100 $\mathrm{dB}W/m^2$
n_{high}	Largest pathloss exponent	7
n_{low}	Smallest pathloss exponent	2
m	Number of bits per word	8

Figure B-2 illustrates a surface plot of the range predicted by a propagation map using a single annulus. All values in the propagation map vector are coded, and the meanings of the values are known by their position. For example, an exponent 0 extends from an azimuth 0 to an azimuth 70; an exponent 180 extends from azimuth 70 to an azimuth 130; an exponent 100 from azimuth 130 to an azimuth 200; and an exponent 60 applies the rest of the way around the map. There are no elevation breaks in the example. In propagation maps, smaller exponents generally predict larger ranges, and therefore, the surface labeled a, which corresponds to exponent 100, is further from the center than a surface, labeled b, which corresponds to exponent 180.

Figure B-3 illustrates exemplary surface plots of the range predicted by a common propagation map vector using different scaling factors. This map has two elevation breaks, one below the horizon and one above the horizon. An exponent 115 extends from azimuths 0 to 255, and the next value in the vector, 102, is the coded value of an elevation. In the second annulus, an exponent 0 applies to a sector from azimuths 0 to 40, and then an exponent 115 extends the rest of the way around to an azimuth 255. Since this is the end of the annulus the next vector value, 147, is an elevation value which corresponds to the horizon. The last annulus has an exponent value 115. As 0 follows 115, an exponent 115 applies all the way around the annulus and down to the last elevation. The solid angle projections differ because they use different scaling factors.

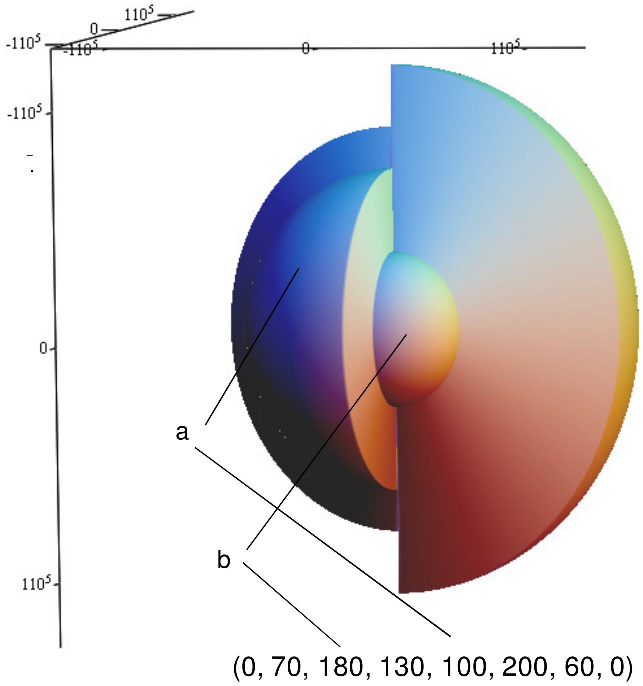


Figure B-2. Encoded spectrum mask of Figure 2-1 using 8 bit values

With scaling factors of 0.98, 1.00, and 1.02, the coded value for the elevation 102 corresponds to actual values 85.07°, 72.28°, and 51.77°, respectively. The elevation 147 corresponds to the actual values 122.02°, 104.17°, and 93.73° for the three scaling factors respectively. As described previously, the exponent 0 has greater range than the exponent 115.

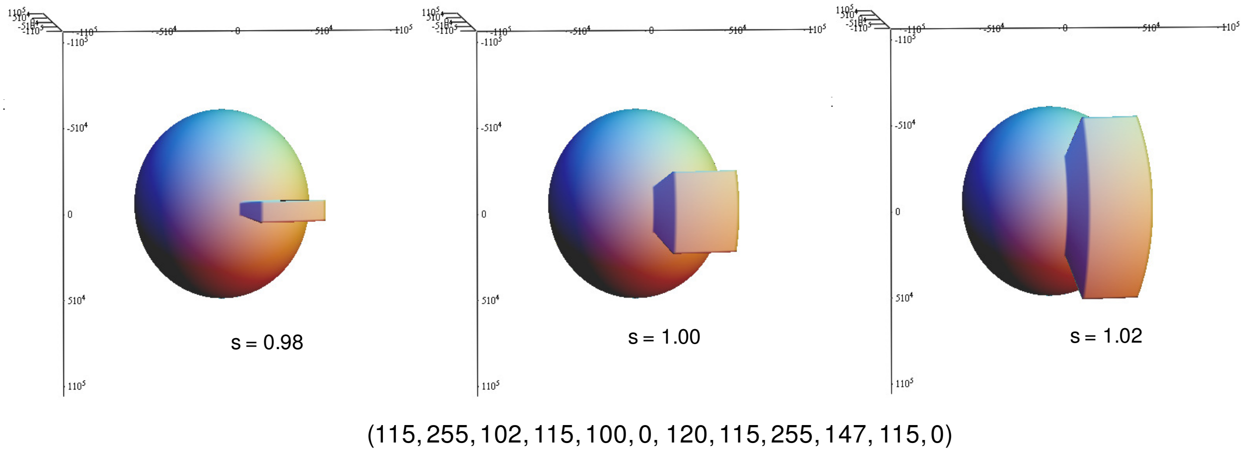


Figure B-3. Encoded spectrum mask of Figure 2-1 using 8 bit values

Appendix C Spectrum Consumption Model Markup Language (SCMML)

As illustrated in Figure 2-20 and described in Section 2.3, spectrum consumption models are conveyed using a set of constructs combined to from transmitter and receiver models, combined with transmitter and receiver models to form system models, or combined with transmitter, receiver, and system models to form collections. This appendix describes the SCMML schema for communicating system models and collections. The SCMML starts by defining the data types that are repeatedly used within the constructs, then defines a data type for constructs, followed by those of transmitters, receivers, and systems, and finally describes the markup for systems and collections using these data types. As described, SCMML is a hierarchy of data types that build upon each other. Here each of the individual data types are described in the order they are defined in the schema.

C.1 Fundamental Types

C.1.1 Power_Density Type

The Power_Density data type is used for both the maximum power density and minimum power density constructs. The values are specified as decimal numbers and they are always expected to have units of ${}^{\mathrm{dBW}}\!/_{\mathrm{m}^2}$.

```
<xs:complexType name="Power_Density">
  <xs:simpleContent>
    <xs:extension base="xs:decimal">
      <xs:attribute name="units" fixed="dBW/m**2"/>
    </xs:extension>
  </xs:simpleContent>
</xs:complexType>
```

C.1.2 Frequency Type

The frequency data type is used in multiple types and constructs of the SCMML. The frequency value is of type decimal and this type provides attributes for the specification of units.

```
<xs:complexType name="Frequency">
  <xs:simpleContent>
    <xs:extension base="xs:decimal">
      <xs:attribute name="units" use="required">
        <xs:simpleType>
          <xs:restriction base="xs:string">
            <xs:enumeration value="kHz"/>
            <xs:enumeration value="MHz"/>
            <xs:enumeration value="GHz"/>
          </xs:restriction>
        </xs:simpleType>
      </xs:attribute>
    </xs:extension>
  </xs:simpleContent>
```

```
</xs:complexType>
```

C.1.3 Relative_Power Type

The Relative_Power type is used in multiple types and constructs of the SCMML. The relative power value is of type decimal and this type specifies that it units is always dB.

```
<xs:complexType name="Relative_Power">
   <xs:simpleContent>
      <xs:extension base="xs:decimal">
         <xs:attribute name="units" fixed="dB"/>
      </xs:extension>
   </xs:simpleContent>
</xs:complexType>
```

C.1.4 Short_Time Type

The Short_Time data type is used in the spectrum mask constructs for the definition of frequency hopping and short duty cycle signals. The value is specified as a decimal value and the type specifies a choice between three units attributes: µsec, msec, or sec.

```
<xs:complexType name="Short_Time">
   <xs:simpleContent>
      <xs:extension base="xs:decimal">
         <xs:attribute name="units" use="required">
            <xs:simpleType>
               <xs:restriction base="xs:string">
                  <xs:enumeration value="usec"/>
                  <xs:enumeration value="msec"/>
                  <xs:enumeration value="sec"/>
               </xs:restriction>
            </xs:simpleType>
         </xs:attribute>
      </xs:extension>
   </xs:simpleContent>
</xs:complexType>
```

C.1.5 Spectrum Mask Types

The spectrum mask types are used by the spectrum mask, underlay mask and intermodulation mask construct types.

C.1.5.1 Inflection_Point Type

The Inflection_Point data type is used to define the inflection points in spectrum, underlay, and intermodulation masks. An inflection point has two data elements, a frequency and a relative power level. This type requires the modeler to specify the units of the frequency as either, kHz, MHz, or GHz. The units of the relative power are fixed as dB.

```
<xs:complexType name="Inflection_Point">
   <xs:sequence>
      <xs:element name="Frequency" type="Frequency"/>
```

```
      <xs:element name="Relative_Power" type="Relative_Power"/>
   </xs:sequence>
</xs:complexType>
```

C.1.5.2 Mask Type

Masks are used within three constructs: the spectrum mask, the underlay masks, and the intermodulation masks. Masks have at least 2 Inflection_Point elements as this is the minimum necessary to specify some quantity of bandwidth. In practice there will likely be more and so the Inflection_Point data element may be reused an unbounded number of times.

```
<xs:complexType name="Mask">
   <xs:sequence>
      <xs:element minOccurs="2" maxOccurs="unbounded" name="Inflection_Point"
         type="Inflection_Point"/>
   </xs:sequence>
</xs:complexType>
```

C.1.5.3 FH_Signal_Timing_Values Type

This structure specifies values that are used together to specify the dwell and revisit period of frequency hop signals. The data type is used in the spectrum mask construct when specifying the mask of a frequency hop system

```
<xs:complexType name="FH_Signal_Timing_Values">
   <xs:sequence>
      <xs:element name="Dwell_Time" type="Short_Time"/>
      <xs:element name="Revisit_Period" type="Short_Time"/>
   </xs:sequence>
</xs:complexType>
```

C.1.5.4 Center_Frequency_List Type

The Center_Frequency_List is used to specify a list of center frequencies as part of the definition of a frequency hop radio signal. The single repeated element uses the frequency type.

```
<xs:complexType name="Center_Frequency_List">
   <xs:sequence>
      <xs:element maxOccurs="unbounded" name="Center_Frequency" type="Frequency"/>
   </xs:sequence>
</xs:complexType>
```

C.1.5.5 Frequency_Band Type

The Frequency_Band type is used to specify a band in which a frequency hop signals may occur. A frequency band is specified by a start frequency and an end frequency.

```
<xs:complexType name="Frequency_Band">
   <xs:sequence>
      <xs:element name="Start_Frequency" type="Frequency"/>
      <xs:element name="End_Frequency" type="Frequency"/>
   </xs:sequence>
</xs:complexType>
```

C.1.5.6 Frequency_Band_List Type

Frequency hop signals may occupy multiple disjoint bands. The Frequency_Band_List type is used to enable the modeler to specify one or more bands to be used by a frequency hop signal. It uses one or multiple elements of the Frequency_Band type.

```
<xs:complexType name="Frequency_Band_List">
   <xs:sequence>
      <xs:element maxOccurs="unbounded" name="Band" type="Frequency_Band"/>
   </xs:sequence>
</xs:complexType>
```

C.1.5.7 BW_Rating_Values Type

The BW_Rating_Values type is used to specify a bandwidth paired with a relative power. This data structure is used together with an underlay mask to adjust the power levels of the mask when considering narrowband interference of a specified bandwidth.

```
<xs:complexType name="BW_Rating_Values">
   <xs:sequence>
      <xs:element name="Bandwidth" type="Frequency"/>
      <xs:element name="Relative_Power" type="Relative_Power">
      </xs:element>
   </xs:sequence>
</xs:complexType>
```

C.1.5.8 BW_Rating_List Type

The BW_Rating_List lists some number of BW_Rating_Values and is used within the underlay construct. It provides an efficient way to use a single underlay mask to specify the performance of a system for narrowband signals of different bandwidths.

```
<xs:complexType name="BW_Rating_List">
   <xs:sequence>
      <xs:element maxOccurs="unbounded" name="Rating_Values"
         type="BW_Rating_Values"/>
   </xs:sequence>
</xs:complexType>
```

C.1.5.9 Bandwidth_Time_Product Type

The Bandwidth_Time_Product type is used to specify a bandwidth time product. A bandwidth time product is used as a measure of the occupancy of frequency hop signals in the band of an underlay mask.

```
<xs:complexType name="Bandwidth_Time_Product">
   <xs:simpleContent>
      <xs:extension base="xs:decimal">
         <xs:attribute name="units" fixed="Hz*sec"/>
      </xs:extension>
   </xs:simpleContent>
</xs:complexType>
```

C.1.5.10 BTP_Rating_Values Type

The BTP_Rating_Values type pairs an element of Bandwidth_Time_Product type with an element of the Relative_Power type and is used to provide a rating for an underlay mask. The relative power element specifies the adjustment in the power of the underlay mask to use for an underlay rated for the specified bandwidth time product.

```
<xs:complexType name="BTP_Rating_Values">
   <xs:sequence>
      <xs:element name="Bandwidth_Time_Product" type="Bandwidth_Time_Product"/>
      <xs:element name="Relative_Power" type="Relative_Power">
      </xs:element>
   </xs:sequence>
</xs:complexType>
```

C.1.5.11 BTP_Rating_List Type

The BTP_Rating_List type is used with an underlay mask and allows a list of BTP_Rating_Values to define several different underlay mask ratings using the same base underlay mask.

```
<xs:complexType name="BTP_Rating_List">
   <xs:sequence>
      <xs:element maxOccurs="unbounded" name="Rating_Values"
        type="BTP_Rating_Values"/>
   </xs:sequence>
</xs:complexType>
```

C.1.6 Map Types

C.1.6.1 Map Type

Maps are used within two constructs: propagation maps and power maps. The "Map_Value" element has a minimum of two occurrences to accommodate the smallest map and is unbounded for more complex maps.

```
<xs:complexType name="Map">
   <xs:sequence>
      <xs:element minOccurs="2" maxOccurs="unbounded" name="Map_Value"
        type="xs:decimal"/>
   </xs:sequence>
</xs:complexType>
```

C.1.6.2 Angle Type

The angle type is used for specifying angles in degrees. It is used within the orientation type.

```
<xs:complexType name="Angle">
   <xs:simpleContent>
      <xs:extension base="xs:decimal">
         <xs:attribute name="units" fixed="degrees"/>
      </xs:extension>
   </xs:simpleContent>
</xs:complexType>
```

C.1.6.3 Orientation Type

The orientation type may be used within a power map construct. It provides three values specifying the rotations about the three platform axis to orient a power map relative to the orientation of a platform.

```
<xs:complexType name="Orientation">
  <xs:all>
    <xs:element name="Z_rotation" type="Angle"/>
    <xs:element name="Y_rotation" type="Angle"/>
    <xs:element name="X_rotation" type="Angle"/>
  </xs:all>
</xs:complexType>
```

C.1.7 Location Types

C.1.7.1 Longitude Type

The longitude type is designed to restrict decimal values to the range of -180 to 180. These values all have units of degrees. The longitude type is used in the specification of points. The definition of the type is done in two steps. First, a simple type called Longitude_Type is created to restrict to the range of the longitude value to be between -180 and 180. In the second step, the Longitude_Type is extended with a definition for the units to form the final Longitude type.

```
<xs:simpleType name="Longitude_Type">
  <xs:restriction base="xs:decimal">
    <xs:minInclusive value="-180"/>
    <xs:maxInclusive value="180"/>
  </xs:restriction>
</xs:simpleType>
<xs:complexType name="Longitude">
  <xs:simpleContent>
    <xs:extension base="Longitude_Type">
      <xs:attribute name="units" fixed="degrees"/>
    </xs:extension>
  </xs:simpleContent>
</xs:complexType>
```

C.1.7.2 Latitude Type

The latitude type is designed to restrict decimal values to the range of -90 to 90. These values all have units of degrees. The latitude type is used in the specification of points. The definition of the type is done in two steps. First, a simple type called Latitude_Type is created to restrict the range of the latitude value to be between -90 and 90. In the second step, the Latitude_Type is extended with a definition for the units to form the final Latitude type.

```
<xs:simpleType name="Latitude_Type">
  <xs:restriction base="xs:decimal">
    <xs:minInclusive value="-90"/>
    <xs:maxInclusive value="90"/>
  </xs:restriction>
```

```
</xs:simpleType>
<xs:complexType name="Latitude">
   <xs:simpleContent>
      <xs:extension base="Latitude_Type">
         <xs:attribute name="units" fixed="degrees"/>
      </xs:extension>
   </xs:simpleContent>
</xs:complexType>
```

C.1.7.3 Distance Type

The Distance type is used to specify a decimal number with the fixed units of meters. It is used to multiple location types as the type for elements that have meter units such as height, altitudes, and radii.

```
<xs:complexType name="Distance">
   <xs:simpleContent>
      <xs:extension base="xs:decimal">
         <xs:attribute name="units" fixed="meters"/>
      </xs:extension>
   </xs:simpleContent>
</xs:complexType>
```

C.1.7.4 Point Type

The Point type defines a point relative to an ellipsoidal surface. A longitude and latitude provides the location on the surface and an altitude value specifies the height above or below the surface. A point value must have all three values. The longitude is specified using an element of type Longitude, the latitude is specified using an element of type Latitude, and the altitude is specified using an element of type decimal that has an attribute for units that is fixed as meters.

```
 <xs:complexType name="Point">
  <xs:all>
   <xs:element name="Longitude" type="Longitude"/>
   <xs:element name="Latitude" type="Latitude"/>
   <xs:element name="Altitude" type="Distance"/>
  </xs:all>
 </xs:complexType>
```

C.1.7.5 Circle Type

The Circle type defines a circle using a center of the Point type above and then a radius. It is assumed the circle is on a plane tangent to the ellipsoid and that the altitude value of the point is the altitude of that plane above the ellipsoid at the point.

```
<xs:complexType name="Circle">
   <xs:all>
      <xs:element name="Center" type="Point"/>
      <xs:element name="Radius" type="Distance"/>
   </xs:all>
</xs:complexType>
```

C.1.7.6 Polygon Type

A polygon is specified using three or more elements of the Point type described above. The points are placed in order with the implication that the polygon is defined by lines drawn between the points in the order that the points are listed with the last point connecting to the first.

```
<xs:complexType name="Polygon">
  <xs:sequence>
    <xs:element minOccurs="3" maxOccurs="unbounded" name="Vertex" type="Point" />
  </xs:sequence>
</xs:complexType>
```

C.1.7.7 Cylinder Type

A cylinder is specified with a base definition of the Circle type and then the height of the cylinder using the Distance type. It is assumed that the base is tangent to the earth's ellipsoid at the altitude of the center point of the base.

```
<xs:complexType name="Cylinder">
   <xs:all>
      <xs:element name="Base" type="Circle"/>
      <xs:element name="Height" type="Distance"/>
   </xs:all>
</xs:complexType>
```

C.1.7.8 Polyhedron Type

A polyhedron is specified with a base definition of the polygon type and then the height of the polyhedron. The height value specifies the height of the polyhedron's top surface above the base polygon. To ensure a flat surface of the polyhedron the point in the base polygon with the lowest altitude specifies the height of the bottom surface and the point with the highest altitude plus the height value specifies the height of the top surface. In effect, the altitude of all points of the base polygon is the lowest altitude of the points and the altitude of the top polygon is the highest altitude of the polygon points plus the height. Both surfaces are on a plane tangent to the earth's ellipsoid.

```
<xs:complexType name="Polyhedron">
   <xs:all>
      <xs:element name="Base" type="Polygon"/>
      <xs:element name="Height" type="Distance"/>
   </xs:all>
</xs:complexType>
```

C.1.7.9 Direction Type

The direction is used in the track data type and specifies an azimuth and an elevation. Both values are of type Angle.

```
<xs:complexType name="Direction">
   <xs:all>
      <xs:element name="Azimuth" type="Angle"/>
      <xs:element name="Elevation" type="Angle"/>
   </xs:all>
</xs:complexType>
```

C.1.7.10 Track Type

A track is specified using a point and then a direction and velocity. A start time elsewhere in the model identifies when the entity's track is at the point, the direction indicates the direction the entity will move and the velocity is its speed in that direction.

```
<xs:complexType name="Track">
   <xs:all>
      <xs:element name="Start" type="Point"/>
      <xs:element name="Direction" type="Direction"/>
      <xs:element name="Velocity">
         <xs:complexType>
            <xs:simpleContent>
               <xs:extension base="xs:decimal">
                  <xs:attribute name="units" fixed="km/hr"/>
               </xs:extension>
            </xs:simpleContent>
         </xs:complexType>
      </xs:element>
   </xs:all>
</xs:complexType>
```

C.1.8 Purpose Type

The purpose type is used within the transmitter and receiver data types and in the SCMML markup to identify the purpose of transmitter and receiver models and of collections of models. There are three choices, Consumption, Authorization, and Constraint.

```
<xs:simpleType name="Purpose">
   <xs:restriction base="xs:string">
      <xs:enumeration value="Consumption"/>
      <xs:enumeration value="Authorization"/>
      <xs:enumeration value="Constraint"/>
   </xs:restriction>
</xs:simpleType>
```

C.2 Constructs Type

The constructs type is a complex type that consists of the 12 elements, each, one of the 12 constructs used in spectrum consumption modeling. The constructs type and its elements are used repeatedly in spectrum consumption modeling and may appear several times in SCMML, as part of transmitter and receiver models and in the heading of system or collection listings. This section describes the constructs data type by describing each of the construct elements. The overarching construct type definition can be found in Section C.9 which provides the complete SCMML schema. In the interest of having a single constructs type, there are relaxed constraints on the required constructs to use. The constructs required for a transmitter, receiver, or heading may differ. Some elements may be used in one and not the others. This data type does not ensure all the appropriate constructs are used in these parts and so checking for completeness of a model resides outside this schema definition. The constructs type in this schema will ensure that the data is well formed for a model.

C.2.1 Maximum_Power_Density Element

The Maximum_Power_Density element is a value of type Power_Density. Although every transmitter and receiver model requires a maximum power density it may appear either in the system heading or as part of transmitter and receiver models themselves and so the minimum occurrence can be 0.

```
< <xs:element minOccurs="0" name="Maximum_Power_Density" type="Power_Density"/>
```

C.2.2 Spectrum_Mask Element

A model may have one or multiple spectrum masks. However, the mask may appear either in the system heading or as part of transmitter and receiver models themselves and so the minimum occurrence can be 0. Spectrum masks may be either for a signal that is continuous or a signal that frequency hops. The mask element identifies the spectral occupancy of signals when used in transmitter or receiver models and identifies the bands of applicability in collection listings. When a mask is part of system heading and the system has a transmitter model with no Spectrum_Mask, then the mask in the heading is also the mask of the transmitter model.

```
<xs:element minOccurs="0" maxOccurs="unbounded" name="Spectrum_Mask">
  <xs:complexType>
    <xs:all>
      <xs:element maxOccurs="1" name="Type">
        <xs:complexType>
          <xs:choice>
            <xs:element name="Continuous">
              <xs:complexType/>
            </xs:element>
            <xs:element name="Frequency_Hop">
              <xs:complexType>
                <xs:sequence>
                  <xs:element name="FH_Timing" type="FH_Signal_Timing_Values"/>
                  <xs:element name="Frequency_Use">
                    <xs:complexType>
                      <xs:choice>
                        <xs:element name="Center_Frequency_List"
                          type="Center_Frequency_List"/>
                        <xs:element name="Frequency_Band_List"
                          type="Frequency_Band_List"/>
                      </xs:choice>
                    </xs:complexType>
                  </xs:element>
                </xs:sequence>
              </xs:complexType>
            </xs:element>
          </xs:choice>
        </xs:complexType>
      </xs:element>
      <xs:element name="Mask" type="Mask"/>
    </xs:all>
```

```
   </xs:complexType>
</xs:element>
```

C.2.3 Underlay_Mask Element

A model may have one or multiple underlay masks. However, these masks may appear either in the system heading or as part of transmitter and receiver models themselves and so the minimum occurrence can be 0. Each Underlay_Mask element has two elements, a Mask element of type Mask and then the Rating element which defines the rating of the mask. Ratings can be specified in one of five ways. In the first, the mask applies to all bandwidth signals and so is unrated and which is specified using the Rating element. In the second, the mask has a bandwidth rating for a single bandwidth signal. In the third, an unrated mask's power rating is adjusted for one or more bandwidth ratings using a list of adjustments and ratings. In the fourth, the mask is given a rating for a bandwidth time product. And in the fifth, an unrated mask's power is adjusted for one or more bandwidth time product ratings. Section 2.1.3 describes and Figure 2-3 and Figure 2-4 demonstrate the difference between the approaches to specifying bandwidth rated and bandwidth time rated underlay masks. Unrated masks are used in system and collections headings to indicate bands of applicability.

```
<xs:element minOccurs="0" maxOccurs="unbounded" name="Underlay_Mask">
   <xs:complexType>
      <xs:all>
         <xs:element maxOccurs="1" name="Rating">
            <xs:complexType>
               <xs:choice>
                  <xs:element name="Unrated">
                     <xs:complexType/>
                  </xs:element>
                  <xs:element name="Rated_Bandwidth" type="Frequency" />
                  <xs:element name="BW_Rating_List" type="BW_Rating_List"/>
                  <xs:element name="Rated_BTP" type="Bandwidth_Time_Product"/>
                  <xs:element name="BTP_Rating_List" type="BTP_Rating_List"/>
               </xs:choice>
            </xs:complexType>
         </xs:element>
         <xs:element name="Mask" type="Mask"/>
      </xs:all>
   </xs:complexType>
</xs:element>
```

C.2.4 Propagation_Map Element

A model of a receiver or a transmitter will always reference a propagation map but the propagation map may appear in the heading of a system or as part of an individual transmitter or receiver model. Because of this option there is a minimum occurrence of zero maps. The Propagation_Map element uses the a single element of the Map type.

```
<xs:element minOccurs="0" name="Propagation_Map" type="Map"/>
```

C.2.5 Power_Map Element

A model of a receiver or a transmitter will always reference a power map but the power map may appear in the heading of a system or as part of an individual transmitter or receiver model and so there is a minimum occurrence of 0. The Power_Map consists of a Power_Map_List and an Orientation. A map consists of the ordered list of values that specifies relative power by direction. There are three choices for orientation. The first is the orientation that matches that of the surface and so is fixed. The second is an orientation relative to the platform orientation. The platform relative orientation is used together with a track location value which indicates the orientation of the platform. The Relative_to_Platform element uses the Orientation type. The third choice is an orientation toward a reference point. The Toward_Reference_Point element uses the Point type.

```
<xs:element minOccurs="0" name="Power_Map">
   <xs:complexType>
      <xs:sequence>
         <xs:element name="Orientation">
            <xs:complexType>
               <xs:choice>
                  <xs:element name="Surface">
                     <xs:complexType/>
                  </xs:element>
                  <xs:element name="Relative_to_Platform" type="Orientation"/>
                  <xs:element name="Toward_Reference_Point" type="Point"/>
               </xs:choice>
            </xs:complexType>
         </xs:element>
         <xs:element name="Power_Map_List" type="Map"/>
      </xs:sequence>
   </xs:complexType>
</xs:element>
```

C.2.6 Intermodulation_Mask Element

The Intermodulation_Mask construct is used when there is a known susceptibility to IM. There may be multiple IM masks per model, each capturing a different order of IM. Thus the order is specified for a mask set. A mask set may consist of just an IM mask for combining signals or this mask for combining signals plus an IM mask for amplification. The first, the IMCMask is always provided and the second, the IMAMask, is optionally provided in some transmitter IM models.

```
<xs:element minOccurs="0" maxOccurs="unbounded" name="Intermodulation_Masks">
   <xs:complexType>
      <xs:sequence>
         <xs:element name="Order" type="xs:integer"/>
         <xs:element name="IMCMask" type="Mask"/>
         <xs:element minOccurs="0" name="IMAMask" type="Mask"/>
      </xs:sequence>
   </xs:complexType>
</xs:element>
```

C.2.7 Platform_Name Element

The Platform_Name is a string. This data element is optional but is usually provided when there is an IM mask specified.

```
<xs:element minOccurs="0" maxOccurs="unbounded" name="Platform_Name"
type="xs:string"/>
```

C.2.8 Location Element

Each model requires a location. However, the location may be specified in a system or collection heading or in individual transmitter and receiver models and so minOccurs="0". When used, there may be multiple locations per model and that location may use one or several of the location constructs which were previously defined as fundamental types. Multiples of these may be used to indicate that the system components may be in multiple locations. When multiple tracks are used it indicates that there is a component located on each track at the start points at the start times. Although system models and collections allow multiple locations in their construction, the canonical transmitters and receivers that are used for computing compatibility use only one and so models with multiple locations would be expanded to multiple models each with a single location.

```
<xs:element minOccurs="0" name="Location">
  <xs:complexType>
    <xs:sequence>
      <xs:element minOccurs="0" maxOccurs="unbounded" name="Point" type="Point"/>
      <xs:element minOccurs="0" maxOccurs="unbounded" name="Circular_Surface"
        type="Circle"/>
      <xs:element minOccurs="0" maxOccurs="unbounded" name="Polygon_Surface"
        type="Polygon"/>
      <xs:element minOccurs="0" maxOccurs="unbounded" name="Cylinder"
        type="Cylinder"/>
      <xs:element minOccurs="0" maxOccurs="unbounded" name="Polyhedron"
        type="Polyhedron"/>
      <xs:element minOccurs="0" maxOccurs="unbounded" name="Track" type="Track"/>
    </xs:sequence>
  </xs:complexType>
</xs:element>
```

C.2.9 Start Element

The Start can be either a date and time or a date and time with the definition of periodic use. The date and time values use the dateTime data type specified in the XML schema. The definition of periodic use uses three values, a time displacement to the beginning of the first on period and then an "On" duration followed by an "Off" duration. All of these duration values use the XML Schema duration data type. Every model must have a start time but may be specified either in a heading or as part of an individual transmitter or receiver model. Thus, the data structure does not require a "Start" element.

```
<xs:element minOccurs="0" name="Start">
  <xs:complexType>
    <xs:sequence>
      <xs:element name="Start_Time" type="xs:dateTime"/>
```

```
      <xs:element minOccurs="0" name="Period">
        <xs:complexType>
          <xs:sequence>
            <xs:element name="Displacement" type="xs:duration"/>
            <xs:element name="On" type="xs:duration"/>
            <xs:element name="Off" type="xs:duration"/>
          </xs:sequence>
        </xs:complexType>
      </xs:element>
    </xs:sequence>
  </xs:complexType>
</xs:element>
```

C.2.10 End_Time Element

The end time is a single value that uses the XML Schema dateTime data type. All models require a reference to an end time but it may be specified either in a heading or as part of a transmitter or receiver model. Thus, the data structure does not require an "End_Time" element.

```
<xs:element minOccurs="0" name="End_Time" type="xs:dateTime"/>
```

C.2.11 Minimum_Power_Density Element

The minimum power density is specified to be a single value of the Power_Density type. It is an optional value.

```
<xs:element minOccurs="0" name="Minimum_Power_Density" type="Power_Density"/>
```

C.2.12 Protocol_or_Policy Element

The Protocol_or_Policy data structure consists of a name for the protocol or policy and then a lists of parameters that provide further definition of the protocol or policy. The data structure allows no or multiple parameters either of a string type or of a decimal type to further define the protocol or policy.

```
<xs:element minOccurs="0" maxOccurs="unbounded" name="Protocol_or_Policy">
  <xs:complexType>
    <xs:sequence>
      <xs:element name="P_or_P_Name" type="xs:string"/>
      <xs:element minOccurs="0" maxOccurs="unbounded"
        name="P_or_P_String_Parameter" type="xs:string"/>
      <xs:element minOccurs="0" maxOccurs="unbounded"
        name="P_or_P_Numerical_Parameter" type="xs:decimal"/>
    </xs:sequence>
  </xs:complexType>
</xs:element>
```

C.3 Transmitter Type

The Transmitter type consists of an optional System_ID element, an optional Purpose element and then the Model element of type Constructs. The Purpose value is optional since it is implied by the purpose of the XML document. This value is always populated in the canonical form where a Transmitter model is expected to standalone.

```
<xs:complexType name="Transmitter">
  <xs:sequence>
    <xs:element minOccurs="0" name="System_ID" type="xs:string" />
    <xs:element minOccurs="0" name="The_Purpose" type="Purpose" />
    <xs:element name="Model" type="Constructs" />
  </xs:sequence>
</xs:complexType>
```

C.4 Receiver Type

The Receiver type is identical to that of a transmitter and consists of an optional System_ID element, an optional Purpose element and then the Model element of type Constructs. Although the receiver and transmitter types are identical in structure, the meaning of an element of the receiver type is different than that of an element of the transmitter type.

```
<xs:complexType name="Receiver">
  <xs:sequence>
    <xs:element minOccurs="0" name="System_ID" type="xs:string" />
    <xs:element minOccurs="0" name="The_Purpose" type="Purpose" />
    <xs:element name="Model" type="Constructs" />
  </xs:sequence>
</xs:complexType>
```

C.5 System Type

The System type consists of a System_ID that identifies the system, a heading of type Constructs, and then 0 or multiple elements of type transmitter and receiver. A system by itself has the purpose of specifying consumption unless it is part of a collection designated for another purpose.

```
<xs:complexType name="System">
  <xs:sequence>
    <xs:element name="System_ID" type="xs:string" />
    <xs:element name="Heading" type="Constructs" />
    <xs:element minOccurs="0" maxOccurs="unbounded" name="A_Transmitter"
      type="Transmitter" />
    <xs:element minOccurs="0" maxOccurs="unbounded" name="A_Receiver"
      type="Receiver" />
  </xs:sequence>
</xs:complexType>
```

C.6 Collection Type

The Collection type consists of a heading of type Constructs and then 0 or multiple elements of type System, Transmitter, and Receiver.

```
<xs:complexType name="Collection">
  <xs:sequence>
    <xs:element name="Heading" type="Constructs" />
    <xs:element minOccurs="0" maxOccurs="unbounded" name="A_System" type="System" />
    <xs:element minOccurs="0" maxOccurs="unbounded" name="A_Transmitter"
      type="Transmitter" />
```

```
    <xs:element minOccurs="0" maxOccurs="unbounded" name="A_Receiver"
      type="Receiver" />
  </xs:sequence>
</xs:complexType>
```

C.7 The SCMML Markup

The SCMML Markup are the elements at the top of the schema hierarchy and provides the definition of the content XML files that are used to communicate system and collection data set. The file starts with the element, Source_ID, for the source of the data set to identify itself. This is followed by the choice of specifying either a system or a collection. If a collection, there is an additional requirement to select the purpose of the collection, either to define consumption, give authorization, or specify constraints. The data element, "The_Purpose", is where a collection's purpose is specified.

```
<xs:element name="SCM_Markup">
  <xs:complexType>
    <xs:sequence>
      <xs:element name="Source_ID" type="xs:string"/>
      <xs:element name="Contents">
        <xs:complexType>
          <xs:choice>
            <xs:element maxOccurs="unbounded" name="A_System" type="System"/>
            <xs:element name="A_Collection">
              <xs:complexType>
                <xs:all>
                  <xs:element name="Purpose" type="Purpose"/>
                  <xs:element name="Collection" type="Collection"/>
                </xs:all>
              </xs:complexType>
            </xs:element>
          </xs:choice>
        </xs:complexType>
      </xs:element>
    </xs:sequence>
  </xs:complexType>
</xs:element>
```

C.8 Canonical Transmitters and Receivers

Canonical transmitter and receiver models are models that can stand alone without reference to the heading of a system or collection. These models have a purpose specified and are each limited to having a single location element. In addition to a purpose and a single location, a canonical transmitter model must have a maximum power density, a spectrum mask, a propagation map, a power map, a start time, and an end time. The requirements for the canonical receiver model are the same as those of the canonical transmitter model except a receiver model must have an underlay mask as opposed to a spectrum mask.

C.9 The Full SCMML Schema

The following is the full SCMML schema described above.

```xml
<?xml version="1.0" encoding="utf-8"?>
<xs:schema xmlns:xs="http://www.w3.org/2001/XMLSchema"
targetNamespace="http://www.mitre.org/SCMML"
  xmlns="http://www.mitre.org/SCMML" elementFormDefault="qualified">
  <xs:complexType name="Power_Density">
    <xs:simpleContent>
      <xs:extension base="xs:decimal">
        <xs:attribute name="units" fixed="dBW/m**2"/>
      </xs:extension>
    </xs:simpleContent>
  </xs:complexType>
  <xs:complexType name="Frequency">
    <xs:simpleContent>
      <xs:extension base="xs:decimal">
        <xs:attribute name="units" use="required">
          <xs:simpleType>
            <xs:restriction base="xs:string">
              <xs:enumeration value="kHz"/>
              <xs:enumeration value="MHz"/>
              <xs:enumeration value="GHz"/>
            </xs:restriction>
          </xs:simpleType>
        </xs:attribute>
      </xs:extension>
    </xs:simpleContent>
  </xs:complexType>
  <xs:complexType name="Relative_Power">
    <xs:simpleContent>
      <xs:extension base="xs:decimal">
        <xs:attribute name="units" fixed="dB"/>
      </xs:extension>
    </xs:simpleContent>
  </xs:complexType>
  <xs:complexType name="Short_Time">
    <xs:simpleContent>
      <xs:extension base="xs:decimal">
        <xs:attribute name="units" use="required">
          <xs:simpleType>
            <xs:restriction base="xs:string">
              <xs:enumeration value="usec"/>
              <xs:enumeration value="msec"/>
              <xs:enumeration value="sec"/>
            </xs:restriction>
          </xs:simpleType>
        </xs:attribute>
      </xs:extension>
    </xs:simpleContent>
  </xs:complexType>
```

```
<xs:complexType name="Inflection_Point">
  <xs:sequence>
    <xs:element name="Frequency" type="Frequency"/>
    <xs:element name="Relative_Power" type="Relative_Power"/>
  </xs:sequence>
</xs:complexType>
<xs:complexType name="Mask">
  <xs:sequence>
    <xs:element minOccurs="2" maxOccurs="unbounded" name="Inflection_Point"
      type="Inflection_Point"/>
  </xs:sequence>
</xs:complexType>
<xs:complexType name="FH_Signal_Timing_Values">
  <xs:sequence>
    <xs:element name="Dwell_Time" type="Short_Time"/>
    <xs:element name="Revisit_Period" type="Short_Time"/>
  </xs:sequence>
</xs:complexType>
<xs:complexType name="Center_Frequency_List">
  <xs:sequence>
    <xs:element maxOccurs="unbounded" name="Center_Frequency" type="Frequency"/>
  </xs:sequence>
</xs:complexType>
<xs:complexType name="Frequency_Band">
  <xs:sequence>
    <xs:element name="Start_Frequency" type="Frequency"/>
    <xs:element name="End_Frequency" type="Frequency"/>
  </xs:sequence>
</xs:complexType>
<xs:complexType name="Frequency_Band_List">
  <xs:sequence>
    <xs:element maxOccurs="unbounded" name="Band" type="Frequency_Band"/>
  </xs:sequence>
</xs:complexType>
<xs:complexType name="BW_Rating_Values">
  <xs:sequence>
    <xs:element name="Bandwidth" type="Frequency"/>
    <xs:element name="Relative_Power" type="Relative_Power"> </xs:element>
  </xs:sequence>
</xs:complexType>
<xs:complexType name="BW_Rating_List">
  <xs:sequence>
    <xs:element maxOccurs="unbounded" name="Rating_Values"
        type="BW_Rating_Values"/>
  </xs:sequence>
</xs:complexType>
<xs:complexType name="Bandwidth_Time_Product">
  <xs:simpleContent>
```

```
      <xs:extension base="xs:decimal">
        <xs:attribute name="units" fixed="Hz*sec"/>
      </xs:extension>
    </xs:simpleContent>
  </xs:complexType>
  <xs:complexType name="BTP_Rating_Values">
    <xs:sequence>
      <xs:element name="Bandwidth_Time_Product" type="Bandwidth_Time_Product"/>
      <xs:element name="Relative_Power" type="Relative_Power"> </xs:element>
    </xs:sequence>
  </xs:complexType>
  <xs:complexType name="BTP_Rating_List">
    <xs:sequence>
      <xs:element maxOccurs="unbounded" name="Rating_Values"
          type="BTP_Rating_Values"/>
    </xs:sequence>
  </xs:complexType>
  <xs:complexType name="Map">
    <xs:sequence>
      <xs:element minOccurs="2" maxOccurs="unbounded" name="Map_Value"
          type="xs:decimal"/>
    </xs:sequence>
  </xs:complexType>
  <xs:complexType name="Angle">
    <xs:simpleContent>
      <xs:extension base="xs:decimal">
        <xs:attribute name="units" fixed="degrees"/>
      </xs:extension>
    </xs:simpleContent>
  </xs:complexType>
  <xs:complexType name="Orientation">
    <xs:all>
      <xs:element name="Z_rotation" type="Angle"/>
      <xs:element name="Y_rotation" type="Angle"/>
      <xs:element name="X_rotation" type="Angle"/>
    </xs:all>
  </xs:complexType>
  <xs:simpleType name="Longitude_Type">
    <xs:restriction base="xs:decimal">
      <xs:minInclusive value="-180"/>
      <xs:maxInclusive value="180"/>
    </xs:restriction>
  </xs:simpleType>
  <xs:complexType name="Longitude">
    <xs:simpleContent>
      <xs:extension base="Longitude_Type">
        <xs:attribute name="units" fixed="degrees"/>
      </xs:extension>
```

```
    </xs:simpleContent>
  </xs:complexType>
  <xs:simpleType name="Latitude_Type">
    <xs:restriction base="xs:decimal">
      <xs:minInclusive value="-90"/>
      <xs:maxInclusive value="90"/>
    </xs:restriction>
  </xs:simpleType>
  <xs:complexType name="Latitude">
    <xs:simpleContent>
      <xs:extension base="Latitude_Type">
        <xs:attribute name="units" fixed="degrees"/>
      </xs:extension>
    </xs:simpleContent>
  </xs:complexType>
  <xs:complexType name="Distance">
    <xs:simpleContent>
      <xs:extension base="xs:decimal">
        <xs:attribute name="units" fixed="meters"/>
      </xs:extension>
    </xs:simpleContent>
  </xs:complexType>
  <xs:complexType name="Point">
    <xs:all>
      <xs:element name="Longitude" type="Longitude"/>
      <xs:element name="Latitude" type="Latitude"/>
      <xs:element name="Altitude" type="Distance"/>
    </xs:all>
  </xs:complexType>
  <xs:complexType name="Circle">
    <xs:all>
      <xs:element name="Center" type="Point"/>
      <xs:element name="Radius" type="Distance"/>
    </xs:all>
  </xs:complexType>
  <xs:complexType name="Polygon">
    <xs:sequence>
      <xs:element minOccurs="3" maxOccurs="unbounded" name="Vertex" type="Point"/>
    </xs:sequence>
  </xs:complexType>
  <xs:complexType name="Cylinder">
    <xs:all>
      <xs:element name="Base" type="Circle"/>
      <xs:element name="Height" type="Distance"/>
    </xs:all>
  </xs:complexType>
  <xs:complexType name="Polyhedron">
    <xs:all>
```

```
    <xs:element name="Base" type="Polygon"/>
    <xs:element name="Height" type="Distance"/>
   </xs:all>
  </xs:complexType>
  <xs:complexType name="Direction">
   <xs:all>
    <xs:element name="Azimuth" type="Angle"/>
    <xs:element name="Elevation" type="Angle"/>
   </xs:all>
  </xs:complexType>
  <xs:complexType name="Track">
   <xs:all>
    <xs:element name="Start" type="Point"/>
    <xs:element name="Direction" type="Direction"/>
    <xs:element name="Velocity">
     <xs:complexType>
      <xs:simpleContent>
       <xs:extension base="xs:decimal">
        <xs:attribute name="units" fixed="km/hr"/>
       </xs:extension>
      </xs:simpleContent>
     </xs:complexType>
    </xs:element>
   </xs:all>
  </xs:complexType>
  <xs:simpleType name="Purpose">
   <xs:restriction base="xs:string">
    <xs:enumeration value="Consumption"/>
    <xs:enumeration value="Authorization"/>
    <xs:enumeration value="Constraints"/>
   </xs:restriction>
  </xs:simpleType>
  <xs:complexType name="Constructs">
   <xs:sequence>
    <xs:element minOccurs="0" name="Maximum_Power_Density" type="Power_Density"/>
    <xs:element minOccurs="0" maxOccurs="unbounded" name="Spectrum_Mask">
     <xs:complexType>
      <xs:all>
       <xs:element maxOccurs="1" name="Type">
        <xs:complexType>
         <xs:choice>
          <xs:element name="Continuous">
           <xs:complexType/>
          </xs:element>
          <xs:element name="Frequency_Hop">
           <xs:complexType>
            <xs:sequence>
             <xs:element name="FH_Timing" type="FH_Signal_Timing_Values"/>
```

```
                        <xs:element name="Frequency_Use">
                          <xs:complexType>
                            <xs:choice>
                              <xs:element name="Center_Frequency_List"
                                  type="Center_Frequency_List"/>
                              <xs:element name="Frequency_Band_List" type="Frequency_Band_List"/>
                            </xs:choice>
                          </xs:complexType>
                        </xs:element>
                      </xs:sequence>
                    </xs:complexType>
                  </xs:element>
                </xs:choice>
              </xs:complexType>
            </xs:element>
            <xs:element name="Signal_Mask" type="Mask"/>
          </xs:all>
        </xs:complexType>
      </xs:element>
      <xs:element minOccurs="0" maxOccurs="unbounded" name="Underlay_Mask">
        <xs:complexType>
          <xs:all>
            <xs:element maxOccurs="1" name="Rating">
              <xs:complexType>
                <xs:choice>
                  <xs:element name="Unrated">
                    <xs:complexType/>
                  </xs:element>
                  <xs:element name="Rated_Bandwidth" type="Frequency" />
                  <xs:element name="BW_Rating_List" type="BW_Rating_List"/>
                  <xs:element name="Rated_BTP" type="Bandwidth_Time_Product"/>
                  <xs:element name="BTP_Rating_List" type="BTP_Rating_List"/>
                </xs:choice>
              </xs:complexType>
            </xs:element>
            <xs:element name="Mask" type="Mask"/>
          </xs:all>
        </xs:complexType>
      </xs:element>
      <xs:element minOccurs="0" name="Propagation_Map" type="Map"/>
      <xs:element minOccurs="0" name="Power_Map">
        <xs:complexType>
          <xs:sequence>
            <xs:element name="Orientation">
              <xs:complexType>
                <xs:choice>
                  <xs:element name="Surface">
                    <xs:complexType/>
```

```
            </xs:element>
            <xs:element name="Platform" type="Orientation"/>
            <xs:element name="Reference_Point" type="Point"/>
          </xs:choice>
        </xs:complexType>
      </xs:element>
      <xs:element name="Power_Map_List" type="Map"/>
    </xs:sequence>
  </xs:complexType>
</xs:element>
<xs:element minOccurs="0" maxOccurs="unbounded" name="Intermodulation_Masks">
  <xs:complexType>
    <xs:sequence>
      <xs:element name="Order" type="xs:integer"/>
      <xs:element name="IMCMask" type="Mask"/>
      <xs:element minOccurs="0" name="IMAMask" type="Mask"/>
    </xs:sequence>
  </xs:complexType>
</xs:element>
<xs:element minOccurs="0" maxOccurs="unbounded" name="Platform_Name"
    type="xs:string"/>
<xs:element minOccurs="0" name="Location">
  <xs:complexType>
    <xs:sequence>
      <xs:element minOccurs="0" maxOccurs="unbounded" name="Point" type="Point"/>
      <xs:element minOccurs="0" maxOccurs="unbounded" name="Circular_Surface"
          type="Circle"/>
      <xs:element minOccurs="0" maxOccurs="unbounded" name="Polygon_Surface"
          type="Polygon"/>
      <xs:element minOccurs="0" maxOccurs="unbounded" name="Cylinder"
          type="Cylinder"/>
      <xs:element minOccurs="0" maxOccurs="unbounded" name="Polyhedron"
          type="Polyhedron"/>
      <xs:element minOccurs="0" maxOccurs="unbounded" name="Track" type="Track"/>
    </xs:sequence>
  </xs:complexType>
</xs:element>
<xs:element minOccurs="0" name="Start">
  <xs:complexType>
    <xs:sequence>
      <xs:element name="Start_Time" type="xs:dateTime"/>
      <xs:element minOccurs="0" name="Period">
        <xs:complexType>
          <xs:sequence>
            <xs:element name="Displacement" type="xs:duration"/>
            <xs:element name="On" type="xs:duration"/>
            <xs:element name="Off" type="xs:duration"/>
          </xs:sequence>
```

```
            </xs:complexType>
          </xs:element>
        </xs:sequence>
      </xs:complexType>
    </xs:element>
    <xs:element minOccurs="0" name="End_Time" type="xs:dateTime"/>
    <xs:element minOccurs="0" name="Minimum_Power_Density" type="Power_Density"/>
    <xs:element minOccurs="0" maxOccurs="unbounded" name="Protocol_or_Policy">
      <xs:complexType>
        <xs:sequence>
          <xs:element name="P_or_P_Name" type="xs:string"/>
          <xs:element minOccurs="0" maxOccurs="unbounded"
              name="P_or_P_String_Parameter"
            type="xs:string"/>
          <xs:element minOccurs="0" maxOccurs="unbounded"
              name="P_or_P_Numerical_Parameter"
            type="xs:decimal"/>
        </xs:sequence>
      </xs:complexType>
    </xs:element>
  </xs:sequence>
</xs:complexType>
<xs:complexType name="Transmitter">
  <xs:sequence>
    <xs:element minOccurs="0" name="System_ID" type="xs:string"/>
    <xs:element minOccurs="0" name="Purpose" type="Purpose"/>
    <xs:element name="Model" type="Constructs"/>
  </xs:sequence>
</xs:complexType>
<xs:complexType name="Receiver">
  <xs:sequence>
    <xs:element minOccurs="0" name="System_ID" type="xs:string"/>
    <xs:element minOccurs="0" name="Purpose" type="Purpose"/>
    <xs:element name="Model" type="Constructs"/>
  </xs:sequence>
</xs:complexType>
<xs:complexType name="System">
  <xs:sequence>
    <xs:element name="System_ID" type="xs:string"/>
    <xs:element name="Heading" type="Constructs"/>
    <xs:element minOccurs="0" maxOccurs="unbounded" name="Transmitter"
        type="Transmitter"/>
    <xs:element minOccurs="0" maxOccurs="unbounded" name="Receiver" type="Receiver"/>
  </xs:sequence>
</xs:complexType>
<xs:complexType name="Collection">
  <xs:sequence>
    <xs:element name="Heading" type="Constructs"/>
```

```
   <xs:element minOccurs="0" maxOccurs="unbounded" name="System" type="System"/>
   <xs:element minOccurs="0" maxOccurs="unbounded" name="Transmitter"
     type="Transmitter"/>
   <xs:element minOccurs="0" maxOccurs="unbounded" name="Receiver" type="Receiver"/>
  </xs:sequence>
 </xs:complexType>
 <xs:element name="SCM_Markup">
  <xs:complexType>
   <xs:sequence>
    <xs:element name="Source_ID" type="xs:string"/>
    <xs:element name="Contents">
     <xs:complexType>
      <xs:choice>
       <xs:element maxOccurs="unbounded" name="A_System" type="System"/>
       <xs:element name="A_Collection">
        <xs:complexType>
         <xs:all>
          <xs:element name="Purpose" type="Purpose"/>
          <xs:element name="Collection" type="Collection"/>
         </xs:all>
        </xs:complexType>
       </xs:element>
      </xs:choice>
     </xs:complexType>
    </xs:element>
   </xs:sequence>
  </xs:complexType>
 </xs:element>
</xs:schema>
```

Appendix D The World Geodetic System (WGS)-84 Ellipsoid Datum

The World Geodetic System – 1984 (WGS 84) defines an earth-centric ellipsoid to serve as a reference datum for location. It is a global system and is the datum for GPS. The WGS 84 datum defines an ellipsoid that approximates the surface of the earth. A WGS 84 coordinate consists of a latitude, φ, and a longitude, λ,which define a point on the surface of the ellipsoid and then a height, h, that defines the distance above or below that point normal to the ellipsoid surface. These coordinates can be converted to earth centric Cartesian coordinates <x,y,z>. Figure D-1 illustrates a geographic ellipsoid datum demonstrating the meaning of these coordinates and the parameters required to define an ellipsoid. Table D-1 provides the parameters of the WGS 84 ellipsoid.

Ellipsoids are formed by rotating an ellipse about one of its axes, the minor axis in the case of geographical reference datums. An ellipsoid formed by rotating an ellipse about its minor axis has four measures, the diameter of the semimajor axis, *a*, the radius of the semiminor axis, *b*, the flattening, *f*, and the eccentricity, *e*. These measures are related as follows.

$$f = \frac{a-b}{a} \qquad (2\text{-}1)$$

$$e = \frac{a^2 - b^2}{a^2} = \sqrt{2f - f^2}$$

The minor axis is coincident with the axis of rotation of the earth. For a global datum reference

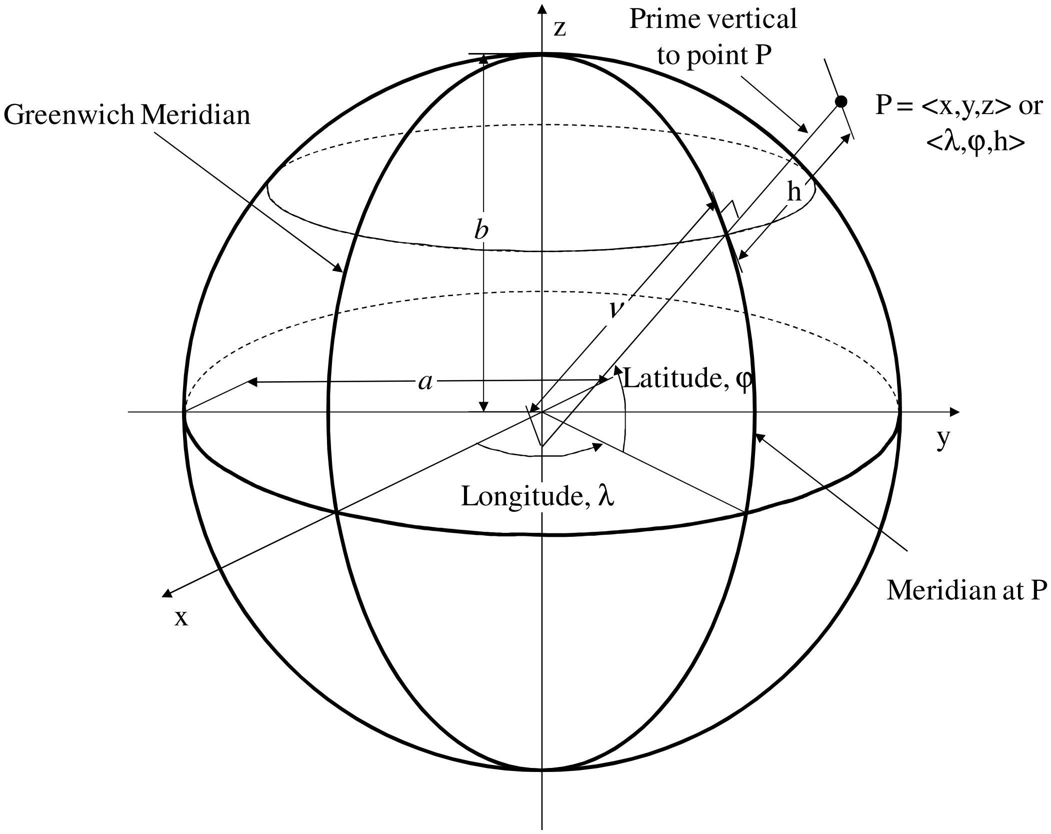


Figure D-1. The WGS 84 Ellipsoid

Table D-1. The WGS 84 Ellipsoid Parameters

Parameter	Value	Units
a	6378137	meters
b	6356752.31245	meters
f	$1/298.257223563$	
e	0.0818191908426	
e^2	0.00669437999014	

the center of the coordinate system is located at the center of the earth with the z axis coincident to the minor axis of the spheroid with positive direction toward the north pole. The x axis lies on the equatorial plane pointing toward the meridian passing through the Greenwich Observatory. The positive direction of the y axis is chosen to get a right handed coordinate system. Figure D-1 illustrates the relationship between ellipsoidal and Cartesian coordinates.

There are just two parameters that are needed for specifying an ellipsoid, a and b, a and f, or a and e. Normally a and f are given. Conversion between ellipsoidal and Cartesian coordinates requires an initial calculation of the radius of curvature of the prime vertical ν which is a function of latitude. The geodetic latitude is the angle between the plane at the equator and the geodetic normal to the ellipsoid surface. Note that the prime vertical is perpendicular to the ellipsoid surface and extends to the minor axis and may not intersect at the ellipsoid origin, (x,y,z) = (0,0,0). This radius of curvature is determined by

$$\nu = \frac{a}{\sqrt{1-e^2\sin^2\varphi}} = \frac{a}{\sqrt{1-\left(2f-f^2\right)\sin^2\varphi}}$$

The radius to the point P is $\left(\nu+h\right)$. The WGS 84 Cartesian coordinates follow using the equations

$$x = \left(\nu+h\right)\cos\varphi\cos\lambda$$

$$y = \left(\nu+h\right)\cos\varphi\sin\lambda$$

$$z = \left(\nu\left(1-e^2\right)+h\right)\sin\varphi$$

The conversion from WGS 84 Cartesian coordinates back to ellipsoidal coordinates is much more involved. An effective technique suitable for spectrum consumption modeling applications are described in [12].

Appendix E Criteria for Planar Approximations

The ellipsoidal earth and the associated coordinate systems that follow based on location add a complexity to compatibility computations that is desirable to avoid. A preferred option is to assume a planar earth in doing compatibility computations. In this analysis we seek the criteria for using planar approximations.

Using a planar representation of the Earth's surface causes three relevant differences listed below and illustrated in Figure E-1:

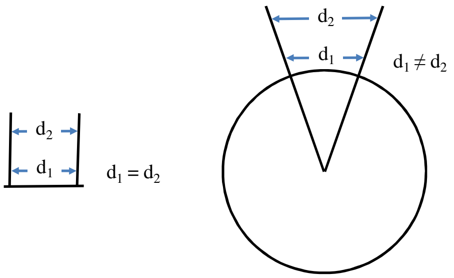
- It results in constant difference in distance on points at the same relative height on different prime verticals that would be different distances on an ellipsoidal Earth,
- It allows line-of-sight (LOS) observation of points that would be occluded on a curved earth, and
- Directions between points on the planar Earth are different than those on the ellipsoidal Earth.

We look at each of these differences separately to determine their significance.

E.1 Difference in Distances

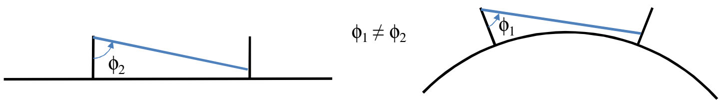
As illustrated in Figure E-1, the separation distance between points on the prime vertical varies with altitude. These differences in distance affect the strength of propagated signals. A fortunate feature of propagation, however, is that it is proportional to the log of distance and so differences that are likely to be larger at larger separation distances on the earth will have a smaller difference in the logarithm because of the larger distances. Our goal in this analysis is to determine at what separation distance on the Earth that a planar approximation is inappropriate.

For two points on the globe that are not collinear with the center of the earth, there exists a unique plane containing these points and the earth’s center. The shortest path between these two points that follows along the earth’s surface is completely contained within this plane. As we consider the effect that the curvature of the earth has on distance calculations, it is therefore sufficient to restrict our attention to this two dimensional plane. For simplicity of computation in



Differences in distances

Occlusion



Differences in angular directions

Figure E-1. Significant differences between the planar approximation of the ellipsoidal Earth

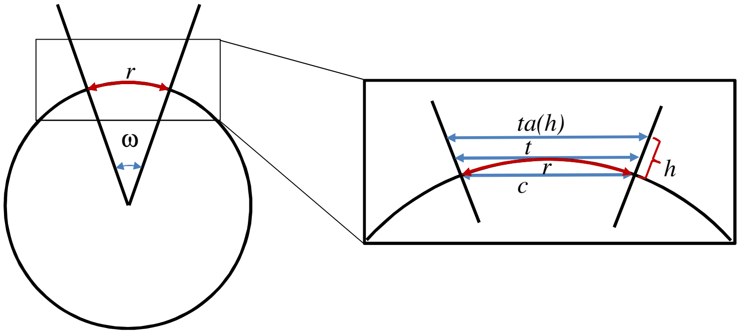


Figure E-2. Analysis scenario to assess the ramification of distance differences between spherical and planar systems on pathloss estimates

this analysis we assume a spherical rather than ellipsoidal earth with a radius, *er*, of 6,367,495 meters, the average of the semimajor and semiminor axes of the WGS-84 Ellipsoid.

Figure E-2 illustrates the analysis scenario. Given a separation distance on the surface of the earth, *r*, we consider the linear distance between those points, *c*, as well as between other points at various elevations on the prime verticals through the arc's end points including that tangent to the earth, *t*, and between points at different altitudes, *h*, defined as *ta*(*h*). We then compare the difference of the logarithms as a fractional difference with log(*r*). The following summarize the computations.

Start by defining the function for the angle ω in radians associated with the surface distance *r*.

$$\omega(r) = \frac{r}{er}.$$

Define a function for the linear distance between the points as a function of the surface distance:

$$c(r) = 2 \cdot er \cdot \sin\left(\frac{\omega(r)}{2}\right).$$

Define a function for the linear distance at the tangent to the earth to the prime verticals of the surface points:

$$t(r) = 2 \cdot er \cdot \tan\left(\frac{\omega(r)}{2}\right).$$

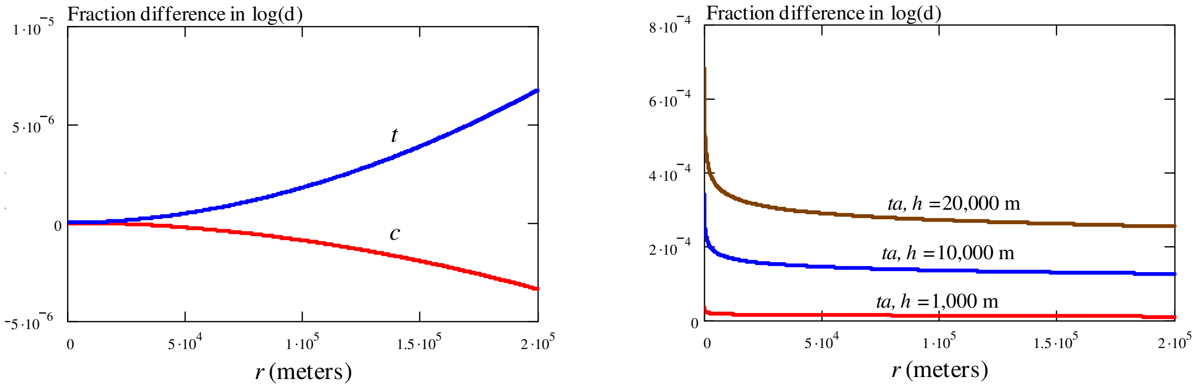
Define a function for the linear distance as a function of the altitudes on the prime verticals of the surface points:

$$ta(r,h) = 2 \cdot (er + h) \cdot \sin\left(\frac{\omega(r)}{2}\right).$$

And finally for all of these we define generally the relative change in the logarithm of distance as:

$$lc(r) = \frac{\log(c(r)) - \log(r)}{\log(r)}.$$

Figure E-3 illustrates the relative change in the log of these distances as a function of the surface distance. From these graphs we see that pathloss estimates at the surface of the earth would vary by less than 10^{-5} out to a separation distance of 200 km and that estimates at altitude would be



a. Differences in the cord and tangent to the arc with length *r*

b. Differences as a function of height on the prime verticals at the end points of the arc with length *r*

Figure E-3. Fractional differences in pathloss estimates as a result of distance differences between planar and spherical systems.

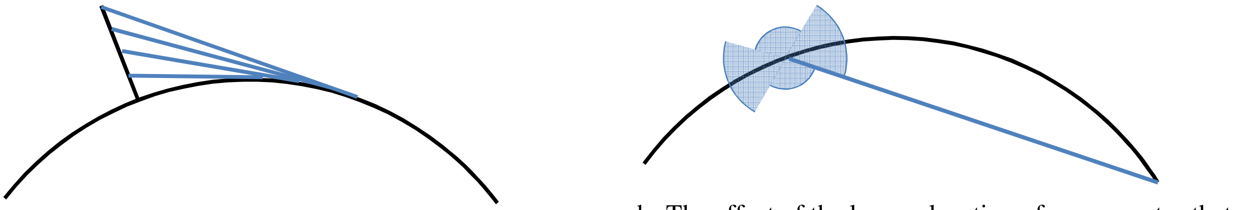
less than 10^{-3} and would actually improve as the surface distance increases. These are well within the accuracy of the model and it can be concluded that difference in separation distances are not a constraint to using planar approximations.

E.2 Occlusion Range

The range to LOS occlusion is a function of antenna height and is illustrated in Figure E-4a. The illustration also shows that the angle to occlusion changes as a function of height. Since terrain is not considered in the arbitration of the compatibility of models (terrain effects are built into the models) the assessment of when a planar approximation is acceptable is dependent on how propagation maps and power maps are formed. Figure E-4b illustrates the profile of a map on the horizon. In this case, the map indicates that occlusion is not an issue for some distance beyond the horizon. Figure E-5a illustrates how the lower angle beneath the sector at the horizon can be used to indicate the distance at which a planar approximation would have no effect on compatibility assessments. Given ϕ, the elevation of the start of the sector that includes the horizon, we can compute the range to which a planar approximation of the Earth's surface remains valid for compatibility computations:

$$r(\phi)=\frac{2\cdot(90-\phi)}{360}\cdot 2\pi\cdot er$$

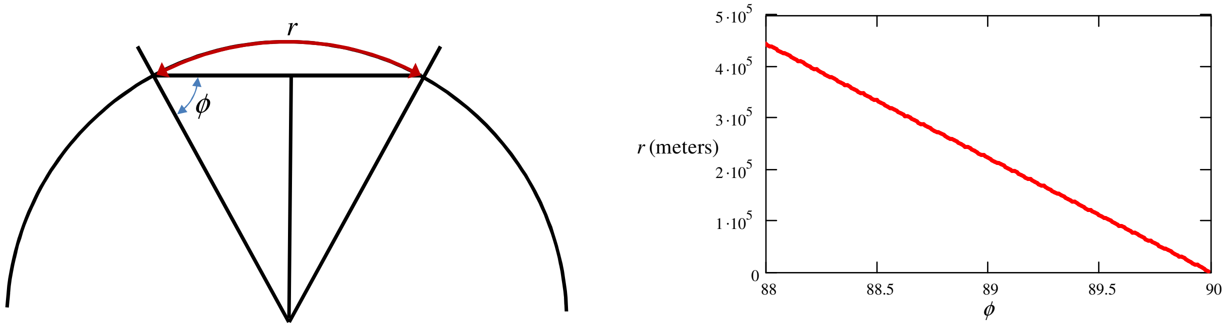
Figure E-5b graphs the range as a function of this elevation and shows that for an elevation as little as 2° below the horizon the planar approximation applies out beyond 400 km. Table E-1 lists the threshold elevations for some benchmark distances. It can be concluded that so long as



a. The effect of height on the range to occlusion

b. The effect of the lower elevation of a map sector that crosses the horizon on the range that the parameter at the horizon applies

Figure E-4. The effect of angles on the occurrence of occlusion by the Earth's surface



a. An illustration of the relationship between the lower elevation of the sector on the horizon and its planar range

b. The surface range that can be reached in a planar approximation as a function of the lower elevation of the map sector that crosses the horizon

Figure E-5. The effect of sector elevations on the occurrence of occlusion by the Earth's surface

Table E-1. Lower elevations of the map sector that crosses the horizon for some benchmark ranges for valid planar approximations that avoid occlusion errors

r (meters)	ϕ
1,000	89.996°
10,000	89.995°
50,000	89.775°
100,000	89.550°
200,000	89.100°

the lower elevation of sectors at the horizon reach below the horizon a planar approximation can be used.

E.3 Differences in Angular Directions

The final issue in using planar approximations is the effect of sector elevations on the range of using linear approximations. This issue is not too different from that of occlusion; however, the significance of the effect is a function of the elevation considered and the range of separation. Figure E-6 illustrates a scenario for evaluating the effect. In comparing the two reference systems we assume the separation of points, *r*, and the relative heights at which a line of sight vector intersects the prime verticals of those points are the same for both scenarios and we compare the differences in the angles that follow. We parameterize the result as a function of the separation distance, *r*, and the angle of elevation for the spherical scenario, ϕ_1. Figure E-7 illustrates the geometry of the problem. Given h_1 and *r* and using the law of sines, the height h_2 is

$$h_2 = \frac{\sin(\phi_1)(er + h_1)}{\sin\left(180 - \left(\omega(r) + \phi_1\right)\right)} - er\,,$$

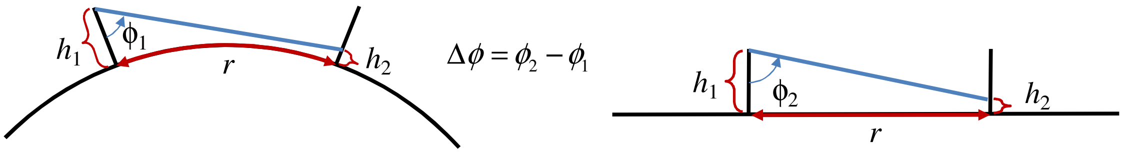


Figure E-6. Scenario for evaluating the significance of angle discrepancy in using planar approximations

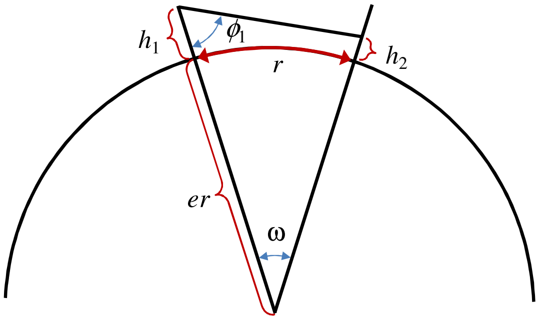


Figure E-7. Geometry of the spherical earth scenario used to determine h_2

and ϕ_2 follows as

$$\phi_2 = \arctan 2\left(h_1 - h_2, r\right)$$

where

$$\arctan 2\left(x, y\right) = \begin{cases} \arctan\left(\dfrac{x}{y}\right) & x > 0 \\ 180° + \arctan\left(\dfrac{x}{y}\right) & y \geq 0, x < 0 \\ -180° + \arctan\left(\dfrac{x}{y}\right) & y < 0, x < 0 \\ 90° & y > 0, x = 0 \\ -90° & y < 0, x = 0 \\ \text{undefined} & y = 0, x = 0 \end{cases}.$$

Figure E-8 illustrates the differences in angles as a function of surface distance and for various elevations angles for the spherical earth scenario. It illustrates that discrepancies increase as the elevation varies from 90 and that they increase as the surface distance increases. Figure E-8 illustrates the effect out to 200 km. The linear trend of these graphs continues out beyond

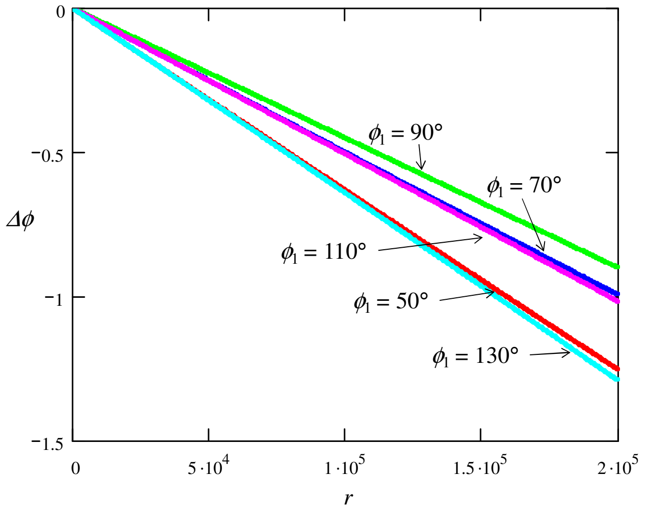


Figure E-8. Angular discrepancies between a spherical earth and a planar earth as a function of surface separation and elevation angle

500 km with all discrepancies less than 3°. The significance of these discrepancies depends on the intent of the model and how conservative the modeler is in creating it. If the model is trying to provide a very fine representation of antenna effects then a planar approximation may not be appropriate for large separation distances.

E.4 Conclusion

This analysis has considered the discrepancies of distance, occlusion, and angular differences in determining whether a planar approximation is practical. We conclude that:

Distance differences are too small to be an issue.

Modelers can convey that occlusion is not an issue by specifying the lower elevation of the sector that crosses the horizon as being below the horizon. A lower elevation of this sector as little 1° below the horizon indicates a planar equivalence for a range of over 200 km,

Angular differences are the most significant of the three but still not very large, usually less than 2° for ranges as far as 200 km and at angles as much as 40° off the horizon. If the systems being considered are not airborne these angles are likely insignificant. Further modeling is likely to be conservative and so accommodating these differences in the models.

Thus, planar approximations are appropriate for most terrestrial uses of spectrum.

Appendix F Rotation Matrices

The orientation of objects and the directional components of spectrum consumption models are referenced to their location on the globe. Since locations differ so too will the coordinate systems of their directional modeling components. Further, coordinate systems are also associated with platforms and of antennas with respect to platforms. Thus, converting physical directions to directions for looking up values in the directional model components (i.e. maps and trajectories) will require conversion of the coordinate systems. Conversions of system centric coordinate systems, discussed later, are accomplished through the displacement of origins and the rotation of axis system. Rotations of axis systems are accomplished through the use of rotation matrices. There are three basic rotation matrices:

$$R_x(\theta) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{bmatrix},$$

$$R_y(\theta) = \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix},$$

and

$$R_z(\theta) = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}.$$

The directions of the rotation are as follows: $R_x(\theta)$ rotates the y-axis towards the z-axis, $R_y(\theta)$ rotates the z-axis towards the x-axis, and $R_z(\theta)$ rotates the x-axis towards the y-axis. The order of rotation affects the final orientation. Given a series of rotations, the inverse rotation applies the rotation matrices in reverse order with negative angles

F.1 Coordinate Rotations

F.1.1 Rotation of Earth Surface Coordinates (Propagation Maps Coordinates) Relative to the Earth Centric Coordinates

The orientation of an Earth surface coordinate systems, the same system used for propagation map coordinate systems, on the surface of the earth will vary by its location on the Earth. The x axis always points to the north, the y axis points east, and the z axis points toward the Earth. Meanwhile the Earth's axis system is a right handed coordinate system with the z axis coincident to the axis of rotation and the x axis pointing to the prime meridian. The conversion of a coordinate system from one coincident to the Earth's system to one with appropriate orientation on the Earth's surface requires three rotations the first is a 180° rotation about the y axis which brings the z axis toward the center of the earth, the second about the z axis which aligns the x axis with the longitude and the final rotation is again about the y axis which brings the x axis to an angle that is tangent to the earth's surface at the latitude φ. The cumulative rotations are obtained by the product

$$R_{E2S}(\phi,\lambda) = R_y(90^\circ - \varphi) R_z(-\lambda) R_y(180^\circ)$$

And the inverse of these rotations is obtained by the product

$$R_{S2E}(\varphi,\lambda) = R_y(-180^\circ)\cdot R_z(\lambda)\cdot R_y(\varphi - 90)$$

Further details of this conversion are found in Appendix G.

F.1.2 The Rotation of Travel Direction Coordinates Relative to Earth Surface Coordinates

The direction of travel is typically specified by an azimuth and elevation in the Earth's surface coordinates. By convention the x axis points in the direction of travel. Moving an Earth's surface coordinate system to the direction of travel requires two rotations, the first is about the z axis to by the azimuth of travel, θ, and the second is about the y axis by the elevation, ϕ. The cumulative rotation matrix is

$$R_{S2T}(\varphi,\theta) = R_y(\phi) R_z(\theta)$$

and the inverse cumulative matrix is

$$R_{T2S}(\phi,\theta) = R_z(-\theta) R_y(-\phi),$$

F.1.3 Rotation of Platform Coordinate Systems Relative to the Direction of Travel

The coordinate system of a platform by convention makes the positive x direction point in typical forward direction of the platform (e.g. coincident to the fuselage of the aircraft), the y axis point to the right parallel to the horizon and the z axis points to the earth. Figure F-1 illustrates the orientation and defines the typical rotations of yaw, φ, pitch, θ, and roll, ψ. The rotations are applied in the order of yaw, pitch, and roll and the cumulative rotation is obtained by the product

$$R_{T2P}(\varphi,\theta,\psi) = R_x(\varphi) R_y(\theta) R_z(\psi)$$

and the inverse cumulative matrix is

$$R_{P2T}(\varphi,\theta,\psi) = R_z(-\psi) R_y(-\theta) R_x(-\varphi)$$

F.1.4 The Rotation of Power Map Coordinates Relative to Platform Coordinates

The direction of an antenna power map on a platform has a reference that is coincident to the coordinate system of the platform. There are cases where, because of the symmetry of the mask structure, it is appropriate to model the antenna as rotated on the platform. By convention,

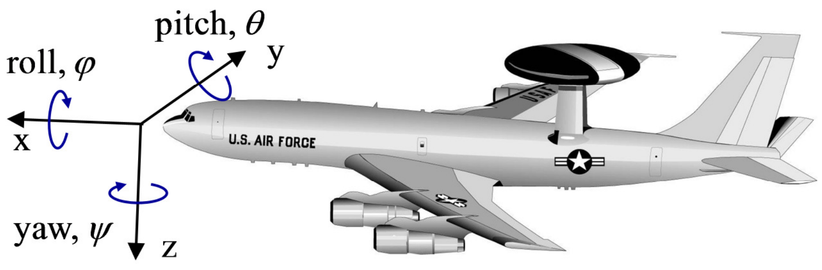


Figure F-1. Platform coordinate systems and the yaw, pitch, and roll rotation directions

changes in orientation are specified with three values with a rotation order of about the z axis, about the y axis, and then about the x axis. The cumulative rotation matrix is the same used for the aircraft roll, pitch, and yaw,

$$R_{P2A}(\gamma,\beta,\alpha) = R_x(\gamma)\,R_y(\beta)\,R_z(\alpha)$$

and so is its inverse

$$R_{A2P}(\gamma,\beta,\alpha) = R_z(-\alpha)\,R_y(-\beta)\,R_x(-\gamma)$$

F.2 Directional Computations

F.2.1 Convert Earth's Surface Directions to Platform Power Map Directions

Given the following:

Earth's surface direction:

Azimuth : θ_S
Elevation : φ_S

Direction of Travel:

Azimuth : θ_T
Elevation : ϕ_T

Roll, Pitch, and Yaw:

Yaw : ψ_P
Pitch : θ_P
Roll : φ_P

Power Map Orientation:

Zrot : α_A
Yrot : β_A
Zrot : γ_A

Find the azimuth, θ_A , and elevation, ϕ_A , in the power map that are coincident to the direction (θ_S , φ_S) on the Earth's surface.

The solution requires converting the earth surface direction to a unit vector, rotating it using the appropriately ordered rotation matrices, and then converting the new unit vector to an azimuth and direction. These computations follow:

$$\begin{pmatrix} x_A \\ y_A \\ z_A \end{pmatrix} = R_{P2A}(\gamma_A,\beta_A,\alpha_A)\cdot R_{T2P}(\varphi_P,\theta_P,\psi_P)\cdot R_{S2T}(\phi_T,\theta_T)\begin{pmatrix} \sin\varphi_S\cos\theta_S \\ \sin\varphi_S\sin\theta_S \\ \cos\varphi_S \end{pmatrix}$$

$$\phi_A = \arccos(z_A)$$

$$\theta_A = \arctan 2(x_A, y_A)$$

F.2.2 Convert Platform Power Map Directions to Earth's Surface Directions

Given the following:

Power map direction:

Azimuth : θ_A

Elevation : ϕ_A

Direction of Travel:

Azimuth : θ_T

Elevation : ϕ_T

Roll, Pitch, and Yaw:

Yaw : ψ_P

Pitch : θ_P

Roll : φ_P

Power Map Orientation:

Zrot : α_A

Yrot : β_A

Zrot : γ_A

Find the azimuth, θ_S , and elevation, φ_S , in Earth's surface coordinates that are coincident to the direction (θ_A , ϕ_A) in the platform power map.

The solution to this problem is the same as above except we apply the inverse matrices.

$$\begin{pmatrix} x_S \\ y_S \\ z_S \end{pmatrix} = R_{T2S}\left(\phi_T, \theta_T\right) \cdot R_{P2T}\left(\varphi_P, \theta_P, \psi_P\right) \cdot R_{A2P}\left(\gamma_A, \beta_A, \alpha_A\right) \cdot \begin{pmatrix} \sin\phi_A \cos\theta_A \\ \sin\phi_A \sin\theta_A \\ \cos\phi_A \end{pmatrix}$$

$$\varphi_S = \arccos\left(z_S\right)$$

$$\theta_S = \arctan 2\left(x_S, y_S\right)$$

Appendix G Coordinate Conversions

A conversion between two Cartesian coordinate systems, say from WGS 84 coordinates to platform centric coordinate, involves a translation to account for the displacement between origins and rotations of the axis to account for differences in orientation. Translation is assessed by subtracting the coordinates of the new origin from the point whose coordinates are being converted. After a translation of the coordinates the coordinate system retains the original orientation. Differences in orientation are accomplished by rotating the coordinate system. Rotations of a coordinate system about a common origin are made using a combination of three rotation matrices that define how the new system was rotated about its axes.

Conversion of a WGS 84 oriented coordinate system to a local tangent plane system with an <n,e,v> orientation, that of a propagation map, can be accomplished in three rotations as illustrated in Figure G-1. The sizes of the rotations are determined by the longitude and latitude of the point. The very first rotation is to place the Z axis downward retaining the original y direction which requires a 180° rotation about the y axis. The second rotation is about this z_1 axis to bring the x_2 axis to point toward the Earth's z axis and to point the y_2 axis toward the east. The third rotation is about the y_2 axis and brings the z axis coincident to the prime vertical, maxes the x-y plane tangent to the Earth's surface with the previous x axis pointing north so the n axis, the y axis pointing east so the e axis, and the z axis indicating the vertical displacement and so labeled the v axis. The rotation matrix from changing orientation from the earth centric coordinate system to an Earth's surface system located at longitude θ and latitude φ is

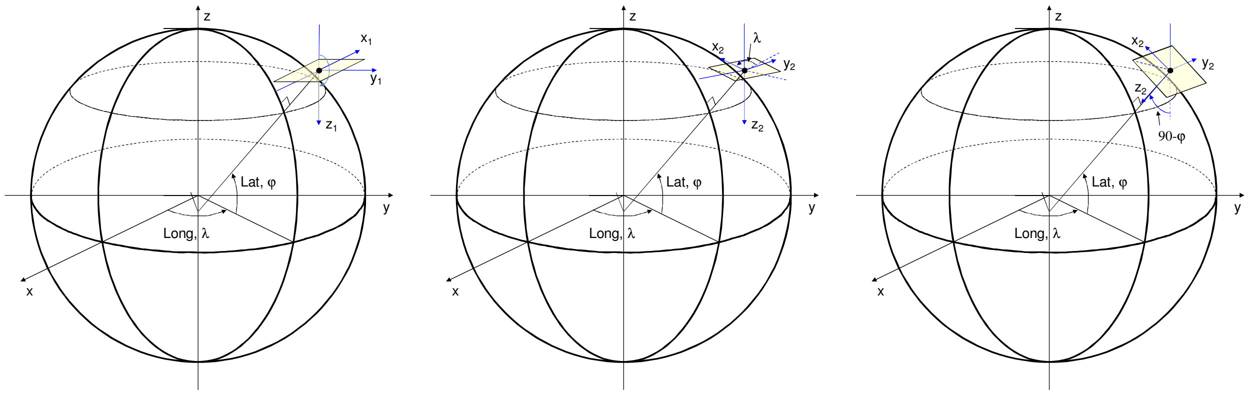
$$R_{E2S}(\lambda,\varphi)=R_y(90-\varphi)\cdot R_z(-\lambda)\cdot R_y(180°),$$

and the inverse rotation

$$R_{S2E}(\lambda,\varphi)=R_y(-180°)\cdot R_z(\lambda)\cdot R_y(\varphi-90°).$$

The transformation of the WGS 84 Cartesian coordinates to propagation map coordinates is then

$$\begin{bmatrix} n \\ e \\ v \end{bmatrix}_{\mathrm{S}} = R_{E2S}(\lambda,\varphi)\left(\begin{bmatrix} x \\ y \\ z \end{bmatrix}_{\mathrm{WGS84}} - \begin{bmatrix} x_o \\ y_o \\ z_o \end{bmatrix}_{\mathrm{WGS84}}\right).$$



a. Rotation about the y axis b. Rotation about z_1 c. Rotation about y_2

Figure G-1. Axis rotations to arrive at the propagation map coordinate system

where the coordinate (x_o , y_o , z_o) is the WGS 84 location of the origin of the local tangent plane. The inverse transformation reverses the process, first returning the axis system to WGS 84 orientation and then translating the coordinate to WGS 84 origin.

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix}_{\mathrm{WGS84}} = R_{S2E}\left(\lambda,\varphi\right)\begin{bmatrix} n \\ e \\ v \end{bmatrix}_{\mathrm{S}} + \begin{bmatrix} x_{\mathrm{o}} \\ y_{\mathrm{o}} \\ z_{\mathrm{o}} \end{bmatrix}_{\mathrm{WGS84}} .$$

Appendix H Acronyms

A2P	Antenna to Platform Direction
ACK	Acknowledgement
CDMA2000	Code Division Multiple Access 2000
CR	Collision Resolution
CTS	Clear to Send
DSA	Dynamic Spectrum Access
DTED	Digital Terrain Elevation Data
DySPAN	Dynamic Spectrum Access Networks
E2S	Earth to Surface Coordinates
EI	Echo Invoke
EW	Electronic Warfare
FCC	Federal Communications Commission
GCS	Ground Control Station
GSM	Global System for Mobile Communications
IEEE	International Electrical and Electronics Engineers
IM	Intermodulation
ITU-R	International Telecommunications Union – Radiocommunications Sector
LOS	Line of Sight
LTE	Long Term Evolution
MAC	Medium Access Control
MANET	Mobile Ad Hoc Network
MBSM	Model-Based Spectrum Management
NM	Network Manager
NTIA	National Telecommunications and Information Agency
P2A	Platform to Antenna Direction
P2T	Platform to Travel Direction Directions
PBSM	Policy-Based Spectrum Management
RF	Radio Frequency
RTS	Request to Send
S2E	Surface to Earth Coordinates
S2T	Surface to Travel Directions Coordinates
SMADEF	Spectrum Management Allied Data Exchange Format
SCMML	Spectrum Consumption Model Markup Language
SCM	Spectrum Consumption Modeling
SCR	Synchronous Collision Resolution
SINR	Signal to Interference and Noise Ratio
SM	Spectrum Management
T2P	Travel Direction to Platform Direction
T2S	Travel Direction to Surface Coordinates
TDL	Tactical Data Link
TDMA	Time Division Multiple Access
TIREM	Terrain Integrated Rough Earth Model

UAS	Unmanned Autonomous System
UAV	Unmanned Autonomous Vehicle
UTC	Coordinated Universal Time
WiMAX	Wireless Interoperability for Microwave Access
WRC	World Radiocommunication Conference
XML	Extensible Markup Language