DOCUMENT NUMBER 130654

MITRE TECHNICAL REPORT

Model-Based Spectrum Management

Part 1: Modeling and Computation Manual
Version 2.0

John A. Stine
Samuel E. Schmitz
December 2013

Sponsor: U.S. Air Force
Dept. No.: J84A
Contract No.: FA8702-13-C-0001
Project No.: 03147K01-AD

McLean, VA

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **DEC 2013**	2. REPORT TYPE	3. DATES COVERED **00-00-2013 to 00-00-2013**

4. TITLE AND SUBTITLE **Model-Based Spectrum Management. Part 1: Modeling and Computation Manual Version 2.0**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **MITRE Corporation,7515 Colshire Drive,McLean,VA,22102**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S)
	11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Radio frequency (RF) spectrum is a finite resource that is essential to many enterprises, including those of governments, militaries, businesses, and citizens. The broad utility of RF spectrum guarantees that demand for access will not wane and will probably increase continuously. Obtaining greater utility from spectrum would have universal benefits. However, current trends to achieve greater utility have focused on prioritizing uses to those considered most valuable or most effective, and thus obtaining the greatest benefits from a particular use of spectrum, rather than developing the means to use spectrum most efficiently, i.e., use the least amount of spectrum for a particular task. An alternative means to obtaining greater utility from spectrum than converting spectrum between uses are to manage spectrum in a more agile way and to build systems that can respond to that agile management so that uses can share spectrum more effectively. This approach can enable greater broadband access 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 mitigate many of the challenges confronted by the large users of spectrum such as the defense and intelligence communities. Model-Based Spectrum Management (MBSM) is a new SM approach based on the creation and exchange of spectrum consumption models (SCMs). The SCMs capture not only the technical aspects of spectrum consumption but also such aspects as human judgment and the knowledge not present in mere datasets of system characteristics. The modeling approach provides computational methods to arbitrate the compatibility of SCM. The vision is that a standardized approach to modeling spectrum consumption and arbitrating compatibility would serve as a loose coupler among the systems that manage and use spectrum. This type of loose coupler would encourage the innovation in SM and RF system design that could enable the agile management and use sought. This modeling approach to SM can also yield benefits across SM communities ? In regulation, SCM can be used to define a user?s spectrum usage rights. ? In commerce, SCMs can capture the quanta of spectrum traded. ? In technology, SCMs convey spectrum assignments and spectrum policy to RF systems. ? In operations, SCMs increase reuse by enabling dynamic and flexible management An effective spectrum consumption modeling approach achieves three objectives 1. It provides constructs for capturing the many facets of spectrum use within models 2. It provides well-defined, tractable, and efficient methods for computing the compatibility of modeled uses. 3. It provides a means to use the models to convey both the consumption and the

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**225**	

Abstract

Radio frequency (RF) spectrum is a finite resource that is essential to many enterprises, including those of governments, militaries, businesses, and citizens. The broad utility of RF spectrum guarantees that demand for access will not wane and will probably increase continuously. Obtaining greater utility from spectrum would have universal benefits. However, current trends to achieve greater utility have focused on prioritizing uses to those considered most valuable or most effective, and thus obtaining the greatest benefits from a particular use of spectrum, rather than developing the means to use spectrum most efficiently, i.e., use the least amount of spectrum for a particular task.

An alternative means to obtaining greater utility from spectrum than converting spectrum between uses are to manage spectrum in a more agile way and to build systems that can respond to that agile management so that uses can share spectrum more effectively. This approach can enable greater broadband access 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 mitigate many of the challenges confronted by the large users of spectrum such as the defense and intelligence communities.

Model-Based Spectrum Management (MBSM) is a new SM approach based on the creation and exchange of spectrum consumption models (SCMs). The SCMs capture not only the technical aspects of spectrum consumption but also such aspects as human judgment and the knowledge not present in mere datasets of system characteristics. The modeling approach provides computational methods to arbitrate the compatibility of SCM. The vision is that a standardized approach to modeling spectrum consumption and arbitrating compatibility would serve as a loose coupler among the systems that manage and use spectrum. This type of loose coupler would encourage the innovation in SM and RF system design that could enable the agile management and use sought. This modeling approach to SM can also yield benefits across SM communities:

- In regulation, SCM can be used to define a user’s spectrum usage rights.
- In commerce, SCMs can capture the quanta of spectrum traded.
- In technology, SCMs convey spectrum assignments and spectrum policy to RF systems.
- In operations, SCMs increase reuse by enabling dynamic and flexible management

An effective spectrum consumption modeling approach achieves three objectives:

1. It provides constructs for capturing the many facets of spectrum use within models
2. It provides well-defined, tractable, and efficient methods for computing the compatibility of modeled uses.
3. It 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 computation of compatibility among models. It also discusses how to combine models to convey system and enterprise use of spectrum, how models convey spectrum availability, and how to use models 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 on for safety, operations, routine communications, and entertainment. It represents a necessary resource for products and services that much of the technology community builds and sells. Thus, spectrum has value and is in high demand. Further, we see no indication that this demand will do anything but increase.

Unfortunately, spectrum assignment to uses occurs primarily through a static, reservation-based methodology. Therefore, satisfying any particular demand requires freeing spectrum either by displacing current users or by shifting or more finely managing assignments to create or find space for new uses. Current policy trends favor the former approach: they seek to change assignments based on the relative value of the usage. This preference results from several factors, one of them being the lack of technical means to do the latter. Model-Based Spectrum Management (MBSM) is intended to overcome this shortcoming by providing the technical means to manage spectrum more agilely and thus allow spectrum to satisfy the needs of more users and enable users to share spectrum effectively.[1]

In this document we describe why current spectrum management (SM) approaches lack this agility and how MBSM does something different. The document begins with a brief description of SM and the underlying mindset to identify persistent and broadly applying assignments only after what usually amounts to be a prolonged study. MBSM attempts to improve SM by basing SM on the creation and exchange of spectrum consumption models (SCMs). Spectrum consumption modeling is designed to reduce and in most cases eliminate the need to perform such lengthy studies by capturing the salient features of spectrum consumption in models so that generic algorithms can compute whether uses are compatible.

Spectrum is consumed by RF devices when their use of the spectrum precludes use of the same spectrum by other users. The time frequency and geographic extent of spectrum consumption depends strongly on the characteristics of both the incumbent systems and the systems that want to share the spectrum. SCMs capture these characteristics for that assessment. Using SCMs as the core element of SM allows more agile management. The adoption of this modeling approach in SM can further solve other technical challenges in SM such as articulating and managing policy for future dynamic spectrum access (DSA) systems. This manual serves as a guide to the methods of spectrum consumption modeling.

1.1 Spectrum Management Processes

Traditionally, SM has been performed globally through international agreements and nationally by government administrations. Spectrum managers divide bands of spectrum into allocations designated to support particular services, and then subdivide the allocations into allotments that administrations may use in specified geographic areas. National administrations may further allot the spectrum to 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 government agencies such as defense.

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[1] Concepts of MBSM have been presented earlier in a paper [1] and in a book chapter [2]. This manual represents an evolution of the concept of modeling spectrum consumption. Thus, it contains more constructs and in many cases the constructs in this manual differ from similar constructs described in these foundational documents.

Current SM methods are based on persistent assignments that account 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 SM have encouraged this deliberative approach, as spectrum managers must arbitrate among the many competing demands for spectrum, most specifically in the international arena.

The scientific study of alternatives creates objectivity that mitigates the risk of distributing allocations, allotments, and assignments solely on the basis of 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 assigns each of these proposals 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, as well as the techniques and tools used to perform SM worldwide. The work groups employ various tools and methods to achieve precision in arbitrating compatibility of spectrum use.

This deliberateness and precision in SM can result in the loss of temporal agility in spectrum assignment and the dependence of SM on data sets and computational methods that are impractical to consolidate. The U.S. Department of Defense (DoD) offers a case study, where a recent survey of SM tools identified at least 46 different SM tools in use.[2] This large number of management systems results from the large number of RF systems that must be managed. Further, 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. These tools have the common characteristic of being designed to support decision making: identifying spectrum assignments, namely the frequencies and transmit powers RF systems may use. The shortcoming of this approach of using multiple tools is the absence of of a means to share information with other SM 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 knowledge of the operational use of the system and other systems operating in the same bands and decide what channels to assign. The output fails to capture the knowledge created by managers during this process. Enabling a second manager to fully understand the decision and its impact on other spectrum users would require a transfer of data between tools, a common set of models used within the tools, and transfer of the knowledge about the RF system's use between the managers. In most cases, this is impractical, perhaps 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. As a result, SM in the operational setting remains an activity of study and deliberate consideration in which analysis and decisions aim at creating as persistent a solution as possible.

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

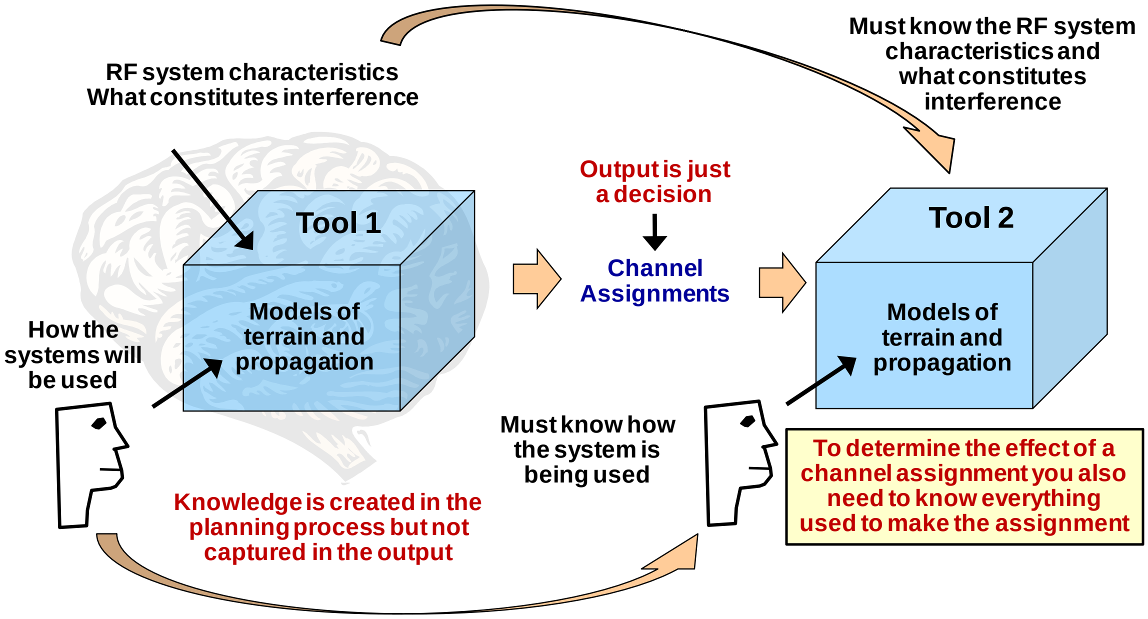

Figure 1-1. The Problem with Spectrum Management Outputs

The actions of the Commerce Spectrum Management Advisory Committee (CSMAC) efforts to manage the sharing of spectrum in the 1755–1850 MHz band between federal and commercial users illustrate this tendency. Neither community wants to fully share data on its system's use of spectrum. Data sharing has become the center of negotiation because neither party trusts the other's analysis and each has its own models of what constitutes interference. Both parties negotiate the sharing of spectrum with the goal of achieving a persistent agreement based on agreed conditions of operation.[3]

Fixing two deficiencies in the current SM processes can result in more agile SM and consequently, greater spectrum reuse. First, SM seeks persistent solutions. As long as SM uses persistent assignments based on prolonged study, it will remain inefficient and forfeit many opportunities for spectrum reuse. Spectrum management should continuously seek and exploit 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 about SM do more than assign channels; that they also convey the knowledge underlying the analysis that reveals the extent of the use of the spectrum in time, frequency, and space and what constitutes acceptable reuse.

1.2 Objectives of Spectrum Consumption Modeling

Spectrum consumption modeling seeks to provide a solution to the second deficiency listed above by capturing 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 rather than data sets of system and component characteristics constitutes the significant advance. Given data sets of the characteristics of RF systems and components, the spectrum managers must assess whether the systems are compatible. They base their assessments on their knowledge of the use of the systems, the technical details describing the susceptibility of the systems to interference, the terrain, propagation, and interference models generated by the

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[3] The minutes of a recent CSMAC meeting reveal the contention over these issues. See http://www.ntia.doc.gov/other-publication/2013/02212013-csmac-meeting-minutes#_Toc350430009

tools they use, and their judgment of whether actual use would mitigate or exacerbate interference. But, in the end, the output is the same data set, with the only addition being the new channel assignments; the data set does not include the knowledge of use, the judgment used, and the criteria for assessing compatibility. This leaves the next manager the task of repeating the same analyses when assessing the same system. By contrast, SCMs attempt to capture the relevant aspects of a system's use of spectrum by modeling it. These models provide an unambiguous definition of the extent to which a system emits radiation and what would constitute harmful interference with that system's operation. They portray specific uses of spectrum as opposed to the general characteristics of systems captured in system data. Thus, 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 about SM as compared to the use of simple channel assignments illustrated in Figure 1-1. A SCM created by one system provides sufficient information to allow other management tools to compute compatible reuse. Management tools and spectrum managers do not have to share details about the RF components of systems and about specific system missions; the model captures these details abstractly. Spectrum managers can decide much more rapidly where the next use can begin, without having to understand what the incumbent system does with the spectrum it uses. Thus, using SCMs as the core interface of SM systems offers a solution to the first deficiency: the lack of agility in management.

Further, SCMs can serve as loose couplers between and among SM systems and the RF systems that use spectrum. Loose coupling can greatly enhance innovation in SM and use that will result in ever more agile use of spectrum.

MBSM promises two fundamental improvements to SM from which many other improvements can evolve. First, the SCMs can capture all dimensions of spectrum use, thereby enabling additional resolution in SM. Second, SCMs, as described here, allow loose coupling in SM systems. The ability to communicate spectrum consumption in models and then to compute reuse opportunities using these models would make modeling a common method for disparate systems to convey and resolve spectrum demands. The approach would benefit all systems that can capture their use of spectrum in models.

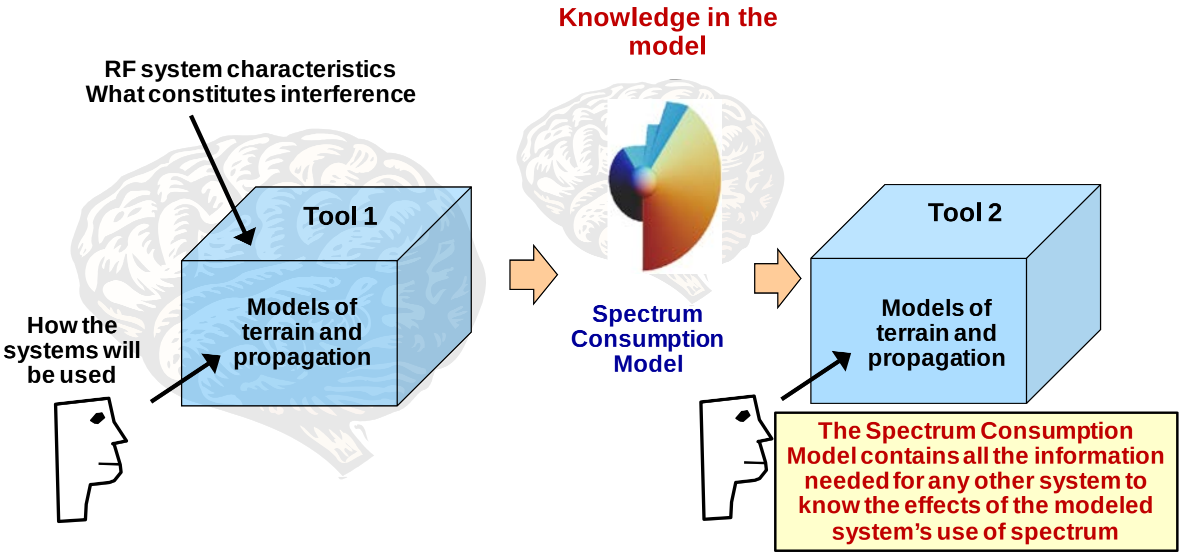


Figure 1-2. Effect of Spectrum Consumption Models on Spectrum Management

1.3 Document Structure

The next chapter begins with a brief introduction to loose couplers and followed by a comparison between the coupling characteristics of SCM and those of existing SM systems. The chapter then presents some details about modeling and the use of models to arbitrate compatibility, as well as the functioning of MBSM. The remainder of the manual provides details on how to model spectrum use. Chapter 3 describes a proposed set of constructs for SCMs and the methods to combine these constructs to build models. The fourth 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 fifth chapter represents a first attempt to discuss the art of modeling and how various types of RF systems might be modeled using the specified constructs, and chapter 6 discusses follow-on activities and issues for implementing a MBSM system including the development of algorithms, tools, architectures and technology that use the SCM and regulation that encourages their use for dynamic SM.

2 Changing Spectrum Management

This chapter begins with an overview of loose coupling and a description of how SCM loosely couples spectrum management. Further the chapter compares the coupling characteristic of current tools with those of MBSM. It then describes the MBSM system that SCM enables and its anticipated benefits.

2.1 Loose Coupling

Loose couplers are data exchange specifications based on the simple, useful, rough intersection of data sharing needs among many systems. They can exist at the intersection of a large set of systems and allow those systems to interoperate and to be integrated

Several well-known systems serve as examples. In the electrical power system, the loose coupler is the specification for power distribution at the user end, covering frequency, voltage, and interface definition. This standardized coupler then allows innovation in both power generation and electrical appliances and tools. It poses no constraint to development of means for generating power as long as power can be converted into the frequency and voltage necessary at the end of the distribution. Further, it does not constrain the development of appliances and tools so long as they can accept power at the specified voltage and frequency. In the second example, the Internet, the Internet Protocol (IP) serves as a loose coupler with the two layers being the means of transport and the services provided by the Internet. Innovation can occur in the means of enabling transport so long as the systems can accept and route IP packets, and in the services and applications that ride the network and use the transport so long as their communications conform to the standards of IP.

Loose coupling also works within the layers. In the power distribution example, loose coupling allows a power distribution system to combine multiple means of power generation, and lets systems integrate multiple sets of appliances and tools, as happens with a home and its appliances. In the Internet, IP enables multiple transport technologies to interoperate in supporting the larger transport function and permits integration of multiple services and applications within the same network.

As seen in these examples, an effective loose coupler standardizes a small 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.

Spectrum consumption modeling serves as a loose coupler among SM systems and RF systems because it provides a means of sharing the data necessary at their intersection. The shared data consist of models of spectrum consumption and the attendant computations used with these models to arbitrate compatibility. Figure 2-1 is a bowtie diagram that illustrates the loose coupler role of SCMs. At the top layer SCMs provides a means for systems that collectively perform SM to convey their vision of spectrum consumption to each other. At the bottom layer SCMs allows RF systems that use the spectrum to coexist.

Spectrum consumption models enable SM systems to describe to RF systems what spectrum they can use. This includes means to convey machine-readable protocols and policies to DSA systems as well as a means for RF systems to identify the actual spectrum they are using to SM systems.

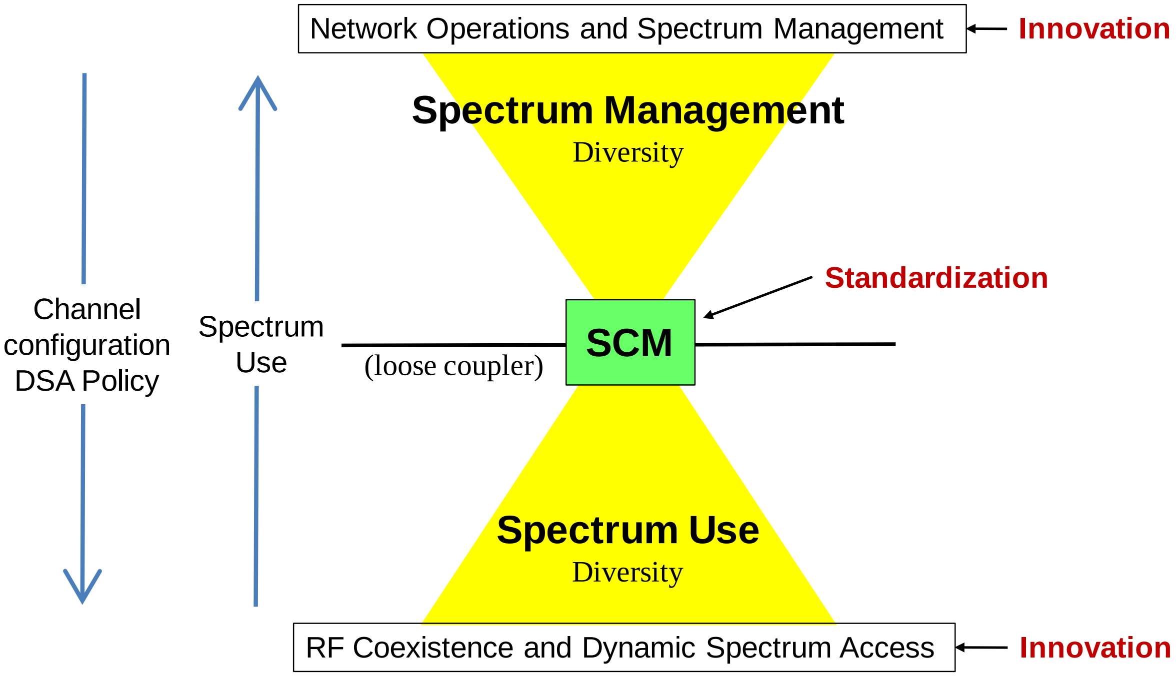


Figure 2-1. SCMs Loose Coupling SM

The path toward realizing this vision involves the creation of a standardized approach to modeling spectrum consumption. This manual represents a first attempt to create such a standard. An effective SCM standard will allow innovation to occur in both the SM and RF system domains while enabling integration and interoperability because of their use of the common SCM standard.

2.2 Comparison of Coupling Characteristics

Existing management approaches use tightly coupled systems, which are characterized by the necessity to change multiple modules of a system to accommodate the change or addition of one module. Adding RF systems that must be managed thus requires adding algorithms within the SM tools to capture the unique aspects of each system’s consumption of spectrum and additional algorithms to assess the system’s compatibility with systems that compete for the same spectrum. Further, the operators of the tools must be trained to use these new models, and the operational changes in spectrum use by a particular system must be explained to all relevant spectrum managers. In contrast, the use of SCMs eliminates the need to modify the SM system as long as the models can convey the new type of use. Providing all details of operational use of spectrum in the form of models eliminates any need for SM tool operators to exchange information about the operational use of the systems. Table 2-1 compares coupling in the two approaches.

Table 2-1. Comparison of Coupling Characteristics of Spectrum Management Systems

Condition	Coupling Characteristics of Existing Spectrum Management Systems	Anticipated Coupling Characteristics of Using SCMs 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 SM 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 SM systems but MBSM tools will not need modification.
	Has a development ripple effect. Analytical approaches must be developed and implemented in SM 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 SM models and analytical methods to SM tools requires operators to be trained in their use.	MBSM tool operators would require no additional training
New SM capabilities are created (e.g., Dynamic Spectrum Access).	Integration of new capabilities requires broad revisions of SM tools and sister systems. For example, although DSA has been proposed for a while there are only very crude methods of SM 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 SM solution or the details of the operational use must be conveyed to the spectrum manager. The spectrum manager then needs to study the SM 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 an SM tool, e.g., compatibility issues, reuse opportunities, and requirements to change SM plans.

2.3 Model-Based Spectrum Management (MBSM)

Model-Based Spectrum Management is characterized by two features. First, it uses SCMs to convey SM decisions. Second, arbitration regarding compatible reuse of spectrum among systems is determined using their SCMs and specified computational methods based on the models. The SM processes 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 by being designed specifically to operate on the models. The next subsection describes the impact of MBSM on existing SM practices.

2.3.1 Spectrum Management

MBSM is not intended as a wholesale replacement of existing SM approaches and business processes. Spectrum users still collect data on the characteristics of systems and exchange those data 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. They will perform the same tasks as before: assess spectrum supportability, request and provide frequency allotments and assignments, and report and resolve interference. Modeling will simplify these tasks and enable additional processes that should improve the effectiveness of SM. SCMs represent the outputs of a first step of analysis and managers will use them to perform subsequent activities of SM more effectively.

The first step in using SCMs for SM consists of constructing a model of a particular operational use of spectrum – without considering any other competing uses of spectrum. Assuming that competing uses of spectrum exist and that those uses are also modeled, then tools applied to the collection of models can quickly assess whether compatibility issues will arise. Developers may also create tools that perform even more sophisticated analysis, such as determining how to best distribute frequency assignments in a given a set of models and identifying opportunities to reuse spectrum. When spectrum is congested, the tools might suggest modifications to spectrum assignments or modifications to models and therefore to the operational use of systems to enable full support.

Modeling has the benefit of enabling those most familiar with the operational aspects of systems to build the models of system use and communicate those models to a centralized activity where assignments are made. Thus, SM activities can be distributed to the individuals best capable of performing them, thereby relieving the spectrum manager of some of the harder tasks that tend to encourage pursuit of persistent assignments.

The new efficiency should also foster a change in mindset from one where spectrum users attempt to stake claims to the bandwidth they need and prevent intrusion to one where the participants collectively attempt to minimize their spectrum consumption, to mine the collections of models for opportunities to reuse spectrum, and then to find ways of exploiting those opportunities. RF systems themselves may be able to mine a set of models and make autonomous decisions on which spectrum to use based on the system's deployment and the incumbent uses.

2.3.2 Modeling

Spectrum consumption unfortunately has a complex relation with the design and deployment of RF systems, including the environment where they are deployed. This complexity makes the use of datasets of RF system characteristics insufficient to drive SM 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 how to overcome that interference. This deficiency makes SM processes slow, based on study, and focused on persistent solutions. Modeling can expose the critical parts of human judgment so that aspects may be reused in subsequent management activities. Further, effective modeling can enable automated processes to accomplish tasks that otherwise would require long, thoughtful, manual efforts.

A modeling methodology must capture multiple phenomena and activities; therefore, a full SCM consists of multiple sub-models. These sub-models capture factors such as pathloss and intermodulation, system characteristics such as spectral occupancy, what constitutes interference, and possibly how the system manages its access to spectrum. They can also describe deployment characteristics such as location and time of operation and antenna directivity. Further, modeling must capture the differences in how transmitters, receivers, and systems consume spectrum. 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.

Spectrum consumption modeling uses twelve constructs to capture the different aspects of spectrum consumption. The remainder of the manual describes the use of these constructs to define spectrum consumption. It should be understood that the authors selected these constructs on the basis of the attendant computations necessary for computing compatibility and chose the modeling abstractions to simplify and keep these computations tractable.

2.3.3 Using SCM to Perform Spectrum Management Tasks

The fundamental computation in SM is the determination of compatibility. Two systems are compatible if they do not harmfully interfere with each other. The basic computation determines the strength of a signal transmitted by one system at the receiver of the second. If the strength exceeds an acceptable level then the systems are incompatible.

Preliminary computations for compatibility determine whether the models overlap in time and in spectrum. If so, the models are checked to determine if systems interfere with each other. Given the location of a victim receiver and an interfering transmitter, computing compatibility requires two steps before the check can be made. The first computation determines the strength of the interfering signal at the victim receiver. This computation begins at the interfering transmitter where the total power, spectrum mask, and the power map model components are used to determine the strength of the signal from this transmitter in the direction of the victim receiver. That signal is then attenuated based on the directional rate defined by the propagation map of either the transmitter model or the victim receiver model (the worse of the two being the default), and the distance between transmitter and receiver. The second step determines "acceptable" interference by using the total power, the power map, and the underlay 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 occurs when the power level of the interfering signal is beneath that for acceptable interference.

Although seemingly simple, actual computations are complex. Rather than being single points, a victim receiver and interfering transmitter may be located within spaces, making it 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 becomes more complex if there are directional differences in transmission power and pathloss. Additionally, multiple systems may compete for the same spectrum, and so a series of pairwise assessments may be necessary.

Given the ability to compute compatibility between models, other functions may follow. In cases where options are available for channel assignment – for instance, when assigning channels from a pool for a collection of networks using the same technology – developers can build algorithms on top of the compatibility computations to assign channels and minimize the potential for interference among users. Algorithms can search through a collection of models with assigned channels and information on available channels to find the best channel to assign to a new user, all based on the user's model of consumption.

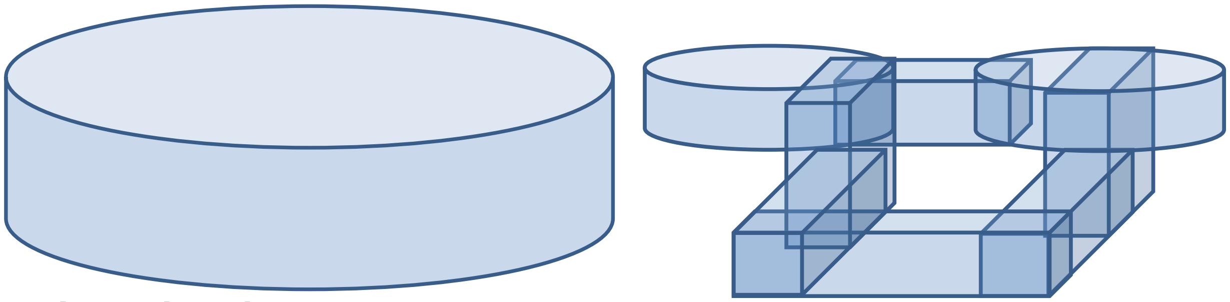
2.4 Anticipated Benefits of MBSM

In the following subsections we show how MBSM can enable a more effective SM capability and the creation of systems that use spectrum more dynamically. These subsections incrementally build the case that use of SCMs not only benefit SM tasks but also enable dynamic spectrum access systems.

2.4.1 Greater Resolution in Spectrum Management

Greater resolution in spectrum use comes from the ability to subdivide spectrum use in time and space. Figure 2-2 shows an example. In Figure 2-2a, a large volume is used to capture a persistent assignment of a system's use of spectrum, which is typical of today's SM. It captures the entire volume of spectrum where the system may be used in all operations over a long period of time that lasts until an assignment is changed. As illustrated in Figure 2-2b, subdividing that volume based on actual mission use of the spectrum can create reuse opportunities. The figure presents several volumes, each of which 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. These smaller volumes would offer opportunities for other systems to use the same spectrum as the system being modeled.

The ability to capture the spatial, spectral, and temporal dimensions of spectrum use also makes it possible to use SCMs to compute where spectrum reuse could occur. This would justify use of the models to optimize use, both within systems and among spectrum users. An example of using this concept in planning aerial unmanned aerial vehicle (UAV) 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 2-2. Using the Spatial and Temporal Dimensions of Spectrum to Subdivide Use

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 located on the aircraft and at a ground control station (GCS). The GCS is likely to remain stationary while the aircraft is highly mobile. If the aircraft has a spatial boundary for some time period then the service volume where a second UAS may be flown using the same spectrum controlled by another GCS can be identified. Figure 2-3 illustrates an example scenario in which two GCSs are separated by half their control range. The blue GCS at the top of the illustration is the primary GCS; 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 with 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. The first panel illustrates this volume. It is also 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). The second panel illustrates this volume. Further, 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 that it receives the green GCS's transmissions with adequate SINR over the interfering blue GCS transmission. The third panel illustrates the volume. The intersection of these three volumes is the service volume in which a second mission may be flown and 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, launch of the green UAV may require synchronization with the launch of the blue UAV, assuming the launch site is co-located with the GCS.

This example uses omnidirectional antennas. Directional antennas would enable a larger operating region and more operational flexibility.

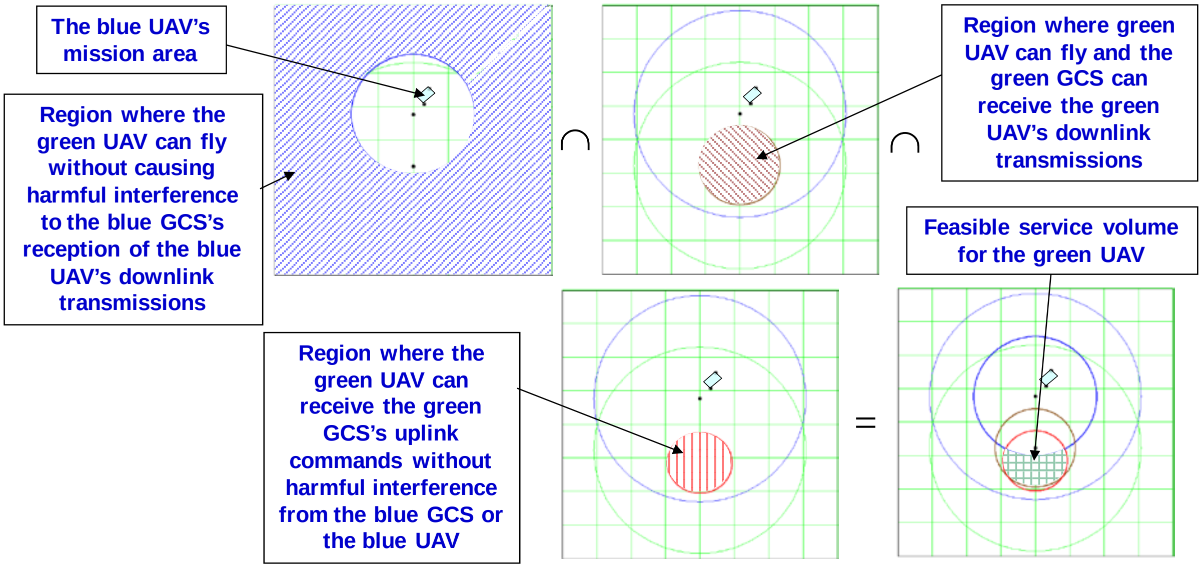


Figure 2-3. Scenario Using Spectrum Consumption Models

2.4.2 Integration of Spectrum Management Systems

This document emphasizes throughout that SCMs 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 about the details of these salient aspects is distributed among the planners and managers who handle the systems. Who can best distribute channels among networked radios: the network manager or the spectrum manager? Who should specify the model of the deployment of a UAV the mission planner or a spectrum manager? And, in both cases, should a spectrum manager have the role of resolving the use of spectrum among competing systems . It is impractical to consolidate all these types of planning into an overarching SM 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. A single, consolidated tool would likely become a bottleneck in planning and reduce the agility of SM. Thus, SM would function best as a distributed process across multiple planning systems and their users.

Herein lies the next great benefit of MBSM: the SCMs enable the integration of these disparate planning systems into a single integrated spectrum planning system of systems that permits arbitration among the judgments of multiple parties 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 apply to a larger piece of spectrum within which an RF system's use of spectrum would be 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, and would capture their final plan 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 would conflict.

Using MBSM would have an additional benefit in that the models would convey spectrum consumption with minimal detail about what the spectrum is used to do. This vagueness about the mission of spectrum use should encourage cooperation of spectrum users with highly sensitive equipment and missions, since they could inform spectrum managers about their systems' consumption without revealing the sensitive details of equipment capabilities and missions. If necessary, modelers can obfuscate use in imprecise models, and spectrum managers can execute their tasks without violating this secrecy.

Creating this type of distributed and cooperative SM capability will require new processes to govern distributed planning, sharing of plans, and arbitration regarding priority of use. These new processes would take advantage of distributed SM. First, the distribution of spectrum planning would ensure that the most capable individuals model the operational and technical aspects of a system's use. Second, it would enable the arbitration of conflicts among the competitors for the same spectrum, because they would be able to share their models of spectrum use and would know best what compromises are practical, especially if the conflict results from overly conservative modeling. The centralized part of management will involve governing this process and resolving conflicts that parties cannot resolve themselves.

2.4.3 Easy Policy for Dynamic Spectrum Access (DSA)

Dynamic spectrum access refers to a collection of different technologies that allow RF systems and devices to determine autonomously which spectrum to use at the time when demand arises, rather than as a preset configuration. The many different approaches include requesting a channel from a broker, coordinating use with a database of existing users, selecting from a set of channels based on location, or selecting a channel based on policy informed by spectrum sensing. All of these techniques are guided by processes or policies that humans create based on their judgment regarding effective spectrum sharing. This dependence on judgment makes MBSM especially well-suited to support the DSA vision.

As already described, models are a means to capture the judgment aspects relative to where devices will be, how they will emit RF radiation, and what would constitute interference. In this way they serve as an obvious complement to PBSM.

SCMs provide a bound to spectrum consumption and therefore can be readily used to convey limits for spectrum use. Spectrum consumption modeling can 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 constitute a policy. Assuming radios are cognizant of how they use spectrum, these models provide sufficient information for a DSA system to determine the locations where they can use specific channels and the limits to their transmit power at those locations. Many developers of DSA systems seek more aggressive sharing that favors behaviors allowing compatible reuse within the spaces of existing use. The "protocol or policy" construct of SCMs was added to the modeling constructs specifically to enable SCMs to provide behavioral guidance that allows finer coexistence mechanisms, e.g., mechanisms based on sensing and timing in addition to location as means to achieve reuse.

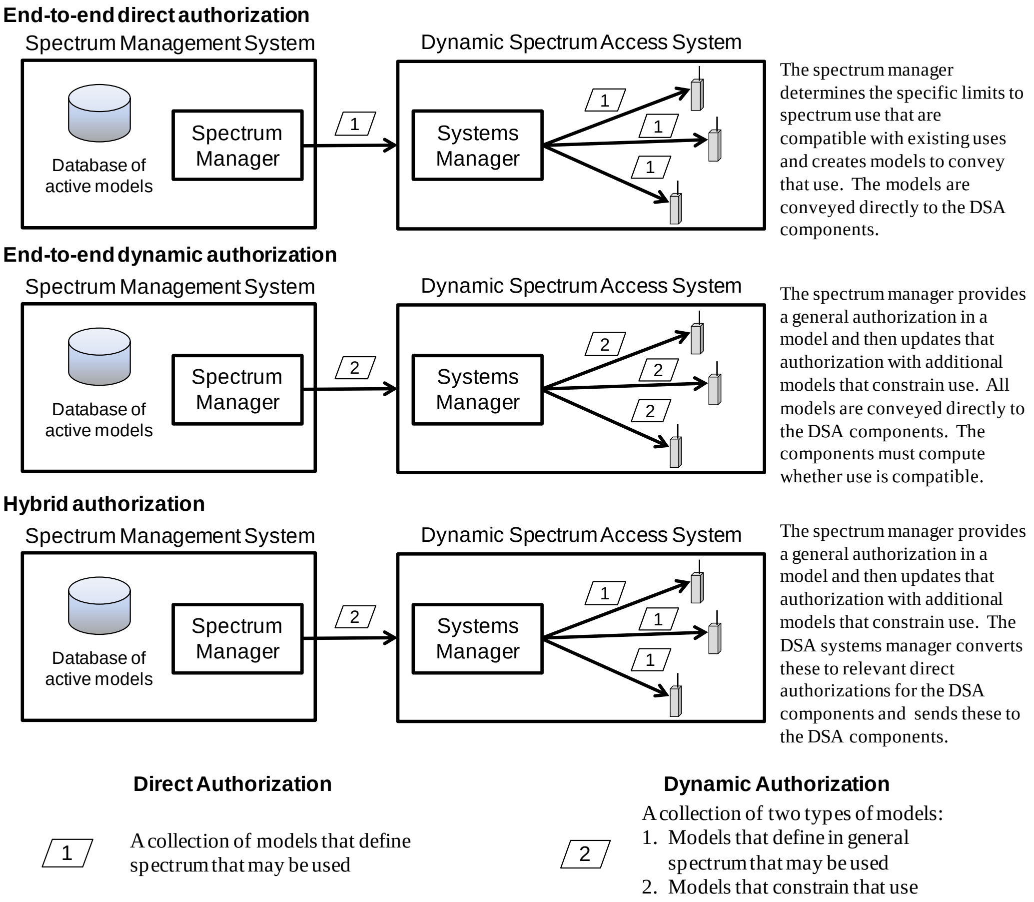
Policies typically have two parts: a permissive part identifying what the DSA system may do and a restrictive part that constrains what the DSA system may do. When using SCM models for DSA policy, the models of incumbent users would constitute the restrictive part; additional models can convey the permissive part. Section 3.3.4 describes the methods for conveying restrictions and Section 3.3.3 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: as either direct or dynamic authorization. They differ in the computations expected at the DSA system.

With direct authorization, the spectrum manager determines the requirements for compatible reuse, creates a set of permissive models of that compatible reuse, and gives these models as policy to the DSA systems. Components of the DSA system would simply determine where they are and the time and lookup which models apply and so which channels can be used. If this results in choices, they can use other criteria of their own to select which option to use.

With dynamic authorization, policy is conveyed using two types of models: permissive models, which are broad in scope and describe the spectrum that might be considered, and restrictive models, which consist of the SCMs of other incumbent systems that have precedence in spectrum use. The DSA system would make the computations necessary to 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 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 created for new uses.

Figure 2-4 illustrates three methods for DSA policy management. The first simply applies the direct authorization. The second applies dynamic authorization, where both the permissive and constraining models are given to the radios of a system with an expectation that the radios will



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.

1 A collection of models that define spectrum that may be used

2 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 2-4. DSA Management Methods

all independently use the two types of models to compute reuse opportunities. This end-to-end dynamic authorization raises possible concerns that individual radios may be unable to compute compatible reuse fast enough. The third method of DSA policy management attempts to mitigate this concern by using a system management function that accepts the dynamic authorizations from a spectrum manager and translates them into the purely permissive policy of a direct authorization that the radio of the systems can use. At the very least, DSA policy created using SCMs could identify the channels a system may use based on location.

2.4.4 Dynamic Spectrum Management

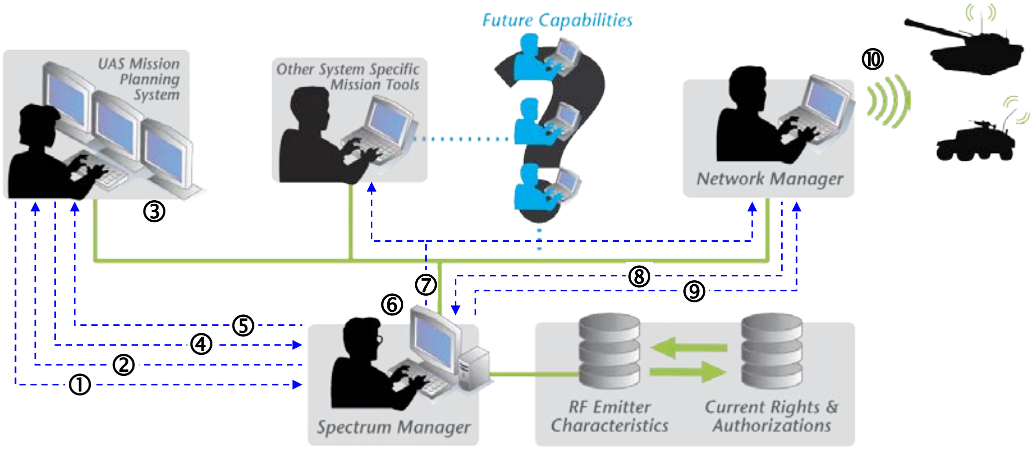
A dynamic SM system combines all the benefits previously defined for MBSM. The SCMs would enable higher resolution management of spectrum with temporal resolution that requires more active interaction among systems. The resulting SM would distribute the SM problem across multiple systems with mission planners, spectrum managers, and system managers working as part of a larger SM process. Collectively, they would form a system that could facilitate the greatest use of a pool of spectrum. The example below and Figure 2-5 illustrate a scenario of dynamic SM in action.

Example: Dynamic Spectrum Management Scenario

Figure 2-5 illustrates a dynamic spectrum management scenario. It begins with the mission planning system requesting spectrum from a spectrum manager. The spectrum manager responds with authorizations for the UAS 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 a set of missions, she requests authorization for the required spectrum from the spectrum manager. If the requests contain no errors, 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 who may also be able to use the spectrum in a compatible way. In this case the network manager identifies ways that his system can use a portion of the available spectrum and responds to the spectrum manager with a request. The spectrum manager grants this request. Because the network manager requested spectrum for cognitive radios, those radios are informed of the spectrum that they may try to use.

In this example, spectrum may be set aside for a system. All of some set of channels may be available for a UAS system at any time and the UAS planning system would work autonomously to find opportunities for reuse within its own domain. At the completion of planning when it requests authorizations, Step 4, the system does not really receive the opportunity to use spectrum, since it already has authorization, but instead actually frees 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 authorization
2. Spectrum manager sends relevant models
3. Mission planner creates plan and the appropriate spectrum models
4. Mission level spectrum authorization requested
5. Mission level spectrum authorization granted
6. Spectrum manager identifies reuse opportunities
7. Potential users of spectrum notified of opportunities
8. Network manager (NM) identifies reuse and requests authorization
9. Spectrum manager reviews NM's request and grants authorization
10. NM informs cognitive radios of authorization

Figure 2-5. Dynamic Spectrum Management Scenario

2.5 Summary

This introduction to MBSM describes the motivation for modeling RF spectrum consumption and building SM around those models. MBSM and the use of SCMs enables a very dynamic form of SM. The SCMs 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 SM. Characteristics of this approach include greater spectral, spatial, and temporal resolution; distribution of 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 SM system. Further, SCMs loosely couple 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.

3 Spectrum Consumption Models

Spectrum consumption modeling captures 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 that comprise the 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 devices make the consumption stochastic. Therefore, modeling consumption does not attempt to capture these effects precisely, but instead to create a bound on these effects – one that ultimately protects the uses that require protection.

This chapter describes the constructs of SCMs, the model types, and the conventions for combining the constructs into models. The reader should be attuned to the interaction of the constructs and how they are used collectively to capture consumption. Ultimately, the models should make the computation of compatible reuse unambiguous and tractable and should help to bound the uncertainty regarding what actually happens in spectrum use.

3.1 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 the way the multiple constructs are combined and assembled ultimately makes the final product – in this case a SCM. Every model may contain constructs such as total power, while other constructs, such as the protocol or policy construct, may be used infrequently. Some constructs may appear multiple times in the same model. There are twelve constructs, as shown in Table 3-1.

Table 3-1. Spectrum Modeling Constructs

Construct	Description
1. Total Power	The power at the transceiver to which values of the spectrum mask, underlay mask, and power map refer
2. Spectrum Mask	A variable-sized data structure that defines the relative spectral power density of emissions by frequency
3. Underlay Mask	A variable-sized data structure that defines the relative spectral power density of allowed interference by frequency
4. Power Map	A variable-sized data structure that defines a relative power flux density per solid angle
5. Propagation Map	A variable-sized data structure that defines a pathloss model 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
8. Location	The location where system components may be used
9. Start Time	The time when the model takes effect
10. End Time	The time when the model no longer applies
11. Minimum Power Spectral Flux Density	A power spectral flux density that when used as part of a transmitter model implies the geographical area in which receivers in the system are protected
12. Protocol or Policy	Documentation that accounts for system behaviors that allow different systems to be co-located and to coexist in the same spectrum

Many of the constructs include elements that define the certainty of the construct. A single model may have multiple versions of the same construct differentiated by a particular probability or certainty measure.[4] These measures may be one of two types: alternative and cumulative. In the alternative type, the constructs define an alternative operational mode and the uncertainty measure indicates the probability that the system is in one mode or the other. The probabilities of the multiple constructs should add to one. In the cumulative type, the constructs subsume each other: the constructs with smaller probabilities fit within the constructs of larger probability, and the largest construct has a probability of one.

The probabilistic elements of the models may also have two natures: a persistent nature or a fleeting nature. A persistent probability indicates that something has a chance of occurring and would persist if it did occur, while a probability with a fleeting nature indicates that the modeled phenomenon does not persist and comes and goes. In the persistent case, the phenomenon being described may never occur while in the fleeting case the phenomenon is always occurring and the probability indicates its average duty cycle (DC).

The description of each construct starts with a brief overview, followed by a discussion of the rationale for the construct, the data structure(s) used, the units for the elements in the data structures, and then a discussion on how the construct interacts with other constructs and their collective use in computing compatibility. Appendix A contains specific conventions for combining the data structures of the constructs and combining the constructs to form models and describes the eXtensible Markup Language (XML) schema for spectrum consumption modeling, known as Spectrum Consumption Modeling Markup Language (SCMML).

3.1.1 Total Power

The total power is a reference value for a model. For transmitters it may specify the total power that drives an antenna and for receivers it may specify the total power received after passing through the antenna. The power term is used together with the power map and spectrum mask to specify the power spectral flux density of the signal a transmitter radiates and is used with the power map and underlay mask to specify the power spectral flux density of an interfering signal that a receiver may tolerate.

3.1.1.1 Rationale

The goal of capturing power in spectrum use is to follow the physics so that modeling is more natural. The total power construct captures the total amount of power perceived between an RF device (i.e., a transmitter or a receiver) and its antenna. Other constructs define how the power is distributed spectrally and spatially. Specifically, the spectrum or underlay masks of models define how power is distributed spectrally and the power map defines how that power is spatially distributed and radiated by direction. Together they define the power spectral flux density.

Regulators and standards bodies often use effective isotropic radiated power (EIRP) to define power emissions. EIRP establishes the maximum power spectral flux density for any direction based on the premise that power radiation is isotropic. The EIRP value can lead to confusion when users specify the power driving an antenna and fail to account for antenna directionality. EIRP is larger than the power driving the antenna when an antenna has any sort of directionality.

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[4] An interim version of modeling proposed a separate probability construct. However, the close association of the uncertainty and probability measures to the particular quality or phenomena the constructs capture made this convention impractical and so these measures are now elements of the individual constructs.

However, the EIRP provides no information on the direction in which the radiation is strongest or on the power-density spectrum.

Many systems have variable power levels because of internal power controls intended to optimize spectrum reuse and to conserve energy. The power construct provides a probability element that allows a modeler to establish confidence that the power level will be below the power level of the construct. A modeler can use multiple power constructs to define a cumulative probability distribution for the system's power. Although a modeler may use any number of power constructs to specify the power level, one power construct should always define the upper bound on the power that may be used.

3.1.1.2 Data Structure

The data structure consists of two single real numbers, one for the power level and one for the probability. If the probability term is used, the probability may be alternative or cumulative and persistent or fleeting. Most models are likely to use the cumulative and fleeting attributes. If the probability term is used, then all masks must have the same attributes and the bounds on the power with confidence 1 must be unambiguous.

3.1.1.3 Units

The power value is specified in units of dBW or dBm. The probability term is dimensionless and is a value from 0 to 1.0. The probability has the type and nature attributes described earlier.

3.1.1.4 Dependencies

All other transmitter power constraints in models are relative to the total power, so changing this value changes all power constraints in a model. Specific construct elements referenced to this value are the spectrum mask, the underlay mask, and the power map.

Multiple power constructs could be used to define a cumulative probability distribution and estimate an average power level. However, a modeler may specify multiple power constructs based purely on judgment. Thus, confidence levels are only based on the particular values provided, without interpolation. For example, if a modeler were to provide two power levels, p_1 and p_2, with 0.8 and 1.0 confidence, the power level for all confidence levels less than or equal to 0.8 is p_1 and for confidence levels greater than 0.8 is p_2.

Example: Compute the average power level given a model with multiple power constructs that collectively define a cumulative probability distribution for power level.

Given a model with five power constructs, (p_1, c_1), (p_2, c_2), (p_3, c_3), (p_4, c_4), and $(p_5, 1.0)$ where $0 < c_1 < c_2 < c_3 < c_4 < 1.0$, the average power is computed as follows:

$$\overline{p} = p_1 \cdot c_1 + p_2 \cdot (c_2 - c_1) + p_3 \cdot (c_3 - c_2) + p_4 \cdot (c_4 - c_3) + p_5 \cdot (1 - c_4)$$

3.1.2 Spectrum Mask

The spectrum mask specifies the power-density spectrum (i.e., the power per unit bandwidth as a function of frequency) relative to the total power. It is presented as a piecewise linear graph of relative power spectral density (i.e., relative power per unit bandwidth versus frequency). In the case of frequency-hopping systems, a generic mask (i.e., one without a specific frequency reference) shows the spectral content of signals and additional data specifies the frequency hopping characteristics. Pairs of masks convey spectrum occupancy: one to show the range of frequency traversed in hopping and one to show the spectral content of the signals. Only the latter mask provides a power spectral density. Additional data structures in the construct convey the dwell and average period between revisits, and in some cases, specifics on the particular channels used.

3.1.2.1 Rationale

The spectrum mask construct conveys the spectral content of RF emissions and their power spectral density. RF signals occupy a band of spectrum and may extend beyond the nominal bounds of their channel or fit well within that channel. The spectrum mask attempts to convey the bounds to the spectral content of the signal. This construct enables use of SCM to determine when adjacent band interference will occur.

In a frequency-hopping system, transmissions do not occur persistently on a single channel and therefore offer an opportunity for other systems to operate in the same frequency bands of the hopping. 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 consists of the generic spectral characteristics 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 can use multiple spectrum mask data structures to capture the variation in these characteristics.

Probability is also a part of modeling spectrum masks. Some transmitters may have operational characteristics where they may be in one state or another with some probability. For example, electronically steered radars may move from a scanning mode to a tracking mode. A receiver in the tracking direction would perceive a much greater pulse rate. An alternative probability measure can be used to convey the likelihood that a secondary receiver would perceive one or the other of the modes. These differences in operation may influence whether a secondary would take the risk of using the channel.

Spectrum masks may also be created with cumulative probabilities. The probability measure would define the likelihood that transmissions in a system fall within the boundary of the mask. A system may consist of radios from different manufacturers that vary in their quality, some allowing more leakage of signals into adjacent bands. The cumulative probability measure would show that the boundary of the masks of the poorer performing transmitters subsumes the boundaries of the masks of the better performing transmitters.

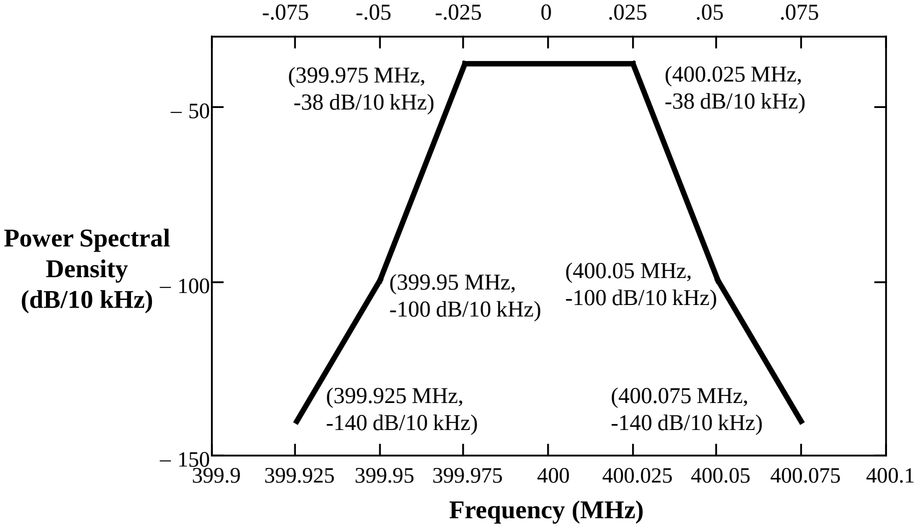
3.1.2.2 Data Structure

Spectrum masks are specified with a resolution bandwidth reference and a variable length (1 × n) array of real values alternating between frequency and relative power 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-numbered terms are powers. The power for all frequencies outside the frequency band covered by the mask is considered to be less than or equal to those frequencies at the closest end of the mask. The power term in spectrum masks is a relative power referenced to the total power. Together, the total power, the relative power of the mask, and the bandwidth reference specify the spectral density of power (i.e., power per unit bandwidth) at each frequency covered by the mask. Figure 3-1 shows an example of a spectrum mask.

An alternative approach for specifying a mask is to make the frequency terms in the array relative to a center frequency reference. The mask used to capture the spectral content of a signal is generic, where frequency terms are referenced to the center frequency of the signal. In the case of a signal with the same bandwidth and shape as those illustrated in Figure 3-1, the generic spectrum mask is $\left(-0.075,-100,-0.05,-60,-0.025,0,0.025,0,0.05,-60,0.075,-100\right)$. This mask together, with a 400 MHz center frequency reference, would be identical to that in Figure 3-1. These masks are referred to as relative spectrum masks.

Frequency-hopping systems require the modeling of the signals transmitted and also of the characteristics of the frequency hopping. Models of frequency hopping use a relative spectrum masks and complement this type of spectrum mask 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 $\left(f_0, f_1, f_2, \cdots f_x\right)$, or a listing of the end frequencies of the bands that are used. In the second case, the tuple $\left(f_{b1}, f_{e1}\right)$ defines 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 $\left(f_{b1}, f_{e1}, f_{b2}, f_{e2}, \cdots f_{bx}, f_{ex}\right)$.

The relative spectrum mask and the frequency specifications are paired with two additional data elements that define the frequency hopping: the dwell time and the average revisit period. When using specific center frequencies the dwell time refers to the length 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. When bands are specified for



(399.925, -140, 399.95, -100, 399.975, -38, 400.025, -38, 400.05, -100, 400.075, -140)

Figure 3-1. Example Spectrum Mask with Its Corresponding Spectrum Mask Vector

the hopping frequencies, the dwell time also specifies the dwell time of a signal as determined by the relative mask at a particular frequency. In this second case, the average revisit period, however, takes into account that individual signals may overlap in spectrum. The revisit period is a function of the bandwidth of the signal conveyed in the relative mask as compared to the bandwidth of the hopping frequency band and the DC for that band. As an example, if the ratio of the bandwidth of the relative mask to the bandwidth for the signal occupancy (the bandwidth between the end frequencies) is 1 to 50 and the DC 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.

Probabilities may be associated with individual masks to indicate either an alternative or cumulative probability. In these cases, transmitter models would have multiple masks, but all masks would use the same probability approach, either alternative or cumulative.

3.1.2.3 Units

Frequency terms in mask arrays are in kHz, MHz, or GHz and relative power terms in mask arrays are in dB. The resolution bandwidth term has units of Hz, kHz, or MHz. Together, the power term in the mask arrays and a resolution bandwidth term convey a power spectral density, dB/x, where x is the resolution bandwidth. Dwell times and revisit periods are specified in units of either μsec or msec. Probabilities are dimensionless.

3.1.2.4 Dependencies

The power terms in the spectrum mask are relative to the total power of the model. If the total power accurately represents the power of transmission, then the highest power in a spectrum mask will be beneath 0 dB, since a power spectral density with a resolution bandwidth that is a fraction of the total bandwidth of a signal will only have a fraction of the total power. For example, if the bandwidth of a signal is 1 MHz but the resolution bandwidth is just 1 kHz, then the relative power reduction within the resolution bandwidth would be

$$p = 10 \cdot \log\left(\frac{10 \text{ kHz}}{1 \text{ MHz}}\right) = -20 \text{ dB}.$$

The spectrum mask is used together with the total power, a propagation map, and a power map to estimate the power spectral flux density at any location covered by the model. Section 4.1.3.1 describes these computations.

Spectrum masks are intended to support not only in-band but also out-of-band compatibility computations. Computation of compatibility depends on the extent of spectrum modeled by the spectrum mask. Ideally, the spectral breadth of a spectrum mask should be broad enough that the power at the end points is beneath the ambient noise floor at the locations considered for compatibility. In cases where the mask does not reach this level, it can only be assumed that the power of the signal outside the mask is lower than that of the end points. For the purposes of compatibility computations the level of the end points is assumed for all frequencies up to twice the spectral distance from the mask center frequency as the end point.[5]

The determination of compatibility using the spectrum mask will depend on the underlay masks used in models of the systems with which spectrum is shared. Modeling the details of frequency hopping or short DCs allows use of underlay masks that match these characteristics and accommodate either higher levels of power in the transmitting system or allow the receiving system modeled in the underlay to be in closer proximity to the transmitting system. The method for determining compatibility will depend on the masks used to model both systems. Section 0 provides further discussion on selecting the approach for computing compatibility.

3.1.3 Underlay Mask

The underlay mask specifies the power spectral density that a receiver can tolerate from a remote interfering transmitter. It conveys both the total power of tolerable interference and the spectral sensitivity to interference. In the latter case, the underlay map conveys the filtering by frequency that the receiver performs. Like the spectrum mask, it is a piecewise linear graph of relative power versus frequency combined with a resolution bandwidth to specify the spectral resolution. A single underlay mask may apply to any signal of any bandwidth, or a model may provide multiple underlay masks – each for different conditions of interference usually differentiated by the temporal nature of interfering transmission. The power in these masks may be relative to either the total power in a receiver model for all locations of the model or relative to the power estimated at a location by the combination of the total power, power map, and propagation map in a transmitter model. In this latter case, the underlay mask is part of a transmitter model and we call it a *referenced* model.

Underlay masks may be used to define the conditions that a new user must accept in order to use the spectrum. The underlay mask defines the maximum power level of the anticipated interference as a function of frequency. These conditions may be expressed using multiple underlay constructs, each with its own probability. A cumulative probability indicates the likelihood that the power of interfering signals will be below the power level indicated by the mask. An alternative probability indicates the likelihood the mask applies to the interfering signal. If it does, all signals are beneath the power level of the mask.

3.1.3.1 Rationale

Underlay masks are the constructs of spectrum consumption modeling that define 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 and so change with propagation or be defined for a location and so remain the same for all potential locations of receivers. The former method is used for a single transmitter; in this case the reference power for the underlay mask is the same as that used for the spectrum mask and adjusts with propagation. The latter method is used for systems with multiple transmitters or mobile transmitters and receivers. The reference power for these masks is the total power of the receiver model. Figure 3-2 illustrates the difference between these masks. Panel A illustrates a mask that uses a transmitter spectrum mask as a reference and Panel B illustrates a similar mask that would apply to a location. The constraints of the first provide a margin relative to the spectrum mask and the

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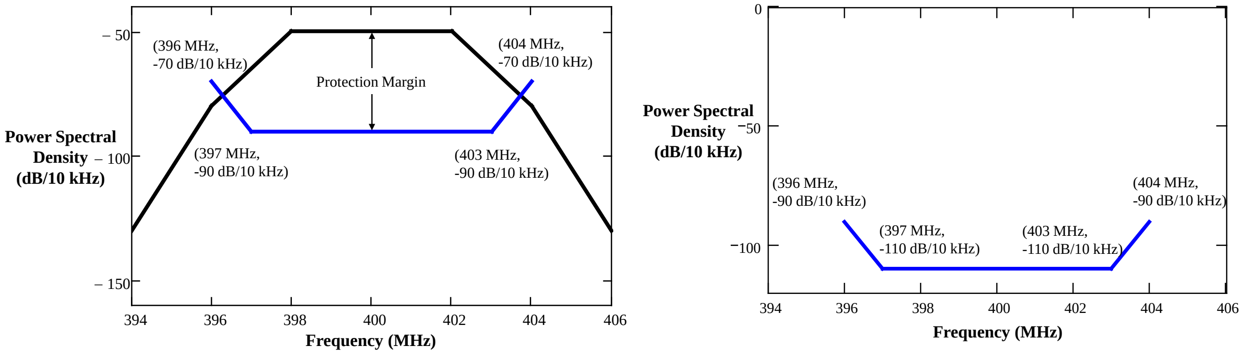
[5] This rule attempts to account for the use of masks that were built to show in-band spectrum use only. We expect that with time, spectrum masks will extend beyond in-band representations to fully show the potential for out-of band interference with end points where out-of-band interference is unlikely.



a. An underlay mask referenced to a spectrum mask $(396,-70,397,-90,403,-90,404,-70)$

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

Figure 3-2. Comparison of Underlay Masks with Alternative References

constraints of the second are fixed for all locations. The frequency terms of the two are the same, but the power terms of the mask referenced to a location are much smaller.

Underlay masks convey both the power of allowed interference and the frequency-dependent filtering of the receiver. The mask is presented graphically to indicate the allowed power of an interferer as a function of frequency. This depiction makes it very easy to compare the relative performance of different receiving systems. By convention, the total power allowed by the underlay mask in the 3 dB bandwidth of the mask conveys the total allowed interference. The difference in relative power at a point of the mask with respect to the relative power in the passband of the underlay mask (i.e., the lowest power of the mask) indicates the frequency-dependent attenuation of the filtering of the receiver.

A receiver model may use multiple underlay masks to indicate differences in sensitivity based on particular signal spaces or sensitivity to different DCs of interference. The criteria of all the underlay masks must be met to assess that two RF systems are compatible.

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 spectral 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 enable more reuse opportunities.

Underlay masks may also differ based on the duration of interference and its bandwidth as caused by frequency-hopping 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-hopping system occupies the band only infrequently, briefly, or weakly. Underlay masks with bandwidth-time product (BTP) ratings allow modelers to convey the resilience of receivers to this type of interference.

Similar to the underlay masks for frequency-hop systems are systems that can tolerate interference from certain low DC signals that might be transmitted from radars and some frequency-hop systems. Rather than a BTP, a DC and a maximum dwell time rate each of these masks.

Receivers may have additional tolerance to RF systems that use particular policies or protocols. Thus, underlay masks may be rated for policies or protocols.

The energy margin from the interaction of an interfering transmitter spectrum mask and an underlay mask may be computed as total power or maximum density. The total power computation uses the underlay mask to assess the level of power that would enter the receiver and cause interference. The maximum density computation assesses whether the maximum spectral power density of a transmitter spectrum mask exceeds any threshold level of the underlay mask. Section 0 describes the methods for these computations and the rules for applying them to interference scenarios.

3.1.3.2 Data Structure

Underlay masks are specified with a resolution bandwidth reference and a variable length (1 × 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-numbered terms are powers. The power term in spectrum masks is a relative power referenced to the total power. Together, the total power, the relative power of the mask, and the bandwidth reference specify the spectral density of power (i.e., power per unit bandwidth) at each frequency covered by the mask. Unlike a spectrum mask, there are no restrictions or assumptions made about the power at frequencies outside the mask.

As with spectrum masks, an alternative approach for specifying an underlay mask is to make the frequency terms in the array relative to a center frequency reference. The mask used to capture the spectral content of a signal is generic, where frequency terms are referenced to the center frequency of the signal. In the case of a signal with the same bandwidth and shape as Figure 3-2 illustrates, the generic spectrum mask is $\left(-4,-90,-3,-110,3,-110,4,-90\right)$. The center frequency is 400 MHz.

A classifier of either "total power" or "maximum power density" identifies whether the mask specifies the conditions for determining the power margin using a total power or maximum power density type computation.

When modelers use multiple underlay masks to indicate allowed interference for different bandwidth signals, they provide the maximum bandwidth, *BW*, of the interfering signal considered by the mask. 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 BTP with a power level of the form $\left(\left(BW \cdot T\right)_0, p_0, \left(BW \cdot T\right)_1, p_1, \cdots \left(BW \cdot T\right)_x, p_x\right)$. The BTPis 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 BTP is the sum of the individual BTPs.

Underlay masks rated for low DC interference use a similar format. A single mask is given several ratings that combine DC, maximum dwell time, and a power level of the form $\left(DC_0, DT_0, p_0, DC_1, DT_1, p_1, \cdots DC_x, DT_x, p_x\right)$. These masks identify two constraints that define the DC limitation: DC in the list identifies the total fraction of time the interferer is present and DT identifies the maximum continuous period of time an interfering signal may be present. When multiple low duty signals arrive from distant interferers, margin computations add their DCs and their dwell times in order to select the correct mask.

Figure 3-3 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 specification for the masks. Figure 3-4 illustrates the use of these data structures to convey the allowed interference from frequency-hopping systems, and Figure 3-5 illustrates the use of these data structures to convey the allowed interference from low DC interferers.

Underlay masks rated for a policy or protocol are associated with a particular policy or protocol identified by a policy or protocol index. The underlay mask and the protocol or policy constructs use a common index.

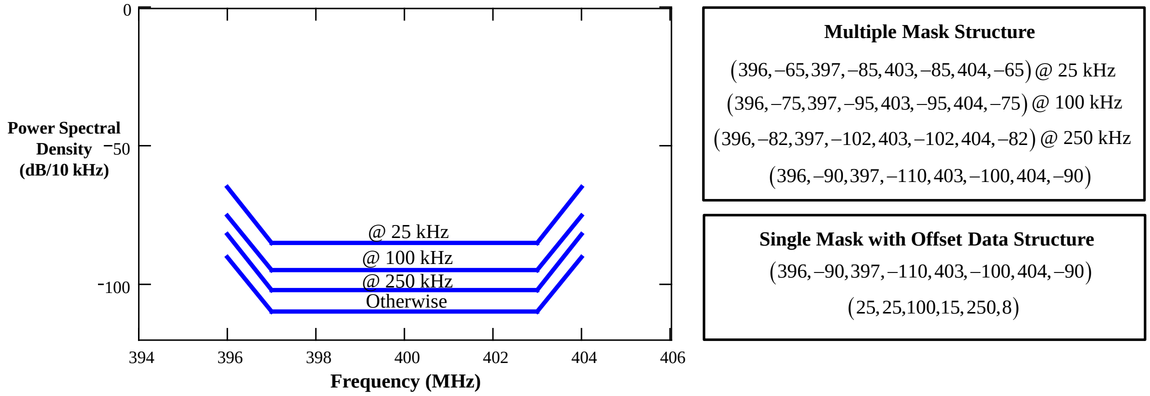


Figure 3-3. Using Multiple Masks to Specify Different Interference Constraints for Different Interference Bandwidths and a Comparison of Data Structures Specifying these Masks

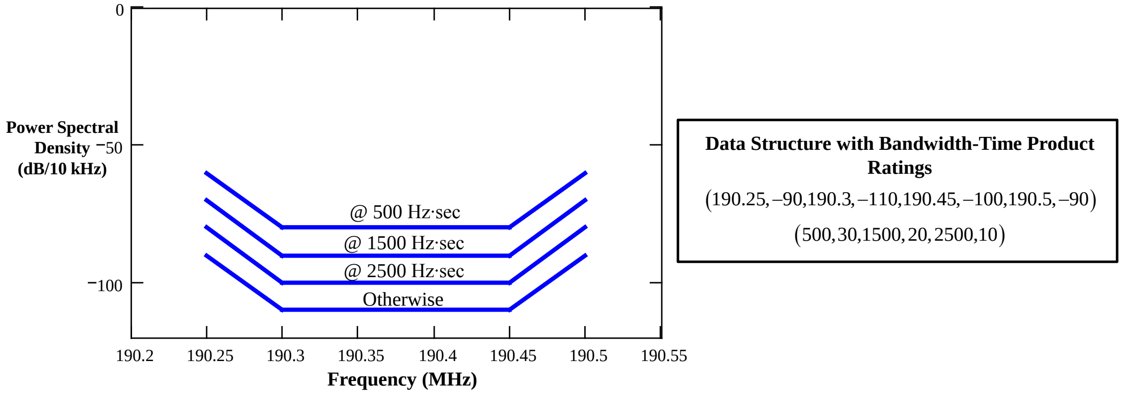
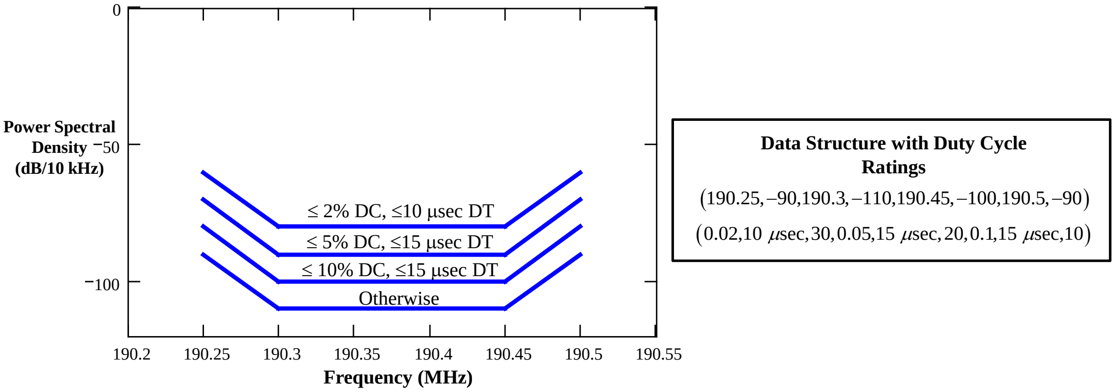


Figure 3-4. Using Underlay Masks to Specify Ratings for Frequency Hopping Interference



Data Structure with Duty Cycle Ratings

$$\left(190.25,-90,190.3,-110,190.45,-100,190.5,-90\right)$$

$$\left(0.02,10\ \mu\text{sec},30,0.05,15\ \mu\text{sec},20,0.1,15\ \mu\text{sec},10\right)$$

Figure 3-5. Using Underlay Masks to Specify Ratings for Low Duty Cycle Interference

Modelers may assign probabilities to spectrum masks. However, assigning a probability to a model of a receiver's tolerance for interference is not very useful. The variety of underlay mask ratings achieves the objective of classifying tolerance to interference based on statistical properties of the interference. Use of a probability attribute in an underlay mask has greater value in negotiating the sharing of spectrum. Negotiators may use probabilities together with spectrum masks to specify a softer restriction on interference levels that accounts for factors that users cannot fully control: for example, variation in propagation conditions or operational use that determine the specific power levels a receiver experiences. Section 4.2.3 describes the use of probabilities and confidence levels in arbitrating compatibility. Compatibility is governed by mutually agreed upon approaches as opposed to a standardized method.

3.1.3.3 Units

Frequency terms in the underlay mask are in kHz, MHz, or GHz and power terms are in dB. The resolution bandwidth term has units of Hz, kHz, or MHz. Together the power term in the mask arrays and a resolution bandwidth term convey a power spectral density, dB/x, where x is the resolution bandwidth. The bandwidth terms for bandwidth-rated masks are in kHz or MHz. The time-spectral ratings are a product of time and bandwidth and so have units of Hz-sec. The DC is a decimal number less than 1 and has no units. The maximum dwell time of a DC mask has units of time, either µsec or msec.

3.1.3.4 Dependencies

The spectrum mask, applied together with the total power and power map constructs, conveys the total interference that a distant transmitter may cause. Typically, the total power term tries to capture the total allowed interference as a power and the underlay mask captures the distribution of power as a function of frequency. The power map captures other factors that affect the power received, including antenna gain and insertion losses. There is no requirement to adhere to this modeling approach, but it is the most intuitive.

The main role of the underlay mask is to identify the spectral and small-scale temporal limits to interference. The mask directly interacts with the spectrum masks of interfering signals. Determining whether a transmitted signal interferes with a receiver requires use of multiple constructs to perform a link budget assessment. The interaction between an underlay mask and a spectrum mask provides a power margin that is part of a link budget computation.

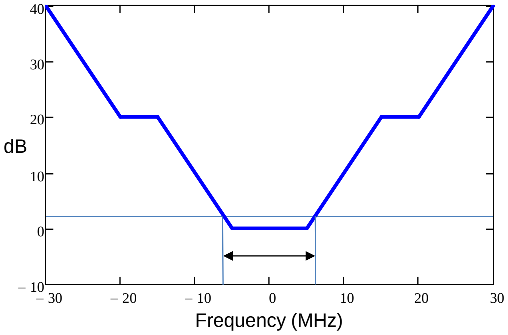
Modelers can use two methods to compute the margin: the total power method and the maximum power spectrum density method. The modeler of the underlay mask specifies the method that should be used. This section begins with descriptions and examples of the computations made in the two approaches, explaining the difference in the use of relative and location based underlay masks. It then describes and provides examples of determining power margin when using rated underlay masks.

3.1.3.4.1 Total Power Method of Computing Power Margin

In the total power approach, the modeler uses the shape of the mask to convey the attenuation that the receiver filter performs on arriving signals and uses the power levels of the mask to convey the total amount of power of the allowed interference. The following text box and the illustration give an example of the scaling of an underlay mask for total allowed interference power. We then describe the use of the mask to convey attenuation and provide an example of using the total power method to determine the power margin between a spectrum mask and an underlay mask.

Example: Scaling an underlay mask to specify the total power of allowed interference

Given that the total power of allowed interference to the receiver illustrated in Figure 3-6 is -90 dBm, what is the proper scaling of the power term of the underlay mask if the resolution bandwidth (RBW) is 10 kHz, the total power is modeled as –90 dBm, and the power map captures antenna gain and insertion loss?



(-30, 40, -20, 20, -15, 20, -5, 0, 5, 0, 15, 20, 20, 20, 30, 40) frequency terms have units of MHz

Figure 3-6. Underlay Mask that Requires Scaling for Spectral Density

Since the total power of allowed interference is captured in the total power construct, the underlay mask must predict a total adjustment to the interference of 0 dB. By convention, we consider the power within the 3 dB bandwidth which extends from -6.5 to 6.5 MHz in this example. The adjustment in the power terms of this mask includes an adjustment for the total power within the 3 dB bandwidth of the underlay mask. The total power in the 3 dB bandwidth is determined by integration. All segments of underlay masks are linear. Given two consecutive inflection points, (f_1, p_1) and (f_2, p_2), $f_1 < f_2$, the equation for the line is $p = b_0 + b_1 f$ where

Example (cont.): Scaling an underlay mask to specify the total power of allowed interference

$b_1 = \frac{p_2 - p_1}{f_2 - f_1}$ and $b_0 = p_1 - b_1 f_1$. The total power under the segment is determined in the linear scale and so within the segment between f_a and f_b, $f_1 \le f_a < f_b \le f_2$, is $p = \int_{f_a}^{f_b} \frac{10^{\frac{b_0 + b_1 f}{10}}}{RBW} df$. For segments where $b_1 \ne 0$ and $f_a < f_b$, $p = \frac{10}{RBW \cdot \ln(10) \cdot b_1} \cdot 10^{\frac{b_0 + b_1 f}{10}} \Big|_{f_a}^{f_b}$, where $b_1 = 0$ and $f_a < f_b$, $p = \frac{10^{\frac{b_0}{10}}}{RBW} f \Big|_{f_a}^{f_b}$, and where $f_a = f_b$, $p = 0$. In the example, the total power in the 3 dB bandwidth in the linear scale is:

$$p = \frac{10}{RBW \cdot \ln(10) \cdot \left(-2 \cdot 10^{-6}\right)} \cdot 10^{\frac{-10 - 2 \cdot 10^{-6} \cdot f}{10}} \Bigg|_{-6.5 \cdot 10^6}^{-5 \cdot 10^6} + \frac{f}{RBW}\Bigg|_{-5 \cdot 10^6}^{5 \cdot 10^6} + \frac{10}{RBW \cdot \ln(10) \cdot \left(-2 \cdot 10^{-6}\right)} \cdot 10^{\frac{-10 + 2 \cdot 10^{-6} f}{10}} \Bigg|_{5 \cdot 10^6}^{6.5 \cdot 10^6}$$

$$p = 1.4322 \cdot 10^3$$

and in dB $p = 10\square\log\left(1.4322 \cdot 10^3\right) = 31.56 \text{ dB}$. To adjust the mask to predict a 0 dB gain over the 3 dB bandwidth, we must reduce the power of all inflection points by -31.56 dB at a 10 kHz rbw. The scaled mask is (-30, 8.44, -20, -11.56, -15, -11.56, -5, -31.56, 5, -31.56, 15, -11.56, 20, -11.56, 30, 8.44) where the frequency terms are in MHz.

In the total power method, the underlay mask specifies a filter that adjusts the spectral power density of the interfering signal. After this adjustment, integration similar to that used to scale the underlay mask power levels is used to determine the total power of the interfering signal. This integration extends across the frequencies of the underlay mask. In cases where this underlay band extends beyond the limits of the spectrum mask, the power level at the edge is assumed for the bandwidth extension. Figure 3-7 illustrates an underlay mask and the amount of attenuation it would add to the spectrum masks of interfering signals. No attenuation occurs from 395 to 405 MHz, 10 dB of attenuation occurs at 410 MHz, and 20 dB of attenuation occurs at 420 MHz. The power margin is then the amount of power by which the reshaped interfering signal must be attenuated to meet the total allowed interference specified in the 3 dB bandwidth of the underlay mask. The allowed interference of the underlay mask is also determined using integration.

Before computing the power margin between the underlay and spectrum mask, the two masks should scale by the same resolution bandwidth. In cases where they do not, a mask is readily converted to a different resolution bandwidth by adjusting the power spectral density levels of the mask as follows

$$PSD_{new} = PSD_{old} + 10\log\left(\frac{RBW_{new}}{RBW_{starting}}\right).$$

where *PSD* means power spectral density and *RBW* means resolution bandwidth.

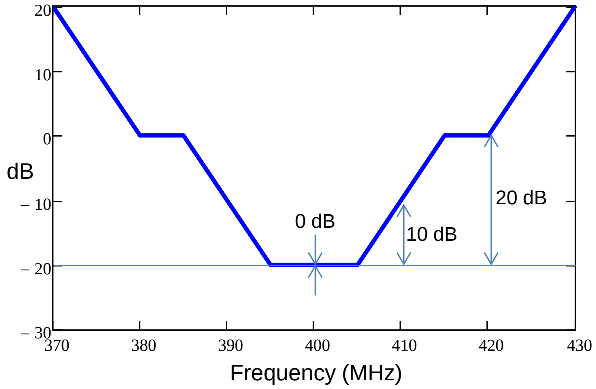
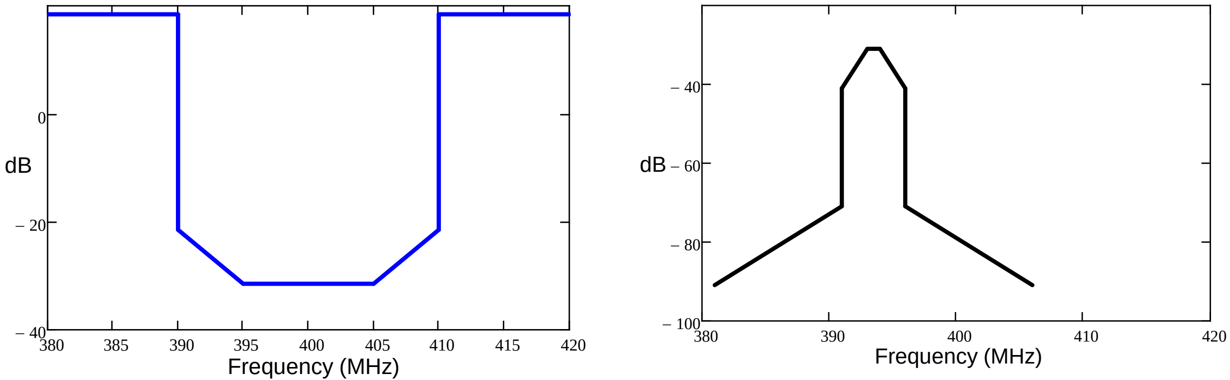


Figure 3-7. Attenuation Indicated by an Underlay Mask

The following text box shows an example of using the total power method to determine the power margin. This example demonstrates the underlay mask shaping the interfering signal spectrum mask and then the total power computations that follow.

Example: Determine the power margin using the total power method

Given the underlay mask in Figure 3-8a and the spectrum mask in Figure 3-8b, determine the power margin for the link budget computation of their compatibility using the total power method.



(380, 18.44, 390,18.44, 390, -21.56, 395, -31.56,
405, -31.56, 410, -21.56, 410, 18.44, 420, 18.44)

a. Underlay mask of the receiver,10 kHz RBW

(381, -91, 391, -71, 391, -41, 393, -31
394, -31, 396, -41, 396, -71, 406, -91)

b. Interfering transmitter spectrum mask, 1 kHz RBW

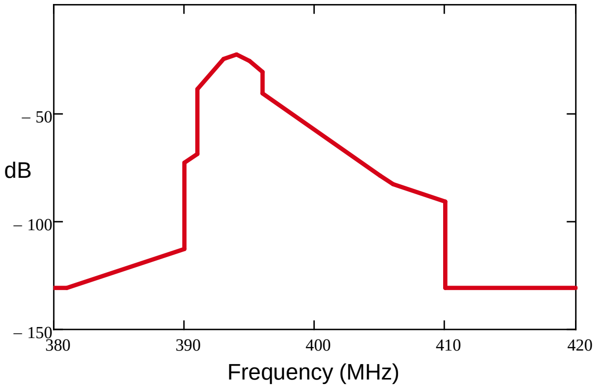
Figure 3-8. Underlay Mask of a Receiver and the Spectrum Masks of an Interfering Transmitter

The first step in solving this problem is to adjust the scale of underlay mask and the spectrum mask to the same resolution bandwidth. We choose to raise the spectrum mask to the resolution bandwidth of the underlay masks which is achieved by adding 10 dB to all power terms.

The second step is to reshape the spectrum mask by the attenuation of the underlay mask. The new mask will extend for the full bandwidth of the underlay mask. Figure 3-9 illustrates the shaped spectrum masks of this example. Each inflection point in this new mask matches one of the inflection points in either the underlay mask or the spectrum mask of this example.

Example (cont.): Determine the power margin using the total power method

Here are two of the examples of determining the power of an inflection point. First, consider the first inflection point of the underlay mask that occurs at 380 MHz. The attenuation conveyed by the underlay mask is 50 dB. Since this frequency is below the lowest frequency of the spectrum mask we assume that the power level is the same as the closest inflection point of the spectrum masks: –81 dB. The inflection point with adjusted power is 380 MHz, –131 dB. Consider the inflection point in the spectrum mask at 393 MHz. The underlay mask indicates an attenuation of 4 dB at this point and so the power level of the adjusted mask is 25 dB.



(380, -131, 381, -131, 390, -113, 390, -73, 391, -69, 391, -39, 393, -25, 394, -23, 395, -26, 396, -31, 396, -61, 405, -79, 406, -83, 410, -91, 410, -131, 420, -131)

Figure 3-9. The Shaped Spectrum Mask

The third step is to determine the total power within the shaped mask using integration. As demonstrated previously, there is a closed-form solution to compute the power in the portion of the mask between any two adjacent inflection points. These powers are computed on a linear scale. There are three possibilities. In the case where the powers are the same, such as between the first two inflection points of this example, (380, –131) and (381, –131), the total power in the portion of the mask is the power level of the points times the bandwidth of the portion.

$$p = 10^{\frac{-131}{10}} \cdot \left. \frac{f}{RBW} \right|_{380 \cdot 10^6}^{381 \cdot 10^6} = 10^{-13.1} \cdot \frac{10^6}{10^4} = 10^{-11.1} = 1.259 \cdot 10^{-11}$$

In the case were the inflection points have different power levels and frequencies, such as between the second and third points of the shaped mask, (381, –131) and (390, –113), the power is computed using the following equation where b_0 and b_1 are the intercept and slope of the line between the points.

$$p = \frac{10}{RBW \cdot \ln(10) \cdot b_1} \cdot 10^{\frac{b_0 + b_1 f}{10}} \Bigg|_{f_a}^{f_b} = \frac{10}{10^4 \cdot \ln(10) \cdot \left(2 \cdot 10^{-6}\right)} \cdot 10^{\frac{-893 + 2 \cdot 10^{-6} \cdot f}{10}} \Bigg|_{381 \cdot 10^6}^{390 \cdot 10^6} = 1.071 \cdot 10^{-9}$$

The third case is when the two points have the same frequency, such as between the third and fourth inflection points, (390, –113) and (390, –73). There is no bandwidth and so no power.

Integrating across the entire shaped mask (i.e. adding the powers of each segment of the masks using these three rules) results in a total power of 1.101, which is 0.418 dB.

Example (cont.): Determine the power margin using the total power method

The fourth step is to determine the interference that the underlay masks permits. By convention, it is the power within the 3dB bandwidth. The 3 dB bandwidth of the underlay mask of Figure 3-8a is the same as that of Figure 3-6, and so we know by design it indicates an allowed interference of 0 dB.

The fifth step is to determine the power margin which is the amount of power the spectrum mask must be adjusted to exactly match the power of allowed interference indicated by the 3 dB bandwidth power. In this case, the power margin is –0.418 dB.

3.1.3.4.2 Maximum Power Spectral Density Method of Computing Power Margin

In the maximum power spectral density method, an interfering signal is compatible with an underlay mask if its power levels are beneath those of the spectrum mask. Figure 3-10 illustrates several instances of acceptable interfering signals as determined by an underlay mask. Before making this assessment modelers must convert both the underlay mask and the interfering signal's spectrum mask to the same resolution bandwidth. The power margin is the power adjustment that must be made to the spectrum mask to make it just touch the underlay mask. If a spectrum mask and an underlay mask occupy any portion of the same spectrum, then after adjustment they will meet at one of their inflection points. This observation allows us to limit the computation for determining power margin to the inflection points. The power margin is the minimum adjustment across the overlapping inflection points that causes the two masks to meet.

Most models will likely use the total power method. The maximum power spectral density method is used when multiple interferers do not coordinate their interference with each other to ensure that they collectively stay within the limits of allowed interference. So long as each stays within the limits of the underlay mask their collective interference will also not harm the system of the underlay mask. This method, however, results in a more conservative constraint on interference from individual interferers as compared to the total power method.

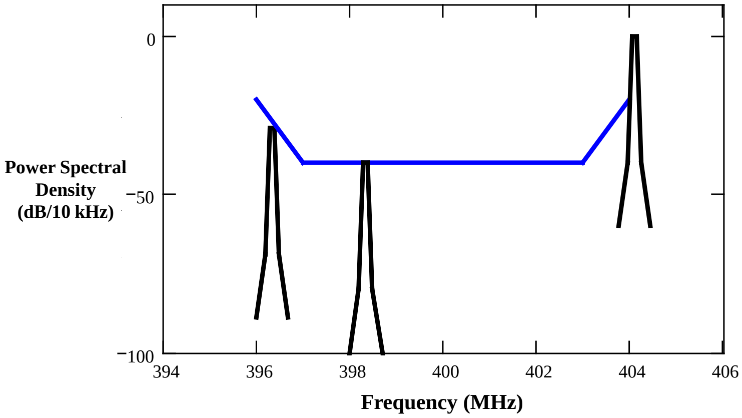


Figure 3-10. Compatible Interfering Signals Using the Maximum Power Spectral Density Method

Example: Determine the power margin using the maximum power spectral density method

What is the power margin for the scenario illustrated in Figure 3-8 using the maximum power spectral density method?

In this case the power margin is the power to adjust the spectrum mask to just meet the underlay mask. The first task is to convert the masks to the same resolution bandwidth. In our case we convert the spectrum mask by adding 10 dB to all the power terms. The new mask is (381, -81, 391, -61, 391, -31, 393, -21, 394, -21, 396, -31, 396, -61, 406, -81). Figure 3-11 illustrates the pair of mask, both with the same resolution bandwidth, and demonstrates how they overlap initially and then that a -8.56 dB adjustment to the spectrum mask makes them just touch. This adjustment of -8.56 dB is the power margin.

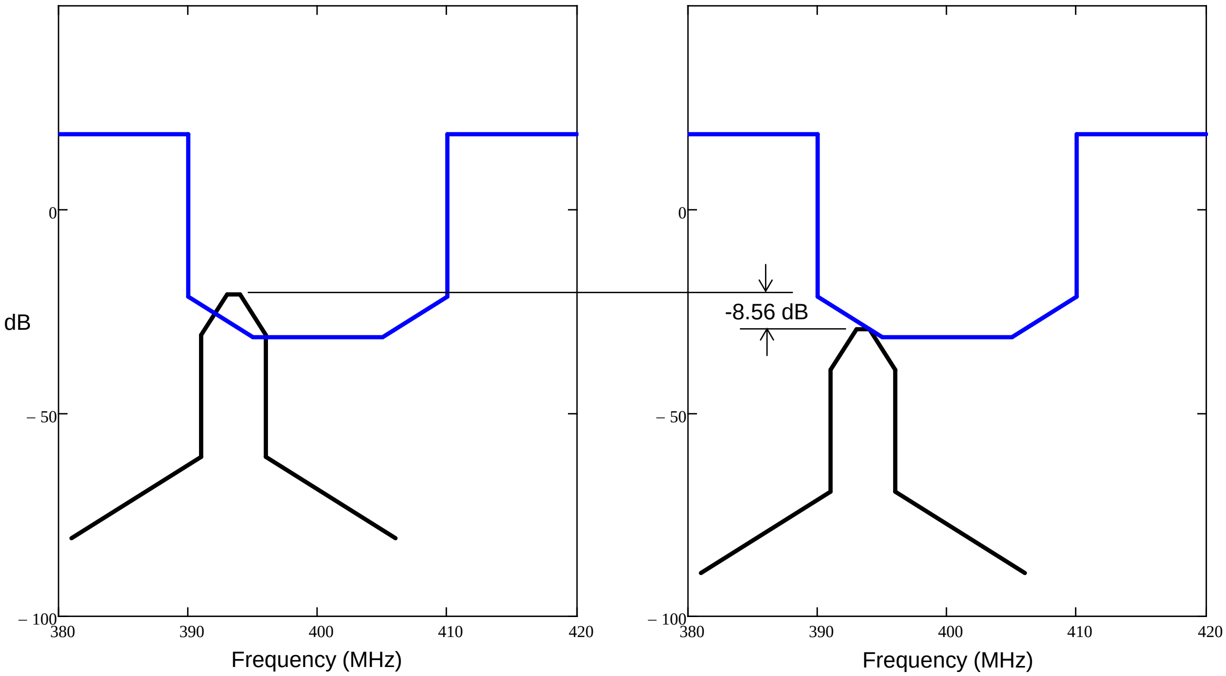


Figure 3-11. Example of Determining the Power Margin Using the Maximum Power Spectral Density Method

3.1.3.4.3 Relative versus Location-Based Underlay Masks

The reference powers for underlay masks differ between masks that are relative to transmitter models and those that apply to a location. When the underlay mask is relative to a transmitter model, the reference power is the total power at a location after considering attenuation from propagation. When the underlay mask applies to a location the reference power is the same everywhere and is not affected by the transmitter model. The former is used when the underlay mask is part of a transmitter model and the latter is used when the underlay mask is part of a receiver model. When the mask is part of a transmitter model, the reference power is determined using total power and the accompanying power map and propagation map of the model. Section 4.1 describes these computations.

3.1.3.4.4 Evaluating the Compatibility of Multiple Interferers Using Total Power

Power margin computations allow analysts and management systems to determine the contribution of the masks' portions of models to larger link budget computations of compatibility between models. These computations can be done at any time leading up to the final determination. In cases where interference involves multiple signals arriving at a receiver, there is no single power margin. Rather, assessments must consider whether the collection of arriving signals is compatible or not. In these computations, the analysis first considers the effects of the other constructs to determine the reference powers for the masks at the point of interest. The computations using the masks occur at the end and determine whether the combination of signals exceed the total interference thresholds.

Example: Determine compatibility with multiple interferers in the case of an underlay mask specified for total power computations

Figure 3-12 illustrates an interference scenario with multiple narrowband interfering signals. The underlay mask is (396, -90, 397, -110, 403, -110, 404, -90) where frequencies are in MHz, the resolution bandwidth is 10 kHz and the powers are the power spectral flux density in $\frac{\text{dBm}}{\text{Hz}\cdot\text{m}^2}$ at the location where the interference is being evaluated. Table 3-2 lists the particular details of the interfering signals.

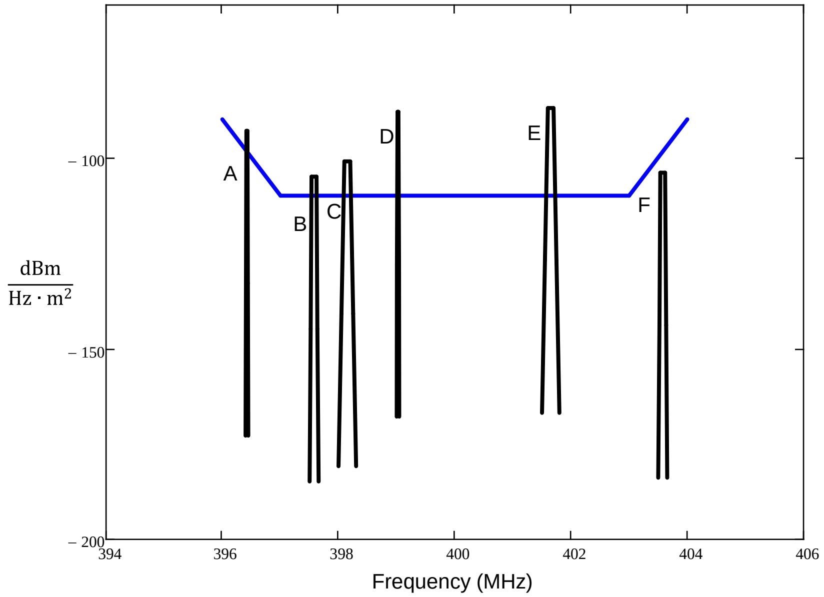


Figure 3-12. Receiver Underlay Mask and Multiple Interfering Transmitter Spectrum Masks

Table 3-2. Scenario Spectrum Masks

(Frequencies are in MHz, power terms are in $\frac{\text{dBm}}{\text{Hz}\cdot\text{m}^2}$, resolution bandwidth is 10 kHz)

Signal	Mask	Signal	Mask
A	(396.4, -173, 396.405, -133, 396.415, -93, 396.430, -93, 396.440, -133, 396.445, -173)	D	(399,-168, 399.005, -128, 399.015, -88. 399.030, -88, 398.04, -128, 398.045, -168)
B	(397.5, -185, 397.52, -145, 397.535, -105, 397.620, -105, 397.75, -145, 397.8, -185)	E	(401.50, -167, 401.55, -127, 401.60, -87, 401.70, -87, 401.75, -127, 401.8, -167)
C	(398, -181, 398.05, -141, 198.1, -101, 398.2, -101, 398.25, -141, 398.3, -181)	F	(403.5, -184, 403.52, -144, 403.535, -104, 403.62, -104, 403.635, -144, 403.655, -184)

Example (cont.): Determine compatibility with multiple interferers in the case of an underlay mask specified for total power computations

The determination begins with computing the interference threshold conveyed by the underlay mask and then computing the interference caused by each of the signals. In the final step, we find the combinations that interfere at a level below that threshold. The total allowed interference $6.432 \cdot 10^{-9} \frac{\text{mW}}{\text{m}^2}$. Table 3-3 lists the interference caused by each of the interfering signals.

Table 3-3. Effective Interference Power of Each Signal

Signal	$\frac{\text{mW}}{\text{m}^2}$	$\frac{\text{dBm}}{\text{m}^2}$	Signal	$\frac{\text{mW}}{\text{m}^2}$	$\frac{\text{dBm}}{\text{m}^2}$
A	$3.259 \cdot 10^{-10}$	–94.87	D	$2.721 \cdot 10^{-9}$	–85.652
B	$3.186 \cdot 10^{-10}$	–94.968	E	$2.212 \cdot 10^{-8}$	–76.552
C	$8.806 \cdot 10^{-10}$	–90.952	F	$2.476 \cdot 10^{-11}$	–106.062

Only Signal E exceeds the power limits of the underlay mask. All the other signals and all combinations of the other signals (i.e. all combinations of the sums of their powers) are within the power limit specified by the underlay mask.

3.1.3.4.5 Using Bandwidth-Rated Masks

The bandwidth-rated masks exist to provide a similar approach to accommodating higher power spectral densities when there are narrowband interfering signals for masks that use the maximum power density method of power margin computation. 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.[6] Figure 2-13 illustrates an example of this bandwidth determination for a pair of signals.

When computing the compatibility of multiple narrowband signals, any signal beneath the full bandwidth underlay mask may be ignored. The effective bandwidth of multiple signals is the sum of their bandwidths. The effective maximum power spectral density, EPSD, is a normalized

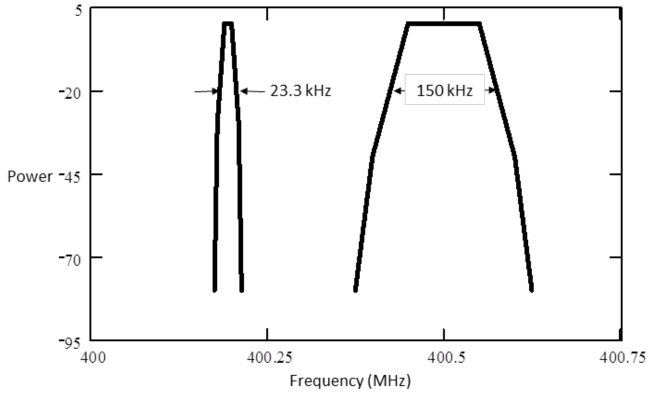


Figure 3-13. Example Measurements of Narrowband Signal Bandwidth

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

power spectral density of the collection of signals determined by the following equation:

$$EPSD = 10 \cdot \log_{10}\left(\frac{\sum_x \left(BW_x \cdot 10^{\frac{\max PSD_x}{10}}\right)}{\sum_x BW_x}\right).$$

If both the effective bandwidth (i.e., the sum of the bandwidths) and the effective power spectral density (EPSD) are 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 masks should be adjusted to the bandwidth of the next highest bandwidth underlay and a bandwidth-adjusted EPSD (BAEPSD) is computed for use with this underlay mask to spread the power density to that of the bandwidth of the underlay mask.

$$BAEPSD = 10 \cdot \log_{10}\left(10^{\frac{EPSD}{10}} \cdot \frac{\sum_x BW_x}{BW_{mask}}\right) \quad BW_{mask} > \sum_x BW_x$$

A use is acceptable if the BAEPSD 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.

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

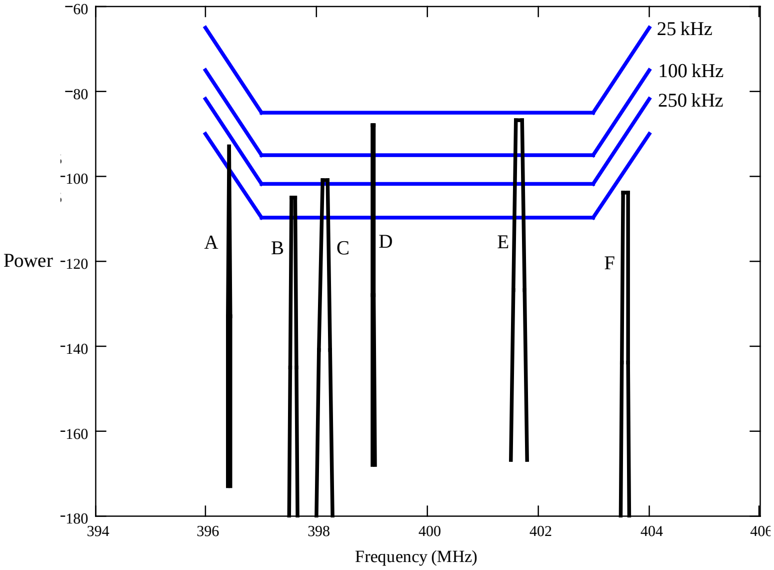


Figure 3-14. Dynamic Spectrum Management Scenario

Figure 3-14 illustrates the same scenario as Figure 3-12 but with bandwidth-rated masks that use the maximum power density method to determine power margin. Table 3-4 lists the maximum power spectral density and bandwidth of the interfering signals.

Example (cont.): Determining effective PSD and effective bandwidth of combinations of narrowband signals and checking for compatibility with narrowband underlay masks

Table 3-4. Underlay Mask Scenario Signal Characteristics

Signal	Bandwidth	Max PSD per 10 kHz	Signal	Bandwidth	Max PSD per 10 kHz
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 comply 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. Thus, 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 3-5 lists the effective bandwidth and effective PSD of combinations of the signals A, B, C, and D; for those combinations that are compliant, it identifies the bandwidth mask with which the compliance check was made.

Table 3-5. Assessment of Underlay Mask Compliance of Narrowband Signal Combinations

Signals	Effective Bandwidth	Effective PSD	Mask Bandwidth	Bandwidth Adjusted Effective PSD	Mask PSD 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 rest have BAEPSDs that exceed the criterion of the mask.

Using multiple bandwidth-specific underlay masks enables modelers to compute differences in allowed interference based on the bandwidths of signals – a method that simplifies compatibility computations. At present, no theory exists that would form the basis for creating these underlay masks and creating such a theory would likely require experiments with the modeled equipment.

3.1.3.4.6 Evaluating the Compatibility of Low Duty Cycle Signals

Modelers may use either the DC-rated underlay masks or the BTP-rated underlay masks to capture a greater tolerance to the power of interfering signals when they occur briefly and have narrow bandwidth. The DC-rated masks use the total power method of determining power margin and the BTP masks use the maximum power density method. Compatibility computations in these cases start by verifying that the combination of interfering signals meets the DC and maximum dwell time limits of DC-rated underlay masks or the BTP rating of BTP - rated underlay masks. If so, the next step is to assess whether the power levels of the signals meet the power thresholds specified by the underlay mask.

Frequency-hop-rated spectrum masks of interfering systems provide the characteristics of signals that allow modelers to compute the DC and determine whether the maximum dwell time constraint is met. The DC is the average fraction of time that a signal is present within the bandwidth of the underlay mask. The dwell time comes directly from the spectrum mask. When multiple frequency- and time-hopping signals arrive at a receiver we assume that they do not overlap in time, and so the effective DC is the sum of their DCs and the effective dwell time is the sum of their dwell times. Since frequency hopping is generally random, the assessment of the total power of interference uses the signal with least attenuation from the underlay mask as the representative signal to determine the power of the interference.

Example: Determining which duty cycle rated masks to use and the power level of interference to the receiver

This example scenario considers the interference of two frequency hopping systems with the following spectrum masks on a third system with the underlay masks described below and illustrated in Figure 3-15a. Frequencies are in MHz.

System 1

Spectrum mask: (-0.0125, -20, -0.0075, 0, 0.00750, 0, 0.0125, -20)
Frequency list: (790.0125, 790.0375, 790.0525, … , 794.9875) (i.e. signals spaced every 25 kHz starting at 790.0125 MHz and ending at 794.9875 MHz)
Resolution bandwidth: 10 kHz
Dwell time: 10 μsec
Revisit time: 5 msec
Reference power spectral flux density: -52 $\frac{\text{dBm}}{\text{Hz}\cdot\text{m}^2}$

System 2

Spectrum mask: (-0.025, -20, -0.020, 0, 0.020, 0, 0.025, -20)
Frequency band list: (790.0,797.5, 800.0, 805.5, 810.0, 815.0)
Resolution bandwidth: 10 kHz
Dwell time: 25 μsec
Revisit time: 1.0 msec
Reference power spectral flux density: -75 $\frac{\text{dBm}}{\text{Hz}\cdot\text{m}^2}$

The receiver underlay mask is (-785, -58, 792, -58, 793, -98, 797, -98, 798, -58, 805, -58) where frequencies are in MHz and power terms are in $\frac{\text{dBm}}{\text{Hz}\cdot\text{m}^2}$ with the following duty cycle ratings (0.05, 50 μsec, 18, 0.02, 20 μsec, 43). Figure 3-15a illustrates these underlay masks.

The first step in determining compatibility is to determine if the duty cycle and dwell time criteria are met. System 1 meets the dwell time criteria of both duty cycle rated masks and System 2 meets the dwell time criteria of the 5% duty cycle rated mask only. The combination of System 1 and System 2 is also within the 5% dwell time criteria.

Example (Cont.): Determining which duty cycle rated masks to use and the power level of interference to the receiver

The duty cycle of a system with respect to a receiver is a function of its dwell and revisit time and then the fraction of the transmissions that are within the spectrum of the underlay mask. In the case of System 1, all of individual signals are within the frequency band of the underlay mask and so all contribute to the duty cycle.

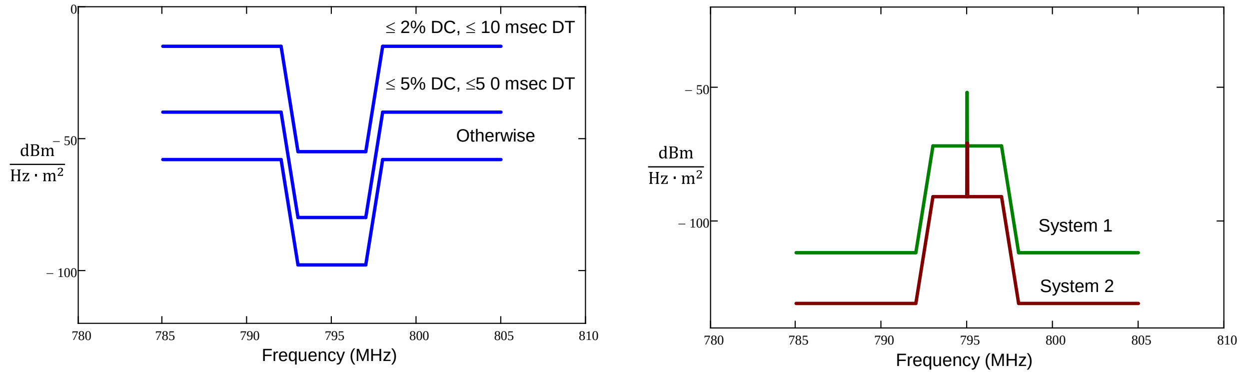
$$DC = \frac{10\ \mu\text{sec}}{5\ \text{msec}} = 0.002 = 0.2\%$$

In the case of System 2, only a fraction of the transmissions are present and so the duty cycle is reduced by that fraction.

$$DC = \frac{25\ \mu\text{sec}}{1\ \text{msec}} \cdot \frac{7.5+5.5}{7.5+5.5+5} = 0.0181 = 1.81\%$$

The duty cycles of both systems meet the criteria of all masks and the combination at 2.01% is compliant with only the 5% duty cycle rated mask.

The power margin computation for the frequency hopped signals considers the signal of the collection of the hopped signals with the worst interference. The worst interference is usually from the signal with a center frequency closest to the center. In this example, it is the signal that occurs at 794.9875 MHz in System 1 and the signal that occurs 795 MHz in System 2. Figure 3-15b illustrates the shaped signals for these two cases. Note that graphically in frequency the underlay mask dominates the shape but the small peak signal contains most of the power. The effective power in the System 1 signal is $3.728\cdot10^{-5}\frac{\text{mW}}{\text{m}^2}$ or $-44.285\frac{\text{dBm}}{\text{m}^2}$ and the effective power in the System 2 signal is frequency of the underlay mask. $6.659\cdot10^{-7}\frac{\text{mW}}{\text{m}^2}$ or $-61.766\frac{\text{dBm}}{\text{m}^2}$.



a. Duty cycle rated underlay masks,10 kHz RBW

b. Shaped interfering spectrum mask, 10 kHz RBW

Figure 3-15. Example Duty Cycle-Rated Underlay Masks and Shaped Interfering Signals

The interference threshold specified by the three masks are $6.682\cdot10^{-8}\frac{\text{mW}}{\text{m}^2}$, $4.216\cdot10^{-6}\frac{\text{mW}}{\text{m}^2}$,

Example (Cont): Determining which duty cycle rated masks to use and the power level of interference to the receiver

and $1.333 \cdot 10^{-3}\,\frac{\text{mW}}{\text{m}^2}$ or $-71.751\frac{\text{dBm}}{\text{m}^2}$, $-53.754\frac{\text{dBm}}{\text{m}^2}$, and $-28.751\frac{\text{dBm}}{\text{m}^2}$ that respectively for the unrated, 5%, and 2% duty cycle rated masks. We see that the interference from System 1 is compliant with the 2% but not the 5% duty cycle rated underlay mask. We see the interference from System 2 is compliant with both rated masks. From these results for the three different criteria, we see that System 1 is compliant with the 2% rated masks but not the 5% rate mask and that System 1 is complaint with the 5% mask but not the 2% mask. Both systems can coexist with the system of the underlay mask but only one at a time.

3.1.3.4.7 Evaluating the Compatibility of Frequency-Hopped Signals

Frequency-hop rated spectrum masks of interfering systems provide the characteristics of signals that allow the computation of the BTP. 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 contained within or partially extending into that range. Then the overall BTP 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 signal's bandwidth 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 falls partially in the range then only the portion of the bandwidth 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 BTP of a collection of frequency-hop signals is the sum of their BTPs. In the case of multiple frequency-hop signals, no effective bandwidth power is computed. The BTP of a collection of frequency-hopped signals determines the mask to use. The BTP masks only use the maximum power spectral density power margin computation. When the sum of the BTPs of multiple systems complies with a particular underlay mask, then the next assessment is made to ensure the signals of each of the systems have a power density less than that specified by this underlay mask. If the signals of systems meet this power criterion, then the combination is compliant. An example computation follows.

Example: Determining compatibility of frequency-hop systems with bandwidth-time product-rated underlay masks

This example scenario considers the interference of two frequenc- hopping systems with the following spectrum masks on a third system with the underlay masks illustrated in Figure 3-4 where the reference power is 0 $\frac{\text{dBm}}{\text{Hz} \cdot \text{m}^2}$.

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)
Resolution bandwidth: 10 kHz
Dwell time: 100 μsec
Revisit time: 20 msec

Reference power spectral flux density: -97 $\frac{\text{dBm}}{\text{Hz} \cdot \text{m}^2}$

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)
Resolution bandwidth: 10 kHz
Dwell time: 200 μsec
Revisit time: 1.0 msec

Reference power spectral flux density: -94 $\frac{\text{dBm}}{\text{Hz} \cdot \text{m}^2}$

Figure 3-16 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.

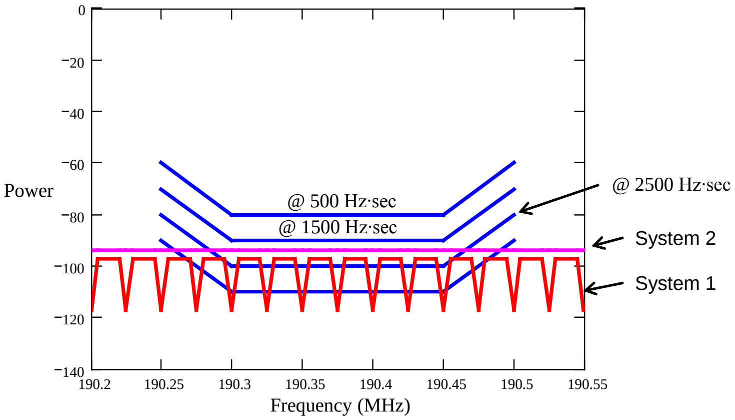


Figure 3-16. A Scenario where Multiple Frequency-Hopped Signals are Present

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

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

.

Example: Determining compatibility of frequency hop systems with bandwidth-time product rated underlay masks

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

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

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.

3.1.3.4.8 Evaluating the Compatibility with Particular Policies or Protocols

When a transmitter model identifies a particular protocol or policy that matches the protocol or policy associated with an underlay mask then that underlay mask may be used with the transmitter model in the power margin computations. Generally, the use of a protocol or policy that allows coexistence with an RF system permits the use of an underlay mask that is much less restrictive than an unrated underlay mask.

3.1.3.4.9 Selecting the Right Underlay Mask and Power Margin Computation Method

Although this discussion has emphasized using rated underlay masks, most modeling of RF systems uses a single underlay mask with no specific rating. Assessments of compatibility would require a single power margin computation that could be reused in all geographic scenarios.

Modelers use rated underlay masks to reveal greater opportunities to share spectrum. In cases where models have multiple underlay masks with some of those masks being rated, the power margin computation uses the underlay mask that provides the greatest power margin and still sets an upper bound to the signal modeled in the spectrum mask of the transmitter. As above, once a power margin is computed it can be used in all geographic scenarios involving the pair of models.

3.1.4 Power Map

The power map captures the dispersion of electromagnetic energy transmitted by antennas and the concentration of electromagnetic energy received by antennas. It specifies a relative power flux density by direction that is relative to the power that drives the antenna in transmitters and the power received by a radio at the output of the antenna at receivers. The relative power flux density is added to the total power spectral density defined by the total power and spectrum masks' constructs of transmitters to convey a total power spectral flux density by direction. The opposite occurs at receivers where signals with a total power spectral flux density arrive at the antenna from a single direction and the relative power flux density is subtracted to provide the total power spectral density that has arrived at the receiver. This constitutes the input to the assessments performed using the underlay mask. Thus the power map captures antenna gain and any insertion losses.

The power map uses a special data structure that allows the modeler to specify a relative power flux density for any particular direction. Section 3.1.4.2 describes the map data structure that enables the specification of values by direction. These values, together with the total power and the power spectral density of the spectrum mask, indicate the power spectral flux density one meter from an antenna, $RP(1\mathrm{m})$, for a far field computation of signal strength using either of the two versions of the log-distance pathloss model described in Section 3.1.5.1.

3.1.4.1 Rationale

Power maps attempt to capture the directional transmission characteristics of a system. Transmit power may vary directionally because of directional antenna effects or because of the local environment. Local obstructions can affect the directional gain. They include 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 close to the antenna). Structures can affect directional gain in several ways. They can serve as obstacles that block signals in their direction or may give the perception of higher gain in a direction because they reflect signals arriving in a direction of low antenna gain into the antenna where the gain is larger. The power map allows modelers to capture the effects of antennas and certain environmental effects if they are known.

The terms of power in the power map are a power flux density expressing the power relative to a surface area emanating from the point of transmission or reception at a one-meter distance. This term takes into account the losses that occur when the transmission first leaves the antenna because of the transition from the antenna to the ether

$$10 \cdot \log\left(\frac{c}{f \cdot \mathrm{L}}\right) \mathrm{dB},$$

where c is the speed of light, f is the frequency of the signal, and L is the loss in the media. It includes the losses associated with the distribution of power to the surface of a sphere with a one-meter radius

$$10 \cdot \log\left(\frac{1}{4\pi}\right) = -11 \ {}^{\mathrm{dB}}\!\big/_{\mathrm{m}^2}.$$

It also includes the insertion losses that occur in connecting an antenna to a radio and the relative gains of the directional antenna to the power flux density if the transmission were isotropic, i.e., no directional gain.

The power map together with total power and either a spectrum mask or an underlay mask defines a power spectral flux density. The combination of these constructs conveys the power spectral flux density at particular frequencies toward any direction from a transmitting antenna for a transmitter model or at a receiving antenna from any direction for a receiver model.

Antennas play a large role in determining the compatibility of systems. Many systems have dynamically changing antenna characteristics, including radars where antennas scan and track and smart antennas in communications systems that attempt to optimize reception of a desired signal in the presence of interfering transmitters by dynamically steering either beams or nulls. These antennas may mitigate the occurrence of interference with external systems; however, their effectiveness depends largely on the particular scenario of use and the particular behaviors of the antennas. Not all of these behaviors can be modeled in a power map. Power maps can capture the more deliberate behaviors such as scanning and tracking, but at best can assign a probability to the success of adaptation. In modeling cases where particular pairs of systems are known to be compatible based on the adaptation methods used, the protocol and policy construct is more appropriate.

The SCM captures the geospatial limit of a use of spectrum. Constraints to transmit power are defined as the effective power spectral flux density at a particular frequency at a specified distance from the antenna rather than the power driving an antenna. Transmitters with high-gain antennas must still conform to the power spectral flux density constraints. Users cannot switch to a higher gain antenna using the same driving power and assume they can remain compliant with a use approved for the previous antenna at that driving power.

3.1.4.2 Data Structure

The data structures 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 specifies 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 annuli are defined ultimately to establish parameters for all directions. The number and spacing of elevations and azimuths listed in the vector are arbitrary and used as necessary to provide resolution. The vector takes the form $\left(0°,0°,p_{0,0},\theta_{0,1},p_{0,1},\theta_{0,2},\ldots,360°,\phi_1,0°,p_{1,0},\theta_{1,1},\ldots,360°,\phi_2,0°,p_{2,0}\ldots,p_{last},360°,180°\right)$. Figure 3-17 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 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 $p_{x,y}$ 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 3-17, the model parameter $p_{1,0}$ applies from elevation ϕ_1 to ϕ_2 and from azimuth 0° to $\theta_{1,1}$.

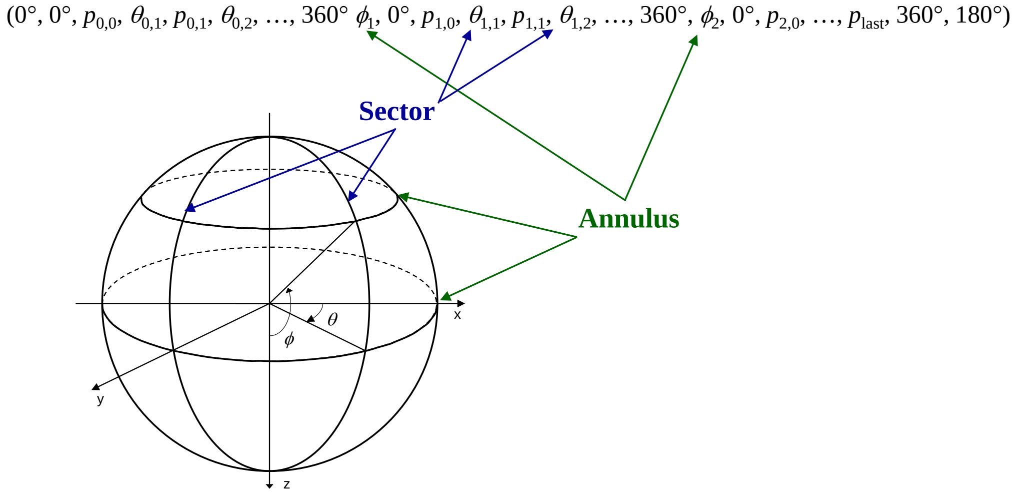


Figure 3-17. Example Map Vector Used in Propagation Map and Power Map Modeling

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 reduced vector format is the last value and therefore indicates the end of the vector. The general form of the reduced vector is $\left(p_{0,0}, \theta_{0,1}, p_{0,1}, \theta_{0,2}, \ldots, 360°, \phi_1, p_{1,0}, \theta_{1,1}, \ldots, 360°, \phi_2, p_{2,0} \ldots, p_{last}, 0°\right)$. The map vectors vary in length depending on the resolution desired. When there is just one value specified for all directions the reduced vector has only two values, $\left(p_{0,0}, 0°\right)$.

Using maps in SCMs requires that they have a reference location and an orientation to the physical environment. The default orientation of a power map is 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 approach is similar to measuring directional azimuths in land navigation. The elevations, however, are different. Typically, elevations in navigation 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 3.1.8.2. The transformations between coordinates systems are described in Appendices F and G.

Ideally a power map should 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, in specific scenarios the orientation is best referenced to that of a platform. In this case, we assume that the starting reference matches the coordinate system of the platform and then use coordinate rotations to reorient the antenna from that reference. Figure 2-18 illustrates the standard platform coordinate system, where the x axis is coincident with the normal direction of travel of a platform (e.g.,

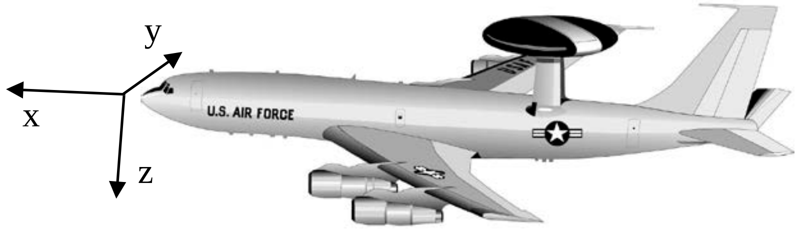


Figure 3-18. Example Platform Coordinate System

coincident to the fuselage of an aircraft), 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 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 D. An additional feature available for power map modeling is to define a point toward which the vertical axis of a power map points as it moves. This modeling approach accounts for the benefits of using directional antennas that can point to a specified stationary transmitter or receiver even while the system moves.

An additional method of modeling antennas in power maps is to use two concentric maps. One of these masks describes a directional antenna that is scanned and the second map indicates the space over which it is scanned. The map of the directional antenna places the scanned beam on the vertical axis. The map that indicates the region of scanning assigns a positive value to the scanning directions and the value 0 to other directions. The directional values of scanning region power maps are Boolean. These maps are surface or platform oriented. The vertical axis, the positive z direction of the directional antenna power map, moves through the directions of the scanning region power maps indicated by the unit values. The x axis of the directional antenna model remains parallel to the x-y plane of the scanning region map. In most cases, the effects of scanning in transmission are captured in the pulsing characteristics of the spectrum masks. This articulation of scanning is most relevant in receiver modeling to indicate the spatial extent of higher gain that should be considered in assessing the total power of interference from external systems. The goal is to reveal that the high gain at any point in time is confined to the limits of the beam as opposed to the entire region over which the beam is scanned.

Probability is an optional element of a power map. When this element is used, a model will have more than one power map. Probability is used primarily to indicate the likelihood of one power map over another, and is mostly used with directional and smart antennas. In the case of directional antennas it would indicate the probability of one pointing direction over another. In the case of smart antennas, it may be used to indicate the probability that the antenna systems would point a null or low power lobe toward a distant receiver as opposed to a main beam. The probability may be either cumulative or alternative, but it must be consistent among the power maps and indicate a 100% condition or else the assessment algorithms will scale probabilities to that level.

3.1.4.3 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 total power or total power spectral density and have units of dB/m^2. The directional values in scanning region maps have no units. The angles in the 3-tuple $<\alpha, \beta, \gamma>$ all have units of degrees in decimal format. The point location used in this model is described in Section 3.1.8.1.1.

3.1.4.4 Dependencies

Determining the power flux density in a direction involves a simple lookup in the power map. The example below demonstrates a possible search algorithm.

Example: Determining the power flux density 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 pseudocode 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
    $i = i+2$
$\theta \mathrm{s} = \phi s + 2$
while $\theta s < \phi e$
    if $P_{\theta s} > \theta$, return $P_{\theta s-1}$
    else $\theta \mathrm{s} = \theta \mathrm{s} + 2$
return $P_{\theta s-3}$
```

Example: Find the pathloss exponent in the direction θ = 38°, ϕ = 95°, given the propagation map (-30, 360, 85, -50, 30, -30, 270, -40, 360, 110, -30, 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 -30.

The determination of the transmit power spectral flux density by direction uses the total power, the power map, and either the spectrum mask or underlay mask. The following example demonstrates searching for a value in a map for a specified direction and computing the power spectral flux density in that direction.

Example: Determining the power spectral flux density from a transmitter

Given a total power, 10 dBw, a spectrum mask (400,–60,401,–40,402,–40,403,–60) with a 10 kHz resolution bandwidth, and a power map (–35,360,70,–20,360,110,–35,0) determine the power spectral flux density specified by the model at an azimuth of θ = 100° and an elevation of

Example (cont): Determining the power spectral flux density from a transmitter

ϕ = 10° at the center frequency of the signal.

The one-meter power spectral density at the transmitter is $\frac{-30 \text{ dBW}}{10 \text{ kHz}}$. This power is the sum of the total power of the model and the maximum gain of the spectrum mask, 10 dBW + $\left(\frac{-40 \text{ dBW}}{10 \text{ kHz}}\right)$. The power map specifies $-20 \ {}^{\text{dB}}\!/_{\text{m}^2}$ at the specified azimuth and elevation and so the power spectral flux density is $-50 \ {}^{\text{dBW}}\!/_{(10 \text{ kHz})\text{m}^2}$. This value can now be converted to a 1 kHz resolution bandwidth.

$$PSD_{new} = PSD_{old} + 10\log\left(\frac{RBW_{new}}{RBW_{starting}}\right)$$

$$-50 + 10 \cdot \log\left(\frac{1}{10}\right) = -60 \ {}^{\text{dBW}}\!/_{\text{kHz} \cdot \text{m}^2}$$

Determining the power of a steered antenna requires determination of the azimuth and elevation that apply to the direction of interest. Appendix D describes the use of rotation matrices and Section D.2 provides examples of converting between platform power map directions and Earth surface directions. Once a power map direction is known, the same lookup algorithm described above applies to determining the gain in the direction of interest.

The scanned region version of the power map identifies where a narrow beamwidth antenna may point. This is modeled to allow determination of the interference that the narrow beamwidth antenna may experience. The following is an example that demonstrates how to model this type of scanning and how to scale power maps for frequency and power spreading.

Example: Create a power map for a scanned antenna

Model a radar with a highly direction antenna with a 2.5º beamwidth that scans across an azimuth extending from 33º to 135º and from the horizon to an elevation 30º above the horizon. The directional antenna has a gain of 25 dBi on the main lobe and a worst case sideslobe gain of –1.5 dBi. The radar operates at a frequency of 3.5 GHz and has a 2 dB insertion loss.

The scanning region map follows directly from the problem statement. The value 1 is assigned to the directions that are scanned and the value 0 to all other directions. The power map for the scanning region is (0, 360, 90, 0, 33, 1, 135, 0, 360, 120, 0, 0).

The gains of the directional antenna are provided as dBi and so the modeling first attempts to determine what the isotropic power would be and then adjusts the power levels based on the antenna directivity. The spreading of power across a 1 meter radius sphere reduces the power to $-11 \ \frac{\text{dB}}{\text{m}^2}$. Frequency losses are $10 \cdot \log\left(\frac{c}{f}\right) = 10 \cdot \log\left(\frac{3.0 \cdot 10^8}{3.5 \cdot 10^9}\right) = -10.7 \text{ dB}$. Combining these

Example (cont): Create a power map for a scanned antenna

with the insertion loss we have an isotropic power level of $-23.7\ \frac{\text{dB}}{\text{m}^2}$. Applying the directional gain, the relative power flux density is $1.3\ \frac{\text{dB}}{\text{m}^2}$ in the mainbeam and $-25.2\ \frac{\text{dB}}{\text{m}^2}$ in all other directions. The 2.5º mainbeam on the axis is modeled as having a uniform power from its center on the vertical axis to 1.25º which results in the 2.5º beam. The power map of the directional antenna is (1.3, 360, 1.25, -25.2, 0).

3.1.5 Propagation Map

The propagation map specifies the rate of attenuation by direction. This rate is specified by either a single parameter of a linear model or by three parameters of a piecewise linear model: a pathloss exponent, a distance, and then a second pathloss exponent. Both models are variants of the log-distance pathloss model and are linear on a log of power to log of distance scale. Discussions of these models follow in the next section.

3.1.5.1 Rationale

Including a propagation model in a SCM enables modelers to account for the attenuation of RF emissions and therefore the location-based differences in the strength of a signal 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. Because of the rich diversity of environmental effects, the literature reports no shortage of propagation models, 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 must capture attenuation trends but result in tractable computations for spectrum reuse. The models chosen for this purpose are two variants of the log-distance pathloss model [7]. The received power predicted by these log-distance pathloss models decreases monotonically at a rate specified by their parameters. These are compact and allow tractable computations.

The two variants of the log-distance pathloss model are:

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

and

$$RP(d) = \begin{cases} RP(1\text{m}) - 10n_1\log(d) & d \le d_{breakpoint} \\ RP(1\text{m}) - 10n_1\log(d_{breakpoint}) - 10n_2\log\left(\dfrac{d}{d_{breakpoint}}\right) & d > d_{breakpoint} \end{cases}.$$

In these propagation models, the power spectral flux density determined using the total power, spectrum mask, and power map of a transmitter model is the one-meter pathloss, $RP(1\text{m})$. It is the power spectral flux density at one meter for a far field propagation result. The power spectral flux density at the antenna of a receiver at a distance *d* from the transmitter is $RP(d)$. The linear model has one parameter, the pathloss exponent *n*. The piecewise linear model has three parameters, n_1, $d_{breakpoint}$, and n_2.

In the linear log-distance pathloss model, a pathloss exponent of 2 corresponds to the freespace pathloss model, i.e., Friis equation. 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.

Figure 3-19 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. Assuming that the 2-ray model accurately predicts the attenuation of the signals, the range model uses the exponent that predicts the same range and the conservative model uses an exponent that exceeds that range. The conservative model will cause greater separation between users than the range model. This illustration demonstrates that attenuation has a linear trend on these scales. Where attenuation is a little more complex, a linear model can still be used to provide a bound on the effects.

The piecewise linear version of the log-distance pathloss model allows a more accurate estimate of propagation modeling, which comes at the cost of larger models and more complex computations. The piecewise linear model is very useful for terrestrial propagation modeling where sudden changes in propagation occur because of obstructions or rough terrain. Figure 3-20 illustrates a piecewise linear model fitted to the 2-ray model previously illustrated.

The use of the log-distance pathloss model is a significant feature of modeling. Typically, SM 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 requires 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 databases might be

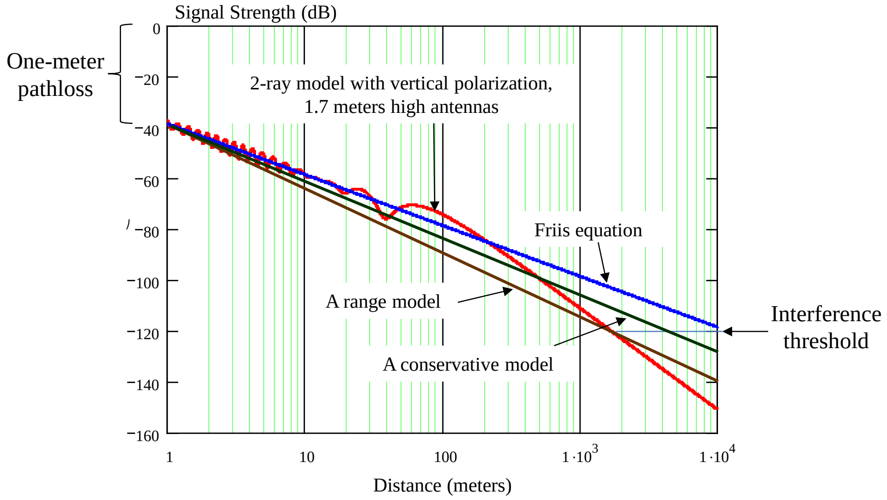


Figure 3-19. Examples of Propagation Model Predictions Graphed on a Log-Log Plot.

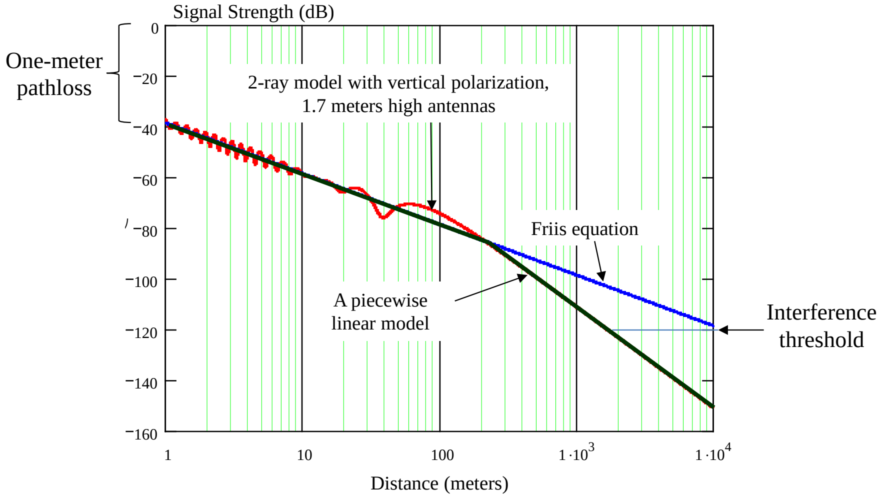


Figure 3-20. Example of a Piecewise Linear Model Fitted to a 2-Ray Model.

part of the tool sets that a modeler uses to select the appropriate log-distance pathloss model parameters for the propagation map.

Terrestrial propagation is dominated by the heights of antennas. At long ranges, the directional variations of maps are not appropriate for capturing the differences caused by antenna heights, as the elevations that correspond to the changes in antenna height that cause significant differences in pathloss are very small and may not be appropriate for all ranges. For this reason, maps modeling long range terrestrial propagation may be rated for particular antenna heights. These antenna-height rated maps only apply to propagation on the horizon. Multiple height-rated propagation maps may be part of an SCM. When multiple antenna-height-rated maps are used, and a receiver has an antenna height that straddles two maps, the pathloss is computed as the interpolation between the two values on a log scale.

The seemingly random differences in power that occur between radios in practice result largely from variation that can occur over short distance because of fast and slow fading effects. Multiple maps can be used with probability ratings to provide a bound to the pathloss by a probability. These probabilities would be cumulative and the lower probabilities would be associated with the higher pathloss versions.

3.1.5.2 Data Structure

The propagation map data structure is similar to that of the power map, but with the directional value(s) being either a single pathloss exponent of a linear pathloss model,

$$\left(n_{0,0},\theta_{0,1},n_{0,1},\theta_{0,2},\ldots,360^\circ,\phi_1,n_{1,0},\theta_{1,1},\ldots,360^\circ,\phi_2,n_{2,0}\ldots,n_{last},0^\circ\right),$$

or the 3-tuple of a pathloss exponent, distance, and pathloss exponent of a piecewise linear model,

$$\left(n1_{0,0},d_{0,0},n2_{0,0},\theta_{0,1},n1_{0,1},d_{0,1},n2_{0,1},\theta_{0,2},\ldots,360^\circ,\phi_1,n1_{1,0},d_{1,0},n2_{1,0}\ldots,n1_{last},d_{last},n2_{last},0^\circ\right).$$

Pathloss models are consistent. The propagation models for all directions are the same: either all linear or all piecewise linear.

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 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.

When maps are rated by antenna heights then the height-rating data element is used in the propagation map construct. When maps have a probability rating, the Confidence data element is used in the propagation map construct. In both cases, the SCM would have multiple maps. SCM using height-rated maps will require at least a map to capture propagation in the directions above the horizon and then several height-rated maps. The confidence-rated masks would have multiple maps or else the confidence value has no meaning. The confidence data element is a cumulative probability that must provide a model for a confidence of 1. If that element is missing, the existing models are scaled. Multiple height-rated maps for the same height can be further qualified by the confidence value.

The spaces across which mobile systems move may have varied terrain and therefore varied propagation effects. Different propagation models would apply to different regions. Spectrum consumption modeling allows division of spectrum use into multiple models. As a convenience, when other constructs remain the same, the propagation map, location, start time, and end time constructs can be grouped and associated by an index. Many such groups can appear in a single SCM, with each group differing by location, propagation map, or time of use.[7]

3.1.5.3 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. Distances are in meters. The height elevations used by the height-rated masks are in meters. The location index has no units.

3.1.5.4 Dependencies

The computation of location-specific signal strengths using the models requires the coordinated use of the propagation map, the total power, the power map, and the spectrum mask. The log-distance model is generally considered 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 possesses advantages over comparable models, including the simplicity of the model. Further, because the model provides a monotonic trend it leads to tractable computations of compatible reuse.

The following example is a continuation of the second example in Section 3.1.4.4. Here we continue to predict the range to the point where the signal strength reaches a threshold.

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[7] It is a goal of modeling to create some level of abstraction that applies over a large area. Modelers should avoid creating models of multiple spaces because it appears to provide better resolution. Such modeling can be counterproductive in an agile SM system. Modeling for multiple spaces is used when it provides a resolution that assists sharing.

Example : Determining the power spectral flux density at a distance from a transmitter

Given a total power, 10 dBW, a spectrum mask (400,-60,401,-40,402,-40,403,-60) with a 10 kHz resolution bandwidth, a propagation map (7,360,85,2.3,360,110,2,0), and a power map (-35,360,70,-20,360,110,-35,0) determine the power spectral flux density specified by the model at a point at a distance of 6500 meters at an azimuth of $\theta = 100°$ and an elevation of $\phi = 10°$ at the center frequency of the signal.

We know from the previous example in Section 3.1.4.4 that power spectral flux density at one-meter from the antenna in the specified direction is $-60\ {}^{\text{dBW}}\!/_{\text{kHz}\cdot\text{m}^2}$. The propagation map indicates that the pathloss exponent is 2.3 at the specified azimuth and elevation. The distance based power is easily determined as

$$RP(6500) = -60\ {}^{\text{dBW}}\!/_{\text{kHz}\cdot\text{m}^2} - 10\cdot 2.3\cdot\log_{10}(6500)\ \text{dB} = -147.7\ {}^{\text{dBW}}\!/_{\text{kHz}\cdot\text{m}^2}$$

Figure 3-21 illustrates a surface plot of the range of the combined power and propagation map to the threshold power of $-170\ {}^{\text{dBW}}\!/_{\text{kHz}\cdot\text{m}^2}$.

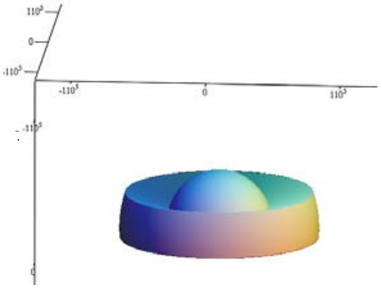


Figure 3-21. Surface Plot of the Range to a $-170\ {}^{\text{dBW}}\!/_{\text{kHz}\cdot\text{m}^2}$ Threshold

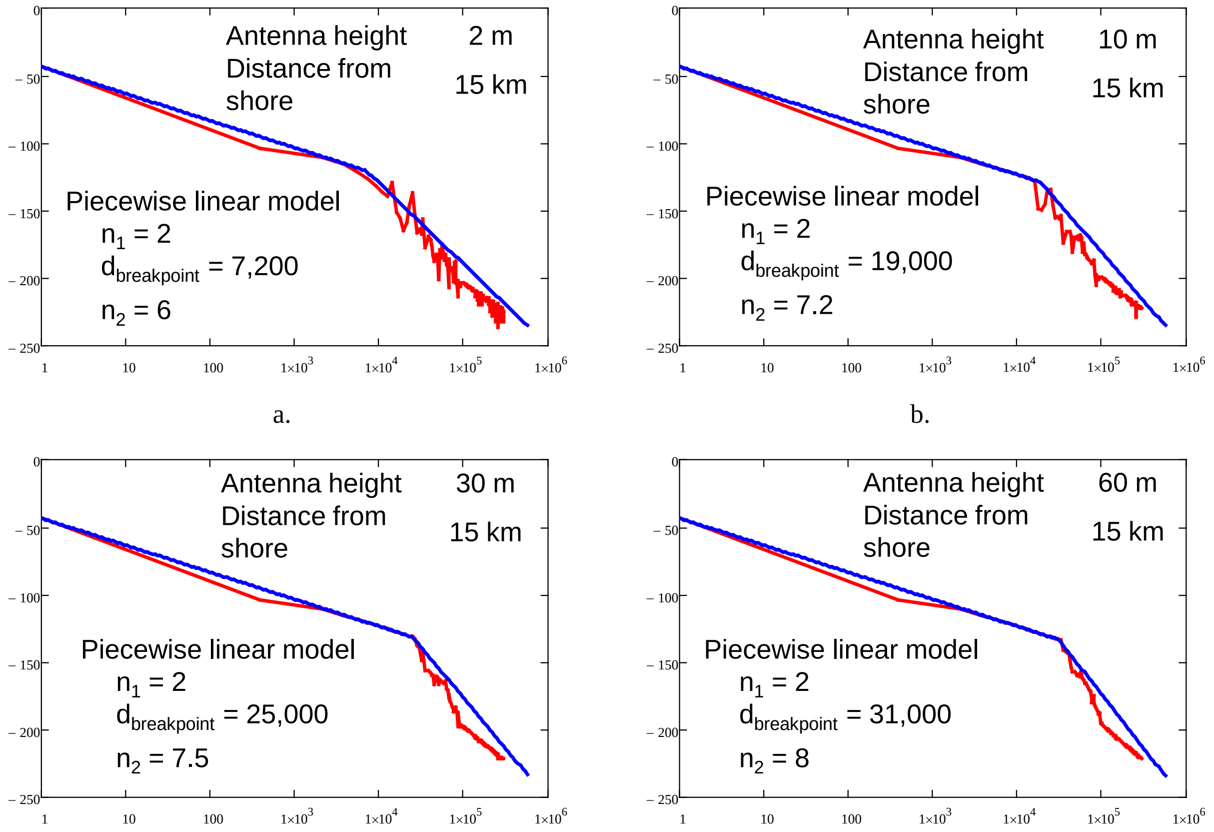
In cases of long-range transmissions it may be necessary to use multiple propagation maps to capture the large variations that can occur because of changes in antenna height. These differences are not easily captured in directional sectors of a single map. The following example demonstrates the multiple maps that might be created based on differences in the antenna heights of a sharing system. The subsequent example demonstrates how to determine the pathloss when an antenna does not match one of these heights.

Example: Creating height-rated propagation maps

Figure 3-22 illustrates four propagation scenarios in a littoral environment of a radar pointed toward shore that differ by the antenna height of the distant receiver. These illustrations show the propagation pathloss predicted by TIREM and a piecewise linear model that attempts to create a bound on the loss for each of them. Due to the high powers used by the radar, the region of the model that is most interesting occurs when the pathloss is between –150 and –200 dB. The sharing systems are at least 15 kilometers away. At that range, the difference in elevation between a 2 meter high antenna and a 10 meter high antenna is 0.031° and using the same angle

Example (cont.): Creating height rated propagation maps

as used to capture a 2-meter high antenna at 15 kilometers, the antenna height at 100 kilometers, which remains within the range of interest, would correspond to an antenna at a height of 13.3 meters. Modeling by direction alone would result in pathloss values that would deviate from the data that we have and would result in precision in elevation in the model that would be impractical to build. Further, this sort of model would be less intuitive in discussions and negotiations. It is much easier to negotiate limits to antenna height as opposed to limits in elevation. As a result, multiple height-rated models are a more effective method of modeling.



a.

b.

c.

d.

Figure 3-22. Long-range Littoral Propagation and Piecewise Linear Log-Distance Pathloss Approximations

The SCM for this spectrum use has five propagation maps, one that is unrated and four that are antenna-height rated. The unrated map is (2, 0) and rated maps are (2, 7200, 6, 0) rated for 2 meters, (2, 19000, 7.2, 0) rated at 10 meters, (2, 25000, 7.5, 0) rated at 30 meters, and (2, 31000, 8, 0) rated at 60 meters.

Example: Determining the distance-based pathloss to a receiving antenna using height-rated propagation maps

Given a one-meter pathloss of 43.4 dB and using the maps of the previous example, what is the pathloss of a 40-meter high antenna at 40 km of a 100-meter high antenna at 75 km.

For the 40-meter high antenna, we see that the antenna height lies between the 30 meter and 60 meter models. Thus the answer is the interpolation of the distance-based pathloss predicted by these two models. The equation for distance-based pathloss follows:

$$PL(d) = PL(1m) + 10n_1 \log\left(d_{breakpoint}\right) + 10n_2 \log\left(\frac{d}{d_{breakpoint}}\right)$$

Evaluating for the two models of 30-meter high antennas and 60-meter high antennas the total predicted pathlosses are 146.7 dB and 142.1 dB respectively and so the interpolated loss at 40 meters height is 143.6 dB.

In the second case of a 100-meter high antenna, the antenna height exceeds that of all the height rated maps and so we use the unrated map, which predicts a -143.4 dB pathloss.

Terrestrial environments with varied terrain and manmade structures can exhibit quite complex propagation that results in fading and shadowing effects. Modeling can accommodate the variance caused by fading and shadowing by establishing bounds on the expected pathloss. Modelers can use the power levels in the total power, spectrum mask, underlay mask, and power maps of SCM to move the one-meter pathloss of the propagation model. Power maps are usually the preferred construct for this modeling, but the modeler has the choice. Modelers may also use exponents and breakpoints of propagation maps to place a bound on the variations. Through the combinations of these constructs modelers can create multiple propagation models and assign probabilities that one or the other occurs. The following is an example.

Example: Creating probability rated propagation maps

Panel a in Figure 3-22 illustrates the pathloss in a littoral environment of a naval radar pointed toward shore to distant receivers with 2-meter high antennas. Create a model that defines a 90%, 95%, and 100% bound on power levels assuming the TIREM model is an appropriate representation of the actual pathloss.

(Modelers may capture propagation variation using the constructs that capture the one meter pathloss level or qualifying the parameters of propagation map. The purpose of this example is to demonstrate the use of the probability element in the propagation map structure and so this example uses the second technique and varies the parameter of the pathloss model.)

Figure 3-23 illustrates three models that capture these variations by simply changing the breakpoint of the model. These models seek fidelity between the -150 dB and -200 dB range. The pathloss models are (2, 8000, 7, 0), (2, 9000, 7, 0) and (2, 11000, 7, 0) and are all rated for a 2-meter high antenna and with confidence of 0.9, 0.95, and 1 respectively.

Example: Creating probability rated propagation maps

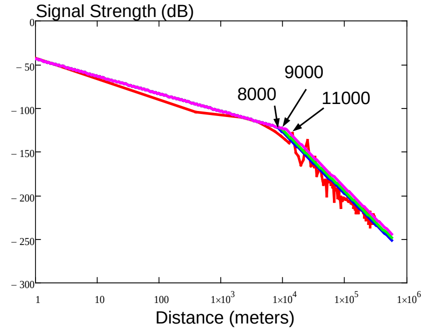


Figure 3-23. Long-Range Littoral Propagation and Piecewise Linear Log-Distance Pathloss Approximations with Confidence
(2-meter high rated antenna with 0.9, 0.95, and 1 confidence created by varying break point

3.1.6 Intermodulation (IM) Mask

Intermodulation masks convey the susceptibility of transmitters or of receivers to generating IM products from externally received signals.[8] The IM products of transmitters are transmitted and cause interference at distant receivers on channels adjacent to that of the transmitter. The IM products of receivers result in interference within the receiver. IM masks are optional construct elements of SCMs 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 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. This mask may reshape incoming signals. 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 that identifies both the frequencies of signals likely to create IM and also their likely amplification. Receiver IM may occur between externally arriving signals or between an external arriving signal and the local oscillator of superheterodyne receivers. Receiver IM masks may also shape the inputs. Analysis of receiver IM is only concerned with those IM products that would interfere with a signal the receiver tries to obtain. In addition to using separate masks for receivers and transmitters, modelers use separate sets of masks for different-order IM products when different-order IM is possible.

3.1.6.1 Rationale

IM 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 $2f_2 - f_1$.[9] The IM products of most interest are those close to the passband of the

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[8] Intermodulation distortion that occurs within a radio and its effect on the signals the radio generates should be captured in the spectrum masks of these systems. The IM masks model intermodulation involving externally generated signals.

[9] 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.

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 IM products are those of signals external to the receiver that combine with each other or with the local oscillator of superheterodyne receivers.

The output power of IM products is an attenuated product of the inputs. The relevance of this observation is that the output power spectral density is proportional to the sum of the dB power spectral densities of the combining signals. If the power of each of the input signals of a third-order IM product were to increase by 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 underlying the model is that the bandwidth is this sum unless reduced as shaped by the IM masks.

Typically, the signals that 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 generation of harmful IM. 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 facility
- Co-location of susceptible radios in the same device
- High power transmitters that are prone to generating IM in passive components

Modelers use the platform name modeling construct to identify when different systems are co-located on a platform, in a facility, or in a device. IM modeling is less concerned about mobile systems that by 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 away from each other. Spectrum managers may use SCMs to mitigate this risk. Modelers can assign risk to this occurrence by specifying a probability with a platform name.

IM products that result from the mixing of an image frequency with the local oscillator of a superheterodyne receiver are less dependent on proximity than on the filtering characteristics of the front end of the receiver as conveyed by the IM mask.

3.1.6.2 Data Structure

IM masks differ from spectrum and underlay masks in that they define a spectrum-dependent filter as opposed to a power spectrum density. IM masks have no resolution bandwidth.

IM masks are specified using a variable length vector of real values alternating between frequency and amplification power 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-numbered terms are powers. There are two types of IM masks: input IM combining (IMC) masks and IM amplification (IMA) masks. IMC masks shape incoming signals and convey how the signals combine with each other, providing an IM product power spectrum density that is a function of the input signal power spectrum densities. This value is used directly in receivers as the IM product power spectrum density at the receiver. IMA masks are used with transmitters to convey how the combined signal – the IM product– is amplified in transmission.

Each IM mask in an SCM applies to a particular order of IM. The IM mask data structure includes an entry for order. The order of IM for superheterodyne receivers and image frequencies is one, and these masks have additional data elements that describe the heterodyning, specifically the particular intermediate frequency (IF) of the filters and an indicator whether the local oscillator frequency is below or above the received frequency.

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 its own IM masks and platform names.

IM masks do not have a probability element. Modeling assumes that if powers are strong enough that IM will occur. However, with mobile devices, a probability may be assigned to the likelihood that radios will come in proximity and thus warrant an assessment of IM interference. The platform constructs allows modeling of this occurrence. A platform name identifies a point of proximity and the probability indicates the likelihood that radios of a system exist at that point.

3.1.6.3 Units

Frequency terms in the IM mask are in kHz, MHz or GHz and power terms are in dB. The dB level is applied to the sum of power spectral flux densities of the intermodulating signals. IM orders are dimensionless integers and IF frequencies are in kHz, MHz or GHz.

3.1.6.4 Dependencies

The computation of IM products depends on all of the 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 create IM products. The strengths of these signals are computed using the model constructs of the sources, including the total power, 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 total power, the power map and the attenuation that occurs in propagation according to the dominant propagation map.[10] 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 attenuated by the IMC mask, the IM products are computed, and then the product is amplified by the IMA mask. This signal is an input to the power map of the transmitter model and the distant interference is

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[10] 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 the model hat predicts the least pathloss is worst.

computed as one would compute 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 IMC 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 important result of signals mixing is that the IM products they produce have bandwidth that is the sum of the inputs. In our modeling we compute an approximation as follows. First the inputs are shaped as governed by the IM mask and then 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 IMC mask level.

The examples of the IM product computation follow the order of computational complexity. The first example describes image frequency interference that occurs in superheterodyne receivers. Here frequency mixes with a tone rather than with another broadband signal and so the interfering signals that mix do not change bandwidth. The second example is transmitter IM product generation. The third example is receiver IM where received signals intermodulate with each other. The final section describes the requirements for compatibility when the IM masks are specified.

3.1.6.4.1 Evaluating Image Frequency Interference

Computing compatibility for an IM mask of a superheterodyne receiver starts by determining the bands in which image frequencies occur. This determination uses the information in the IM mask and in the receiver's underlay mask. The combination of the intermediate frequency, f_{IF} , and injection side, high or low, in the underlay mask, and the center frequency, f_c, of the passband of the underlay (i.e., either the frequency at the point of the lowest power level of the mask or the center of the region with the lowest power) provides the frequency of the local oscillator, f_{LO}:

$$f_{LO} = \begin{cases} f_c - f_{IF} & \text{if } f_{IF} < f_c \left(\text{Low side injection}\right) \\ f_c + f_{IF} & \text{if } f_{IF} < f_c \left(\text{High side injection}\right) \\ f_{IF} - f_c & \text{if } f_{IF} > f_c \left(\text{Low side injection}\right) \\ f_c + f_{IF} & \text{if } f_{IF} > f_c \left(\text{High side injection}\right) \end{cases}$$

The intermediate frequency is usually below the center frequency. For completeness, we describe the case where it is not. The center frequency of the image is on the opposite side of the local oscillator.

$$f_{image} = \begin{cases} f_{LO} - f_{IF} & \text{if } \left(\text{Low side injection}\right) \\ f_{LO} + f_{IF} & \text{if } \left(\text{High side injection}\right) \end{cases}$$

The frequencies of interest are those within the total bandwidth of the underlay mask shifted in frequency and centered at the image frequency. The attenuation specified by the IM mask is applied to these signals before determining the level of interference they cause.

There are two approaches to computing the compatibility of signals within the band of image frequencies of a receiver. The first is to identify the band of the image frequencies and then to translate the signals present in that band to the frequencies of the underlay mask. The IM mask is applied to these image signals prior to their translations. The equations for this translation are:

$$f_{underlay} = 2 \cdot f_{LO} - f_{image}$$

This translation causes the arriving signals to be their reflection in the underlay. If this is done for each inflection point of an image signal mask, the new mask will be a reflection of the previous mask.

The second, and easier, approach is to translate the underlay mask to the image frequency and to reshape it to account for the effects of the IM mask, thus creating an image underlay mask. The following example demonstrates this process. Note that the image underlay is a reflection of the original underlay mask.

Example: Translating an underlay mask for image frequencies.

A receiver is modeled with the following underlay mask and first order IM mask. What is the underlay mask for the image frequencies? (Frequencies in both masks are in MHz.

Underlay Mask: (910, 21.59, 920, 1.59, 935, 1.59, 945, -38.41, 950, -38.41, 970, 21.59)
rbw = 10 kHz,

IM Mask: (790, -40, 800, 0, 1000, 0, 1010 - 40), $f_{IF} = 70$ MHz, low side injection

Figure 3-24 illustrates the underlay mask, the IM mask, and the resulting image frequency underlay mask for this example. The first step in the analysis is to identify the local oscillator frequency, f_{LO}. Since low side injection is used, $f_{LO} < f_c$.

$$f_{LO} = f_c - f_{IF} = 947.5 - 70 = 877.5 \text{ MHz}$$

The image frequency underlay mask is a reflection of the underlay mask across f_{LO}. The frequencies of this new mask are a function of the distance of the frequencies in the original mask from f_{LO}.

$$f_{image\_underlay} = 2 \cdot f_{LO} - f_{underlay}$$

The IM mask attenuates the power levels of the underlay where appropriate and so the image frequency underlay mask, in this example, is (785, 61.59, 790, 46.59, 800, -23.41, 805, -38.41, 810, -38.41, 820, 1.59, 835, 1.59, 845, 21.59).

Example (cont.): Translating an underlay mask for image frequencies.

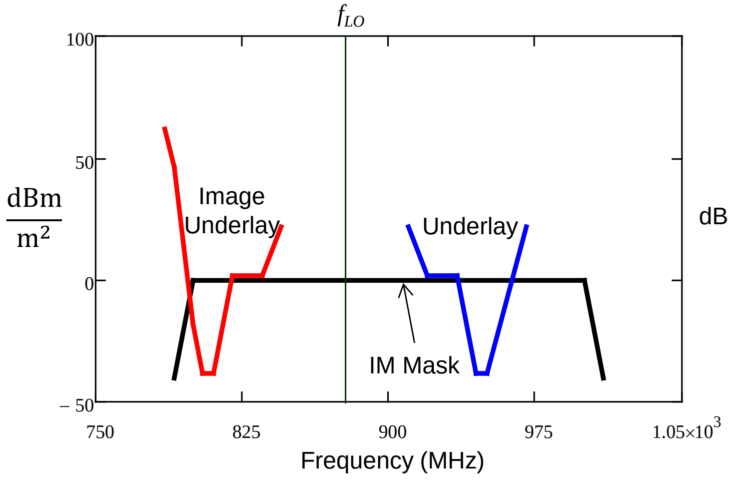


Figure 3-24. Determining an Image Frequency Underlay Mask

3.1.6.4.2 Transmitter IM

Transmitter IM consists of the IM product of the transmitted signal and other signals that arrive at the transmitter antenna. When a transmitter's signal is one of the signals combined in the IM, its amplitude is dominant. For modeling and compatibility computation purposes, the signal amplitude at the one-meter point distance just prior to propagation is its power.

An example of determining the IM products and assessing whether they cause harmful interference for a transmitter follows.

Example: Determining passive IM interference caused by a transmitter

Given a transmitter IMC mask (35, -20, 65, 0, 120, 0, 130, -20) and IMA 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. (All frequencies of masks in this example are MHz.)

The following are the characteristics of the transmitter signals.

Transmitter at the IM source
Total power: 60 dBW
Spectrum mask: (88.4, -60, 88.42, 0, 88.58, 0, 88.6, -60) with 10 kHz RBW
Propagation map: (2, 0)
Power map: (0, 0)

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

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

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 total power and the spectrum mask. The power spectrum density of the neighboring transmitter signal is determined by the separation distance and the propagation and power map effects. The distance is 10 meters, the total power is 10 dBW, the pathloss exponent is 2.1, and the power map power is 0 dB. The total power 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

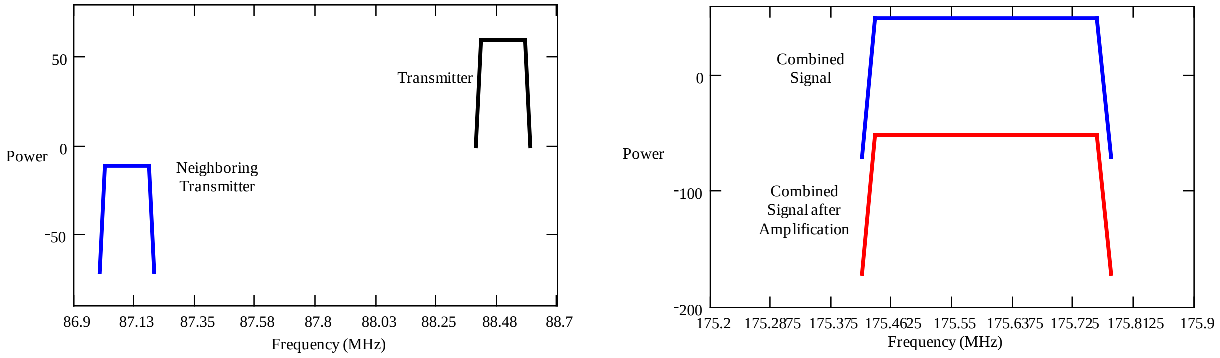
The IMC mask shapes both the transmitter signal and the signal from the adjacent transmitter. In this case the shaping has no effect on the power levels of the signals. The resulting masks of the shaped signals are:
Spectrum mask S1: (88.4, 0, 88.42, 60, 88.58, 60, 88.6, 0)
Spectrum mask S2: (87, -71, 87.02, -11, 87.18, -11, 87.2, -71)
These shaped signals are illustrated in Figure 3-25a.

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 3-25b.

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

The IMA 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 3-25b.



a. The input signal prior to intermodulation

b. The intermodulation product before and after amplification

Figure 3-25. Inputs and Outputs of the Second Order Passive IM Example

3.1.6.4.3 Receiver IM

In receiver IM, multiple arriving signals mix within a receiver and create the IM product. The following is an example of the computation used with receiver IM masks.

Example: Determining IM interference created within a receiver

Given an IMC 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.

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

Co-located Transmitter1
Total power: 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
Total power: 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 power spectral flux 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 IMC 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)
Figure 3-26 shows these shaped signals.

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). Figure 3-26 shows these combined signals.

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

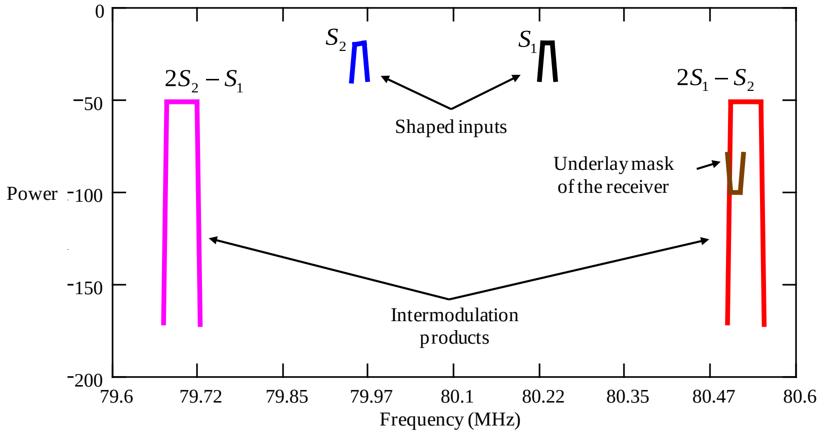


Figure 3-26. Inputs and Outputs of the Third Order Receiver IM Example

3.1.6.4.4 Rules for Applying IM Masks

Whenever IM masks are provided, they should be considered in compatibility computations. Image frequency IM is considered for all signals in the band of image frequencies. Transmitter IM is considered for all signals that fall within transmitter IMC mask and have a power level that will meet the threshold of an interesting IM product. This includes IM from all transceivers on the same platform when the transmitter IM mask is for a high-power transmitter – one that drives the antenna with a total power greater than a threshold established for the SM enterprise. Receiver IM is computed for all signals that fall within the receiver IM masks and are sent from transmitters that are on the same platform.

3.1.7 Platform Name

The platform name construct is used to identify devices, facilities, or platforms on which individual transceivers or receivers of a system are placed. It may be used to identify a particular platform, facility, or device or a particular class of platform, facility, or device. As an example, Vehicle #27 would be a particular platform and "2-41 Company Command Vehicle" would be a class of platforms. A modeler may also use the platform construct to identify a hypothetical rendezvous location as a method to indicate that different systems are likely to come close to each other.

3.1.7.1 Rationale

Transceivers of systems are often combined on the same platform, in the same facility, or in the same device, in which case they are more likely to interfere with each other either through adjacent frequency or IM interference. This construct is used to tag situations where different systems are co-located so that modelers can consider and mitigate these occurrences of interference. Checking for third and higher order receiver IM occurs only for co-located systems.

Mobile systems may come into proximity to a facility or to each other by happenstance. When modelers believes that this might occur and would be disruptive, they may assign a probability to its occurrence. The model would have a platform name of the arbitrary rendezvous point and a probability that the systems being considered would arrive there. The modeling of this probability would not necessarily be used to arbitrate compatibility, but to optimize assignments to avoid this type of interference.

3.1.7.2 Data Structure

The data structure consists of two elements: a platform name, which is a string, and an optional probability measure. The platform or device name must be unique. If a component of a system is co-located at the named platform then there is no need to use the probability element. If the platform name indicates an arbitrary rendezvous point, the model also provides a probability term to indicate the likelihood that a component of a system will arrive at that point.

3.1.7.3 Units

Not applicable.

3.1.7.4 Dependencies

Systems that have common platform names receive greater scrutiny for IM and adjacent frequency interference. 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 cause problems in processes that search for and assign channels. The typical processing identifies systems or collections of transmitters and receivers that are on common platforms or in common devices. Systems on common platforms or devices undergo this scrutiny.

In cases where platform names identify rendezvous points of mobile systems, the construct includes a probability element indicating the likelihood. A rendezvous point may be a real platform or facility such as an operations center that users of a particular system may possibly visit. It may be an arbitrary point used as a tag to indicate that some systems are likely to come into close proximity; for example, leaders of different organizations with radios on different channels may, as a matter of routine or as contingency, meet face-to-face and so bring their radios in proximity. The probability that two systems meet at the rendezvous is the lowest probability in the platform constructs of the two systems. Managers may make an operational decision to establish rules governing whether the probability of the rendezvous is high enough to justify efforts to mitigate interference.

3.1.8 Location

The location construct of a SCM conveys where the components of the RF system being modeled may be used. Locations may be specified as points, areas, volumes, or tracks. Non-point locations indicate uncertainty regarding the location of devices or that the RF devices are mobile. In both cases, for the purposes of determining compatibility, the RF devices may be located anywhere in the area or volume specified. All locations are referenced to a geospatial datum with coordinates given as a longitude, latitude, and altitude.

3.1.8.1 Rationale

Location modeling specifies the limits of the space in which the components of an RF system may be located so that modelers can compute the compatibility of uses. Generally, modeling seeks to define a location that best reduces the uncertainty in the locations of the RF devices.

Location is a required construct element of all models. The common datum for SCMs 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 about this datum are described in Appendix B. Spectrum consumption models do not model terrain or where appropriate terrain effects should be captured in the propagation maps and power maps of SCMs. The assumption in modeling is that the strength of interfering signals at distant receivers can be computed using the models alone. This assumption removes the need for detailed terrain and propagation models and lessens the complexity of using them in the process of computing compatibility. Models of terrain and propagation may be used in the development of SCMs, but what is learned by using these tools must be captured in the constructs of the SCM. Since computations of compatibility for SCMs do not use models of terrain, conveying locations referenced to the WGS-84 coordinate system is sufficient for computing compatibility. Guidance on converting between coordinate systems of different data is described in Appendix E.

The following subsections describe the small set of methods chosen to specify locations that provide sufficient versatility to capture typical types of RF device locations. Locations may be subdivided into parts to allow finer resolution modeling in propagation and time. They may be tagged with an index to associate the locations with particular propagation models and start and end times.

Locations may also be specified with confidence. The confidence term enables the modeler to convey the more likely locations of system devices while simultaneously modeling a larger location that puts a bound on the possible locations where devices may be located.

3.1.8.1.1 Point

The point location is the most restrictive of the location models. It specifies an unmovable location for a device for the duration of the model.

3.1.8.1.2 Terrestrial Surface Area

A terrestrial surface area may be specified in one of three ways: as a point, a circle (i.e., a point and a radius), or a polygon (i.e., a series of points that together form a convex polygon on the surface of the earth). Typically, propagation models and subsequent pathloss computations are based on the antenna height above the terrestrial surface area. Surface areas include a data element to specify the antenna height, *ah*, to use in these computations. When a point and radius are used it is assumed that all points on the locus have the same altitude as the center. When a series of points is used, the altitudes 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. Regardless, most computations of compatibility using terrestrial surfaces are based on the explicit height given for the antenna. 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.

3.1.8.1.3 Cylinder

A cylinder is specified using three elements, 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.

3.1.8.1.4 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 are 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.

3.1.8.1.5 Track

Models may use a track for mobile and stationary objects. A track consists of a point location and a velocity. The velocity consists of a speed and heading. The platform on the track is located at the point at the start time of the model; at a time into the future the location is computed using the 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.

3.1.8.2 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 3-27 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. Point surfaces have the additional value of antenna height $\langle \lambda, \varphi, a, ah \rangle$.A circular surface area is specified with five values: longitude, latitude, altitude, radius, and antenna height $\langle \lambda, \varphi, a, r, ah \rangle$. A polygon surface area is specified as a series of points in a vector, each point specified with three values, followed by an antenna height $\langle (\lambda_0, \varphi_0, a_0, \lambda_1, \varphi_1, a_1, \ldots, \lambda_{n-1}, \varphi_{n-1}, a_{n-1}), ah \rangle$. The assumption is that these points are listed in the order in which 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, $\langle \lambda, \varphi, a, r, h \rangle$. An antenna may be anywhere within the volume of the cylinder. The polyhedron is specified as a polygon surface area but with the addition of a height value, $\langle (\lambda_0, \varphi_0, a_0, \lambda_1, \varphi_1, a_1, \ldots, \lambda_{n-1}, \varphi_{n-1}, a_{n-1}), h \rangle$. The antenna may be anywhere within the volume of the polyhedron. Tracks are specified by giving a point location, a heading, and a speed. Headings are specified by an azimuth and elevation referenced to the earth's surface coordinates that apply to the point. (See Appendix D for the description of the different coordinate systems.) The complete data structure of a track is $\langle \lambda, \varphi, a, \theta, \phi, s \rangle$.

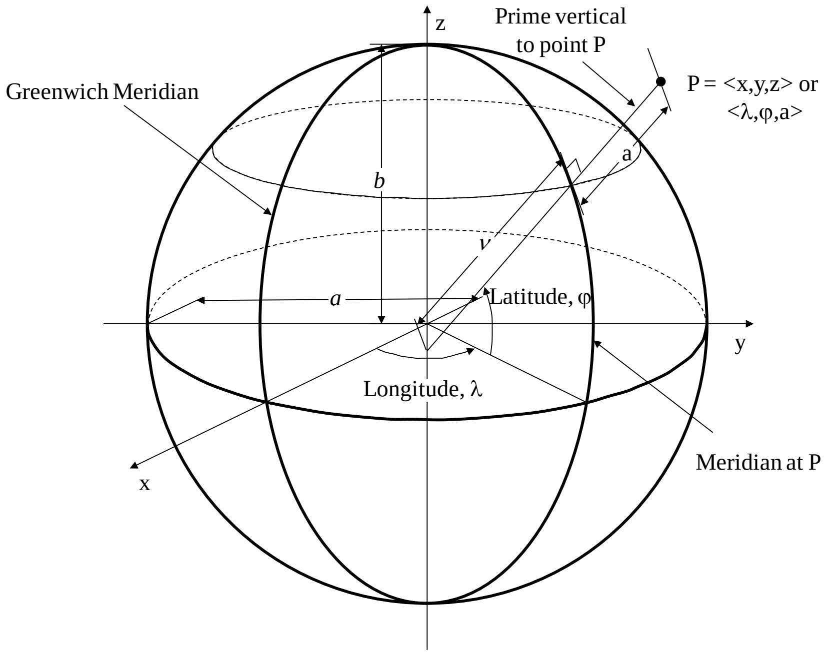


Figure 3-27. An Earth Ellipsoid Datum and the References for Point Locations

The confidence data element is a cumulative probability that must provide a model for a confidence of 1. If that element is missing, the existing models are scaled.

Spectrum consumption modeling allows division of spectrum use into multiple models. As a convenience, when other constructs remain the same, the propagation map, location, start time, and end time constructs can be grouped and associated by an index. Multiples of these groups can appear in a single SCM with each group differing by location, propagation map, or time of use.[11]

3.1.8.3 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 speed of platforms used in tracks is given in kilometers per hour.

3.1.8.4 Dependencies

Computations depending on location are especially important in determining compatibility, because 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. 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 points involves a coordinate conversion from the WGS-84 ellipsoid coordinates to earth-centered Cartesian coordinates and then using a Euclidean distance computation:

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

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[11] A goal of modeling to create some level of abstraction that applies over a large area. Modelers should avoid creating models of multiple spaces because it appears to provide better resolution. Such modeling can be counterproductive in an agile SM system. Modeling for multiple spaces is used when it provides a resolution that assists sharing

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

The harder set of computations at the heart of using spectrum consumption modeling involves determining which points in the spaces defined by a pair of models offer the greatest constraint between modeled uses. The specific points depend 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 4.1.8 describes compatibility computations and the role of searching for the constraining points. Algorithms for identifying constraining points between models are described in [8].

3.1.9 Start Time

The start time is the time when 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.

3.1.9.1 Rationale

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

Locations may be subdivided into parts to allow finer resolution modeling in time. Each of these parts may apply to different time periods. Modelers may make these associations using using the Location Index data element. Locations and times are associated by have the same index.

Time may also be specified with confidence. The confidence term enables modelers to convey their confidence about when the use will start. In practice, models that consume more spectrum start earliest and so when cumulative probability is used the time elements with earlier times will have higher probabilities.

3.1.9.2 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 $\langle YYYY, MM, DD, hh, mm, ss.s, \pm hh_o, mm_o \rangle$. 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 $\langle duration_d, duration_{on}, duration_{off} \rangle$, 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.

The confidence data element is a cumulative probability that must provide a model for a confidence of 1. If this element is missing, the existing models are scaled.

When locations are indexed, start times may be indexed as well. Any index used with a Start time must be matched to a location with the same index. When a location has an index and there is no indexed start time then the start time that has no index is associated with the location.

3.1.9.3 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 time zone. 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. For example, a duration of one day would be written P1D, a duration of one hour would be written PT1H, and a 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. The location index and confidence are dimensionless. The location index is an integer and the confidence is a decimal value between 0 and 1.

3.1.9.4 Dependencies

Modelers must compute whether two uses of the same spectrum are compatible 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 if their start times coincide.

3.1.10 End Time

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

3.1.10.1 Rationale

The end time is the second half of a duration model and identifies when the model ceases to apply. It too may have an index and a confidence level.

When locations are indexed, end times may be indexed as well. Any index used with an end time must be matched to a location with the same index. When a location has an index and there is no indexed end time then the end time that has no index is associated with the location.

Time may also be specified with confidence. The confidence term enables the modeler to convey their confidence when the use will end. In practice, models that consume more spectrum end latest, and so when cumulative probability is used the time elements with later end times will have higher probabilities.

3.1.10.2 Data Structure

End times provide year, month, day, hour, minute, and second with an hour and minute displacement from the UTC. The format for the end time is $\langle YYYY, MM, DD, hh, mm, ss.s, \pm hh_o, mm_o \rangle$. The location index and confidence are dimensionless. The location index is an integer and the confidence is a decimal value between 0 and 1.

3.1.10.3 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.

3.1.10.4 Dependencies

Compatibility computations between SCMs are only necessary they overlap in time. The check described for the start time is sufficient for this assessment.

3.1.11 Minimum Power Spectral Flux Density

The minimum power spectral flux density specifies the attenuation level at which 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 receivers.

3.1.11.1 Rationale

The minimum power spectral flux density allows a transmitter model, such as the model used for a commercial radio or television station, also to 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.

3.1.11.2 Data Structure

A single real number.

3.1.11.3 Units

A power spectral flux density is a power in dB units relative to a resolution bandwidth and surface area. The model allow multiple units for the resolution bandwidth but typically the units of this measure are $\mathrm{dBW}/\mathrm{Hz}\cdot\mathrm{m}^2$ or $\mathrm{dBm}/\mathrm{Hz}\cdot\mathrm{m}^2$

3.1.11.4 Dependencies

The minimum power spectral flux density is used together with total power, 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 broadcaster's ability to deliver a reasonably strong signal identified by this value. The surface of this volume is computed by identifying the range at which a signal attenuates to the minimum power spectral flux density using the transmission power specified by the total power, the spectrum mask, and the power map and then the attenuation specified by the propagation map. This threshold applies to the maximum power of the transmitted signal. The following example demonstrates the use of the minimum power spectral flux density and the computation that follow.

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

Given a transmitter model with the following constructs:
Total power: 30 dBW

Spectrum mask: (107.4, -43, 107.41, -23, 107.59, -23, 107.6, -43) relative

Propagation map (2.2, 0)

Transmitter power map (0, 0)

Minimum power spectral flux density: -93 dBW/Hz/m^2

Underlay mask: (107.4, 0, 107.41, -63, 107.59, -63, 107.6, 0) relative

Receiver power map (0, 0)

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: $-93 \text{ dBW/Hz/m}^2 = 7 \text{ dBW/Hz/m}^2 - 22\log(d)$. Note that the starting power is 7 dBW/Hz/m^2 and the power at the boundary is -93 dBW/Hz/m^2 and we need to solve for *d*. In this case, the range, *d*, is 35 km. The maximum interference level at the boundary is computed using the minimum power spectral flux density and the lowest power of the underlay mask: $-93 \text{ dBW/Hz/m}^2 + \left(-63 \text{ dBW/Hz/m}^2 + 23 \text{ dBW/Hz/m}^2\right) = -133 \text{ dBW/Hz/m}^2$. The level of protection interior to the boundary will be less and will depend on the level of attenuation at the location being considered.

3.1.12 Protocol or Policy

The protocol or policy construct element specifies additional information on how a system uses spectrum or what a system must do to share spectrum. A policy is defined as a set of rules that govern the behavior of a system [18] while a protocol is defined as a strict procedure required to initiate and maintain communications [19]. The distinction used in this document to differentiate a policy from a protocol concerns scope and influence on the behaviors of a radio system. Policy consists of rules specifying the conditions that must be present to consider spectrum available for a particular radio to use it. By contrast, protocols are the detailed procedures that radios use to access spectrum. 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 accomplish the radio system’s purpose.

Modelers can employ the protocol or policy construct element both to specify the conditions for spectrum use when models are used to provide policy and to specify how a system uses the spectrum.

3.1.12.1 Rationale

The protocol and policy construct element provides the means to specify behavioral guidance for spectrum reuse. This has two benefits:

1. It provides a means to specify how to use spectrum sensing 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 policies and protocols consists of understanding how the two would differ from a cognitive perspective. Policy guides the reasoning components of cognitive systems. The cognitive systems would observe the use of spectrum and use the policies to determine alternative courses of action. The cognitive systems would then have many degrees of freedom in choosing the spectrum they use and the access protocol they employ. Meanwhile, protocols specify the mechanics and timing of spectrum access. Given a protocol as guidances, a cognitive system would simply operate using the protocol. There is only one course of action. Compliance with the protocol ensures compatibility. Protocols have the advantage of allowing spectrum sharing at a much finer time resolution and therefore enable a more efficient reuse.

3.1.12.2 Data Structure

The basic data structure of a protocol or policy is a name followed by a set of parameters. The assumption is that the name implies the general behavior of the target system and the parameters fill in the details of timing, levels, structures, and counts. Each policy and protocol name would have an expected number of parameters associated with it that modelers must provide for the policy or protocol to be complete. When used in receiver models these policies are assumed to be associated with all underlay masks unless limited by an index that matches an index of particular underlay masks in the model.

3.1.12.3 Units

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

3.1.12.4 Dependencies

The policy and protocol construct element only applies to the spectrum defined in the rest of the spectrum model. When a behavior is associated with a receiver model, it indicates that the model of the boundary of interference applies if the interfering system engages in the particular behavior. When a behavior is associated with a transmitter model, it indicates the particular behavior of the transmitter. The behaviors within the two models must be the same or else arbitrating compatibility between a receiver and a transmitter becomes impossible. Other than this, there are no further computational dependencies with the other construct elements of the model.

Example: Listen Before Talk Policy

Listen before talk policies use sensing to identify reuse opportunities. This class of polices is further defined by four parameters: sensing threshold, sensing period, abandonment time, and disuse time. A possible sensing policy could require a cognitive system to sense a channel for no signal above a particular power threshold for some duration and once true allow its spectrum to be used. It would then require the cognitive system to continue sensing the channel periodically and if another user is detected 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, in this case "LBT," 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 $\langle \mathrm{LBT}, -120, 300, 0.001, 300 \rangle$ where it is understood that the power term has units of dBW and all timing parameters have units of seconds.

Example: Protocol - 1

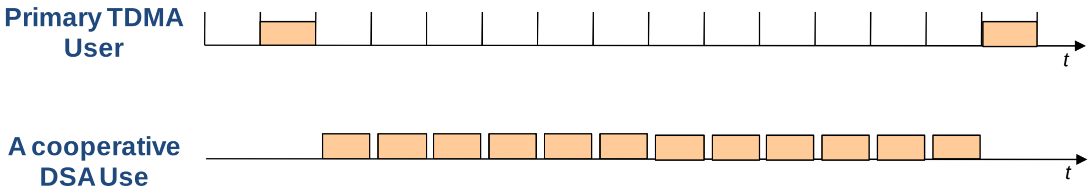


Figure 3-28. TDMA Sharing Example

Figure 3-28 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 [9]. 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 3-29 illustrates the protocol.

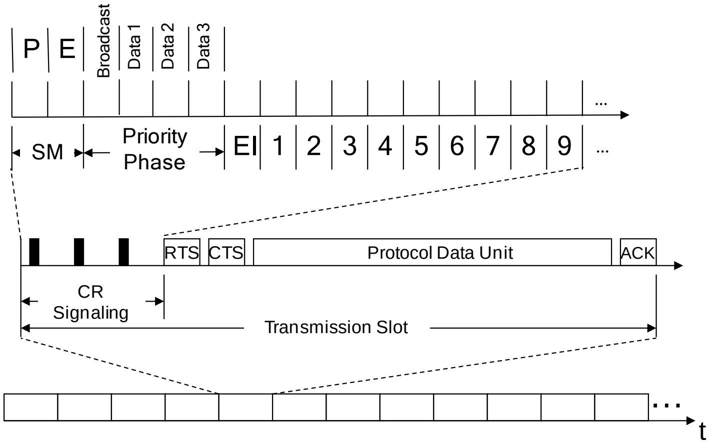


Figure 3-29. SCR Design for Arbitrating Primary and Secondary Spectrum Access

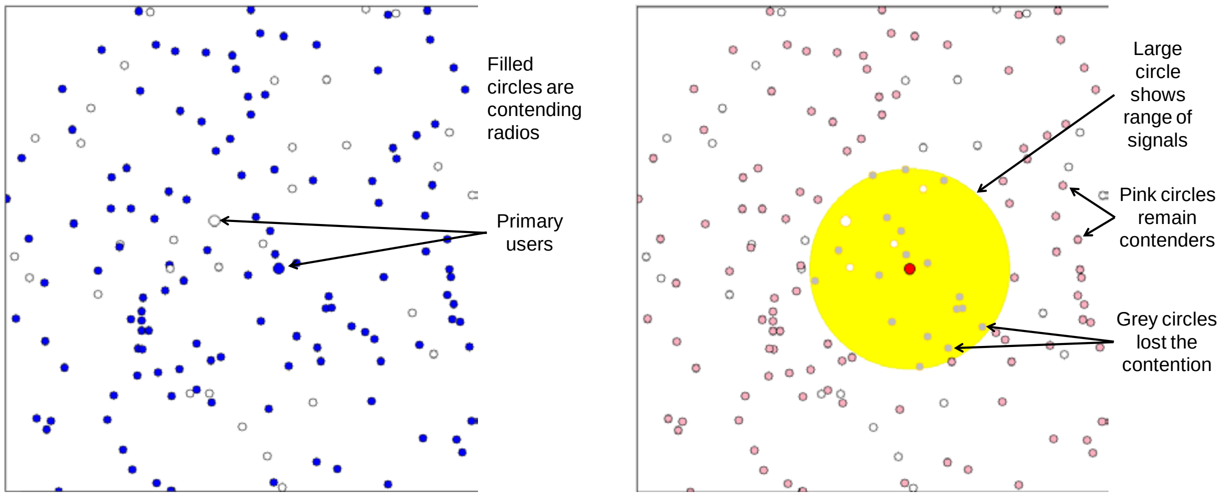
Generally, in the collision resolution signaling, the radio that signals first gains access over its contending neighbors. In this design, there is a special spectrum management (SM) phase of signaling at the beginning that all primary contenders signal to assert their precedence and then the remainder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

Figure 3-30 illustrates an example of arbitrating primary and secondary access. At the start, as illustrated Figure 3-30a, 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 3-30b. 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 3-30c. 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 3-30d 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 $\left\langle \text{SCR PS}, 0.05, 0.035, 2 \right\rangle$ 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 power spectral flux 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

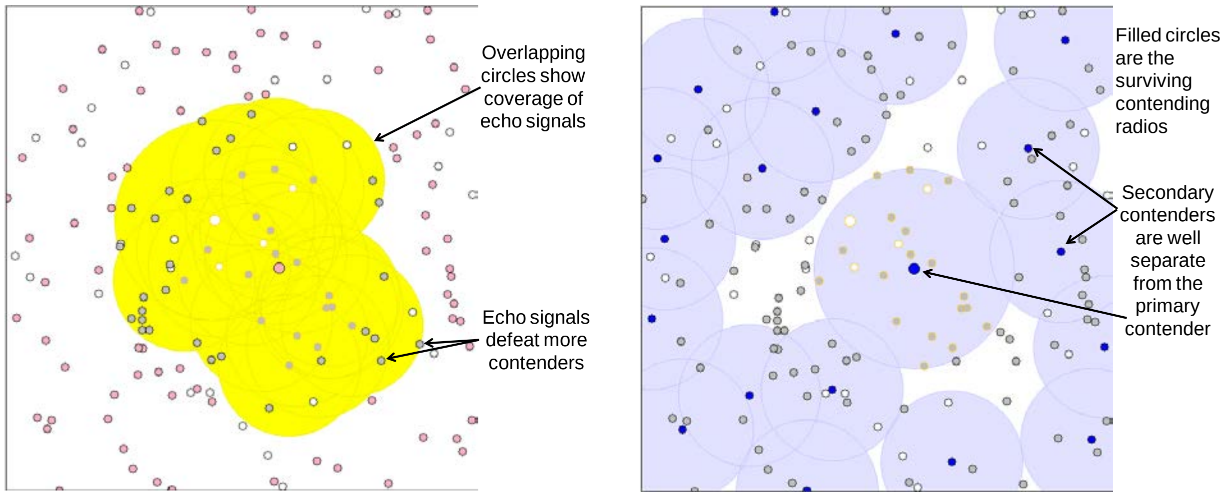
Example: Protocol 2 (continued)

for sharing. Additional information on the details of the SCR protocol and its many other capabilities can be found in [10], [11], [12], and [13].



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 3-30. Example of Signaling Giving a Primary Priority in Access and Filling Spaces with Secondary Users

3.2 Model Types

Both transmission and reception consume spectrum. Transmitters emit radiation and may cause harmful interference with other users. Receivers do not emit radiation, but can suffer interference and so must be protected. Thus, models for transmitters and receivers differ, and have different effects on spectrum consumption. These models must be distinguished from each other since the meanings of the total power, 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 consist of some number of transmitter and receiver models that combine to convey the spectrum consumption of the system.

3.2.1 Transmitter Models

Transmitter models attempt to convey the extent and strength of RF emissions. The essential construct elements that a transmitter model must contain are a total power, a spectrum mask, a power map, a propagation map, a location, a start time, and an end time. Emissions can come from anywhere in the space identified by the location construct element during the time specified. From those locations, the total power, 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 3-31 illustrates this attenuation.

3.2.2 Receiver Models

Receiver models attempt to convey what constitutes harmful interference. The essential construct elements that must be part of a receiver model are a total power, an underlay mask, a power map, a propagation map, a location, a start time, and an end time. A receiver can be anywhere in the space defined by the location construct element.

Receiver models differ from transmitter models in three ways. They require an underlay mask

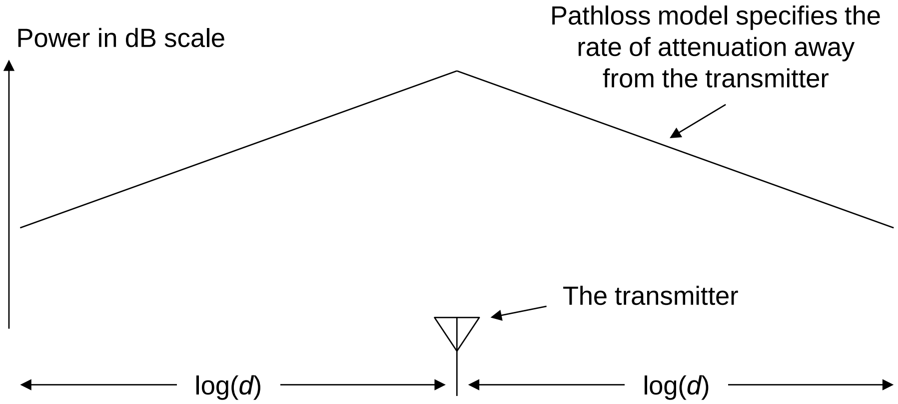


Figure 3-31. Transmitter Models Define Transmitted Signals and their Attenuation

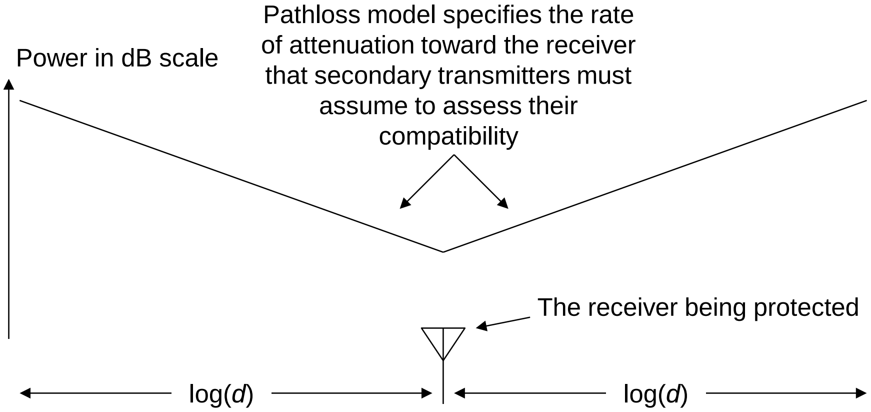


Figure 3-32. Receiver Model Defines the Maximum Allowed Interference at Receivers and the Rate of Attenuation to be used in Determining Interference by Distant Transmitters

rather than a spectrum mask, the construct elements define the allowed strength of an interfering signal at the receiver rather than the strength of transmission, and the propagation model parameters of the propagation map define the rate of attenuation to be used in computing the attenuation of a potentially interfering signal. Figure 3-32 illustrates the attenuation of a receiver model and clearly shows it is the opposite of a transmitter model.

3.2.3 System Models

Most systems consist of both transmitters and receivers, and so spectrum consumption modeling of systems generally contains a collection of both of these types of models. In addition to the different types of devices, 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 antennas

In a few situations a system model would use a single transmitter or receiver model. Surveillance systems, such as radio telescopes and signal intelligence devices, are examples of systems that would use only a receiver model. Jammers are examples of systems that use only a transmitter model.

3.3 Conventions for Combining Construct Elements 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
- To define the constraints to the spectrum used by a system or systems

Two types of standalone model data sets are shared among management and RF systems: system models and model collections. These two standalone data sets contain submodels for transmitters and receivers. System models are used for the first function above and collections are used for the latter three. Figure 3-33 illustrates their relationship, showing that transmitter and receiver models are possible parts of the system models, and all three are possible parts of model collections. Each, however, has its own set of modeling constructs, which apply within the models of transmitters and receivers and in the headers of system models and collections. The construct elements used in the headers of the system models and collection data sets have different roles based on the function of the system model or the collection data set. The next subsection describes the role of the heading model construct elements in systems and collections for the different functions above.

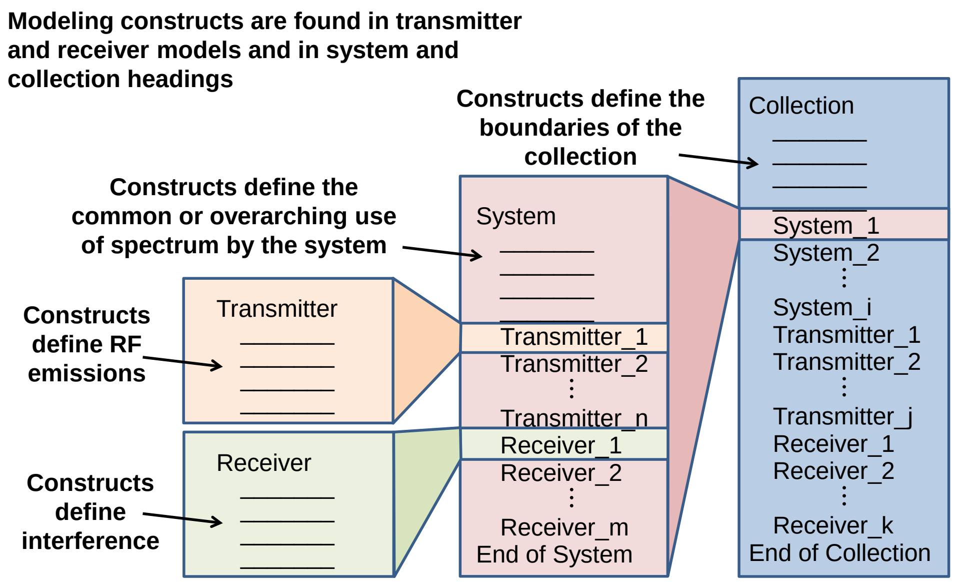


Figure 3-33. Relationship Between Transmitter Models, Receiver Models, Systems Models and Collections

Although the collection data sets may include system 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 A 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.

3.3.1 System Models

The convention for conveying a model of a system is to specify the system model with a list of modeling construct elements in its header 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 construct elements. When a type of modeling construct element 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 element 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 a system's transmitter model has a different model construct element 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. These systems may only use spectrum where their use intersects the boundary of the models that convey availability.

The combination of construct elements 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 construct elements. These standalone models, referred to as canonical models, would likely be conveyed in collections and be used in compatibility computations.

3.3.2 Collective Consumption Lists

Collective consumption lists use model collections to convey spectrum consumption among SM systems. The convention for conveying a collection of consumption models is to specify the construct elements relevant to applying the collection of models as part of the collection heading and then applying a collection of system, transmitter, and receiver models. The collection heading defines the scope of the collection. The typical construct elements included in a collection heading are spectrum masks, locations, and the start and end times. These construct elements 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 construct elements but are included since they affect the use of spectrum within the specified bounds.

Unlike in system models, construct elements in the collection heading are not construct elements 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 construct element in the heading of a collective consumption listing consists of just two points specifying the start and end of the spectral band to which the collection applies. If the collection specifies multiple disjoint bands then it should use multiple spectrum masks of this type.

3.3.3 Spectrum Authorization Lists

Spectrum Authorization Lists use model collections to convey which spectrum a system may use. It can be used to identify spectrum that is available for a system to use, with the expectation that the system chooses from the list and requests the appropriate channels. 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 construct elements 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 applies. 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 the limits in the system, transmitter, and receiver models imply something broader.

Transmitter models, receiver models, and systems models convey spectrum authorizations. Systems models are used for systems that have combinations of transmitters and receivers and in which only certain channel combinations may be used. The construct elements of the transmitter models define the limits to spectrum use. The location element defines where transmitters may emit; the combination of spectrum masks, total power, and power map elements provides the constraints to power spectral flux density of the transmission; the start and end time construct elements provide the period of authorization; and the policy and protocol construct element specifies behaviors necessary for using the spectrum. The receiver models of authorization lists define the limits to protection that receivers operating in the channels can expect. Frequently, a spectrum constraint list complements the authorization lists. In this case, the authorizations extend only to the additional limits provided by these constraints.

3.3.4 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 spectrum authorization listings. The convention for conveying a collection of constraining models is to specify the construct elements relevant to applying the collection of these models as part of the collection heading and then applying a collection of system, transmitter, and receiver models. The typical construct elements included in the constraint listing heading are spectrum masks, locations, and the start and end times. These construct elements specify the extent to which the models in the collection provide a comprehensive set of constraints. The limits of the constraint listing heading do 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.

Transmitter, receiver, and system models may appear in the constraint listings. It is preferable if the system models are decomposed into canonical transmitter and receiver models and not used in their native form. Both transmitter and receiver models appear in the lists and can serve as constraints. The transmitter models convey how other users consume spectrum and serve as constraints to the extent they would indicate interference to a user considering using the same spectrum. The receiver models constrain use of spectrum by specifying what use would harm an incumbent.

3.4 Summary

This chapter has described the twelve constructs of spectrum modeling, including their rationale, the data structures they use, the units for those data structures, the basic computations used with the construct elements, and their dependence on other construct elements in those calculations. The chapter also described how to combine these construct elements into models of transmitters, receivers, and systems and then combine these models into collection data sets that are used to convey spectrum consumption, authorize use of spectrum, and convey constraints on the use of spectrum.

4 Assessing Compatible Spectrum Use

Modeling spectrum consumption enables use of a common set of rules and algorithms to determine the compatibility of spectrum uses. In this chapter we describe the methods used for computing compatibility and the requirements for characterizing systems as compatible. The chapter begins with a discussion of the fundamental computations used to determine compatibility and is followed by a description of the criteria and process for assessing whether uses are compatible.

4.1 Fundamental Computations

Establishing whether two systems that use common spectrum at the same time are compatible relies on objective computations using the SCM of the two models. These computations seek to determine whether the transmitter models of one system are compatible with the receiver models of the other. Given specific locations for a transmitter and a receiver, the computation is equivalent to a link budget computation. The interaction of a transmitter's spectrum mask and a receiver's underlay mask provides a power margin that indicates the propensity of the two systems to interfere with each other. The total power, power map, propagation map, and location are used to calculate the rest of the link budget. If the power predicted from the transmitter model is below the threshold established by the receiver model, that transmitter-receiver pair is compatible. Systems are compatible when all the transmitter and receiver models are compatible with each other.

In cases where systems are susceptible to IM and it is modeled, compatibility assessments must also consider it. However, IM effects are not a function of two systems, but of multiple systems. The IM portion of the model supports the assessment of the interaction. In models of transmitter IM a remote system interacts with a transmitting system that generates an IM product that may interfere with another remote system. In receiver IM, multiple remote signals interact at a receiver and generate new products that may interfere at that receiver.

This section describes the basic computations used in determining the compatibility between systems. It begins with the easier computations: determining whether systems operate in the same time period or spectrum bands. The next subsection describes how to calculate the specific power spectral flux density of a transmitted signal at a distant location and how to determine the allowed power spectral flux density at a receiver. These results generate scaled spectrum and underlay masks. The following subsection describes the computation of the power that results from the interaction of a spectrum mask and an underlay mask. It includes a description of the criteria used to select the underlay mask to use from a receiver model that contains several underlay masks. The fifth subsection discusses the role of IM and IM masks in determining compatibility among systems. The sixth subsection describes how to assess whether systems meet policy or protocol criteria. The seventh subsection identifies the criteria for assessing the compatibility of models by using planar approximations. It describes the conversion of coordinates of multiple systems to a system of common coordinates that share the same tangent plane. The eighth subsection defines constraining points, describes their role in determining compatibility between models, and shows how they are determined. The final subsection describes how to assess whether aggregate interference from multiple transmitters collectively meets compatibility requirements.

The computations described in this chapter create the foundation for the development of algorithms that perform SM and dynamic SM tasks using SCMs as inputs.

4.1.1 Time Overlap

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

4.1.2 Spectrum Overlap

Two models overlap in spectrum if the spectrum mask of one extends into the bandwidth covered by the underlay mask of the second. Only the signal within the bandwidth of the underlay mask is considered in determining the power of interference from a transmitter.

4.1.3 Link Budget Computations Using Models

The intent in creating the constructs of spectrum consumption modeling was to make field strength, i.e., the power spectral flux density, the measure used to assess compatibility and to enable the modeler to model it. This measure is what a third party may observe of a system’s spectrum use. Figure 4-1illustrates that the constructs work collectively to define the power spectral flux density. At the transmitter, the total power, spectrum mask, and the power map collectively identify the upper bound on the transmitted power spectral flux density at the one meter distance from the antenna. The total power, underlay mask, and the power map constructs of the receiver model collectively indicate the allowed power spectral flux density of interference at the input to the antenna. The propagation map construct is used to determine the attenuation of the transmitted power spectral flux density as a result of propagation and pathloss.

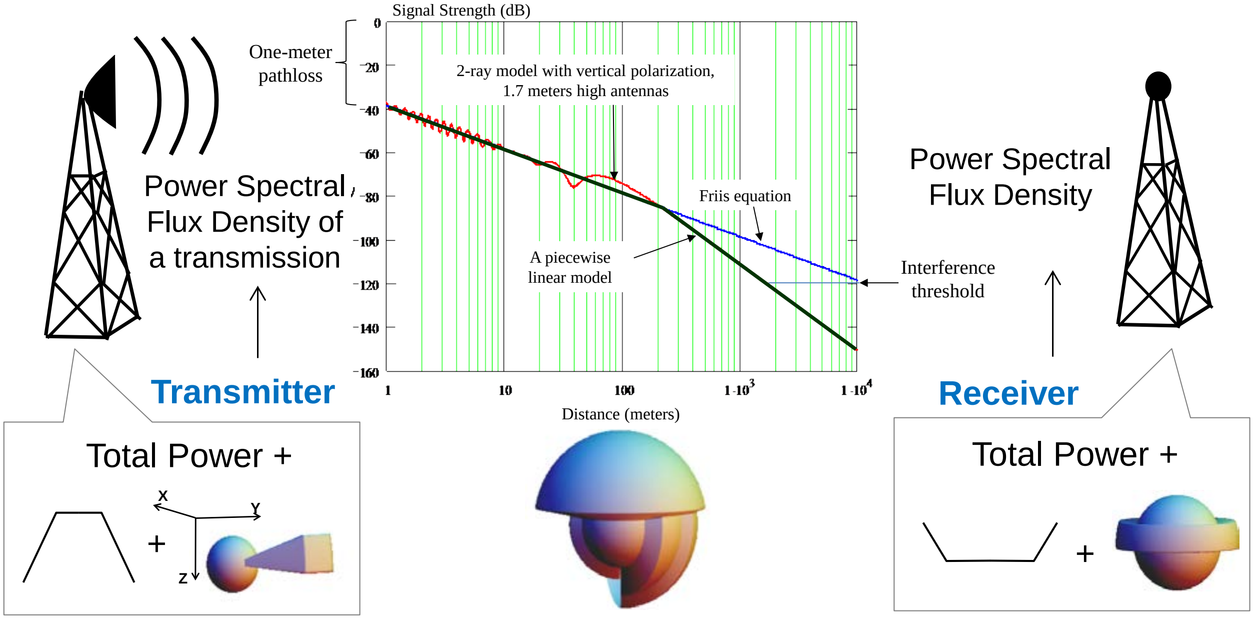


Figure 4-1. Assessing Compatibility Using Power Spectral Flux Density

4.1.3.1 Transmitter Model Link Budget

The power spectral flux density of a signal is presented as a scaled version of the spectrum mask where the power terms have units of dBm/Hz/m^2. Given the location of the transmitter and the location of a receiver, and thus the distance and direction between the two, computing the power spectral flux density at the distant receiver location from a transmitter involves three steps:

1. Adjust the spectrum mask power levels by the total power value.

   Given a spectrum mask of the form $\left(f_0, p_0, f_1, p_1, \cdots f_x, p_x \right)$ and a total power level of x dBm, the new spectrum mask would be scaled to be $\left(f_0, p_0 + x, f_1, p_1 + x, \cdots f_m, p_m + x \right)$. The power terms would have units of dBm/Hz (after adjustment for the resolution bandwidth of the mask).

2. Adjust the spectrum mask power levels by the gain of the power map construct in the direction of the location of interest.

   Given the adjusted spectrum mask above, $\left(f_0, p_0 + x, f_1, p_1 + x, \cdots f_m, p_m + x \right)$, and the gain of the power map in the direction of the location of interest of y dB/m^2, the new spectrum mask would be scaled to be $\left(f_0, p_0 + x + y, f_1, p_1 + x + y, \cdots f_m, p_m + x + y \right)$. The power terms then have units of dBm/Hz/m^2.

3. Adjust the spectrum mask power levels by the pathloss predicted by the propagation map for the direction and distance to the location of interest.

   Given a propagation map that specifies the exponents for a log distance pathloss model, the direction to the location and the distance to the location, d, the pathloss exponent (n) in the direction of the location is determined from the map, and the total pathloss is calculated as $z = 10n\log(d)$ with units of dB and the new spectrum masks would be scaled as $\left(f_0, p_0 + x + y - z, f_1, p_1 + x + y - z, \cdots f_m, p_m + x + y - z \right)$. The power terms then have units of dBm/Hz/m^2.

   In the case of a propagation map that specifies the use of the piecewise linear model, the directional lookup in the map would provide three model parameters: an exponent, n_1, a breakpoint distance, $d_{breakpoint}$, and a second exponent, n_2. In this case, the total pathloss would be calculated to be

$$z = \begin{cases} 10n_1 \log\left(d\right) & d \le d_{breakpoint} \\ 10n_1 \log\left(d_{breakpoint}\right) + 10n_2 \log\left(\dfrac{d}{d_{breakpoint}}\right) & d > d_{breakpoint} \end{cases}$$

   with units of dB. As before, the new spectrum masks would be scaled as $\left(f_0, p_0 + x + y - z, f_1, p_1 + x + y - z, \cdots f_m, p_m + x + y - z \right)$. The power terms then have units of dBm/Hz/m^2.

4.1.3.2 Receiver Model Link Budgets

Receiver models convey the limits to the power of interference or the maximum power spectral flux density allowed at a receiver location. Sections 3.1.3.4 and 4.1.4 describe the differences between these two different interference constraint criteria. The specific allowed power values are a function of the multiple components of the receiver model. Ultimately, it is expresses as a scaled underlay mask. Scaling differs between location referenced underlay masks and transmitter referenced underlay masks.

4.1.3.2.1 Location Referenced Underlay Masks

The power spectral flux density specified by the receiver model would be presented as a scaled version of the underlay mask where the power terms have units of dBm/Hz/m^2. Given the location of the transmitter and the location of a receiver and so the direction between the two of them, the computation of the power spectral flux density allowed from a particular direction has two computations:

1. Adjust the underlay mask power levels by the total power value.

   Given an underlay masks of the form $\left(f_0, p_0, f_1, p_1, \cdots f_x, p_x \right)$ and a total power level of x dBm, the new underlay mask would be scaled to be $\left(f_0, p_0 + x, f_1, p_1 + x, \cdots f_m, p_m + x \right)$. The power terms would have units of dBm/Hz (after adjustment for the resolution bandwidth of the mask).

2. Adjust the underlay mask power levels by the gain of the power map construct in the direction of the location of interest.

   Given the adjusted underlay mask above, $\left(f_0, p_0 + x, f_1, p_1 + x, \cdots f_m, p_m + x \right)$, and the gain of the power map in the direction of the location of interest of y dB/m^2, the new underlay mask would be scaled to be $\left(f_0, p_0 + x + y, f_1, p_1 + x + y, \cdots f_m, p_m + x + y \right)$. The power terms then have units of dBm/Hz/m^2.

4.1.3.2.2 Transmitter Referenced Underlay Masks

The power spectral flux density specified by the receiver model would be presented as a scaled version of the underlay mask where the power terms have units of dBm/Hz/m^2. Given the location of the interfering transmitter and the location of a receiver, the distance and the directions between the two can be detemined. The computation of the power spectral flux density allowed from the direction of the interferer has five steps:

1. Adjust the underlay mask power levels by the total power value of the local transmitter.

   Given an underlay masks of the form $\left(f_0, p_0, f_1, p_1, \cdots f_x, p_x \right)$ and a total power level of x dBm for the local transmitter model, the new underlay mask would be scaled to be $\left(f_0, p_0 + x, f_1, p_1 + x, \cdots f_m, p_m + x \right)$. The power terms would have units of dBm/Hz (after adjustment for the resolution bandwidth of the mask).

2. Adjust the underlay mask power levels by the gain of the power map construct of the local transmitter in the direction of the receiver.

Given the adjusted underlay mask above, $\left(f_0, p_0 + x, f_1, p_1 + x, \cdots f_m, p_m + x \right)$, and the gain of the power map in the direction of the receiver of y dB/m^2, the new underlay mask would be scaled to be $\left(f_0, p_0 + x + y, f_1, p_1 + x + y, \cdots f_m, p_m + x + y \right)$. The power terms then have units of dBm/Hz/m^2.

3. Adjust the underlay mask power levels by the pathloss predicted by the local transmitter propagation map for the direction and distance to the receiver

   Given a propagation map that specifies the exponents for a log distance pathloss model, the direction to the receiver and the distance to the receiver, d, the pathloss exponent (n) in the direction of the receiver is determined from the map, the total pathloss is calculated as $z = 10n\log(d)$ with units of dB, and the new underlay masks would be scaled as $\left(f_0, p_0 + x + y - z, f_1, p_1 + x + y - z, \cdots f_m, p_m + x + y - z \right)$. The power terms then have units of dBm/Hz/m^2.

   In the case of a propagation map that specifies the use of the piecewise linear model, the directional lookup in the map would provide three model parameters: an exponent, n_1, a breakpoint distance, $d_{breakpoint}$, and a second exponent, n_2. In this case the total pathloss would be calculated to be

$$z = \begin{cases} 10n_1 \log\left(d\right) & d \le d_{breakpoint} \\ 10n_1 \log\left(d_{breakpoint}\right) + 10n_2 \log\left(\dfrac{d}{d_{breakpoint}}\right) & d > d_{breakpoint} \end{cases}$$

   with units of dB. As before, the new underlay mask would be scaled as $\left(f_0, p_0 + x + y - z, f_1, p_1 + x + y - z, \cdots f_m, p_m + x + y - z \right)$. The power terms then have units of dBm/Hz/m^2.

4. Adjust the underlay mask power levels by the gain of the power map construct in the direction of the transmitter.

   Given the adjusted underlay mask, $\left(f_0, p_0 + x + y - z, f_1, p_1 + x + y - z, \cdots, f_m, p_m + x + y - z \right)$, and the gain of the power map of the receiver in the direction of the local transmitter of q dB/m^2, the new underlay mask would be scaled to be $\left(f_0, p_0 + x + y - z + q, f_1, p_1 + x + y - z + q, \cdots f_m, p_m + x + y - z + q \right)$. The power terms then have units of dBm/Hz. In this case the power map is recovering the energy from its spatial distribution.

5. Adjust the underlay mask power levels by the gain of the power map construct in the direction of the interfering transmitter.

   Given the adjusted underlay mask, $\left(f_0, p_0 + x + y - z + q, f_1, p_1 + x + y - z + q, \cdots f_m, p_m + x + y - z + q \right)$, and the gain of the power map of the receiver in the direction of the interfering transmitter of r dB/m^2, the new scaled underlay mask is $\left(f_0, p_0 + x + y - z + q + r, f_1, p_1 + x + y - z + q + r, \cdots f_m, p_m + x + y - z + q + r \right)$. The power terms then have units of dBm/Hz/m^2.

4.1.3.3 Choosing a Pathloss Model

Both transmitter and receiver models have propagation maps. As a default, the propagation map that implies greater separation of systems, i.e., the one that predicts least attenuation, is used. However, in some cases other criteria dictate the preference for the transmitter's or receiver's propagation map. The following (possible) exceptions to the default appear in the order they should be considered.

1. The receiver model is part of a system that has precedence over the system that provides the transmitter model. In this case, the propagation map of the receiver shall be used for propagation computations.
2. One component is stationary and the second is mobile and operates in a location that does not intersect with the stationary component. The propagation map of the stationary component has precedence.
3. A receiver is modeled to operate on a surface location with a specified antenna height and the transmitter SCM uses antenna height-rated propagation maps and comparably higher power, ≥10 dB more than the maximum power spectral flux density that the receiver's transmitter emits. In this case, use the transmitter's propagation map.

4.1.4 Power Margin Between a Spectrum Mask and an Underlay Mask

A spectrum mask specifies the spectral and relative power bounds of a transmitted signal, while an underlay mask specifies the limit to interference as a function of frequency and relative power. Actual powers in both cases are a function of other constructs used in modeling, as described in Section 4.1.3. However, in relative terms, these masks, by themselves, allow modelers to compute a power margin. A power margin may be computed using a spectrum mask and an underlay mask in their original form or in the scaled form described in Section 4.1.3. In the former case, the power margin conveys the amount of attenuation necessary between the interfering transmitter and the receiver to achieve compatibility. In the latter case, the power margin conveys whether the transmitter and receiver are compatible.

In many cases the evaluation of compatibility must consider the interference at a receiver from multiple concurrent transmitters. The approach to assessing compatibility in this scenario differs by the computational method specified for the underlay mask.

There are multiple types of masks. Transmitter models may have a spectrum mask for a signal that is continuous, pulses, or frequency hops. Receiver models may have underlay masks that are rated for interferer bandwidth, frequency hopping, or DC. In cases where receiver models have multiple types of underlay masks, part of the power margin computation involves determining the specific underlay mask to use.

4.1.4.1 Methods of Computing Power Margin

Modelers can use two fundamental methods to compute the power margin from the interaction of a spectrum mask and an underlay mask: the total power method and the maximum power density method. The modeler identifies in the underlay mask construct the method to be used with the underlay mask. The method affects the assessment of aggregate interference from multiple signals, as discussed in Section 3.1.3.4. Particular criteria govern the use of the bandwidth, BTP, and DC-rated masks, but all of these masks specify one of these two methods for computing a power margin. The methods described in the rest of this section repeat descriptions in Section 3.1.3.4 but are repeated and organized to clarify the procedures used.

4.1.4.1.1 Total Power Method of Computing Power Margin

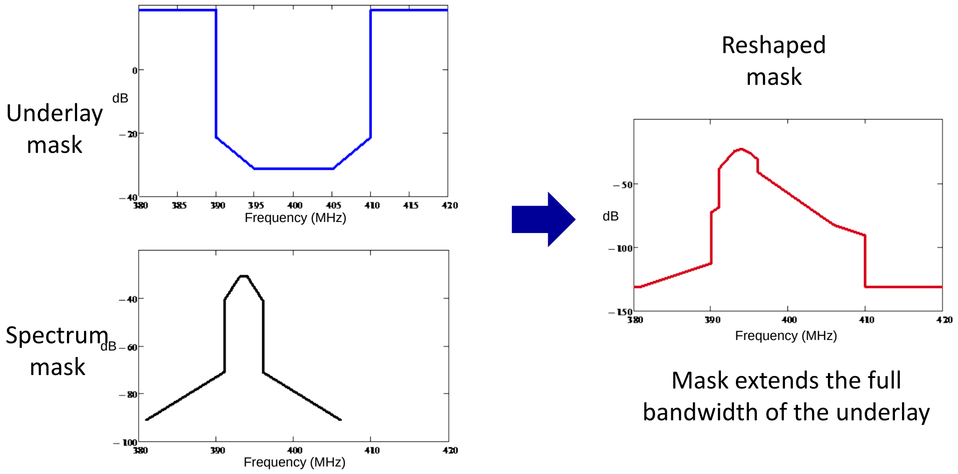
In the total power approach, the modeler uses the shape of the mask to convey the attenuation that the receiver filter performs on arriving signals and uses the power levels of the mask to convey the total amount of power of the allowed interference. The total power approach to determine power margin has four steps:

1. Determine the interference the underlay mask permits.

   The power that an underlay masks permits is specified as the total power within the lower 3 dB bandwidth of the underlay. Determining this value involves identifying the part of the mask that is within the 3 dB band and integrating across that part of the mask for the total power. The typical 3 dB bandwidth underlay mask will have the form $\left(f_0, p_l+3, f_1, p_l, f_2, p_l, f_3, p_l+3\right)$. All segments of underlay masks are linear. Given two consecutive inflection points, $\left(f_1, p_1\right)$ and $\left(f_2, p_2\right)$, $f_1 < f_2$, the equation for the line is $p = b_0 + b_1 f$ where $b_1 = \frac{p_2 - p_1}{f_2 - f_1}$ and $b_0 = p_1 - b_1 f_1$. The total power under the segment is determined in the linear scale and so within the segment between f_a and f_b, $f_1 \le f_a < f_b \le f_2$, is $p = \int_{f_a}^{f_b} \frac{10^{\frac{b_0+b_1 f}{10}}}{RBW} df$. For segments where $b_1 \ne 0$ and $f_a < f_b$, $p = \frac{10}{RBW \cdot \ln\left(10\right) \cdot b_1} \cdot 10^{\frac{b_0+b_1 f}{10}} \Big|_{f_a}^{f_b}$, where $b_1 = 0$ and $f_a < f_b$, $p = 10^{\frac{b_0}{10}} f \Big|_{f_a}^{f_b}$, and where $f_a = f_b$, $p = 0$. Given multiple computed powers from multiple line segments, the allowed interference, $p_{allowed\_interference}$, in dB (or dBm if link budget scaled masks are used) is specified as $p_{allowed\_interference} = 10 \cdot \log\left(p_0 + p_1 ... + p_x\right)$.

2. Adjust the shape of the interfering spectrum mask based on the shape of the receiver underlay mask.

   The underlay mask reshapes the interferer's spectrum mask. The underlay mask specifies a filter that adjusts the spectral power density of the interfering signal. The new mask extends to the full bandwidth of the underlay mask. Each inflection point in this new mask matches one of the inflection points in either the underlay mask or the spectrum mask. The power adjustment made to the spectrum mask is the difference in power of the underlay point at the specified frequency and the lowest power value of the underlay mask. Say the lowest power of the underlay is p_l. and the power of the underlay at f_1 is p_1. Let ps_1 indicate the power of the spectrum mask at f_1. The new power of the spectrum mask at f_1 after the adjustment is $\left(ps_1 + p_l - p_1\right)$. For the points within the underlay mask but outside the original spectrum mask, the points are added and the power levels are derived by determining the adjustment the underlay mask dictates for those frequencies, but are applied to the power levels at the end inflection point of the original spectrum mask.


Underlay mask

Spectrum mask

Reshaped mask

Mask extends the full bandwidth of the underlay

Figure 4-2. Graphical Example of an Underlay Mask Shaping a Spectrum Mask

Figure 4-2 provides a graphical example of reshaping the underlay mask. Each inflection point of both the original spectrum mask and the underlay mask is part of the newly shaped spectrum mask. The difference between the lowest power of the underlay mask and the power at a particular frequency in the underlay mask determines the attenuation at that frequency between the original spectrum mask and the reshaped spectrum mask. The reshaped spectrum mask has the same bandwidth as the underlay mask. In the cases when it covers frequencies outside those covered by the spectrum masks, reshaping uses that power value at the closest frequency of the spectrum mask as the power to adjust in the frequency extension of the mask.

3. Compute the total power in the reshaped spectrum mask.

   Given this new, reshaped spectrum mask, the third step is to determine the total power within the mask. This power is determined by integration: a closed form computation that accumulates the power for each line segment of the spectrum masks in the same manner as described above for determining the total allowed interference power. Given powers for all the segments of the reshaped mask, $\left(p_0, p_1, p_2, \ldots, p_x\right)$, the total interference power is $p_{interference} = 10 \cdot \log\left(p_0 + p_1 \ldots + p_x\right)$. These power values have units of dB for unscaled masks and dBm for link budget scaled masks.

4. Find the difference between the total power of the reshaped spectrum mask and the allowed interference specified by the underlay mask. (When these operations are performed on unscaled masks, the power margin indicates how much the interfering signal must attenuate through transmission, propagation, and reception. When these operations are performed on the link budget scaled spectrum and underlay masks, the power margin indicates if the two models are compatible. $PM_{mask} \le 0$ dBm indicates compatibility.)

   The final step is determining the power margin from the masks. PM_{mask}. The power margin determined from the spectrum and underlay mask, PM_{mask}, is the difference between the interference power predicted by the interaction of the masks and the allowed interference permitted by the underlay mask, $PM_{Mask} = p_{interference} - p_{allowed\_interference}$.

4.1.4.1.2 Maximum Power Spectral Density Method of Computing Power Margin

In the maximum power spectral density method, an interfering signal is compatible with an underlay mask if its power levels are above those of the spectrum mask. Figure 4-3 illustrates several instances of acceptable interfering signals as determined by an underlay mask. Before this assessment can be made the analyzer must convert both the underlay mask and the interfering signal's spectrum mask to the same resolution bandwidth. The power margin is the power adjustment that must be made to the spectrum mask so that it just touches the underlay mask. If a spectrum mask and an underlay mask occupy any portion of the same spectrum, then after adjustment they will meet at one of their inflection points. This observation allows us to limit the computation for determining power margin to the inflection points. The minimum adjustment across the overlapping inflection points that causes the two masks to meet is the power margin.

Figure 4-4 shows a graphical example of the method. Comparing the right to the left panel we see that the spectrum masks is 8.56 dB above the underlay mask (measured as the adjustment necessary to cause the spectrum mask to just touch the underlay mask), so the power margin is 8.56 dB. When the power margin is computed using the link budget adjusted spectrum and underlay masks, the two are compatible if the $PM_{mask} \le 0$ dBm.

The maximum power spectral density method is indifferent to the number of interfering transmitters. Each is compatible if it meets the criteria of the underlay mask.

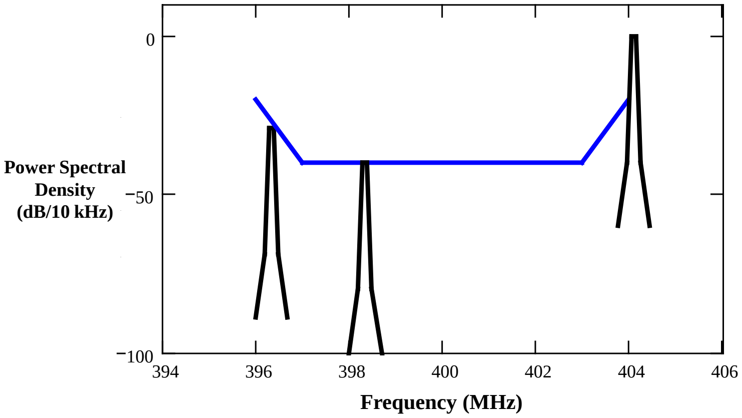


Figure 4-3. Compatible Interfering Signals Given an Underlay Mask that Specifies the Maximum Power Spectral Density Method for Arbitrating Compatibility

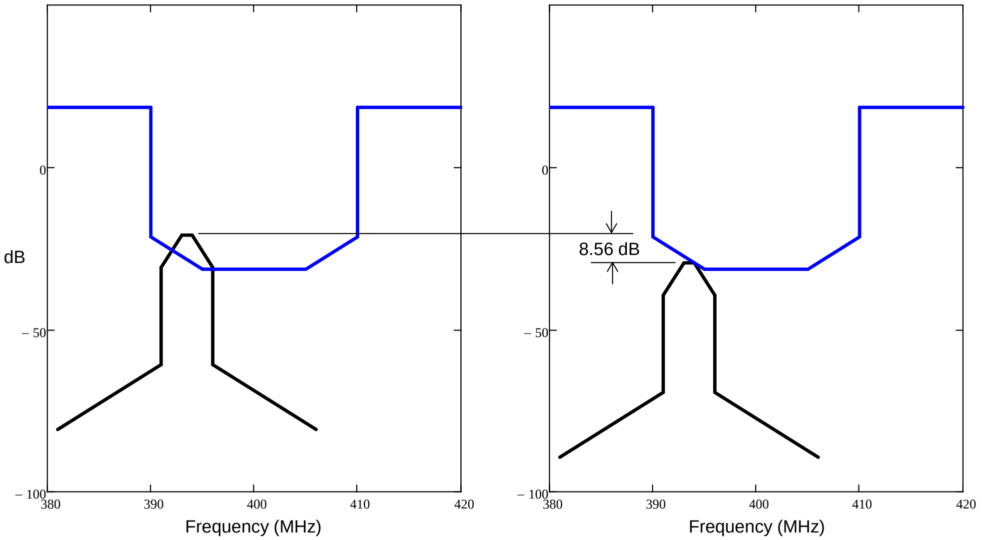


Figure 4-4. Graphical Example of Determining Power Margin Using the Maximum Power Density Method

4.1.4.1.3 Evaluating the Compatibility When There Is a Common Policy or Protocol

When a transmitter model is specified with a policy or protocol, then if the system has a receiver model with a common policy or protocol, that model is used for assessing the compatibility of the receivers in the system as opposed to any of the rated underlay masks. This receiver model specifies the method to use in computing the power margin.

4.1.4.1.4 Determining the Compatibility of Multiple Interferers Using Their Total Interference Power

Power margin computations allow analysts and management systems to determine the contribution of the masks' portions of models for larger link budget computations to calculating compatibility between models. These computations can be performed at any time prior to the final determination. In cases where interference involves multiple signals arriving at a receiver, there is no single power margin. Rather, assessments must consider whether the collection of arriving signals is compatible or not. In these computations, the analysis first considers the effects of the other constructs to determine the appropriate link budget-scaled masks at the point of interest. These link budget-scaled masks allow the computation of power margin for each pair of systems. Given a receiver that experiences interference from multiple transmitters for which each interference power, $p_{allowed\_interference\text{-}i}$, is known, the receiver is compatible with the collection of interfering transmitters if $10 \cdot \log\left(\sum_{i=0}^{n} 10^{\frac{p_{interference\text{-}i}}{10}}\right) - p_{allowed\_interference} \leq 0 \text{ dBm}$.

4.1.4.1.5 Using Bandwidth-Rated Masks

The bandwidth-rated masks enable a similar approach to accommodating higher power spectral densities when there are narrowband interfering signals for masks that use the maximum power density method of power margin computation. 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. Figure 4-5 illustrates an example of this bandwidth determination for a pair of signals.

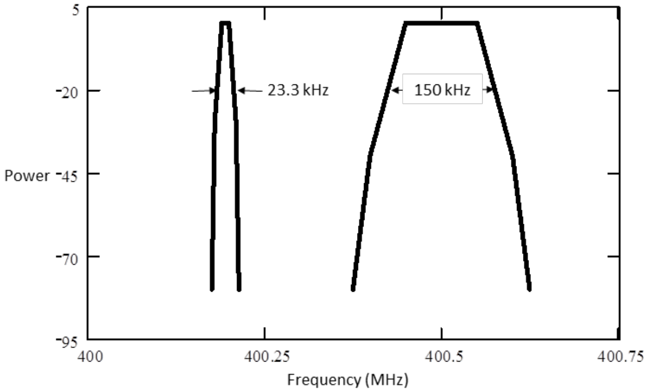


Figure 4-5. Example Measurements of Narrowband Signal Bandwidth

When computing the compatibility of multiple narrowband signals, modelers can ignore any signal beneath the full bandwidth underlay mask. In the case of multiple signals, the effective bandwidth is the sum of their bandwidths. The maximum effective power spectral density (EPSD) is a normalized power spectral density of the collection of signals determined by the following equation.

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

If both the effective bandwidth (i.e., the sum of the bandwidths) and the EPSD are 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 masks should be adjusted to the bandwidth of the next highest bandwidth underlay and a bandwidth-adjusted EPSD (BAEPSD) is computed for use with this underlay mask. This spreads the power density to that of the bandwidth of the underlay mask.

$$BAEPSD = 10 \cdot \log_{10}\left(10^{\frac{EPSD}{10}} \cdot \frac{\sum_x BW_x}{BW_{mask}}\right) \quad BW_{mask} > \sum_x BW_x$$

A use is acceptable if the BAEPSD is less than the restriction of an underlay mask with a reference bandwidth larger than the effective bandwidth. Note that when an underlay mask has multiple levels, 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.

Using multiple bandwidth-specific underlay masks enables modelers to compute differences in allowed interference based on the bandwidths of signals – a method that simplifies compatibility computations simple. At present, no theory exists that would form the basis for creating these underlay masks and constructing such a theory would likely require experiments with the modeled equipment.

4.1.4.1.6 Evaluating the Compatibility of Low Duty Cycle Signals

Modelers may use either the DC-rated underlay masks or the BTP-rated underlay masks to capture a greater tolerance to the power of interfering signals when they occur briefly and have narrow bandwidth. The DC-rated masks use the total power method of determining power margin and the BTP masks use the maximum power density method. Compatibility computations in these cases start by verifying that the combination of interfering signals meets the DC and maximum dwell time limits of DC-rated underlay masks or the BTP rating of bandwidth-time-rated underlay masks. If so, the next step is to assess whether the power levels of the signals meet the power thresholds specified by the underlay mask.

Frequency-hop-rated spectrum masks of interfering systems provide the characteristics of signals that allow modelers to compute the DC and determine whether the maximum dwell time constraint is met. The DC is the average fraction of time that a signal is present within the bandwidth of the underlay mask. The dwell time comes directly from the spectrum mask. When multiple frequency- and time-hopping signals arrive at a receiver we assume that they do not overlap in time, and so the effective DC is the sum of their DCs and the effective dwell time is the sum of their dwell times. Since frequency hopping is generally random, the assessment of the total power of interference uses the signal with least attenuation from the underlay mask as the representative signal to determine the power of the interference.

Example: Determining which duty cycle rated masks to use and the power level of interference to the receiver

This example scenario considers the interference of two frequency hopping systems with the following spectrum masks on a third system with the underlay masks described below and illustrated in Figure 3-15a. Frequencies are in MHz.

System 1

Spectrum mask: (-0.0125, -20, -0.0075, 0, 0.00750, 0, 0.0125, -20)
Frequency list: (790.0125, 790.0375, 790.0525, … , 794.9875) (i.e. signals spaced every 25 kHz starting at 790.0125 MHz and ending at 794.9875 MHz)
Resolution bandwidth: 10 kHz
Dwell time: 10 μsec
Revisit time: 5 msec
Reference power spectral flux density: -52 $\frac{\text{dBm}}{\text{Hz}\cdot\text{m}^2}$

System 2

Spectrum mask: (-0.025, -20, -0.020, 0, 0.020, 0, 0.025, -20)
Frequency band list: (790.0,797.5, 800.0, 805.5, 810.0, 815.0)
Resolution bandwidth: 10 kHz
Dwell time: 25 μsec
Revisit time: 1.0 msec
Reference power spectral flux density: -75 $\frac{\text{dBm}}{\text{Hz}\cdot\text{m}^2}$

The receiver underlay mask is (-785, -58, 792, -58, 793, -98, 797, -98, 798, -58, 805, -58) where frequencies are in MHz and power terms are in $\frac{\text{dBm}}{\text{Hz}\cdot\text{m}^2}$ with the following duty cycle ratings (0.05, 50 μsec, 18, 0.02, 20 μsec, 43). Figure 3-15a illustrates these underlay masks.

The first step in determining compatibility is to determine if the duty cycle and dwell time criteria are met. System 1 meets the dwell time criteria of both duty cycle rated masks and System 2 meets the dwell time criteria of the 5% duty cycle rated mask only. The combination of System 1 and System 2 is also within the 5% dwell time criteria.

The duty cycle of a system with respect to a receiver is a function of its dwell and revisit time.

4.1.4.1.7 Evaluating the Compatibility of Frequency Hopped Signals

Frequency-hop rated spectrum masks of interfering systems provide the characteristics of signals that allow the computation of the BTP. 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 BTP 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 to 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 one bandwidth 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 BTP of a collection of frequency-hop signals is the sum of their BTPs. In the case of multiple frequency-hop signals, no effective bandwidth power is computed. The BTP of a collection of frequency hop signals determines the mask to use. The BTP masks only use the maximum power spectral density power margin computations. When the sum of the BTPs of multiple systems complies with a particular underlay mask then the next assessment is to ensure the signals of each of the systems have a power density less than that specified by this underlay mask. If the signals of systems meet this power criterion, then the combination is compliant.

4.1.4.2 Selecting the Appropriate Underlay Mask

When receiver models provide multiple underlay masks, it becomes necessary to select the underlay mask that applies to a particular transmitter model. The following list provides the precedence for selecting the underlay mask to use when one transmitter or one receiver interact.

1. When the transmitter model specifies a policy or protocol and a receiver model has an underlay mask with a common policy or protocol specified, then use that underlay mask.

2. When a transmitter model indicates that a signal pulses either because it hops or is just infrequent (as would be the case with a radar), first determine if a receiver model has DC-rated masks and assess whether the signal meets the criteria of an underlay mask; i.e., the DC is less than the DC of the underlay mask and the largest dwell time is less than the maximum dwell time of the underlay mask. If the receiver has multiple DC-rated underlay masks, use the underlay mask that has the largest minimum power spectral density level at which the criteria can be met.

3. When a transmitter model indicates that a signal pulses or hops as above and a DC-rated mask cannot apply, then determine if the receiver model has BTP-rated underlay masks. If so, check if the BTP of interfering signal meets the criteria of one or more of the underlay masks. If the receiver has multiple BTP-rated underlay masks, use the underlay mask that has the largest minimum power spectral density level at which the criteria can be met.

4. When the transmitter model has a smaller bandwidth than the receiver model, determine if

the receiver model has bandwidth-rated underlay masks. If so, check if the bandwidth of the transmitted signal meets the criteria of one or more of the underlay masks. If the receiver has multiple bandwidth-rated underlay masks, use the underlay mask that has the largest minimum power spectral density level at which the criteria can be met.

5. When none of the transmitter models can meet the criteria of the rated underlay masks or there are no rated underlay masks, use the unrated underlay mask to determine compatibility.

When interference arrives at a receiver from multiple transmitters, the same rules and precedence apply, but modelers must assess whether the combined effects of the transmitters would meet the criteria of the rated underlay mask used. Thus, this type evaluation would start with assessing whether the combined signals form a low-DC signal or a frequency-hopped signal, or would still combine and be considered a narrowband signal. These methods are described in Section 4.1.4.1.

4.1.5 Assessing Image Frequency and Intermodulation Effects

IM masks capture both image frequency and IM effects. Most radios designs that use heterodyning concurrently select front-end filters and an IF that prevent image frequencies in the bands where they operate, and so the susceptibility to image frequency interference is not modeled. In cases where it is modeled, the modeler indicates this vulnerability and the analysis of interference includes the channel being modeled by the underlay mask and then the channels that fall within the image of the underlay mask as reflected on the opposite side of local oscillator frequency.

IM effects involve the interaction of two or more devices to cause interference at yet another device. The source of the IM is distant from the victim in the case of transmitter IM and is the victim of the interference in the case of receiver IM. The combinatorics that can be involved with arbitrating IM could make arbitrating compatibility among a plurality of devices computationally intensive. Fortunately, IM is usually a problem for high-power transmitters (e.g., commercial broadcasters) or for transmitters and receivers that are close to each other. To consider IM in the SM problem first requires that it be modeled. In the case that the condition would normally require devices to be in close proximity for IM to be an issue, the modeler assists in the reduction of computations by identifying locations where the evaluation should be limited using the platform construct. Thus, IM is evaluated at all high power transmitters with IM masks and for all other systems with IM modeled when devices are co-located at the same platform. The criteria for a high power transmitter would be the lower of that established by the SM enterprise or by the local regulating administration. Parts of this section repeat descriptions in Section 3.1.6.4 and present them again to clarify the procedures used to evaluate IM effects.

4.1.5.1 Power Margin with Receiver Intermodulation Masks That Indicate Susceptibility to Image Frequencies

Computing compatibility for an IM mask of a superheterodyne receiver starts by determining the bands in which image frequencies occur. This determination uses the information in the IM mask and in the receiver's underlay mask. The combination of the intermediate frequency, f_{IF}, and injection side, high or low, in the underlay mask, and the center frequency, f_c, of the passband of the underlay (i.e., either the frequency at the point of the lowest power level of the mask or the center of the region with the lowest power) provides the frequency of the local oscillator, f_{LO}:

$$f_{LO} = \begin{cases} f_c - f_{IF} & \text{if } f_{IF} < f_c \left(\text{Low side injection}\right) \\ f_c + f_{IF} & \text{if } f_{IF} < f_c \left(\text{High side injection}\right) \\ f_{IF} - f_c & \text{if } f_{IF} > f_c \left(\text{Low side injection}\right) \\ f_c + f_{IF} & \text{if } f_{IF} > f_c \left(\text{High side injection}\right) \end{cases}$$

The intermediate frequency is usually below the center frequency. For completeness, we describe the case where it is not. The center frequency of the image is on the opposite side of the local oscillator.

$$f_{image} = \begin{cases} f_{LO} - f_{IF} & \text{if } \left(\text{Low side injection}\right) \\ f_{LO} + f_{IF} & \text{if } \left(\text{High side injection}\right) \end{cases}$$

The frequencies of interest are those within the total bandwidth of the underlay mask shifted in frequency and centered at the image frequency. The attenuation specified by the IM mask is applied to these signals before determining the level of interference they cause.

There are two approaches to computing the compatibility of signals within the band of image frequencies of a receiver. The first is to identify the band of the image frequencies and then to translate the signals present in that band to the frequencies of the underlay mask. The IM mask is applied to these image signals prior to their translations. The equations for this translation are:

$$f_{underlay} = 2 \cdot f_{LO} - f_{image}$$

This translation causes the arriving signals to be their reflection in the underlay. If this is done for each inflection point of an image signal mask, the new mask will be a reflection of the previous mask.

The second and easier approach is to translate the underlay mask to the image frequency and to reshape it to account for the effects of the IM mask, thus creating an image underlay mask. Figure 4-6 illustrates an example. The underlay mask of the receiver model is illustrated on the right. The underlay mask for the image frequencies is reflected about the local oscillator frequency and appears on the left. The shape of the IM masks increases the rate of attenuation of the underlay mask on its left edge.

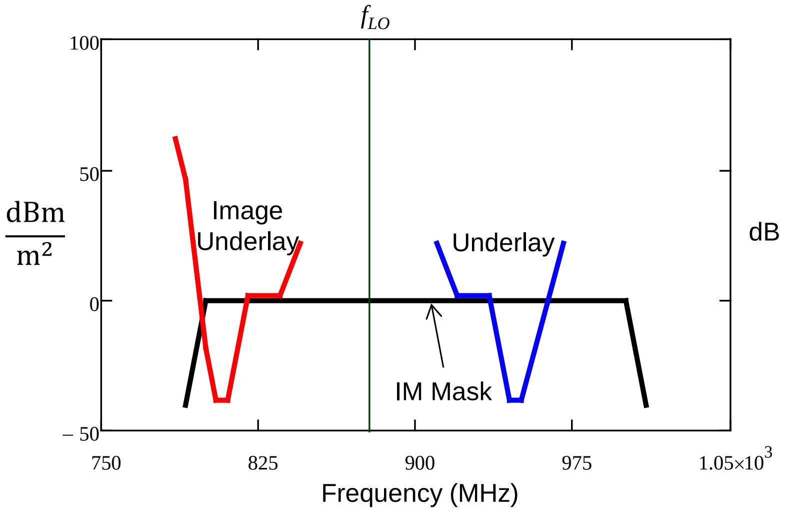


Figure 4-6. Example of Creating an Image Frequency Underlay Mask

4.1.5.2 Power Margin with a Transmitter Intermodulation Mask

Transmitter IM consists of the IM product of the transmitted signal and other signals that arrive at the transmitter antenna. An IM product is interesting if the distant signal falls within the bandwidth of the IM combining (IMC) mask and the IM product falls within the bandwidth of the IM amplification (IMA) mask. The power of the transmitter's signal is dominant in determining the power of the IM product. For modeling and compatibility computation purposes, the transmitted signal input to intermodulation is the scaled spectrum mask at the one-meter point from the transmitter. This is the transmitter's spectrum mask scaled by the model's total power and power map constructs. The distant transmitter input is the link budget-scaled mask at the location of the transmitter where IM occurs. This is the same link budget-scaled spectrum mask that would be used for assessing interference at a receiver at the same location. It includes the scaling from the total power and power map constructs, and propagation using the appropriate model indicated by the propagation map construct and the separation distance between the two transmitters. Given these two inputs, the computation of the IM product that is transmitted has three steps:

1. Reshape the arriving signal by the IMC mask.

   The IMC mask shapes the scaled spectrum mask of the signal that arrives at the transmitter. The power levels of the spectrum masks are adjusted according to the power levels of the IMC mask. The shaped signal only includes the portion of the signal in the frequencies covered by the IMC mask. The portion of the spectrum mask the lies outside this range is truncated from the shaped spectrum mask.

   For example, assume the spectrum mask of the arriving sign is $(f_0, p_0, f_1, p_1, f_2, p_2, f_3, p_3)$, the IMC mask is $(f_{I0}, p_{I0}, f_{I1}, p_{I1}, f_{I2}, p_{I2}, f_{I2}, p_{I2})$, and $f_0 < f_{I0} < f_1 = f_{I1} < f_2 < f_3 < f_{I2}$. The shaped spectrum mask would be

   $$\left(f_{I0}, \left(\left(\frac{f_{I0}(p_1-p_0)}{f_1-f_0}\right)+p_{I0}\right), f_1, (p_1+p_{I1}), f_2, \left(\left(\frac{f_2(p_{I2}-p_{I1})}{f_{I2}-f_{I1}}\right)+p_2\right), f_3, \left(\left(\frac{f_3(p_{I2}-p_{I1})}{f_{I2}-f_{I1}}\right)+p_3\right)\right).$$

2. Combine the signals that are intermodulated.

   Combining masks that intermodulate with each other involves an approximation. The combined signal is assumed to have the sum of the bandwidths of the two masks. The approximation of the combining uses up to four points of each mask: the two end points and then the two highest power points of each spectrum mask. Each point of one mask is paired with a corresponding point in the second mask and their power and frequencies are combined. Consider the two masks $(f_{a0}, p_{a0}, f_{a1}, p_{a1}, f_{a2}, p_{a2}, f_{a3}, p_{a3}, f_{a4}, p_{a4}, f_{a5}, p_{a5})$ and $(f_{b0}, p_{b0}, f_{b1}, p_{b1}, f_{b2}, p_{b2}, f_{b3}, p_{b3})$. The first mask has more than four points with the two highest power terms being p_{a2} and p_{a3}. In the combining process we would use the mask $(f_{a0}, p_{a0}, f_{a2}, p_{a2}, f_{a3}, p_{a3}, f_{a5}, p_{a5})$. If the IM product is a sum of the two signals the combining is performed pairwise between each ordinal point in the two masks. The mask of the IM product would be

   $$((f_{a0}+f_{b0}),(p_{a0}+p_{b0}),(f_{a2}+f_{b1}),(p_{a2}+p_{b1}),(f_{a3}+f_{b2}),(p_{a3}+p_{b2}),(f_{a5}+f_{b3}),(p_{a5}+p_{b3})).$$

   If the IM product is a difference, then the frequencies of the points of the spectrum mask of the subtracted signal are subtracted in reverse order from the first, their powers are added, and the combined signal becomes

$$\left(\left(f_{a0}-f_{b3}\right),\left(p_{a0}+p_{b3}\right),\left(f_{a2}-f_{b2}\right),\left(p_{a2}+p_{b2}\right),\left(f_{a3}-f_{b1}\right),\left(p_{a3}+p_{b1}\right),\left(f_{a5}-f_{b0}\right),\left(p_{a5}+p_{b0}\right)\right).$$

When higher order IM occurs, this process is repeated for each pair. For example, if the signals S_1 and S_2 are combined into the third-order IM product, $2S_1 - S_2$, then the two signals S_1 and S_1 would be combined to create $2S_1$ and then $2S_1$ would be combined with S_2 to form the final product.

3. Amplify the signals intermodulated by the output IM mask.

   The last step is to shape the IM product by the output IM mask. This operation is performed exactly like the shaping done with the input IM mask.

The output of this process is the signal at the transmitter where IM occurs. Assessing whether the IM product is harmful requires determining if it interferes with any distant signal operating in the same band of the IM product.

4.1.5.3 Power Margin with a Receiver IM Mask

In receiver IM, multiple arriving signals mix within a receiver and create the IM product. Rather than use an input and an output IM mask, receiver IM only uses one mask: an input IM mask. Each receiver input IM mask is rated for a particular IM order. The arriving signals of interest are those that fall within the bandwidth of the input IM mask. The IM products of interest are those that fall within the bandwidth of the receiver underlay mask.

The intermodulating signals that arrive are first shaped by the input IM mask and are then combined. Shaping follows the procedure described in Step 1 of the transmitter IM process and combining follows the procedure described in Step 2.

4.1.6 Meeting Protocol or Policy Criteria

The policy or protocol construct identifies a policy or protocol with a name and a list of parameters. This manual does not define the policy or protocol names and the meaning of the parameters; they can be added as they are developed. It is anticipated that the parameters defined would in turn define particular performance measures. All parties that respond to these policies or protocols will know what they mean. The particular parameters may be specific or could take the form of an upper bound or lower bound on a particular measure of performance. When a receiver model specifies a policy or protocol, it provides a restriction that can only be applied to a transmitter that uses the same policy or protocol with parameters that meet or exceed (less than an upper bound or greater than a lower bound) the measures listed in the receiver model.

4.1.7 Criteria for 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 C 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 perform the computations in a planar approximation than in the actual elliptical representation, and so the planar approximation is the preferred representation. Therefore, when the distance between a primary user's location and that of a second user's location is 200 km or less that a planar approximation should be used. In this section we define how to convert model locations and directions to a planar approximation.

Converting a pair of models to a planar approximation for analysis of compatibility has 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.[12]
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.

4.1.8 Constraining Point

In most cases the models of spectrum consumption will use surface areas or volumes, rather than points, to define the locations of the systems. Given either a surface area or a volume for a transmitter and a constraining receiver, determining the maximum interference that the modeled transmitter causes to the modeled receiver requires identifying the pair of locations of the transmitter and the receiver that result in the greatest interference with the receiver. These points are referred to as the constraining points. If the transmitter and receiver combination is compatible at the constraining points they are compatible for any placement in their respective locations.

Since signals attenuate over distance, if all other factors are equal then shorter distances result in stronger signals. The constraining points will be the closest pair points in the two operating locations. However, the two closest points in the two locations are not necessarily the most constraining when power maps or propagation maps have direction differences. Determining the constraining points is non-trivial and provides opportunity for the development of algorithms and heuristics to accomplish the tasks efficiently. The following is a brute force method for determining constraining points.

1. For both the transmitter and the receiver, combine the effects of the power map and the propagation map to create a new map vector where the values associated with solid angles are the pathloss model and power pairs.
2. Execute a pairwise comparison for 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 then 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.

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[12] The azimuths of the two tangent planes will likely not point to each other at the great circle distance and so the centroids are shifted so that the error in azimuth from one centroid to the other as compared to what it was for the tangent planes is the same regardless of which centroid is the origin.

Step two is the most complex of the computations. 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 toward each other. Others, however, may only be found in subspaces of the two locations. The computation requires identifying the subspace and then the constraining points in those subspaces.

4.1.9 Assessing Aggregate Compatibility

Aggregate compatibility occurs when a receiver is compatible with all possible sources of interference in aggregate. This computation is usually executed in the process of considering whether a new use can be added to a collection of incumbent uses. These computations are necessary when receiver underlay masks use the total power computation method for mask power margin or with bandwidth-rated and BTP-rated underlay masks that use the maximum power density method of computing power margin.

4.1.9.1 Aggregate Interference

Given two models, compatibility requires determining the constraining points between the two models and then verifying that the interference does not exceed the thresholds defined by the models at those points.

The assessment of aggregate interference at a receiver uses an assessment at each of the receiver constraining points of the previous pairwise assessments for the combined interference of the set of interfering transmitters. If the SCM of a transmitter or receiver uses several areas or volumes to define the location of use,[13] then each will have a constraining point relative to the individual surfaces or volumes of another model. All of these constraining points, not just the dominant point of the aggregate location, are assessed to determine the aggregate interference.

It is likely that additional constraining points will have to be determined for the transmitters that cause additional interference at each of these fixed receiver point locations. If the aggregate interference at each receiver constraining point is less than the threshold specified for the receiver then the receiver can tolerate the aggregate interference. For example, say there are two transmitter models, A and B, that interfere with a receiver model and that the constraining points between the receiver and transmitter A are pnt_{RA} and pnt_{TA} and the constraining points between the receiver and transmitter B are pnt_{RB} and pnt_{TA}. A new constraining point for transmitter B would be determined for the operation of the receiver only at pnt_{RA} and the interference from the transmitter B at this point would be combined with the interference from transmitter A from pnt_{TA}. A similar assessment would be made for the combination at pnt_{RB}. The aggregate interference is acceptable if the aggregate interference at each of these points is acceptable.

4.1.9.2 Aggregate Interference with Transmitter IM

Multiple transmitters can combine to create interfering transmitter IM products. When a transmitter model includes a construct for transmitter IM, then assessments are made whether neighboring transmitters create IM products with that transmitter. Assuming they do, the computations of its contribution to interference at distant receivers use all the constructs of the original transmitter model but with the power spectral density of the IM product. The final assessment uses the same process of identifying the constraining points at the receiver and

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[13] Locations constructs must be convex and so to define a non-convex location requires the use of multiple location construct elements.

measuring the aggregate interference at each of these points discussed in Section 4.1.9.1, where one of the interfering signals is the IM product. By this specification, transmitter IM products only occur for high-power transmitters, which are usually stationary, or at devices where all the sources of the IM product are co-located as indicated by the platform computation. These qualifications reduce the number of combinations considered in the evaluation of transmitter IM products.

4.1.9.3 Aggregate Interference at Receivers with Receiver IM

The signals arriving from multiple transmitters may cause IM products at a receiver with an IM mask construct. The aggregate interference assessment includes those transmitter combinations that create IM products in the band of a receiver underlay mask in addition to those operating in the band. This interference assessment uses the constraining point method for determining aggregate interference but with additional constraining points added: one for each transmitter that contributes to an IM product that interferes. Receiver IM usually requires radios to be co-located with the receiver. In this case, the space used for the receiver IM aggregate assessment is limited to the space where this proximity condition applies. That space would then become the space in which the receiver would operate. If it is different from that modeled by the receiver, new constraining points would have to be computed for the distant transmitters that interfere but not for those generating IM products, since they are co-located with the receiver.

4.2 Assessing Compatibility

Modeling spectrum consumption allows a common set of rules and algorithms to be applied to determine the compatibility of spectrum uses or whether spectrum uses can coexist. Section 4.1 provided the rules for the fundamental computations used in determining compatible use of spectrum. This section provides the general rules for assessing whether a new use is possible given an authorization listing or an authorization listing with a constraint listing.

4.2.1 Model Precedence

Spectrum managers establish the precedence of models. If management guidance permits systems to use spectrum by issuing 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 with 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 no explicit guidance is available, it is assumed that incumbent uses have precedence over new uses.

4.2.2 Assessment Process

Compliance with an authorization listing requires that:

- The transmitted signal fall within the spectrum mask
- The power of emission at the transmitter comply with the combined guidance of the total power, spectrum mask, and the power map
- The transmitter only transmit when it is in a location where it is authorized to use the spectrum
- The transmissions fall within the time limits of the authorization

Compliance with a constraint listing requires that:

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

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

1. 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.

2. 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.

Of these two approaches, the first offers more opportunities of finding spectrum to use and greater visibility regarding its suitability, since potential transmitter interference from incumbents conveyed in the constraint listings may be used directly to assess if interference with the proposed secondary use would be unacceptable. The second approach is likely to be used in systems where radios only respond to authorization listings and require a system manager to pre-process the guidance received from a spectrum manager.

The process for arbitrating the compatibility of a new use given the restrictions of authorization and constraining lists follows a sequence of computations that first determines that the use is feasible within the authorization listing, and then determines if it is feasible within the constraints of the SCM of a constraint list, if one is provided.

4.2.2.1 Compatibility with an Authorization List

Compatibility with an authorization list requires that the transmitter SCM of the new use fall within the combined constraints of the total power, spectrum masks, power map, location, propagation map, and time limits. Further, when specified, the transmitter SCM must use the listed policy or protocol of an SCM in the authorization list. Compatibility also demands that the receiver of the SCM be modeled to require no more protection than that specified in the receiver portion of an SCM in the authorization list. The receiver SCM must have a total power, underlay mask, and power map that specifies a power spectral flux density for all frequencies less than that predicted by those constructs in the authorization SCM.

An authorization SCM does not constrain IM characteristics. New users will be expected to model their IM characteristics. IM characteristics may impose restrictions on the new users if IM products caused through the interaction with constraint listing models cause interference at receiver models of the constraint listing. Thus, only constraint list SCMs place restrictions on IM characteristics.

4.2.2.1.1 Determining If One Transmitter Model Falls Within the Constraints of Another

A transmitter model falls within the constraints of an authorization model if:

1. The time limits of the new transmitter model fall within the time constraints of the authorization transmitter model

2. The location of the new transmitter model lies within the boundaries of the location of the authorization transmitter model.

3. The transmitter model specifies a policy or protocol that matches one specified by the authorization transmitter model.

   The restriction only applies if a policy or protocol appears in the authorization model. If no policy or protocol is specified, there is no restriction. The new transmitter model may specify a protocol or policy it will use, but that protocol or policy is not considered in determining compatibility.

4. The power spectral flux density of the model is less than that of the authorization model

   The power spectral flux density is determined by scaling the spectrum mask using the total power and power map of the model. The scaled masks are determined for both the new transmitter model and for the authorization transmitter model. The new use is compatible if, for all frequencies of the two masks, the powers spectral flux density of the new model is less than or equal to that of the authorization model.

5. The propagation map, together with the scaled spectrum mask, predicts a power spectral flux density less than or equal to that predicted by the authorization transmitter model for all frequencies at all locations.

   Putting a propagation map in an authorization transmitter model prevents new users from placing a more strict restriction on the new users who follow them. The less restrictive mask does not affect compatibility computations with a constraining receiver model and potentially allows greater interference than the receiver model allows, since the receiver model propagation map has precedence if it predicts greater separation.

   One propagation map falls within the constraints of another if the power spectral flux density predicted at distant locations for the transmitter model is less than or equal to that of the power spectral flux density predicted by the authorization transmitter model at the same locations. Generally, this can be tested by determining if the pathloss predicted by the new system SCM is greater than or equal to the authorization SCM in all directions. If the location of use is reduced in the new model or if the starting power spectral flux density is less, the propagation model can predict less pathloss as long as the stated power spectral flux density requirement is met.

4.2.2.1.2 Determining If One Receiver Model Falls within the Constraints of Another

A receiver model may not impose constraints on new users that exceed those specified by an authorization receiver model. A receiver model falls within the constraints of an authorization model if:

1. The new receiver model time limits fall within the time constraints of the authorization receiver model.

2. The new receiver model location lies within the boundaries of the location of the authorization receiver model.

3. The receiver model specifies a policy or protocol that matches one specified by the

authorization receiver model or specifies no policy or protocol.

4. The power spectral flux density of the model is greater than or equal to that of the authorization model.

   The power spectral flux density is determined by scaling the underlay mask using the total power and power map of the model. The scaled underlay masks are determined for both the new transmitter model and for the authorization transmitter model. The new use is compatible if, for all frequencies of the two masks, the power spectral flux density of the new model is greater than or equal to that of the authorization model.

5. The propagation map together with the scaled underlay mask predict a power spectral flux density greater than or equal to that predicted by the authorization receiver model for all frequencies at all locations

   Putting a propagation map in an authorization receiver model prevents a new user from placing a more strict restriction on even newer users than the authorization model does.

   One propagation map falls within the constraint of another if the power spectral flux density predicted at distant locations for the receiver model is greater than or equal to that of the power spectral flux density predicted by the authorization receiver model at the same locations. Generally, this can be tested by determining if the pathloss of the new SCM is greater than or equal to that of the authorization SCM in all directions. If the location of use is reduced in the new model or if the starting power spectral flux density is larger, the propagation model can predict less pathloss so long as the stated power spectral flux density requirement is met.

4.2.2.2 Compatibility with a Constraint List

A new SCM is compatible with a constraint list if the transmitter models of the SCM are compatible with all receiver models in the constraint list and if the new user accepts all interference specified by the transmitter models in the constraint list. The new user SCM should have a receiver model that conveys that interference, even if the receiver model underestimates the actual susceptibility of the receiver being modeled.

4.2.2.2.1 Determining If a Transmitter Model Is Compatible with a Collection of Constraint Models

A new transmitter model is compatible with the SCM of a constraint list if, for every receiver model in the constraint list, either condition 1 or 2 below applies or the combination of conditions 3, 4, and 5 below applies.

1. The new transmitter model time limits fall outside the time constraints of the receiver model.

2. The new transmitter model does not have an IM mask and has a spectrum mask that falls outside the bandwidth of the receiver model underlay mask and, if modeled, the IM mask bandwidth.

3. The new transmitter model does not cause interference that exceeds the constraints specified by the receiver model underlay mask either individually or in aggregate with other transmitter models in the constraint list. Alternatively, if it only interferes individually with a receiver model, it uses a protocol or policy specified by that receiver model as allowing compatibility.

4. The new transmitter model does not generate transmitter IM products with other transmitter models in the constraint list that cause interference that exceeds the constraint specified by the receiver model underlay mask either individually or in aggregate with other transmitter models in the constraint list.

5. The new transmitter model does not generate receiver IM products with other transmitter models in the constraint list that cause interference at receivers in the constraint list with receiver IM models.

4.2.2.2.2 Determining If a Receiver Model Is Compatible with a Collection of Constraint Models

A new receiver model is compatible with the SCM of a constraint list if the receiver model is compatible with every transmitter model or combination of transmitter models in the constraint list. A receiver model is compatible with a transmitter model if:

1. The new receiver model time limits fall outside the time constraints of the transmitter model.

2. The new receiver model has neither an underlay mask nor a receiver IM mask that falls within the bandwidth of the transmitter model spectrum mask or of the transmitter model output IM mask.

3. The power spectral flux density of the individual transmitter model, in aggregate with any other transmitter model and any IM product, does not exceed the interference thresholds of the receiver model.

4. The receiver model specifies a policy or protocol and the transmitter model uses the same policy or protocol and the combination meets criterion 3 above. (A receiver model with a policy or protocol provides no other allowance. It is anticipated that systems will have a complementary unrated mask with a greater restriction on transmitter power spectral flux density levels.)

4.2.3 Using Probabilities and Confidence

Probability is used to specify confidence in the boundaries inferred by the constructs of a model. Models may articulate any number of submodels at different confidence levels, but must always provide a cumulative set of models that captures the full confidence of the use, i.e., no use is outside the boundaries of the submodels. From the modeler's perspective, probabilities offer a means to qualify judgment in modeling, e.g., confidence regarding where mobile RF components will be used or the expected intensity of use sometime in the future, the likelihood that particular environment effects will dominate, or the consistency of the performance and behavior of the devices. From the spectrum manager's perspective, probabilities offer a means to capture softer boundaries that enable more spectrum reuse when systems might be able to tolerate some amount of interference or when interference is only a remote possibility. Modeling with probabilities can also assist spectrum managers to mitigate interference when the availability of spectrum demands that multiple RF systems or networks share it.

Arbitrating compatibility between spectrum uses, however, still requires a clear and unambiguous boundary for a decision. By default, worst case interference predicted by a set of models determines that boundary. Using the softer boundaries enabled by the probability construct requires a concurrent agreement among parties on what that boundary should be. It may be part of a negotiated service level agreement (SLA) between users of spectrum, it may be dictated by regulation or by executive order across an enterprise, or it may be required because the availability of spectrum will not support the more conservative arbitration and still provide the quantity of assignments.

Modelers may also use probability to convey their acceptance of interference or to provide insight into the variability in the interference they may cause. The publication of this information is non-binding and may alert secondary users to constraints on their use that they could tolerate. The two parties can then negotiate and create an SLA. However, without a corresponding SLA, the computation of compatibility is based on the worst case conditions across the full breadth of possible spectrum use.

The output of a negotiated SLA is a set of SCMs that the parties agree capture their use of spectrum and the protections they demand. The SCMs would be complemented by a probability of interference based on the persistent states of the SCMs. These SCMs must interfere less than the specified probability. Because parties could easily game this process, SLAs are likely to include additional information beyond that in the SCMs that address enforcement and arbitration of disputes. These exceed the scope of this manual. Here we describe how SCMs are assessed for compatibility.

The assessments of compatibility among models that use probability assume the models are independent. The probability that one model will assume a particular state is not modeled on the presumption that an interfering model will be in a state that causes it to move to that state.

4.2.3.1 Probability Attributes

The probability attributes clarify what is probable and how the probability of the different states has become known.

4.2.3.1.1 Approach

The probability approach is either alternative or cumulative. The alternative probability identifies the probability that one among several alternative models will capture the performance of the system. The sum of the probabilities of all alternatives must be 1.0. The cumulative probability identifies the probability that a particular model captures all of the possibilities. Higher probability cumulative constructs subsume the lower probability constructs of the same model. One of the cumulative probability constructs will have a probability of 1.0 and will subsume all other smaller probability constructs of the same type in the same model.

In constructs using probability elements with the cumulative approach attribute, the model specifies that the use beneath the boundary of the construct would occur with the specified probability. The difference between the probabilities of two models of probability p_1 and p_2, $p_2 > p_1$, $\left(p_2 - p_1\right)$, indicates the probability that the use is above the boundary of the construct with probability p_1 and less than the boundary of the construct with probability p_2.

4.2.3.1.2 Nature

A probability can have either a fleeting or a persistent nature. One or the other is used in all constructs of the same type in a model. A fleeting nature implies a brief, stochastic presence. In models using the alternative approach, the model specifies that the use of spectrum shifts among the alternatives that spend a fraction of their time in each alternative state. A fleeting dwell time is provided in models when using the fleeting nature. This dwell time indicates the maxiumum duration of a fleeting event. Underlay masks that use a fleeting nature may specify a maximum signal duration at a power level in order for it to be considered fleeting. If a probabilistic state last longer than this threshold, it is treated as a persistent state in assessing compatibility.

A persistent nature indicates the probability that the use moves to within the boundaries of the construct and that it stays there. Thus, in the alternative approach, a probability with a persistent nature measures the likelihood that one or the other of the constructs captures the behavior and does so continuously. In the cumulative approach, a probability with a persistent nature measures the likelihood that the use moves to and stays within the space of the construct. Similarly, the probability that the use moves to the state between two cumulative probability constructs of the same model is the difference between their probabilities.

4.2.3.1.3 Derivation

The derivation attribute indicates how a probability value was determined. There are three values: judgment, estimated, and measured. Derivation can be an important consideration in the resolution of an SLA, but has no effect on the computation of compatibility. Parties may not agree to probabilities that are mere judgments. Negotiations may require that modelers back up probabilities based on measured use or theoretical estimation by the sharing the data or analysis that yielded the particular values. The methods and data models for those exchanges exceed the scope of this manual.

4.2.3.1.4 Attribute Meaning in SLAs

SLA negotiations consist of owners and secondary users of spectrum exchanging SCMs until their models are compatible. The spectrum owners specify the amount of interference they are willing to accept, the nature of that interference, and the probability of its occurrence. Their SCMs specify the boundaries for the allowed interference, and additional probability values indicate the acceptable probability that the interference from secondary users exceeds those boundaries. Spectrum owners provide probability values for both fleeting and persistent interference, and may specify that one or both of these probabilities be zero. Fleeting probability values are more likely because they can be verified in operations. The use of a non-zero persistent probability value of interference requires trust among the parties because persistent probability values indicate the probability that a system will arrive at a state as opposed to being in a state. It is impossible to measure compliance.

The computation of compatibility between SCMs using constructs with probability measures differs for the determination of interference of a fleeting or persistent nature. If the persistent value of allowed interference for an agreement is zero and persistent probability values are used with the model constructs, compliance computations will use the interference that occurs with the worst case persistent states as the criteria for compliance, regardless of how rare they might be. If the SLA includes a non-zero persistent probability, then persistent states that result in unacceptable interference are weighted by their probability of occurrence. The assessment considers all possible combinations of states between a pair of models. It computes the probability of the occurrence of each combination of states, determines whether the combinations are compatible, and sums the probabilities of those combinations that are not. If the sum of the probabilities of all states in which unacceptable interference occurs is less than the persistent probability value of the SLA, then the SCMs are compatible.

Generally, each party in a negotiation builds its own SCM and chooses the constructs that it uses and the particular boundaries those constructs capture. Methods of negotiation may evolve to a point where parties can suggest the particular propagation models to use and the delineation by probability for particular constructs. These aspects of negotiation are beyond the scope of this manual.

4.2.3.1.5 Attribute Meaning in Spectrum Management

Spectrum managers and operators may use probabilities to optimize spectrum assignments. Modelers do not negotiate, but attempt to generate models that best represent operations and their system's characteristics. The modelers use the probabilities to create a measure of interference between two systems if they were assigned the same channel or were assigned adjacent channels. These measures represent the computation of the total probability of interference between the systems in the operations modeled, based on the proximity of their channel assignments. The spectrum manager can decide whether these measures should be based on worst case persistent states or be weighted by the probability that particular states would occur.

A challenging aspect of this analysis is that system operations may be correlated, and so managers cannot assume the model states are independent. Additional weighting may be assigned to systems that have correlated operations. Channel assignment optimization attempts to minimize the total probability of interference among the plurality of systems that use the same spectrum.

4.2.3.2 Probability of States

The assessment of probability for a particular model state differs between the alternative and cumulative approaches. In the alternative approach, the probability of any state matches the probability of the construct. In the cumulative approach, the states are the differences between each of the consecutive constructs and their probability is the difference in probabilities of the constructs. For example, if there are four cumulative probability constructs with probabilities $p_1 < p_2 < p_3 < 1.0$, there are four states: the state of being in the first construct, which has a probability of p_1; the state of being between the first and second construct, which has the probability of $(p_2 - p_1)$; the state of being between the second and third construct, which has the probability of $(p_3 - p_2)$; and the state of being between the third and fourth construct, which has the probability of $(1.0 - p_3)$. This does not apply to cumulative underlay masks at receivers since they do not define different states but rather the allowed probability of a type of interference at a particular state.

A system SCM may use multiple constructs with probability elements. In this case, the number of possible system states is the product of the number of states possible in each construct. The probability of a particular combination of construct states is the product of the probability of each of the construct states that make the combination.

Given each state a system may be in and its probability, the probability that a pair of states of two systems occurs concurrently is the product of the probabilities of these two states. For example, if system X is in state *x* with probability p_x and system Y is in state *y* with probability p_y, the probability they occur concurrently is $(p_x \cdot p_y)$.

Receiver underlay masks of cumulative probability do not define different states, but rather the interference for each state defined by other parts of the model. An interfering system is compatible if its interference levels fall within the distribution implied by the multiple underlay masks and that interference has the same nature as the underlay masks.

4.2.3.3 Assessment of Compatibility of SCM that Use Probabilistic Constructs

The assessment of interference among SCM that use probabilistic constructs determines the probability that two systems, as modeled by their respective SCMs, interfere with each other. The assessment requires consideration of each pair of states of the two modeled systems. The probability of interference is the sum of the probabilities of the persistent states in which interference occurs.

4.2.3.3.1 Underlay Masks

A set of cumulative probability underlay masks with a fleeting nature in a receiver SCM defines interference that allows higher interference levels as long as they are relatively infrequent. These masks allow modelers to account for the resilience of receivers to some interference. Many systems can work through interference by adapting their signal processing, by managing their access to use the lower interference periods, or by some other system-specific method (e.g., routing around where interference occurs in an ad hoc network). Although systems have resilience to this type of interference, it does degrade performance and modelers therefore use underlay masks to reveal their judgment as to what is tolerable. These masks use the fleeting dwell time to indicate maximum duration of an event for it to be considered fleeting.

Cumulative underlay masks provide a relaxed definition of interference compared to modeling the likelihood of system states with other constructs that use probability elements. So long as the statistical nature of the modeled interference of a transmitter model falls below the levels defined in the cumulative underlay mask the systems are assessed as compatible. For example, consider the masks in Figure 4-7. These masks identify the four different levels of cumulative probability. So long as 95% of a signal's interference power falls beneath the most restrictive mask (i.e., the lowest), 97% falls beneath the next most restrictive, and so on, it is not assessed as harmful.

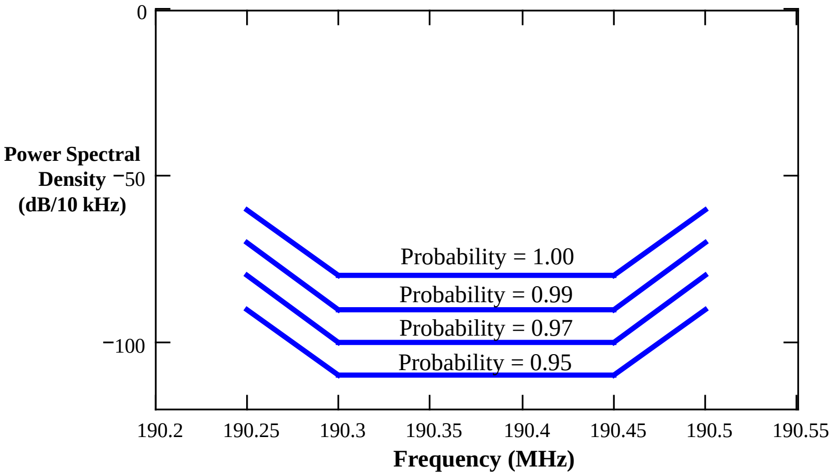


Figure 4-7. Example of a Set of Cumulative Probability Underlay Masks

4.2.3.3.2 Assessment Differences between Persistent and Fleeting Sets of States

Multiple constructs of the same type appear when probability elements are used. All of the constructs of the same type are either persistent or fleeting. The states specified by the fleeting constructs affect the distribution of the interference power levels. The states of persistent constructs indicate the probability that a system will arrive at the state. The fleeting states affect the distribution of interference and are evaluated according to how they interact with the underlay masks. The persistent states are checked individually and the probability of interference between two SCMs is the sum of the probabilities of all the persistent states in which unacceptable interference occurs. Thus the treatment of fleeting states and persistent states differ.

An SCM may consist of multiple constructs that use the probability element. Some may have a persistent nature and some may have a fleeting nature. Consider those of a fleeting nature first. The combinations of fleeting constructs affect the distribution of interference. This is best explained by an example. Let *A* be the set of fleeting constructs in SCM_A and let *B* be the fleeting constructs in SCM_B. Let A_{ij} indicate the j^th state of the i^th construct that uses a fleeting probability in SCM_A and B_{mn} indicate the n^th state of the m^th construct that uses a fleeting probability in SCM_B. Let $p_{A_{ij}}$ indicate the probability of A_{ij} and $p_{B_{mn}}$ indicate the probability of B_{mn}. Let *I* indicate the total number of constructs in SCM_A that use fleeting probability and J_i indicate the total number of states in construct A_i. Let *M* indicate the total number of constructs in SCM_B that use fleeting probability and N_m indicate the total number of states in construct B_m. Then there are a total $\prod_{i=1}^{I} J_i \cdot \prod_{m=1}^{M} N_m$ system states in the compatibility assessment. An individual fleeting system state in the compatibility assessment of the two SCM would consist of one of each of the states of all of the constructs in both models that use fleeting probability elements. The total probability of each of these states would be the product of the probabilities of the individual construct states, $p_{system\_state} = \prod_{i=1}^{I} p_{A_{i,j\in J_i}} \cdot \prod_{m=1}^{M} p_{B_{m,n\in M_n}}$.

If a simple mask is used then the power levels of all these fleeting system states must be compatible with the underlay mask. Any incompatible state makes the two SCMs incompatible. A cumulative fleeting underlay mask indicates several bins of interference levels bounded by the conditions of each underlay mask. The assessment of compatibility considers all states. The power level of each state is associated with the bin it falls in and the probability of that state is added to the tally for that bin. The final probability of interference within a bin is the tally of all the probabilities of states that resulted in interference within the bin. The SCMs are compatible if the distribution falls within that specified by the cumulative underlay mask. In other words, the total probability of interference of the bins beneath each boundary defined by each of the cumulative fleeting probability underlay masks is greater than or equal to the probability assigned to each of those underlay masks. If the probability is less than any one of the boundaries then the SCMs are not compatible.

In a similar fashion, when persistent states are used, they collectively identify multiple system states. Each system state has a probability that is a product of the construct states that make up that system state. All of these systems states are checked for compatibility. If there is no SLA or if the SLA has a zero probability of interference then any incompatible system state results in the SCMs' being assessed as incompatible. If there is an allowed probability of interference then the probabilities of the persistent system states that result in interference are summed. If the sum is less than or equal to the agreed probability of interference the systems are assessed to be compatible. If the sum is greater than the agreed probability they are incompatible.

Systems that use constructs of both natures, persistent and fleeting, would sweep through the persistent system states. At each state they would assess compatibility using the process for fleeting states with their criteria for compatibility, as described above.

4.3 Summary

Spectrum consumption modeling offers a common way to define spectrum use and a common set of computations to arbitrate compatibility among SCMs when the modeling approach is used. Section 3 defined the constructs of modeling, while this section described the computations. The discussion covered the fundamental computations used to assess compatibility between two SCMs based on the constructs used in the SCMs to model use of spectrum, as well as the overall process for arbitrating a new use of spectrum with incumbent users. It also explored the use of probability in articulating softer boundaries and how to assess compatibility among models that use probability. These descriptions provide the sequence of computations and the anticipated results, but do not present the particular algorithms. An MBSM algorithms manual will provide those details [8].

5 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. Collectively, the models should enable spectrum users to consume the least amount of spectrum and thereby increase opportunities to reuse spectrum. This chapter describes approaches to capture the spectrum consumption of specific types of systems in models, methods within those approaches to ensure system performance is bounded within the models, and approaches to divide or to aggregate models to support efficient management and spectrum reuse. It then gives some examples of unique methods of reuse that modeling can support, but sensing cannot.

5.1 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 summarize several common systems, describe their typical spectrum use case, and present potential modeling methods for each. However, the modeling approaches listed here are suggestions only. Specific technical details and operational use of systems may afford other approaches that provide better resolution of the spectrum that is consumed.

5.1.1 Broadcasters

Broadcasters are single transmitters that send signals to a number of surrounding receivers. These communications are continuous and involve only a downlink. Users of broadcasting include, but are not limited to, commercial television stations, commercial radio stations, and broadcast satellites as used for both radio and television. Currently, government agencies regulate broadcasters by placing limits on the amount of power they may use in their broadcasts and controlling where a broadcast may originate. Employing an SCM to define a broadcaster’s use of spectrum has the advantage of determining the geospatial limits on the broadcaster’s use and would reveal the conditions required for reusing the spectrum.

Several methods can model broadcaster spectrum consumption. The first models the broadcaster's transmitter with a transmitter model that provides the location of the transmitter, a total power, a power map, a propagation map, and a spectrum mask. Then a model is developed for the typical receiver in a location that covers the area where such receivers are anticipated to be. The receiver model uses a total power with a fixed underlay mask to specify the protection necessary to shield the weakest receivable signal from interference. It provides a power map and a propagation map to specify the attenuation that should be used in computing power levels of interfering signals. An authorized secondary user could use the spectrum so long as such use would not interfere with any receiver at any point in the location modeled in the broadcaster's receiver model. An additional consideration related to secondary use of the broadcaster's spectrum is whether the secondary receivers 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 referenced to the transmitter spectrum mask, as well as a total power, a power map, a propagation map, and a minimum power spectral flux density. The components of the transmitter model specify the location of the receiver model as the volume subsumed by the surface defined by where the transmit power attenuates to the minimum power spectral flux density predicted by the model. The receiver model has a power map and a propagation map that are used in computing interference. The interesting dynamic is that the power level of the underlay mask varies with location, thereby 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. In this case, an IM mask may be added to the transmitter model. Table 5-1 and Table 5-2 list the different components and constructs underlying the two different modeling approaches.

Table 5-1. Components Used in a Broadcaster Model with an Explicit Location for Receivers

Model Constructs	System Heading	Transmitter	Receiver
Total Power		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 Spectral Flux Density			
Protocol or Policy			O

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

Table 5-2. Components Used in a Broadcaster Model with a Relative Underlay Mask

Model Constructs	System Heading	Transmitter	Receiver
Total Power		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 Spectral Flux Density		R	
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 5-1 illustrates an asymmetric broadcaster scenario where the location of the antenna, labeled as A, 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 total power, an underlay mask, a power map, a propagation map, and the time constraints to complete the model. Figure 5-2 illustrates a terrestrial polygonal surface that encloses the receiver area.

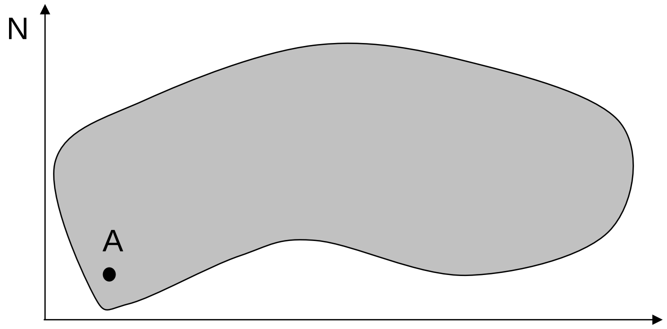


Figure 5-1. Asymmetric Broadcast Scenario

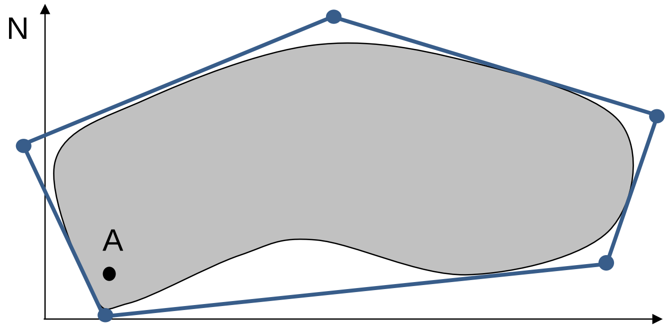


Figure 5-2. Capturing the Receiver Area with a Convex Polygon

The second approach to modeling the consumption is to combine a spectrum mask and an underlay mask in the transmitter model. 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 total power, a power map, a propagation map, a minimum power spectral flux 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 5-3 illustrates the directionality of the antenna and the surface of the receiver location volume predicted by the model's total power, power map, propagation map, and minimum power spectral flux density. The surface of this volume is where the predicted transmit power reaches the threshold of the minimum power spectral flux density. In this approach, the upper power of the spectrum mask and the reference power of the underlay mask attenuate with signal propagation at the same rate.

Example: Broadcaster Models (cont.)

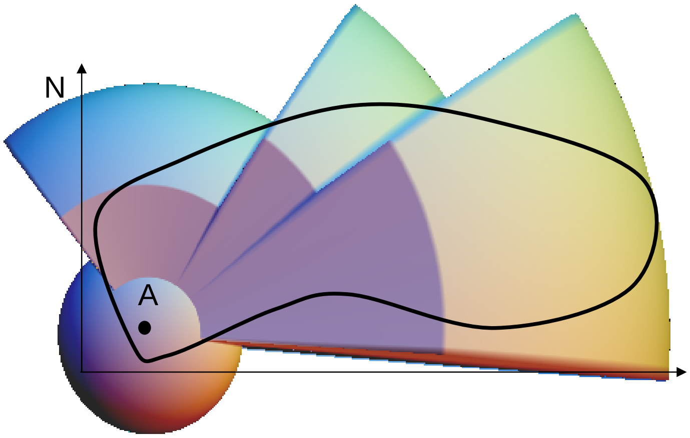


Figure 5-3. Determining the Receiver Area Using the Combination of the Total Power, Power Map, Propagation Map, and Minimum Power Spectral Flux Density

Reuse is feasible so long as the interference is below this underlay reference at all locations within the volume. Figure 5-4 illustrates a generalized example of the distance varying power reference for the underlay mask and shows that at the point where the estimated transmit power reaches the minimum power spectral flux density, the minimum power spectral flux density is the power reference of the underlay mask. Secondary users beyond this surface would likely use a hypothetical receiver on this surface and therefore would apply this underlay mask to determine the constraints to their use of the spectrum.

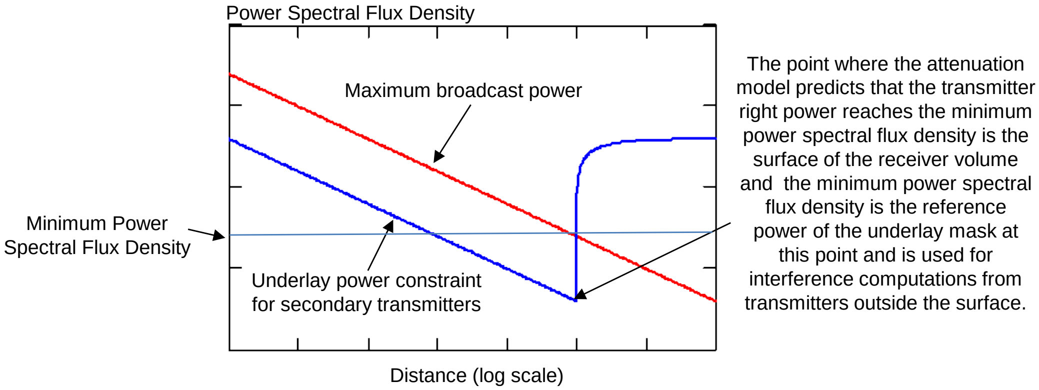


Figure 5-4. The Distance Varying Power Reference when Using a Transmitter Referenced Underlay Mask

5.1.2 Radio Links

Radio links are transmitter-receiver pairs or transceiver pairs 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 cannot 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. Models consist of transmitter and receiver models that capture the characteristics of the end points. 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 links 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.

In addition to location, transmitter and receiver models have the typical components of total power, 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 policy or protocol construct element if the system protocols provide a sharing opportunity. If the transmitters or receivers are susceptible to IM, then the models may include an IM mask to convey that susceptibility. Table 5-3 and Table 5-4 list the typical components and constructs used in radio link system models.

Table 5-3. Components Used to Model a Simplex Radio Link

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

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

Table 5-4. Components Used to Model a Duplex or Half-Duplex Radio Link

Model Constructs	System Heading	Transmitter 1	Receiver 1	Transmitter 2	Receiver 2
Total Power		R	R	R	R
Spectrum Mask		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 Spectral Flux Density					
Protocol or Policy	O				

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

5.1.3 Tactical Data Links

A tactical data link (TDL) is typically defined as a radio system with a set of accompanying messages used for some tactical purpose. The radio portion of these systems consumes spectrum. Generally, the radios are intended to be mobile. The specification of the radio portion usually covers the physical layer and the system's 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. Therefore, the system model consists of both a transmitter and a receiver model, with many of the construct definitions made in the system heading. Although both propagation and power may have directional aspects, most maps are likely to be spheres due to the anticipated mobility of the radios.

The greatest 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 thus capture spectrum consumption over time. Modelers can subdivide model location by time by replicating a system model like that in Table 5-5 with a single transmitter and receiver or by 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 5-6. 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 5-5. Components Used to Model a Mobile Tactical Data Links

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

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

Table 5-6. Components Used to Model Mobile Tactical Data Links as a Single System Model with Multiple Time Periods

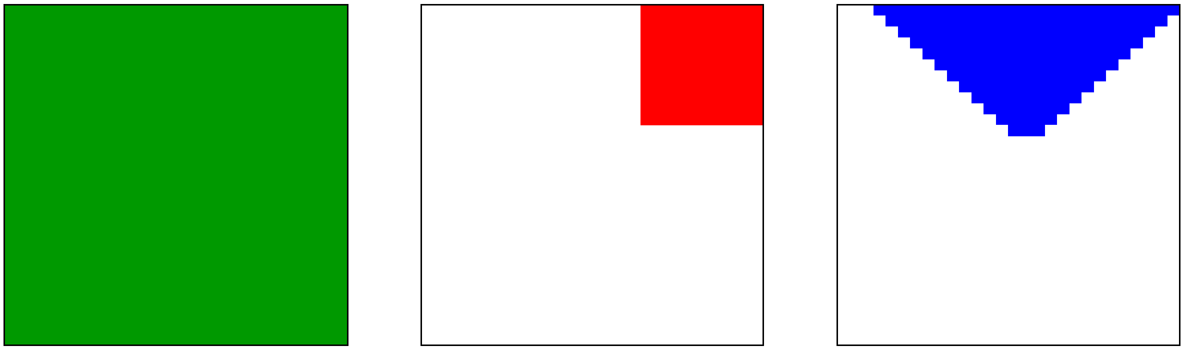
Model Constructs	System Heading	Transmitter 1	Receiver 1	…	Transmitter n	Receiver n
Total Power	R					
Spectrum Mask	R					
Underlay Mask	R					
Power Map	R					
Propagation Map	R					
Intermodulation Mask		O	O		O	O
Platform Name		O	O		O	O
Location	R- Surface or Volume	T- Surface or Volume	T- Surface 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 Spectral Flux Density						
Protocol or Policy	O					

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

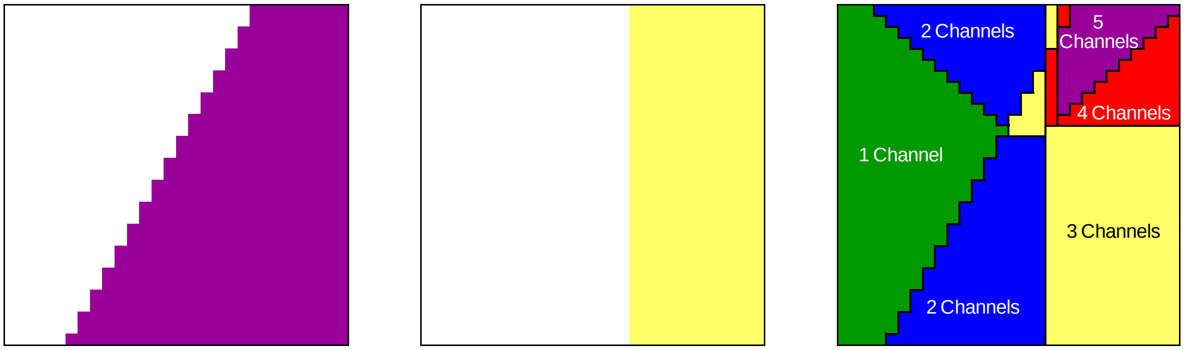
5.1.4 Mobile Ad Hoc Networks (MANETs)

MANETs consist of multiple mobile nodes and may use multiple channels. Further, the radios within the networks may use advanced technologies and protocols to adapt to the environment and to each other for best network performance. In the simplest case, where t a fixed amount of spectrum is assigned 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 that have greater adaptability and cognizance of the environment, the use and modeling of spectrum may be much more interesting and involve DSA technologies. Consider the case shown in Figure 5-5. Portions of a square operating region have different channels available, as illustrated in Figure 5-5 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 5-5f illustrates the number of channels available by location. Inspection of Figure 5-5 a-e makes it 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 a receiver model for each of the channels available. These would each have their own location construct element. Table 5-7 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. 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 5-5. Example Scenario of Channel Availability for a DSA MANET.

Table 5-7. 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
Total Power	R					
Spectrum Mask		R			R	
Underlay Mask			R			R
Power Map	R					
Propagation Map	R	O	O		O	O
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 Spectral Flux Density						
Protocol or Policy	O					

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

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. 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 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 modelers to subdivide operational use over time simply by 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 simplifies the decomposition of system models into independent transmitter and receiver models. Using this latter approach to define transmitter and receiver models makes it possible to model the varying locations of the system over time in a single system model.

Multiple transmitter and receiver models for a channel may be differentiated by their location and time boundaries. Table 5-8 lists the construct elements and models that might be used in this type of model. This differentiation of space and time may also be accomplished using a location index, as discussed in Section 5.2.5.

Table 5-8. Components Used to Model the Change in Location of a Single Channel MANET

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

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

5.1.5 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 underlying 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 occurs 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 is 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, which accounts for the characteristics of the typical phone or data modem and the channels they might use. Table 5-9 identifies the possible components of this type of model for a single cell using a single channel. A cellular system would have many 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 consists of the entire area of the cellular system. It includes a pair of transmitter and receiver models for each channel used by the system and incorporates the models of either the tower transceivers or of the telephone/modem transceivers, depending on the role they play on the channel.

Table 5-9. Components Used to Model a Cell of a Cellular System

Model Constructs	System Heading	Tower Transmitter	Tower Receiver	Subscriber Transmitter	Subscriber Receiver
Total Power		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 Spectral Flux Density					
Protocol or Policy	O				

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

5.1.6 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 and provide an underlay mask of the spectrum where the telescope listens, a power map that captures the gain characteristics of the telescope antenna, and a propagation map to be used by potential interferers. Multiple receiver models would likely be used, since the rotation and orbit of the earth affect the orientation of the telescope, 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 might specify different spectrum bands of interest in different blocks of time. Table 5-10 lists the components and constructs that might be found for a radio telescope operating on multiple bands.

Table 5-10. Components Used to Model a Radio Telescope

Model Constructs	System Heading	Receiver Band 1	…	Receiver Band n
Total Power	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 Spectral Flux Density				
Protocol or Policy				

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

5.1.7 Radars

"Radar" was originally an acronym for radio ranging and detection. A radar system transmits a signal and then waits for it to be reflected and returned to the radar. The radar uses 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 to reveal characteristics of the target.

Radars typically transmit powerful signals and receive very faint reflected signals. Models of radars, in most cases, 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 typically have point locations. The spatial consumption of spectrum for the operational use of a radar system depends on the directionality of the radar's antenna, its sweep in space, the period of signals, and their duration.

The combinations of effects support some artfulness in modeling. For example, the combination of scanning a highly directional antenna and sending periodic pulses can be modeled as a less directional antenna with less frequent pulses. These components of the model require the greatest attention when modeling a radar system's spectrum consumption most effectively. Section 5.2.3.2 describes strategies for modeling radar antenna scanning. The periodicity of radar signals and antenna scanning may make it possible to create other systems that can coexist through the application of a protocol that uses knowledge of these periods to avoid interfering with the radar. If such a protocol exists 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 5-11 provides a listing of the likely components in a radar SCM.

Table 5-11. Components Used to Model a Radar

Model Constructs	System Heading	Transmitter	Receiver
Total Power	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 Spectral Flux Density			
Protocol or Policy	O		O

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

5.1.8 Unmanned Aerial Systems

Unmanned aerial systems (UASs) have multiple RF components that support both the control of the UAV and the transport of the information it senses. For example, the UAS 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 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 5-12 lists the component models and construct elements that would likely be used to model this type of UAS.

Table 5-12. 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
Total Power		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 Spectral Flux Density									
Protocol or Policy									

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

5.2 Building Modeling Constructs for Better Spectrum Consumption

An important means of enabling spectrum reuse is to model systems and their spectrum use efficiently. An efficient model captures use of spectrum that protects other users from interference through compliance with 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. The three dimension of space are functions not only of the location construct element but also of the interaction among the other constructs, particularly the power maps and propagation maps. Models must be efficient in all these dimensions. Further, efficient models reduce the computational requirements to assess compatibility. In many cases there may be trades between better modeling of spectrum consumption and modeling for efficient computation.

5.2.1 Spectrum and Underlay Masks

The spectrum and underlay masks convey the RF bandwidth of spectrum consumption. The spectral envelopes of signals are the most predictable attributes of spectrum consumption, and are readily bounded with a spectrum mask. Modelers design a spectrum mask 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 and the complexity of compatibility computations.

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

Figure 5-6 illustrates these concepts. The figure shows the spectrum content of the transmitted signal. Two spectrum masks are 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 reduces 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 5-6 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 uses the center band of the signal to recover the information in the signal. The underlay mask in this example is relative and potentially modelers could raise or lower its power level. Shifting the power levels of the underlay mask changes the level of protection the mask affords but also changes the

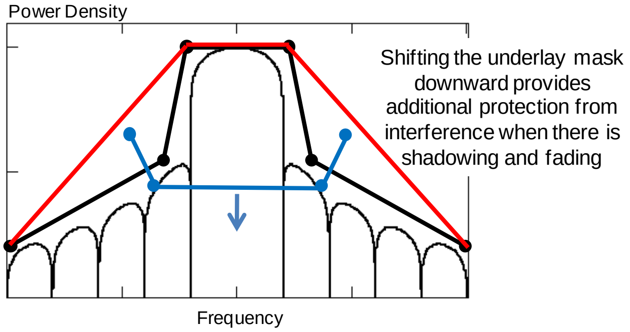


Figure 5-6. Example of Creating a Spectrum Mask Over a Signal Power Envelope

opportunities to reuse this spectrum.

5.2.2 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. More conservative models of propagation predict a lower rate of attenuation, as this will cause the greater separation between users. 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.

MBSM modeling provides two different models for pathloss: the log-distance pathloss model and the piecewise linear log-distance pathloss model. The first has the advantages of being smaller and supporting simpler computations. The second has the advantages of supporting more accurate modeling and capturing abrupt changes in propagation created by obstacles.

Propagation maps also allow modelers to differentiate propagation by direction. This differentiation is not between model types; a single map must use either the log-distance or the piecewise linear log-distance pathloss model, but cannot use both.

5.2.2.1 Log Distance Pathloss Models

The log distance pathloss model performs best in locations where the directions of the greatest concern do not involve interaction with the terrain; for instance, on systems placed on airborne platforms or on terrestrial systems that primarily transmit toward or receive transmissions from airborne systems. Square law attenuation in all directions can be a default for many of these when modelers have no knowledge of the actual propagation conditions or when there is no evidence that a higher rate of attenuation will occur.

The log distance pathloss model may be used for terrestrial modeling. However, some terrestrial propagation phenomena 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 at the furthest region where the signal is strong enough to be received.

Similarly, a log distance pathloss 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 up to the obstacle so that the boundary of consumption matches the location of the obstacle. Thus, the model that best captures the boundary of consumption may not provide the best estimate of signal strength.

Figure 5-7 illustrates several options for choosing a pathloss exponent for a model. Each seeks to satisfy 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 results in the most conservative estimate of pathloss and in the least reuse, because smaller exponents result in greater propagation range.

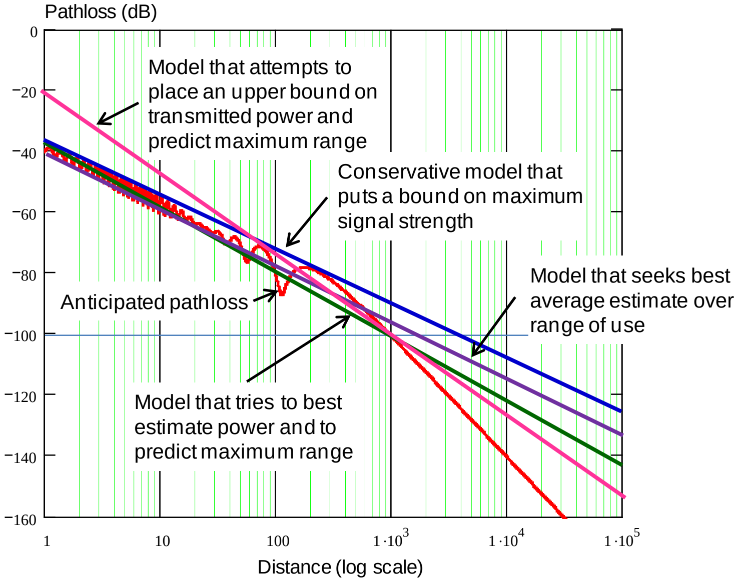


Figure 5-7. Options for Selecting a Pathloss Exponent

Placing an upper-bound on transmitted power ensures the modeled system does not interfere 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 bounds 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.

5.2.2.2 Piecewise Linear Log Distance Pathloss Model

The piecewise linear log distance pathloss model provides a more useful model for terrestrial propagation. It can very closely replicate propagation that matches the two-ray model, as illustrated in Figure 3-20. Modelers can use the breakpoint of the model to transition to a large exponent to capture the effects of obstacles that would block signals. When transitions are not anticipated, the piecewise linear model can still represent a single exponent pathloss by using the same exponent on either side of the breakpoint.

5.2.2.3 Mobility and Subdividing Location and Directional Effects

Mobility poses a special challenge to propagation modeling because propagation depends so strongly on the environment, and mobility continuously changes that environment. 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 systems may move requires dividing the regions of mobility into smaller areas, dividing the use into spatial increments, and then building separate propagation models for those increments. The location indexing in the SCMML schema aids in the subdivision of spaces so that they can be associated with different propagation models.

Although the directional vector of propagation maps provides an unlimited ability to divide directions into different solid angles and therefore 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. Modelers must weigh the benefit of having a higher resolution model against these costs. It may also be reasonable to define a system, such as a broadcaster, with a high-resolution model, but then to determine compatibility with other systems by reducing the model's resolution for more efficient computations and less overhead.

5.2.2.4 Long Distance Terrestrial Effects

The propagation maps allow the modeler to differentiate propagation pathloss based on direction, both azimuth and elevation. On the surface of the earth, however, the differences in antenna elevation are associated with smaller and smaller differences in elevation as the separation between the transmitter and receiver increases making these directional differences difficult to capture efficiently. To address this problem, the power map data structures also allow the creation of multiple maps where each models the pathloss for a particular distant antenna height. These maps are built on assumptions about the height of the modeled transmitter or receiver. Tools would interpolate the pathloss for distant antenna heights that are between those of the propagation maps. This method of modeling may be used to capture ducting effects in propagation.

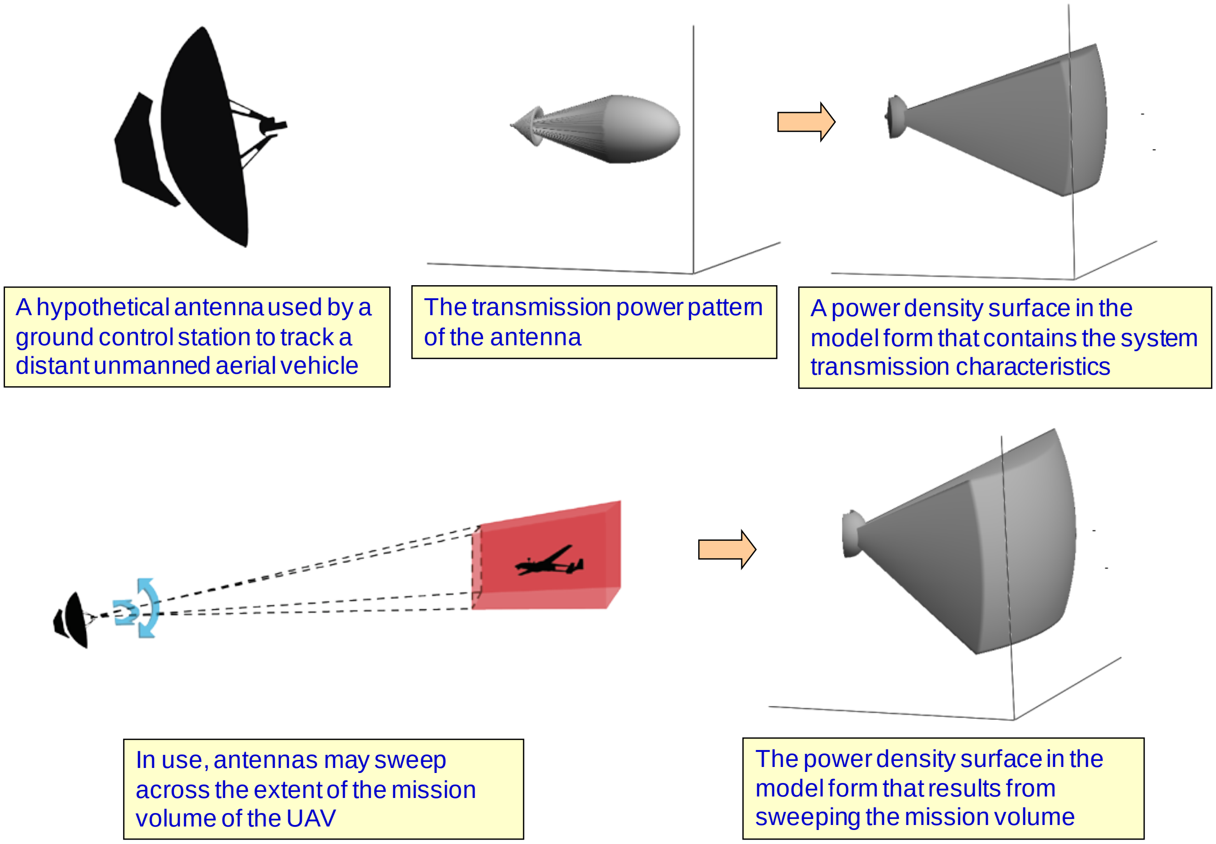
5.2.3 Power Maps

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, but to bound the actual power emitted from an antenna. Combining the power map with the propagation map determines the spatial extent of consumption. 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 typically suffices. As with propagation maps, it is desirable to avoid complexity and overhead.

5.2.3.1 Directional Power Maps and Mobility

Mobility – both the maneuvering of the antenna direction and the mobility of the antenna platform – contributes 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 5-8 illustrates an example of a directional antenna used by a ground control station of a UAS and a hypothetical power pattern for that antenna. It then shows the power density surface of a power map that would contain the antenna power pattern. Next it shows 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 power map with just a few values 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 result from the changing directions in which platforms move or from more unpredictable reorientations such as those caused by the choppy motion of ground vehicles that traverse rough terrain or the undulation of a maneuvering aircraft. The sectors with the largest power values become larger as the variability in orientation becomes larger, thus conveying a greater consumption of spectrum. Dividing a use into temporal or spatial segments in which less variability occurs helps reduce the spectrum consumption shown in the model.



A hypothetical antenna used by a ground control station to track a distant unmanned aerial vehicle

The transmission power pattern of the antenna

A power density surface in the model form that contains the system transmission characteristics

In use, antennas may sweep across the extent of the mission volume of the UAV

The power density surface in the model form that results from sweeping the mission volume

Figure 5-8. Example of Creating Power Maps to Contain the Power Patterns of Antennas and the Operational Use of Antennas

5.2.3.2 Radar Pulsing and Scanning in Directional Power Maps

Radars scan highly directional antennas across spaces. Spectrum consumption modeling provides several alternatives for modeling this activity. One of the most specialized is the ability to define a power map that specifies both the directionality of the antenna and the space across which it sweeps. This is accomplished using two concentric maps. One of these maps describes a directional antenna that is scanned and the second map indicates the space over which it is scanned. The map of the directional antenna places the scanned beam on the vertical axis. The map that indicates the region of scanning assigns a positive value to the scanning directions and the value 0 to other directions. The directional values of scanning region power maps are Boolean. The vertical axis – the positive z direction of the directional antenna power map – moves through the directions that the scanning region power map indicates by the unit values. The x axis of the directional antenna model remains parallel to the x-y plane of the scanning region map.

Radar transmitters and receivers may be modeled differently. For transmitters it is desirable to convey how frequently a pulse may interfere with a distant user. In this case, the transmitter SCM may use a single power map with the directional gain of the antenna applied to the whole region across which it is scanned. The model of the pulsing accounts for the effect of the scanning. Rather than the actual rate at which the radar sends pulses, the modeled rate accounts for the combination of the antenna being pointed in a direction and a pulse occurring. Meanwhile the receiver model focuses on interference with the receiver, and so the directionality of the antenna is important. The antenna beamwidth provides a limit the number of secondary systems that affect the performance of the radar. Using the concentric maps to model the antenna is usually the most appropriate. The effect on compatibility of adding a new sharing system depends on whether it tips the allowed interference past the level allowed when the new system is within the beamwidth of the directional antenna.

As described above, the spectrum mask can capture the periodicity of antenna scanning and pulsing. The pulse rate captures the combination of the scanning and the pulsing. The periodicity of the antenna rotation can also be defined using the start time construct, which can determine repeated on and off periods. The model of the antenna pointing; however, would be limited to the direction to which the timing model applies. The full angle across which an antenna is scanned would be captured in multiple power maps, each modeling a separate sector and a different reference time for its periodicity. The width of these sectors would affect the duration of the on and off periods.

5.2.4 Location and Time

The subdivision of models into smaller operational spaces differentiated by time offers the greatest opportunity to generate reuse opportunities. Ideally, the operational planning for a system's use would produce SCMs. If a system can be confined to a smaller space for some part of a mission, then the model of that smaller space for the time when the system operates in the space will result in less spectrum consumption than a model of the full space of operation for the full duration of a mission. Figure 2-2 shows an example of a subdivision of a space.

5.2.5 Location Indexing

Constructs are naturally grouped into transmitter or receiver models, since transmitters and receivers are the elements considered in assessing compatibility. Modelers can combine multiple transmitter and receiver models into system models to capture the spectrum used by a system, differentiated in any way the modeler wants. Location indexing enables a modeler to subdivide an operational use of spectrum into multiple locations in the same transmitter or receiver model. The location index provides a means to associate a power map, a propagation map, a start time, and an end time with a particular location in a model that covers multiple locations.

5.3 Model Aggregation and Decomposition

The aggregation and decomposition of models allows further efficiencies in SM. Both aggregation and decomposition have meaning in the context of listing models and of combining or subdividing models. A collective listing of models is a collection of transmitter and receiver models, each of which is complete on its own. Section 3.3 discussed the purpose of collective listings.

Listings may use transmitter and receiver models from multiple system models, and may also include subsets of the transmitter and receiver models from various system models. Another possible aggregation of models results from combining 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 covering a larger space or a larger band of spectrum.

A possible decomposition approach involves dividing a model into multiple smaller models 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.

5.4 Service Level Agreements

Under SLAs various parties agree to particular uses of shared spectrum that are compatible with each other. SLAs document a common understanding of spectrum use, as well as the roles and responsibilities of all parties to maintain compatible spectrum use. In addition to setting the boundaries of spectrum use, the SLA may include information concerning how to assess compatibility in operations and what parties can do if their peer violates the SLA.

SLAs are determined through negotiation, in which SCMs play an important role. SCMs provide the means that enable multiple parties to negotiate their spectrum use. The parties each reveal the boundaries of their proposed spectrum use and exchange and revise their models until their models are considered compatible with each other. The methods for reaching agreement and enforcing it are not part of modeling. SCMs would be part of the SLA.

5.5 Model-Based Reuse

Using spectrum consumption modeling as the basis of SM has the advantage of enabling additional coexistent uses that would be impossible using spectrum sensing alone. In many cases a secondary transmitter can use spectrum without interfering with a primary user. Such a transmitter would allow the reception of the second transmission without harmful interference from the primary. This would be impossible with a sensing requirement, because one or the other end of a transmission would sense the spectrum occupied. The subsections below describe three general ways in which models convey reuse opportunities not identifiable with sensor-based technologies.

5.5.1 Scenario-Based Reuse

In scenario-based reuse, specific details about the scenarios and about the modeling of the primary use of spectrum result in reuse opportunities. Figure 5-9 shows an example. The primary use in this scenario is the direct link between two towers, one of which is always transmitting and the other always receiving. Both have highly directional antennas. Surrounding these two RF terminals are several transceivers of a mobile network that could potentially use the same spectrum if they do not cause interference. The system model of spectrum consumption for the

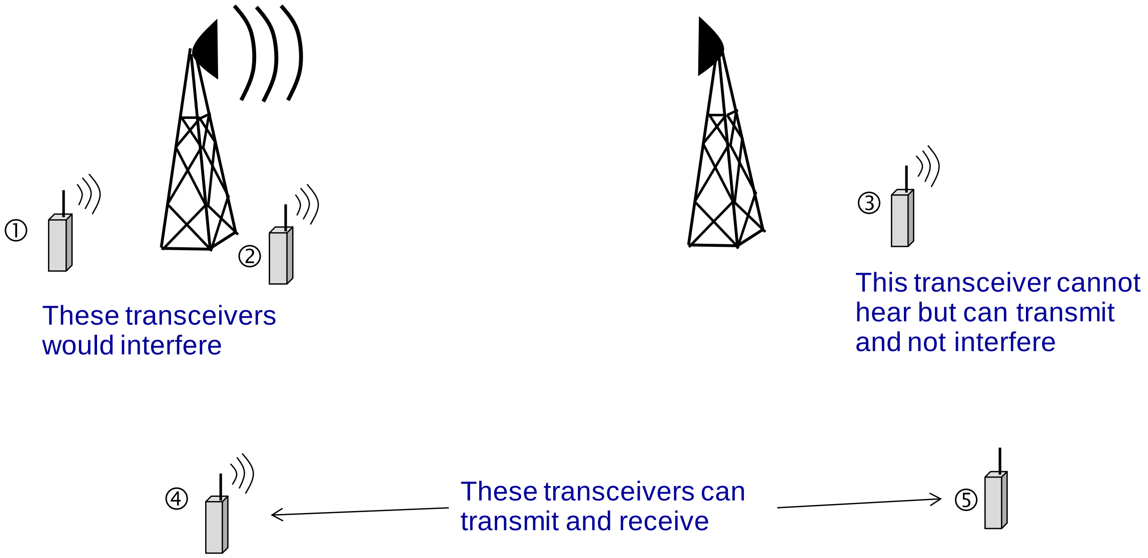


Figure 5-9. Example of a Reuse Scenario Enabled by MBSM

primary use would be built 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 used the spectrum because they failed to sense it was already in use, they might interfere with reception at the receiving tower. Therefore, if pairs of radios in the mobile network were to base their transmission on what they sensed, transceiver 1 might transmit to Transceiver 4, because 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 performed by all nodes in order to avoid causing interference. For some hypothetical scenarios, even sensing by all nodes would not solve this problem. For example, if Transceiver 3 were not part of the scenario illustrated in Figure 5-9 no node would detect the spectrum use but half the nodes would cause interference if they were transmitting.

There are many similar uses of spectrum in which high-gain directional antennas receive remote transmissions that are unlikely to be sensed by any general sensing protocol of a DSA technology. If the DSA technology were to use this spectrum because it had failed to sense the spectrum's use, it could generate harmful interference that would disrupt the sensitive receiver's reception of the transmissions. Satellite terminals are the obvious example. DSA based solely on sensing would have 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, all nodes 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 and should identify themselves and do so. The computations for these assessments at nodes are no different than those described above. Protocol designers would have to build the mechanisms for coordination and selection of nodes to use the channels into the protocols of the mobile network.

5.5.2 Channel Puncturing

Figure 5-10 illustrates the idea of channel puncturing, where a short-range use of spectrum can occur 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 exceed the power of a primary, yet the transmitted signal may still attenuate sufficiently to avoid interference at the distant receiver. Figure 5-10 illustrates the relative signal strength of a primary and a secondary transmission. The primary transmission is sent 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 reuse through this spectrum puncturing 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 data as well to assess the power that the secondary transmitter could use.

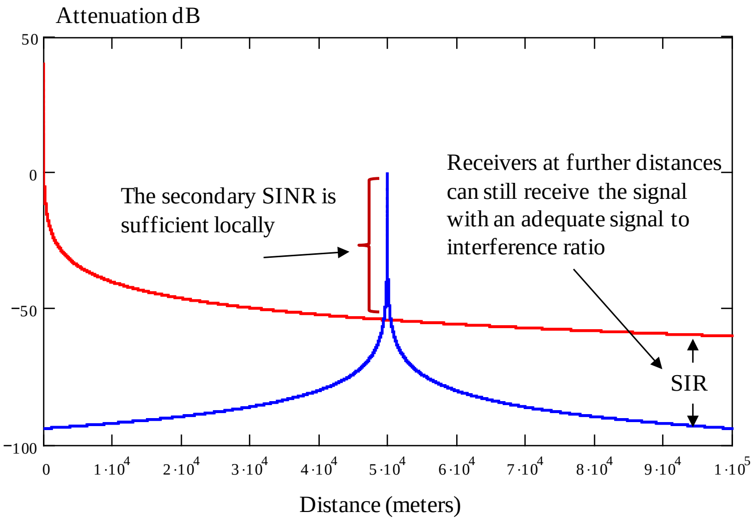


Figure 5-10. A Channel Puncturing Scenario

5.5.3 Sharing

Operational users of spectrum do not use spectrum continuously. Combining an SCM of their own authorization with an SCM of their particular use would reveal opportunities for reuse of spectrum. An SCM may also capture a second possible use of spectrum within the bounds of the authorization SCM and compatible with the primary use SCM.

5.6 Summary

Spectrum consumption modeling is a new concept that will enable innovation in SM. Many of its benefits will come from creativity in building and using the models. This section has provided examples of the construct inventory that would likely constitute part of SCMs of particular types of common systems. It has suggested methods for applying the constructs to capture particular non-static uses of spectrum where the suggested modeling approaches could reveal more reuse opportunities. The section has described capabilities derived from modeling that allow greater reuse and more dynamic access, and indicated the artful aspects of modeling spectrum consumption.

6 Implementation

This manual has presented the motivation for creating a method for spectrum consumption modeling and has attempted to define an approach to building 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 the compatibility of modeled uses
3. Provides a means of using the models to convey both the consumption and the availability of spectrum

Proposing a modeling approach represents only a beginning for MBSM. Validating that MBSM has achieved all of the objectives is a continuous process and will be part of the overall evolution of the MBSM system. SCMs only have value if they are used to increase the sharing of spectrum among systems. The greater benefit comes from the broad adoption of the technique as opposed to any targeted application. As this approach to SM and use constitutes a significant change from the approaches that exist today, a successful implementation will evolve over time, but the definition of how to model and how to arbitrate compatibility must be well defined and accepted community wide at the start in order to become a standard.

In this chapter we identify and describe four important components of implementation: a data model that captures the particular constructs defined in this manual that can also be combined with other data models needed for other aspects of SM, development of algorithms to operate on the models and perform relevant SM tasks, development of tools and architectures that use both the models and algorithms to improve SM, and a regulatory environment that embraces and encourages the use of spectrum consumption modeling.

6.1 Data Models

Spectrum consumption modeling requires a data model. In the interest of creating a loose coupler, that data model should be minimal, simply providing a means to capture spectrum consumption and not seeking to perform other functions. Appendix A in this manual provides one example: an XML-based schema called Spectrum Consumption Modeling Markup Language (SCMML). By limiting the SCMML to convey only spectrum use, it makes this data model broadly applicable. SCMML may be combined with whatever schema is appropriate for a task or community, such as schemata for regulation, enterprise SM, inter-enterprise SM, spectrum markets, SLA negotiation, and machine-readable policy. The definition of spectrum use boundaries and the methods to compute compatibility are the same everywhere, but the schemata with which they are combined reveal the particular role the SCMs play and the business processes in which they are used. Since the definition of spectrum use remains the same, an SCM created as part of SM can be used in processes other than SM; for example, it could be used as a constraint in a policy delivered to spectrum-dependent systems. This flexibility of combining schemata to create relevant SM documents is an important objective in developing an SCM data model.

6.2 Algorithms

Algorithms are complementary components of developing a modeling approach. The modeling approach should support a reasonably tractable and efficient set of algorithms to assess compatibility and to seek reuse opportunities. Therefore, modeling options should be compared on the basis of 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 the model incorporate relevant terrain effects on propagation and specify these effects in the values of a model's propagation map. This eliminates the requirement to maintain and synchronize large databases of terrain data or to agree to apply any specific propagation algorithms that operate using these databases in computing propagation effects. The second significant choice was to require that the model define what constitutes harmful interference, thereby removing the requirement that the SM system make this determination and merely requiring the system to determine if interference is occurring. The third significant choice was to define consumption after the antenna as a power spectral flux density and require that the model capture how a system generates radiation or is affected by radiation. This eliminates the requirement to assess how antennas convert a driving current into a spatial radiation pattern and vice versa as part of the algorithms. As a result, 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 contained in the models.

Four broad categories of algorithms are required for a general SM capability: assessing compatibility, quantifying consumption, searching for reuse opportunities, and visualizing boundaries. The following subsections further describe the significance of these algorithms in SM systems.

6.2.1 Assessing Compatibility

The primary task that spectrum managers must complete using SCMs is determining whether one use of spectrum is compatible with another. Section 3 described this process for the SCMs discussed in this manual. Making a full assessment of compatibility is non-trivial. In most complex system uses, RF components can exist 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-case combinations of pairwise orientations of systems within the constraints of their models and then use these cases as those that constrain use.

Implementation of an MBSM 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 effects those modifications may have on the development of these algorithms. Certain requirements in the models, such as that locations of use must be convex and propagation must be monotonic, are imposed to ensure the tractability of these future algorithms. More simply, trying to increase resolution by adding features to the models, e.g. dependence on terrain databases, could make compatibility computations intractable. Modelers should only make such changes after evaluating their effect on the efficiency of the algorithms.

6.2.2 Quantifying Consumption

A problem in current SM concerns the definition of consumption. If consumption can be quantified, then participants 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. This requires the definition of a nominal transmitter and receiver of a secondary user. The union of the volumes formed by the boundary where these nominal transmitters and receivers can begin operation represents the spatial consumption of a model. Such integration can also capture spectral consumption by allowing the nominal transmitter and receiver to change in frequency and then to integrate across frequencies as well. This four-dimensional integration is then multiplied by the time of use to obtain the full measure of consumption.

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

6.2.3 Searching for and Managing Reuse Opportunities

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

Exploiting unused spectrum may not be so simple. The boundaries of availability will probably not readily match the boundaries of spectrum requested. Searching algorithms may then suggest adjustment to the boundaries of the requested use to match 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. Many alternative algorithms of this nature will likely be developed as systems and management processes allow adjustments.

6.2.4 Visualizing Boundaries

Although using models allows automation of many aspects of SM, operators of spectrum-dependent systems will still need to make informed decisions. To make those decisions, they will need to understand the ramification of their choices. Visualization tools aid in revealing these ramifications. The general objective of visualization is to render the boundaries of the use defined by an SCM relative to those of other competing systems in the same spectrum and spatial proximity. Rendering a boundary involves computing the operating limits of a new use as constrained by the SCMs of incumbent uses and displaying result on an operationally relevant map.

6.3 Architecture

The use of SCM will likely start with the development of more effective SM tools. Subsequently SCM will become the kernel of database SM systems. Ultimately, the SCM could enable the creation of a largely automated SAS that also supports spectrum markets and the negotiation of spectrum reuse.

6.3.1 Tools and Distributed Spectrum Management

Many of the tools currently used for SM require that modelers collect large amounts of data about systems and about the environment and then embed models for computing of spectrum uses within the tools themselves. Given new uses of spectrum by known systems, these tools compute whether the new use is compatible. This becomes possible because a model has been programmed into the tool to support this analysis. A typical lament by users of these tools concerns the lack of data about some systems and some spectrum uses, and the high detail of the data required to enable the tools to operate. This level of detail can cause both commercial and federal spectrum users to balk at cooperating, since in the commercial case it demands revelation of proprietary data and in the federal case the revelation of sensitive and sometimes classified data.

The evolution of tools is likely to occur in two stages. The first stage involves the development of tools to assist in creating SCMs and the second consists of implementing algorithms that operate on the SCMs and perform SM tasks. Figure 6-1 illustrates the anticipated change. The top part of the illustration shows a simplistic view of today's tools. The raw data about systems, their use, and existing assignments feed the tools. Custom algorithms embedded into the tool support solution of specific, recurring SM problems.

SM, however, is tool-centric and requires users employ a common set of tools and synchronize their databases of system capabilities to arrive at the same SM decisions. The use of SCMs creates a very different situation. The advances provided by using SCMs first manifest themselves in a change of process. The first step in the analysis consists of creating the model for each particular system’s use of spectrum. Next comes using the standardized set of algorithms to operate on collections of SCMs to accomplish SM tasks. The users of spectrum do not need to share the same set of tools to build SCMs; they can each have specialized tools that model their systems. They do not need data about all competing RF systems to perform their analyses; they only need the models of the competing systems' uses of spectrum. Given a common set of SCMs, the standardized set of SM algorithms will arrive at the same conclusions as to the compatibility of models and the availability of spectrum for new uses.

Figure 6-2 illustrates the potential change in SM systems for large enterprises that have a

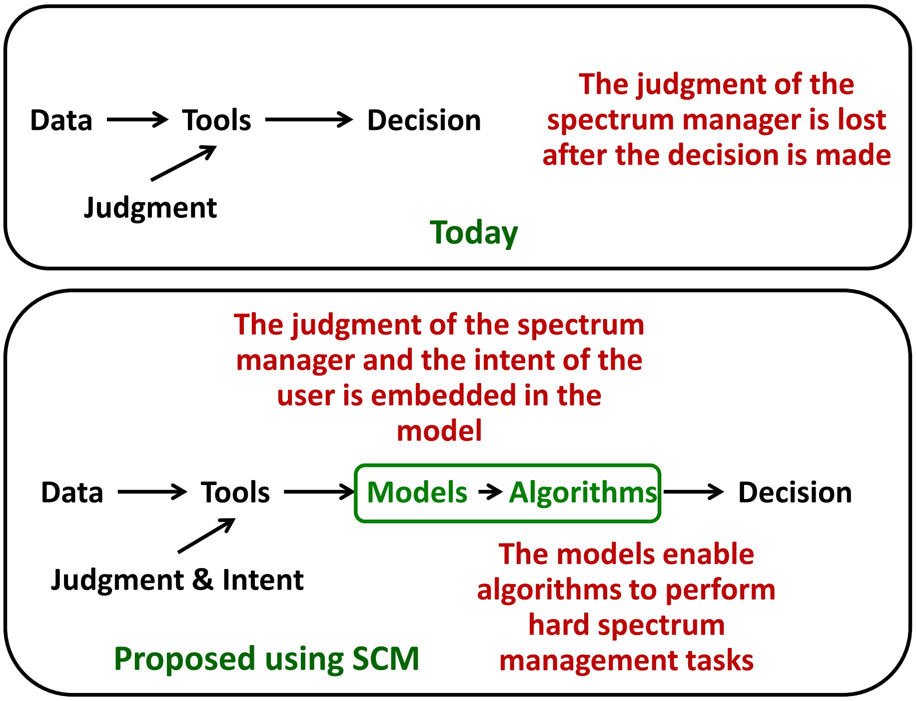


Figure 6-1. Process Change Using Tools that Use SCM

distributed set of managers performing the SM tasks, such as those that might be found in military organizations. Synchronizing the work of managers requires that the managers have access to all the same data about systems, uses, and assignments. The top illustration shows the current trend in tool development, which favors giving all managers access to a common server-based tool and the same data. Managers are trained across all the systems they manage as well as the systems with which their systems compete for spectrum. They must work closely with users to understand operational factors that can cause system competition for the same spectrum. The bottom illustration shows the SCM-enabled alternative. In this construct, managers only need to know about the nuances of the systems their organization uses; they need to share only their SCMs, not their data on the capabilities and operation of their systems. This feature encourages a broader distribution of management roles.

Operational planning tools for specific RF systems can generate their own SCMs and insert them into the larger SM system. Rather than burden the spectrum manager with inserting the data into a shared tool, the operators themselves would create SCMs of their use of spectrum as they plan the use and insert the data into the SM system. The anticipated benefits include greater fidelity in SM and greater agility in SM processes.

This advance in distributed SM can also change the nature of SM. With centralized systems, SM by nature seeks persistent solutions: solutions that last until a new problem demands new analysis that dictates something else be done. The use of SCMs in a distributed system encourages the revelation of operational use of spectrum into the future, which includes spatial and temporal changes in use. Resolution in these dimensions, in turn, encourages less greedy spectrum assignments. Applying SCMs to define spectrum use and fully automating the arbitration of compatibility among SCMs remove much of the burden of dynamic management.

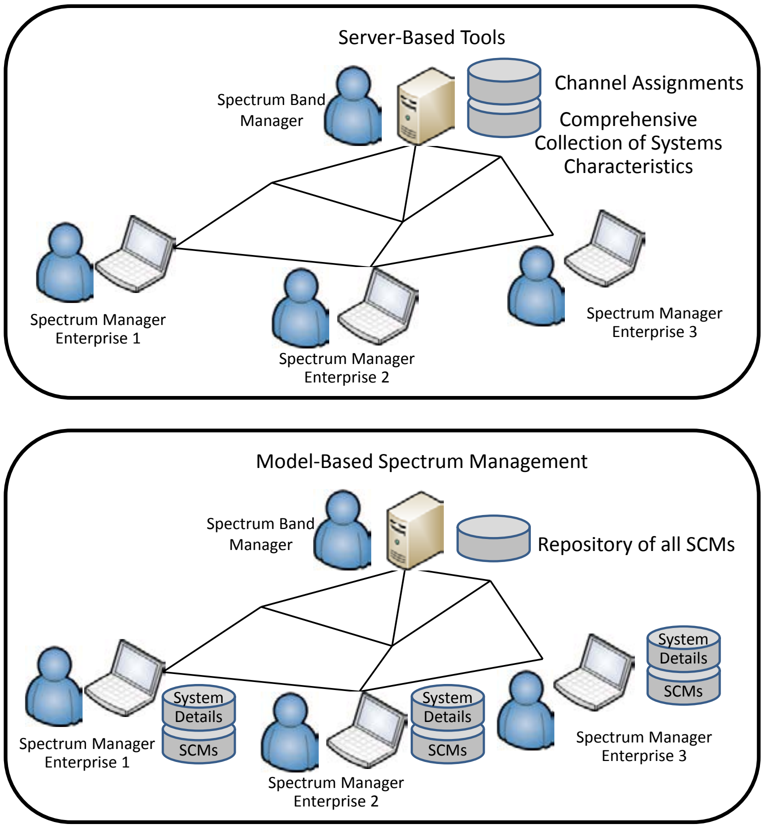


Figure 6-2. Alternative Spectrum Management Architecture

SCMs that identify the changing use of spectrum into the future would allow algorithms that operate on collections of models to reveal opportunities to reuse spectrum.

Further, the mindset surrounding SM 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, perhaps by using the spectrum consumption measures described above as the measure of goodness. Assuming that users can create models that both protect their use of spectrum and require less spectrum consumption, opportunities should emerge for some other system to use the spectrum that becomes available.

SM centers on understanding which systems can exploit unused spectrum and informing them of the opportunity. As an example, consider a case in which a UAS and a terrestrial ground system use the same spectrum. If the UAS's use of spectrum is modeled on a mission basis, then opportunities may arise for the terrestrial communications system to use the spectrum for transport when the UAS is idle. If managers understand these cycles, the transport systems can store routine transmissions until the periods when this additional spectrum is available and then send the messages.

6.3.2 Database Access

Database managed spectrum is already on its way to becoming an important part of the commercial SM landscape. Rules in the United States and the United Kingdom have made possible the database management of television white space (TVWS): the spatial, spectral, and temporal spaces where TV stations do not broadcast. The two countries envision that database administrators will receive requests from TV band devices (TVBDs) and will respond the list of channels in the TV bands that are available for them to use. When the United States announced these rules 10 companies applied to become database administrators, many vendors started producing devices to operate in the TVWS, standards bodies created standards for radios to operate in these bands, and the Internet Engineering Task Force (IETF) began creating a standard for a Protocol for Access to Whitespace (PAWS).

The TVWS database access approach has two significant limitations. First, it involves no effort to manage coexistence among TVBDs. The database merely protects incumbents. Regulators provide database administrators the "contours" used to protect the incumbents. The databases merely compute whether the new TVBD can use a channel and not violate the contour; in essence, the database simply identifies the channels that TVBDs can use without interfering with the incumbent TV stations. At present, there is no experience with large numbers of TVBDs in the same space competing for the same spectrum; thus, managers cannot yet determine if this will be problematic.

Second, these databases were designed to manage access around static incumbents the regulators approve the contours without any anticipation that the set might have to change. Incumbents have no way to inform databases of changes in their use and managers have no way to add spectrum to the database. Both of these features would be important in spectrum bands where the incumbents are mobile operational systems such as those typical of many federal uses of spectrum. These systems do not use spectrum continuously, but only as operations demand. A priori determination of the timescales of TVWS would result in large exclusion zones, since regulators cannot keep up with the minutiae of changes in operational use – yet these changes in use create many of the opportunities for reuse.

MBSM addresses both these limitations. Within an MBSM database, managed spectrum bands have two sets of SCMs: SCMs that describe the bounds of the bands that are managed and SCMs of uses of spectrum within those bands that must be protected and therefore serve as constraints to new uses. Since methods for arbitrating compatibility complement the SCMs, coexistence is readily managed. So long as an SCM captures a new use, that SCM becomes a contour of protection that constrains further new uses.

In a process that manages coexistence, the SCM of a new use must be compatible with the SCMs of all current authorized users before that new use can be added. In a system that manages the reuse of spectrum around an operational incumbent, the incumbent's authorization may also be the authorization for the database to manage its channel. In these situations the incumbent's SCM serves as a constraint. The changes in operational use that constrain new uses can be updated on any timescale practical for the management of reuse. Incumbents can add spectrum to a database by contributing SCMs that serve as either authorizations or constraints. Incumbents have many options as to the SCM they provide to control the reuse authorized and thus control the protection they receive.

Figure 6-3 gives a simple example of alternative approaches to reveal spectrum availability. Panel a illustrates an incumbent use of spectrum – in this case, a coastal radar that points toward the sea. The subsequent panels illustrate methods for using SCMs to reveal increasing opportunities to reuse spectrum. These illustrations only show the location portions of models, but these locations would include a set of constructs that fully protect the incumbent. Panel b provides an example of an authorization SCM that the incumbent may use to define a compatible reuse. In this case, the modeler has already determined that a new use that falls within the authorization will not affect the radar. Panel c contains both an authorization SCM and a constraining SCM. The authorization SCM may be the radar operator's own authorization. The constraining SCM would be a model that contains a low-resolution version of the radar's use of spectrum that, if respected, would protect the radar. Any use that falls within the authorization SCM and avoids interfering with the constraining SCM would constitute feasible reuse. Panel d presents the same idea, but shows that the incumbent has the option to reveal different amounts of detail about its use of spectrum and with that detail provide greater opportunity for reuse. Here, the incumbent uses two SCMs to convey details, differentiating the effects of the directionality of the system so that greater reuse can occur in the directions where its antenna has low gain. Finally, Panel e illustrates an SCM that is even more liberal in its authorization of spectrum. Assuming the existence of a protocol or policy that prevents interference with this type of radar when implemented in a radio, the incumbent can specify a reuse everywhere it can use spectrum, adhering to the restrictions of this protocol.

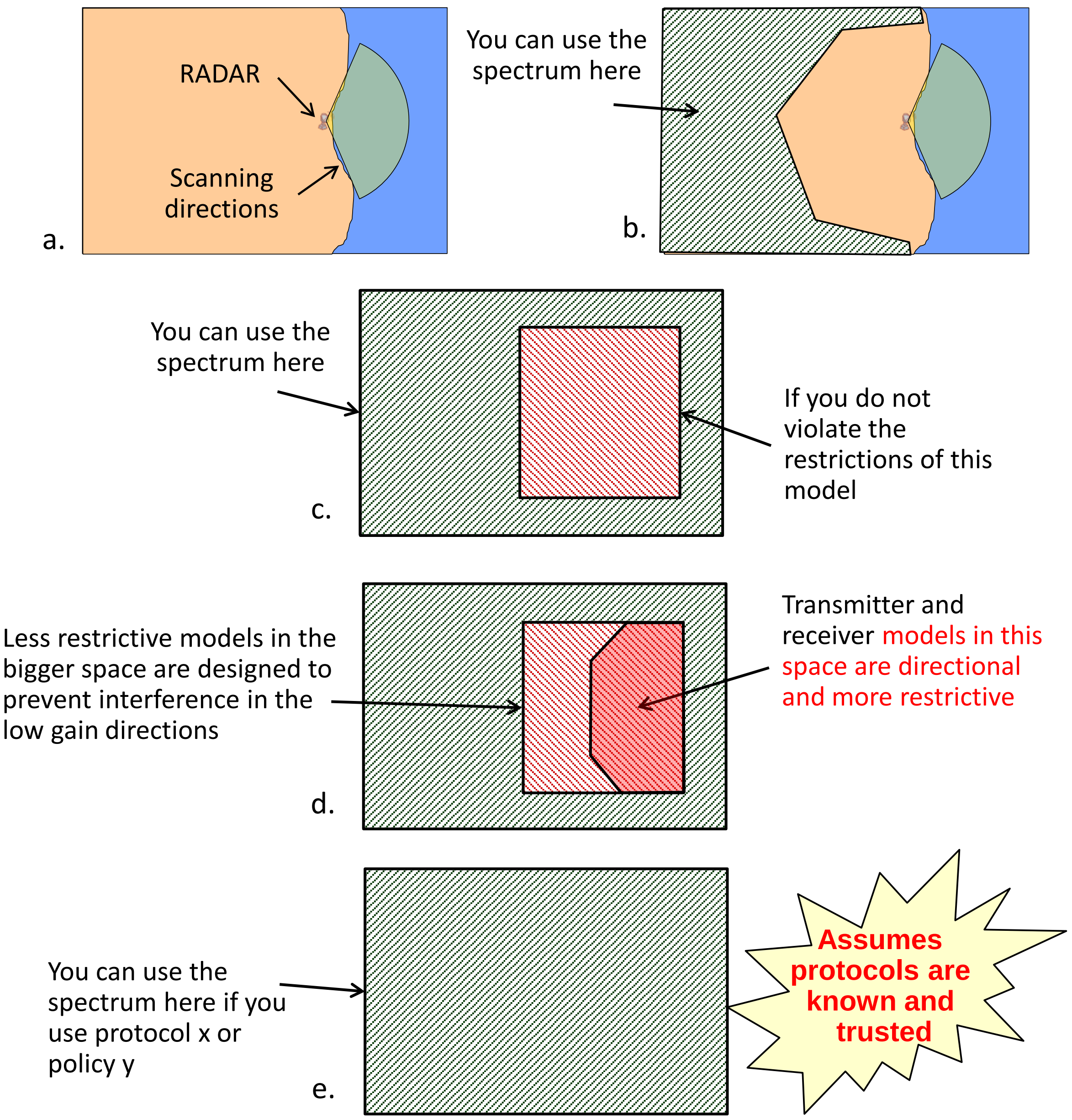


Figure 6-3. Alternative Approaches to Use SCM to Reveal Spectrum Availability

Figure 6-4 illustrates the difference in database managed access from the approach of TVWS to one enabled using SCM. In the TVWS SM systems, the database arbitrates entry of new users based on their compatibility with incumbents. Users must certify that RF devices operate in a way that databases understand, and regulation defines the approach to computing which channels are available to those devices based on device location and established contours of incumbent use. The databases do not manage secondary coexistence. The top illustration shows the regulator providing contours to the database administrators and the spectrum users communicating requests to and receiving authorizations from the database administrators.

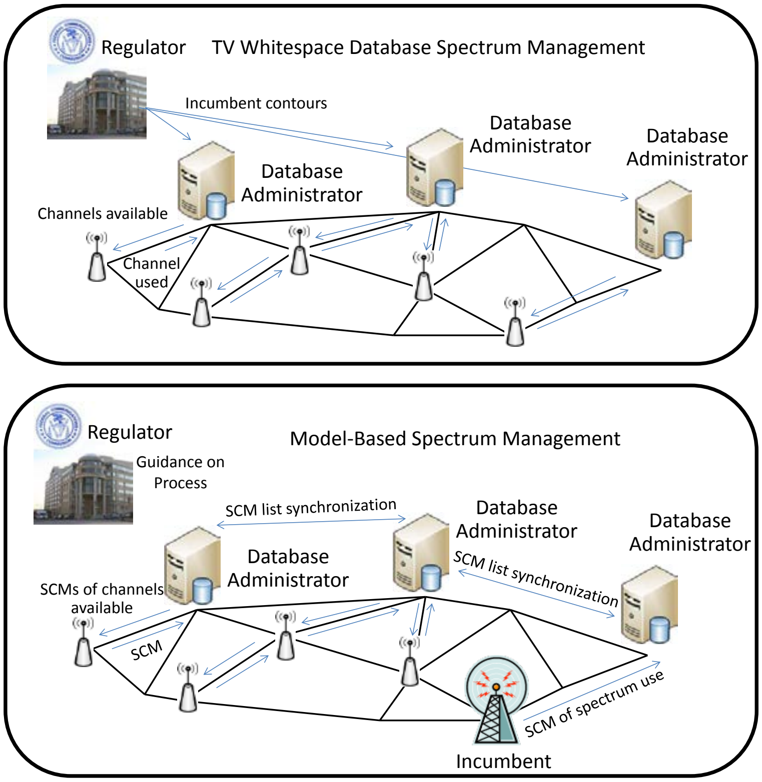


Figure 6-4. Alternative Database Controlled Spectrum Access

Using SCMs allows the database administrators to manage the coexistence of secondary users and to accept and manage spectrum provided to it ad hoc by incumbents. Incumbents can change their contours. Therefore, in the bottom illustration, the incumbents, rather than regulators, provide the models for protection of incumbents. Incumbent users can employ SCMs to convey their spectrum use to databases to databases, and these SCMs would serve as sufficient contours for a database to determine if new uses would be compatible. This outcome also holds true in an environment with multiple database administrators. The illustration shows the databases sharing the SCM they create. As long as all databases have a common set of SCMs of spectrum users they will arrive at the same conclusions on the admission of new users.

6.3.3 Spectrum Access System (SAS)

The advances in database administration afforded through using SCM are fully captured within the vision of the SAS proposed by the President's Council of Advisors on Science and Technology [15]. A system of databases can manage the spectrum of a diverse set of users and RF systems provided the uses are all modeled using the SCM approach and the database administrators synchronize their databases. A particularly attractive feature of using SCMs is that users can share the spectrum without having to reveal the sensitive aspects of systems that use the spectrum or the operations of the users. As revealed in the description of Figure 6-3, modelers have multiple ways to convey the boundaries for sharing the same use of spectrum. Users of spectrum can be quite creative in how they model their boundaries and still provide opportunities for new users of spectrum to share it.

6.3.4 Spectrum Markets

With the ability to add spectrum to the database and to manage coexistence comes the ability to create spectrum markets. The SCM becomes part of the communication among owners, brokers, and users that identifies the quanta of spectrum that owners make available, users request, and brokers authorize for use.

The market can form in two ways. In the first, a single entity manages the spectrum in the market [16]. Figure 6-5 illustrates owners and users employing SCMs to convey the spectrum they are adding to the market and the spectrum they are requesting and leasing respectively.

Standardization of the methods to arbitrate compatibility among models allows a distributed market. The SCMs commoditize the spectrum and so the market can become something similar to a real estate market. Figure 6-6 illustrates the concept. Database administrators can become brokers representing customers who are either sellers or buyers. They help the sellers build models of what they can share and place them in the market. They help market the spectrum and

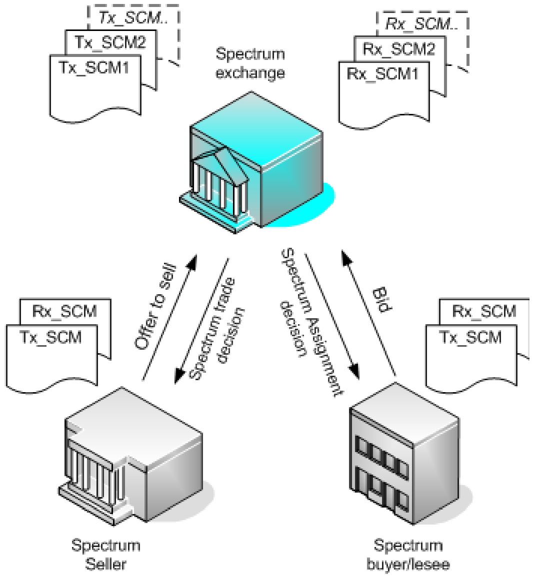


Figure 6-5. A Spectrum Market Using SCM [16]

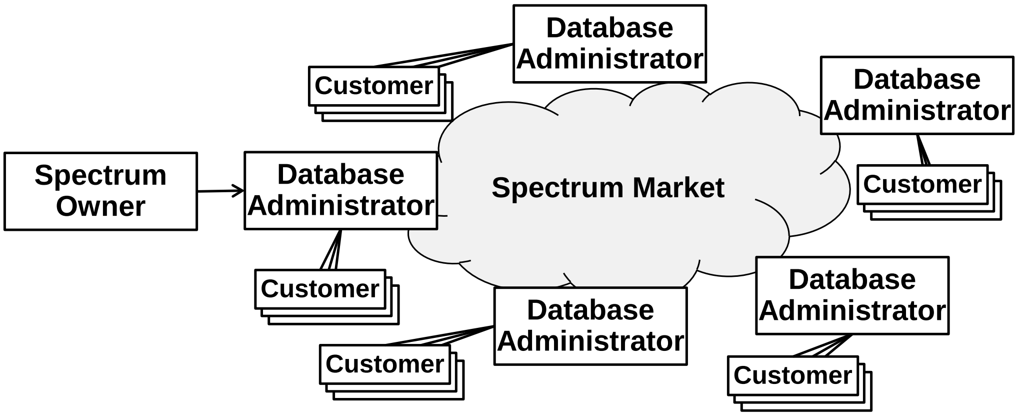


Figure 6-6. Distributed Spectrum Market Using SCM

can even combine it with spectrum from other sources to make it more attractive in the market, or they can subdivide the spectrum to sell it to more secondary users. They can represent the seller in any negotiation over the sale of the spectrum. They can also represent the buyer by searching for suitable spectrum and by aiding in their purchase of spectrum leases.

6.4 Cognitive Radio, Policy-Based Radio, and Policy-Based Spectrum Management

- A cognitive radio is defined as a type of radio in which communication systems are aware of their environment and internal state and can make decisions about their operating behavior based on that information and predefined objectives [18]
- A policy is a set of rules governing the behavior of a system [18].
- A policy-based radio is a type of radio in which the behavior of communications systems is governed by a policy-based control mechanism [18].

The SCMs themselves can be used to convey policy to policy-based radios as part of policy-based SM. The SCMs provide both permissive policy and restrictive policy. An authorization SCM is a permissive policy: as long as the radio operates within the boundaries of the authorization it complies with the policy. A constraining SCM is a restrictive policy: as long as a radio avoids violating the bounds of this SCM it complies with the policy. While managers can give only authorizing SCMs to radios as a permissive policy, they give constraining SCMs together with authorizing SCMs to provide a definition of policy that uses restrictive policy elements.

The typical policy-based radio directed through policy specified using SCMs is also a cognitive radio. Such a radio would be self-aware in two ways. First, it would be aware of its own location; second, it would be aware of how to create the SCM of its own use of spectrum. The radio can assess if it complies with policy by assessing whether the SCM it would build of its own use would fall within the boundaries of a permissive policy and would comply with any restrictive policy.

A likely challenge in exploiting policy-based SM would relate to managing policy itself in an environment consisting of many users of spectrum. Managers have no obvious way to assess whether a policy is compatible with existing users for most policy approaches. The use of SCMs can solve this challenge. By using SCMs as both the core of SM and as the means for giving policy to radios, the very process of managing spectrum results in authoring policy. The SCMs of incumbent uses are restrictive policies, and any policy authored using SCMs is by design compatible with the SCMs of incumbent uses.

6.5 Creating Policy and Protocol Construct Definitions

Modelers use the Policy and Protocol construct to identify behaviors that RF systems perform. This construct allows MBSM to grow and to manage the use of new behaviors and technologies that allow RF systems to coexist autonomously. However, in order to use this construct, it is necessary for some entity to create the policies or protocols that allow sharing, to identify the conditions the policy and protocol is effective, and to provide the naming and relevant parameters used in the construct. With adoption of MBSM as a means to manage spectrum will come the opportunity for standards bodies to perform this role of defining these behavior definitions and their names and parameter lists.

6.6 Supporting Roles

The MBSM approach to SM provides opportunities for a number of supporting roles. Some of these roles may be performed by the database administrators and others may become independent services of the system. Below we describe roles that may be useful to the typical owner of an RF system.

6.6.1 System Characterization

System characterization refers to the creation of the modeling constructs that are a product of the RF components that comprise the system; they include total power, spectrum masks, underlay masks, intermodulation masks, and power maps. Ideally, manufacturers will provide these. However, to ensure they accurately represent the system and to avoid biases, RF owners may request independent labs to build these characterizations, especially of IM effects. Methods to create these constructs could become the subject of regulation.

6.6.2 Model Building

A complete SCM combines constructs that depend on the technology alone, constructs of characterization, the policy and protocol construct, and constructs that depend on operational use. The operational constructs of models include location, propagation maps, start time, end time, and in some cases the power map. The propagation map construct also depends on the environment and the specific location. Its creation will likely require tools with good terrain models and sophisticated propagation models based on the terrain and possibly the season of the year and weather. The models could also be based on a characterization of the environment developed using actual measurement of propagation in the environment.

In creating models, the modeler may find that some parts of an operating area have better propagation than others and therefore warrant propagation maps that are more conservative (i.e. predict better reach). However, applying those models to the whole operating area may predict greater consumption than necessary. Better modeling may result from subdividing the operating area into multiple locations and applying different propagation maps to each. Such subdivision also increases the computational complexity of the model and so must be done wisely. Thus, the modeling of the combination of location and propagation can be very artful. Further, many system users may lack the tools to make these assessments; for example, few policy-based radios would have a sophisticated means to create propagation maps. Thus, support in building models by taking the system characterization parts of models and combining them with the operational and environmental parts could become an important service performed by the administrators in a SAS or of other businesses specializing in this service.

6.6.3 Environmental and Use Monitoring

Users of the SAS will likely want a third-party arbiter to resolve disputes about responsibility when systems share the same spectrum where harmful interference is observed. The arbiter would determine if the interference results from one party's violating the boundaries of the SCM of its use or from a bad model of location and propagation in the SCMs that predicted their compatible reuse, or whether a user has made a false claim. Additionally, users may want monitoring services to provide data on their own compliance with their SCM. Such data may indicate that they must modify their use to remain compliant, could expand their use to take advantage of characteristics modeled in their SCM, or should modify their SCM in the next sharing/leasing cycle since its predictions underestimate their need for spectrum or overestimate that need and should be reduced. These third-party arbiters would likely deploy a grid of sensors that can monitor spectrum use by frequency and time and present sensing results in the bands of interest to users of the service. They may also develop methods of computing and visualizing spectrum use to better reveal the extent of use, and may provide services to indicate how models could be changed to more accurately capture the extent of the observed use.

6.7 Regulation and Enforcement

Spectrum is a regulated resource, and building a SAS will require regulator guidance on the processes used to arbitrate access and on the methods used to characterize the use of spectrum by systems. Implementing a SAS using SCMs can make some parts of this task easier. With the standardization of SCMs comes the standardization of the process for computing compatibility. The regulator can focus on the processes of the SAS, the methods of modeling, the certification of constructs used in modeling, and the certification of systems to reveal the correct models of their use of spectrum. The regulator does not have to define how to compute admittance and does not need to own the models of protection, as occurs in the TVWS. Below we describe some potential regulator roles. These roles are not intended to be comprehensive or essential, but to serve as suggestions for ways regulation could help the operation of a SAS using SCMs.

6.7.1 Certifying Model Constructs

Key to using SCMs for SM is creating constructs that accurately bound the actual use of spectrum by RF devices and systems. Regulators may want to define how to create particular constructs and how to make models.

6.7.1.1 Certifying Characteristics of Systems

The effectiveness of using SCMs to manage spectrum depends on the ability of devices and systems to operate within the boundaries of the constructs used to convey their spectrum consumption. Thus, regulators should define the creation of device-dependent constructs through a process that provides confidence that the constructs are accurate. This sort of certification is appropriate for the total power, spectrum mask, underlay mask, intermodulation mask, power map, and policy and protocol constructs. Regulators would define the testing and measuring methods used to create the constructs and certify the labs authorized to perform them.

This sort of regulated device certification has value beyond just keeping the actors honest. The cost of manufacturing devices is always a business issue and manufacturers often compromise on quality if lower standards result in a functional product at less cost. Perhaps the most significant effect of using SCMs in SM will be that violation of licenses will not be based on the experience of harmful interference with an incumbent but on the violation of the boundaries defined by the SCM. This may provide an incentive for manufacturers to build devices of higher quality, as they will be able to operate in more situations. The constructs that characterize device performance may also be used in their marketing.

The lack of a clear way to certify that dynamically managed DSA devices can coexist with incumbent users of spectrum presents a challenge in the management of DSA technologies. The use of spectrum consumption modeling as the method to convey policy makes this certification realizable. Certification of the radios would verify that radios will choose operating parameters that keep its performance within the SCM given to it as policy.

Testing would consist of two parts. The first part would verify that a radio has a correct perception of its own use of spectrum. Radios will likely have a finite number of operating states; the tests would verify that the radio's SCM constructs for those operating states accurately bound the performance of the radio. The second part of the DSA radio certification would verify that the radio reliably chooses operating states whose SCMs are within the boundaries of SCMs given as policy.

6.7.1.2 Certifying Operational Constructs of Models

Full models require that the operationally dependent constructs be combined with the device characterization constructs. The location, propagation map, start time, end time, and sometimes power map constructs cannot be predefined as the device characterization constructs; they are defined based on where and when they will be used. Users control the location and time aspects, but not propagation associated with location and time, which affects consumption. Regulators may establish methods and tools for creating the combinations of location and propagation maps. Users would likely define the overarching location and time of use and then apply specified methods to subdivide the locations and create and assign propagation maps to those locations. Regulators may want to control this process by defining rules for certifying the tools used by spectrum owners to create these combinations of constructs or the businesses that provide model building services, as noted in Section 6.6.2.

6.7.2 SAS Operations

The operation of a SAS will have many regulatory components, most of which will extend beyond those influenced by the use of spectrum consumption modeling. For example, regulators may establish rules concerning the qualifications of database administrators, users, and their systems, and the precedence among users in gaining access. The use of spectrum consumption modeling may motivate other regulation on matters that make the SCM useful to the SAS. For example, as already described in Section 6.7.1, spectrum consumption modeling would require regulators to address the methods of building models. Other matters that may require regulation include identifying the data in addition to that in the SCM that must be provided, and defining the operational aspects of the SAS that ensure the SCMs are up to date and synchronized among administrators. Regulators may also define the operations that ensure all users have a fair opportunity to compete for spectrum.

6.7.2.1 Business Process and Regulatory Data

As stated in Section 6.1, spectrum consumption modeling constructs were designed as the minimum amount of data required to articulate spectrum use, and spectrum use alone. These constructs do not include data that might be necessary for the business processes of management. This feature would allow the models to perform broader functions. The SCMML schema provided in Appendix A is intended to be combined with other schemata that support particular business processes. Schemata that might be needed in a SAS would include a schema with the business process data necessary to add spectrum to the SAS, a schema used among SAS operators to collaborate in SM, and a schema used by devices and users to request, negotiate, purchase, or accept spectrum access. A regulator will likely want to identify particular data for these processes – at least the identity of users and devices that participate in the activities. The regulator may identify other data that must be conveyed in order to inform the participants about their responsibilities to maintain access (e.g., required frequency of checking the database), or the conditions that may cause them to lose access (e.g., a user with higher precedence needing access). A fully functional SAS will probably require many types of data in addition to that contained in SCMs.

6.7.2.2 Use of the Protocol and Policy Construct

Regulators would have the role of defining the conditions when the Protocol or Policy construct may be used in SM. Rules may differ based on whether the decision that this construct applies is based on spectrum manager's knowledge that it allows sharing with a particular incumbent versus when its use is a pairwise agreement between an incumbent and a new user. In the former, the regulator would probably make the decision through a rule making process that allows full disclosure and discussion on the efficacy of the behavior while in the latter, the regulator would only define the process used to reach agreements and allow the parties in the negotiation to determine the efficacy.

6.7.2.3 Database Synchronization

The full-up version of a SAS would allow a number of administrators to collaboratively manage the use of spectrum. In such a distributed system, the many administrators can only arrive at the same conclusions about the availability of spectrum if they have synchronized databases of SCMs. Regulators may specify the requirements for this process, which would be manifested in specified cycles of management, architecture of management, and management responsibilities. For cyclic management approaches, the regulator may define periods in which certain activities occur: for example, a period for requests, followed by a period of assignment, and then the start of use based on the full sharing of the SCMs of the assignment and the synchronization of databases.

Regulators could also specify an architecture that assists the collaborating administrators to synchronize their databases. For example, it could specify that a single database serve as a master. Rules would require that this database of assignments be updated before any assignment is made. Databases putting spectrum into the system would do so by adding that spectrum to the master database. Databases searching for spectrum would verify that their records are synchronized to the master before they makes suggestions to their customers about spectrum availability.

In a distributed management system, multiple users may request the same spectrum. Regulators might want to specify how to resolve this competition and which database administrators would constitute the ultimate authorities in the granting of leases. An obvious possibility would be the database representing the owner but, as described in Section 6.3.4, the ability to combine spectrum across multiple bands may be useful and thus might cause the leasing to cross multiple administrators. Regulators may define the methods for aggregating spectrum to ensure just one administrator acts as the lease authority.

6.7.2.4 Defining the Responsibilities of Management Entities

Management entities will have a responsibility to each other and to spectrum users at large. Hoarding or otherwise limiting the free advertising of spectrum availability would be contrary to the spirit of the SAS. A database administrator should not be permitted to withhold spectrum from use in order to inflate the value of spectrum. Regulators may establish rules on the methods of collaboration that administrators must employ. For example, a rule might require that all spectrum parcels for lease be advertised to all administrators, with the controlling administrator waiting for either a positive or negative response from each peer administrator before awarding a lease to the highest bidder.

6.7.2.5 Spectrum Aggregation

Spectrum consumption modeling allows parcels of spectrum to be subdivided or aggregated. Ensuring spectrum is available for short-term uses often conflicts with creating parcels that have the greatest value to broadband service providers. The value of spectrum to broadband providers depends on the amount of spectrum measured in all dimensions (especially duration of access) and so encourages aggregation. Regulators may establish policies governing the aggregation of spectrum in order to balance the availability of spectrum to potential users and its value to the most likely users.

6.7.3 The Roles and Methods of Enforcement

The effectiveness of any dynamic SAS will depend on some form of monitoring and enforcement. SCMs support this activity well since they are based on the physics of spectrum consumption. The models themselves do not attempt to predict performance, but instead to bound consumption. The SCMs allow users to estimate an upper bound on the use of spectrum at the boundaries where sharing begins, but constructing the models also provides a means to estimate use anywhere in space, time, and frequency. Measurements across the space of use can verify compliance by assessing whether a particular use falls within the estimated bound and supports the sharing that this boundary predicts.

We anticipate that a SAS for managing spectrum will be complemented by some sort of field of sensors. Businesses may form that provide this service. Parties involved in providing spectrum to the SAS or in leasing spectrum from the SAS may identify a sensing service provider to serve as the arbiter in any use conflict that may occur. SAS participants may use these services to build SCMs that better estimate their use of spectrum or to reveal opportunities for expanding their use. Regulators may have to certify who is qualified to perform these sensing roles and specify the conditions under which SAS participants must use the services they provide.

6.8 Conclusion

This section has further described a likely path for the exploitation of MBSM, with specific emphasis on the commercial aspect of developing a SAS as proposed in [15]. The discussion anticipated and described the roles that may develop in this type of implementation. However, MBSM is also a very powerful tool for SM and analysis within enterprises. Earlier chapters have described the benefits of using MBSM in operational contexts, particularly in some military sharing scenarios. MBSM has the potential to change SM across all activities where SM occurs.

Successfully implementing MBSM and achieving its full set of benefits will require broad adoption of the technique. The first step is to agree on a modeling approach and on the methods to arbitrate compatibility among models. This manual attempts to define that modeling approach so that the concept can be shared and used to seek agreement. In the time since the first version of this manual was released the concept has moved into a formal standardization process, and now form the foundation of a new standardization effort by the IEEE Dynamic Spectrum Access Networks Standards Committee (DySPAN-SC) [20].

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Appendix A Spectrum Consumption Model Markup Language (SCMML)

As illustrated in Figure 3-33 and described in Section 2.3, SCMs 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 used repeatedly 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 all of the individual data types are described in the order they are defined in the schema.

A.1 Fundamental Types

A.1.1 Power Type

The Power data type is used by the total power construct. The values are specified as decimal numbers and are always expected to have units of dBW or dBm.

```
<xs:complexType name="Total_Power">
  <xs:simpleContent>
    <xs:extension base="xs:decimal">
      <xs:attribute name="units" use="required">
        <xs:simpleType>
          <xs:restriction base="xs:string">
            <xs:enumeration value="dBW"/>
            <xs:enumeration value="dBm"/>
          </xs:restriction>
        </xs:simpleType>
      </xs:attribute>
    </xs:extension>
  </xs:simpleContent>
</xs:complexType>
```

A.1.2 Short_Time Type

The Short_Time data type is used in spectrum mask constructs to define frequency-hopping and short DC signals. The value is specified as a decimal, and the type specifies a choice between three unit 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>
```

A.1.3 Zero_to_One Type

The Zero_to_one type is used for probabilities and DCs to restrict decimal numbers to values between 0 and 1. The values are restricted to decimal numbers x such that 0 ≤ x ≤ 1.

```
<xs:simpleType name="Zero_to_One">
  <xs:restriction base="xs:decimal">
    <xs:minInclusive value="0"/>
    <xs:maxInclusive value="1.0"/>
  </xs:restriction>
</xs:simpleType>
```

A.1.4 Likelihood Type

The Likelihood data type is used in the Probability Type to provide the probability measure that the particular construct provides an upper bound to what is being modeled. The values are specified as decimal numbers x such that 0 ≤ x ≤ 1.

- The approach attribute identifies whether the probabilities indicate alternative conditions or a cumulative condition.
- The alternative attribute indicates the probability that one alternative or another is used.
- The cumulative attribute indicates a series of constructs in which the higher probability constructs subsume the lower probability ones.
- The "nature" attribute identifies whether the probability indicates that construct identifies a persistent or fleeting phenomenon. Phenomena that that move to a state with some probability and then stay there are persistent; those that move freely from state to state, spending some fraction of their time in one state or another, are fleeting.
- The "derivation" attribute provides additional information on how the value was determined.
- Judgment means that the value is the modeler's judgment.
- Estimated means the value was determined through a theoretical analysis.
- Measured means the value was determined through a statistically appropriate method of measuring the phenomenon.

```
<xs:complexType name="Likelihood">
  <xs:simpleContent>
    <xs:extension base="xs:decimal">
      <xs:attribute name="approach" use="required">
        <xs:simpleType>
          <xs:restriction base="xs:string">
            <xs:enumeration value="alternative"/>
            <xs:enumeration value="cumulative"/>
          </xs:restriction>
        </xs:simpleType>
```

```
      </xs:attribute>
      <xs:attribute name="nature" use="optional">
        <xs:simpleType>
          <xs:restriction base="xs:string">
            <xs:enumeration value=" fleeting "/>
            <xs:enumeration value="persistent"/>
          </xs:restriction>
        </xs:simpleType>
      </xs:attribute>
      <xs:attribute name="derivation" use="optional">
        <xs:simpleType>
          <xs:restriction base="xs:string">
            <xs:enumeration value="judgment"/>
            <xs:enumeration value="estimated"/>
            <xs:enumeration value="measured"/>
          </xs:restriction>
        </xs:simpleType>
      </xs:attribute>
    </xs:extension>
  </xs:simpleContent>
</xs:complexType>
```

A.1.5 Probablity Type

The Probability data type is used in multiple constructs to indicate the probability that the particular construct provides an upper bound to what is being modeled. It uses an Odds data element of the Likelihood data type with an optional Max_Dwell time. When the nature of the Odds element is fleeting the Max_Dwell time indicates the maximum duration of a fleeting event.

```
<xs:complexType name="Probability">
  <xs:sequence>
    <xs:element name="Odds" type="Likelihood"/>
    <xs:element minOccurs="0" maxOccurs="1" name="Max_Dwell" type="Short_Time"/>
  </xs:sequence>
</xs:complexType>
```

A.1.6 Power_Spectral_Flux_Density Type

The Power_Spectral_Flux_Density data type is used in the minimum power flux density construct. The values are specified as decimal numbers and are always expected to have units of $^{\mathrm{dBW}}\!\big/_{\mathrm{kHz}\cdot\mathrm{m}^2}$ or $^{\mathrm{dBm}}\!\big/_{\mathrm{kHz}\cdot\mathrm{m}^2}$.

```
<xs:complexType name="Power_Spectral_Flux_Density">
  <xs:simpleContent>
    <xs:extension base="xs:decimal">
      <xs:attribute name="units" use="required">
        <xs:simpleType>
          <xs:restriction base="xs:string">
            <xs:enumeration value="dBW/(kHz(m^2))"/>
```

```
      <xs:enumeration value="dBm/(kHz(m^2))"/>
     </xs:restriction>
    </xs:simpleType>
   </xs:attribute>
  </xs:extension>
 </xs:simpleContent>
</xs:complexType>
```

A.1.7 Frequency Type

The frequency data type is used in multiple types and constructs of the SCMML. The frequency value is of type decimal; 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>
```

A.1.8 Bandwidth Type

The Bandwidth data type is used in mask constructs of the SCMML. The bandwidth value is of type decimal; this type provides attributes for the specification of units. Bandwidth specifies the breadth of a contiguous band of frequencies. It is used together with Relative_Power to specify the spectral power density (i.e., the power per unit of bandwidth) in spectrum and underlay masks. It is also used for bandwidth rating values in underlay masks.

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

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

A.1.9 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; this type specifies that its units are 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>
```

A.1.10 Spectrum Mask Types

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

A.1.10.1 Inflection_Point Type

The Inflection_Point data type is used to define the inflection points in spectrum, underlay, and IM 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 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>
```

A.1.10.2 Filter_Mask Type

The Filter_Mask data type is used as part of the IM mask construct to specify a frequency-dependent power amplification. Filter_Masks have at least two Inflection_Point elements, as this is the minimum necessary to specify some quantity of bandwidth over which amplification applies. In practice there will likely be more than two, and so the Inflection_Point data element may be reused any 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>
```

A.1.10.3 Intermediate_Frequency Type

The Intermediate_Frequency data type is used to specify the intermediate frequency used by the filters of a superheterodyne receiver. It includes an attribute for the frequency units and an attribute indicating if the receiver uses high-side or low-side frequency injection. This attribute allows determination of the local oscillator frequency used in the heterodyning and the image frequency.

```
<xs:complexType name="Intermediate_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:attribute name="injection" use="required">
        <xs:simpleType>
          <xs:restriction base="xs:string">
            <xs:enumeration value="high"/>
            <xs:enumeration value="low"/>
           </xs:restriction>
         </xs:simpleType>
       </xs:attribute>
     </xs:extension>
  </xs:simpleContent>
</xs:complexType>
```

A.1.10.4 Power_Margin_Computation Type

The Power_Margin_Computation data type specifies the method to use in computing the power margin. There are two options: total power and maximum power density. Underlay masks are designed according to a particular computation methodology. One of these methods must be identified for all underlay masks.

```
<xs:simpleType name="Power_Margin_Computation">
  <xs:restriction base="xs:string">
    <xs:enumeration value="Total Power"/>
    <xs:enumeration value="Maximum Power Density"/>
  </xs:restriction>
</xs:simpleType>
```

A.1.10.5 PDS_Mask Type

PDS_Masks are used to specify power-density spectra (i.e., power per unit of bandwidth as a function of frequency). PDS_Masks are used in two constructs: the spectrum mask and the underlay masks. PDS_Masks have at least two Inflection_Point elements, as this is the minimum necessary to specify some quantity of bandwidth. In practice there will likely be more than two, and so the Inflection_Point data element may be reused any number of times. These masks also have a Bandwidth_Unit, which is the bandwidth reference of the power spectral density.

```
<xs:complexType name="Mask">
  <xs:sequence>
    <xs:element minOccurs="2" maxOccurs="unbounded" name="Inflection_Point"
      type="Inflection_Point"/>
    <xs:element minOccurs="0" maxOccurs="1" name="Bandwidth_Unit" type="Bandwidth"/>
  </xs:sequence>
</xs:complexType>
```

A.1.10.6 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>
```

A.1.10.7 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>
```

A.1.10.8 Frequency_Band Type

The Frequency_Band type is used to specify a band in which 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>
```

A.1.10.9 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>
```

A.1.10.10 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 in a specified bandwidth.

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

A.1.10.11 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>
```

A.1.10.12 Bandwidth_Time_Product Type

The Bandwidth_Time_Product type is used to specify a BTP. A BTP is used as a measure of the allowed occupancy of frequency-hopped 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>
```

A.1.10.13 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 BTP.

```
<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>
```

A.1.10.14 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>
```

A.1.10.15 DC_Rating_Values Type

The DC_Rating_Values type specifies the three-tuple of values – DC, the maximum dwell time, and the relative power – to rate an underlay mask for different DCs of interference. The DC and maximum dwell time are criteria for applying the mask. The relative power element specifies the adjustment in the power of the underlay mask to use for an underlay rated for the specified DC and maximum dwell time.

```
<xs:complexType name="DC_Rating_Values">
  <xs:sequence>
    <xs:element name="Duty_Cycle" type="Zero_to_One"/>
    <xs:element name="Max_Dwell_Time" type="Short_Time"/>
    <xs:element name="Relative_Power" type="Relative_Power"> </xs:element>
  </xs:sequence>
</xs:complexType>
```

A.1.10.16 DC_Rating_List Type

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

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

A.1.11 Map Types

A.1.11.1 Map Value Type

Map values are used in propagation maps and power maps. All values are decimal. The order of the values indicates the role of the value. An attribute is provided to make models more readable. Refer to Sections 3.1.4 and 3.1.5 for the order and the meaning of values. The units in the data type make the meaning of the values unambiguous for humans reading the values.

```
<xs:complexType name="Map_Value">
   <xs:simpleContent>
      <xs:extension base="xs:decimal">
         <xs:attribute name="units" use="required">
            <xs:simpleType>
               <xs:restriction base="xs:string">
                  <xs:enumeration value="Azimuth (degrees)"/>
                  <xs:enumeration value="Elevation (degrees)"/>
                  <xs:enumeration value="Exponent"/>
                  <xs:enumeration value="Distance(meters)"/>
                  <xs:enumeration value="Flux Density (dB/m^2)"/>
               </xs:restriction>
            </xs:simpleType>
         </xs:attribute>
      </xs:extension>
   </xs:simpleContent>
</xs:complexType>
```

A.1.11.2 Map Type

Maps are used within two constructs: propagation maps and power maps. The "A_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="A_Map_Value"
         type="Map_Value"/>
   </xs:sequence>
</xs:complexType>
```

A.1.11.3 Angle Type

The angle type is used within the orientation type to specify angles in degrees.

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

A.1.11.4 Orientation Type

The orientation type may be used within a power map construct. It provides three values specifying the rotations about the three platform axes 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>
```

A.1.12 Location Types

A.1.12.1 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 type is defined in two steps. First, a simple type called Longitude_Type is created to restrict 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>
```

A.1.12.2 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 type is defined 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>
```

A.1.12.3 Distance Type

The Distance type is used to specify a decimal number in fixed units of meters. It is used in 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>
```

A.1.12.4 Point Type

The Point type defines a point relative to an ellipsoidal surface. A longitude and latitude provide 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 whose attribute for units 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>
```

A.1.12.5 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>
```

A.1.12.6 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 in which 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>
```

A.1.12.7 Antenna_Height Type

The Antenna_Height Type is used with points, circles, and polygons that represent surfaces on the earth. It indicates the height of the antenna above the surface. This height can be above the ground at each point of the surface or above the average height of the terrain across the surface.

```
<xs:complexType name="Antenna_Height">
  <xs:simpleContent>
    <xs:extension base="xs:decimal">
      <xs:attribute name="units" fixed="meters"/>
      <xs:attribute name="Reference" use="required">
        <xs:simpleType>
          <xs:restriction base="xs:string">
            <xs:enumeration value="ground"/>
            <xs:enumeration value="average_terrain_height"/>
          </xs:restriction>
        </xs:simpleType>
      </xs:attribute>
    </xs:extension>
  </xs:simpleContent>
</xs:complexType>
```

A.1.12.8 Point_Surface Type

The Point_Surface type defines a point that is considered to be on the surface of the earth.

```
<xs:complexType name="Point_Surface">
  <xs:all>
    <xs:element name="A_Point" type="Point"/>
    <xs:element name="The_Antenna_Height" type="Antenna_Height"/>
  </xs:all>
</xs:complexType>
```

A.1.12.9 Circle_Surface Type

The Circle_Surface type defines a circle on the surface of the earth. The center point is considered to be on the surface of the earth and the radius reaches to points that are also on the surface.

```
<xs:complexType name="Circle_Surface">
  <xs:all>
    <xs:element name="A_Circle" type="Circle"/>
    <xs:element name="The_Antenna_Height" type="Antenna_Height"/>
  </xs:all>
</xs:complexType>
```

A.1.12.10 Polygon_Surface Type

The Polygon_Surface type defines a polygon on the surface of the earth. All points of the polygon are considered to be on the surface of the earth.

```
<xs:complexType name="Polygon_Surface">
  <xs:all>
    <xs:element name="A_Polygon" type="Polygon"/>
    <xs:element name="The_Antenna_Height" type="Antenna_Height"/>
  </xs:all>
</xs:complexType>
```

A.1.12.11 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>
```

A.1.12.12 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>
```

A.1.12.13 Heading 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="Heading">
   <xs:all>
      <xs:element name="Azimuth" type="Angle"/>
      <xs:element name="Elevation" type="Angle"/>
   </xs:all>
</xs:complexType>
```

A.1.12.14 Track Type

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

```
<xs:complexType name="Track">
   <xs:all>
      <xs:element name="Start" type="Point"/>
      <xs:element name="Direction" type="Heading"/>
      <xs:element name="Speed">
         <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>
```

A.1.13 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>
```

A.2 Constructs Type

The Constructs type is a complex type that consists of the 12 elements: each 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 A.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 that all the appropriate constructs are used in these parts, and so checking for completeness of a model falls outside this schema definition. The Constructs type in this schema will ensure that the data is well formed for a model.

A.2.1 Total_Power Element

The Total_Power construct specifies a power reference. Although every transmitter and receiver model requires a total power, 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. There may also be multiple values, each differentiated by a confidence that it bounds the true value of power. Thus there are two data values: the power level and the confidence in that level. If a cumulative probability is used then one of the power values in the listing must have a confidence of 1. If alternative probabilities are used then the probability values of the alternative must add up to 1.

```
<xs:element minOccurs="0" maxOccurs="unbounded" name="Total_Power">
   <xs:complexType>
      <xs:sequence>
         <xs:element name="Power_Level" type="Power"/>
         <xs:element minOccurs="0" name="Confidence" type="Probability"/>
      </xs:sequence>
   </xs:complexType>
</xs:element>
```

A.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 a transmitter model, and so the minimum occurrence can be 0. 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.

Spectrum masks convey the spectral occupancy of signals. When the mask element is used in the header of a system or a collection it identifies the spectral occupancy of all signals transmitted by the system or the collection of systems. Spectrum masks used in a transmitter model convey the particular spectral occupancy of the signal that the transmitter would emit. Spectrum masks may apply either to continuous signals or signals that pulse or hop frequencies. Continuous signals may be expressed with explicit frequency references or relative frequency references. In the latter case, a center frequency makes the spectrum used explicit. In the frequency-hop case, the mask is always relative and the modeler uses either a center frequency list or a frequency band list to convey the explicit frequencies that the modeled transmitter uses.

```
<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:complexType>
                <xs:choice>
                  <xs:element minOccurs="0" maxOccurs="unbounded"
                   name="Center_Freq" type="Frequency"/>
                </xs:choice>
              </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:element minOccurs="0" name="Confidence" type="Probability"/>
    </xs:all>
  </xs:complexType>
</xs:element>
```

A.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 that 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. 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 BTP. In the fifth, an unrated mask's power is adjusted for one or more DCs with dwell time ratings. In the sixth, the mask is associated with the use of a particular protocol or policy described using the Protocol_or_Policy construct that has the same index value. Section 3.1.3 describes, and Figure 3-3, Figure 3-4, and Figure 3-5 demonstrate, the difference between the approaches to specifying bandwidth-rated, bandwidth-time-rated, and DC-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:element name="DC_Rating_List" type="DC_Rating_List"/>
            <xs:element name=" P_or_P_Index" type="xs:integer"/>
          </xs:choice>
        </xs:complexType>
      </xs:element>
      <xs:element name="Mask" type="PDS_Mask"/>
      <xs:element name="PMC_Method" type="Power_Margin_Computation"/>
      <xs:element minOccurs="0" name="Confidence" type="Probability"/>
    </xs:all>
  </xs:complexType>
</xs:element>
```

A.2.4 Power_Map Element

A model of a receiver or a transmitter always references 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, at minimum, 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 therefore is fixed. The second is an orientation relative to the platform orientation. The model uses the platform-relative orientation together with a track location value that 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.

The Power_Map also has an optional element that identifies a Scanning_Region. When the element is used, the Power_Map identifies the directions of scanning by assigning a map value of 1 to those directions and a 0 to all others. The Orientation element of the Power_Map applies to the Scanning_Region map. The vertical axis – 0º elevation or the positive z direction of the Power_Map_List – may point in any direction within the scanning region. It is assumed that the x axis of the Power_Map_List is always parallel to the x-y plane of the Scanning_Region map.

Power_Maps may also use the optional Confidence element. The Location_Index element supports creating multiple power maps associated with different locations or times. The Confidence element specifies either a cumulative or alternative probability for the Power_Map. When used, models should have more than one Power_Map and the total confidence that one or the other is applicable should be 1.

```
<xs:element minOccurs="0" maxOccurs="unbounded" name="Power_Map">
  <xs:complexType>
    <xs:sequence>
      <xs:element name="Orientation">
        <xs:complexType>
          <xs:choice>
            <xs:element name="Surface"/>
            <xs:element name="Relative_to_Platform" type="Orientation"/>
            <xs:element name="Toward_Reference_Point" type="Point"/>
          </xs:choice>
        </xs:complexType>
      </xs:element>
      <xs:element minOccurs="0" name="Scanning_Region" type="Map"/>
      <xs:element name="Power_Map_List" type="Map"/>
      <xs:element minOccurs="0" name="Location_Index" type="xs:integer"/>
      <xs:element minOccurs="0" name="Confidence" type="Probability"/>
    </xs:sequence>
  </xs:complexType>
</xs:element>
```

A.2.5 Propagation_Map Element

A model of a receiver or a transmitter always references 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 gives modelers the choice between either a linear or piecewise linear map and then uses the element of the Map type to record the map values. The Location_Index supports modeling of multiple locations in an SCM with different propagation maps. This index associates the propagation map with the location. Multiple maps may be used per location if they are differentiated by an antenna height rating or a confidence. Maps that have antenna height ratings usually have no elevation differentiation, since it would be meaningless. Maps that use the Confidence element are matched to other maps that also use confidence. The Confidence element of power maps is a cumulative probability where the map predicting greatest separation between users, i.e., predicts least pathloss, have the highest confidence level.

```
<xs:element minOccurs="0" name="Propagation_Map">
  <xs:complexType>
    <xs:sequence>
      <xs:element name="Propagation_Model">
        <xs:complexType>
          <xs:choice>
            <xs:element name="Linear">
              <xs:complexType/>
            </xs:element>
            <xs:element name="Piecewise_Linear">
              <xs:complexType/>
            </xs:element>
          </xs:choice>
        </xs:complexType>
      </xs:element>
      <xs:element name="Propagation_Map_List" type="Map"/>
      <xs:element minOccurs="0" name="Location_Index" type="xs:integer"/>
      <xs:element minOccurs="0" name="Antenna_Height" type="Distance"/>
      <xs:element minOccurs="0" name="Confidence" type="Probability"/>
    </xs:sequence>
  </xs:complexType>
</xs:element>
```

A.2.6 Intermodulation_Mask Element

The Intermodulation_Mask construct is used when a signal has 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; the second, the IMAMask, is optionally provided in some transmitter IM models. In the case of a receiver IM mask for heterodyning, the order is specified as 1 and an IF element is added to specify the center frequency of the IF section of the receiver.

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

A.2.7 Platform Element

The Platform_Name is a string. This data element is optional but is usually provided when an IM mask is specified. The likelihood term is optional and is used for mobile systems that have some probability of meeting at the named platform location.

```
<xs:element minOccurs="0" maxOccurs="unbounded" name="Platform">
  <xs:complexType>
    <xs:sequence>
      <xs:element name="Platform_Name" type="xs:string"/>
      <xs:element minOccurs="0" name="Likelihood" type="Probability"/>
    </xs:sequence>
  </xs:complexType>
</xs:element>
```

A.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 it may not be used. When a model includes this element, there may be multiple locations per model and those locations may use one or several of the location constructs that were previously defined as fundamental types. Models may use multiples of these elements to indicate that the system components may be in multiple locations. Multiple tracks indicate that a component is 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 used for computing compatibility include only one, and so models with multiple locations would be expanded to multiple models, each with a single location. The Location Index allows modelers to associate all the locations in the same sequence with particular propagation maps and times of use. The Confidence element allows modelers to express the confidence that the modeled system exists within the modeled location.

```
<xs:element minOccurs="0" maxOccurs="unbounded" name="Location">
  <xs:complexType>
    <xs:sequence>
      <xs:element minOccurs="0" maxOccurs="unbounded" name="Point" type="Point"/>
      <xs:element minOccurs="0" maxOccurs="unbounded" name="A_Point_Surface"
        type="Point_Surface"/>
      <xs:element minOccurs="0" maxOccurs="unbounded" name="A_Circular_Surface"
        type="Circle_Surface"/>
      <xs:element minOccurs="0" maxOccurs="unbounded" name="A_Polygon_Surface"
        type="Polygon_Surface"/>
      <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:element minOccurs="0" name="Location_Index" type="xs:integer"/>
      <xs:element minOccurs="0" name="Confidence" type="Probability"/>
    </xs:sequence>
  </xs:complexType>
</xs:element>
```

A.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 this 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. Further, the Start element may have multiple copies when used together with the Location Index. The Location Index allows modelers to associate the Start times with particular locations and propagation maps in the same model. The Confidence element allows modelers to express the confidence that the modeled system will start its use at the modeled time.

```
<xs:element minOccurs="0" maxOccurs="unbounded" 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:element minOccurs="0" name="Location_Index" type="xs:integer"/>
      <xs:element minOccurs="0" name="Confidence" type="Probability"/>
    </xs:sequence>
  </xs:complexType>
</xs:element>
```

A.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 this 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. Further, the End_Time element may have multiple copies when used together with the Location Index. The Location Index allows modelers to associate the End_Time elements with particular locations and propagation maps in the same model. The Confidence element allows modelers to express the confidence that the modeled system will end its use at the modeled time.

```
<xs:element minOccurs="0" maxOccurs="unbounded" name="End_Time">
  <xs:complexType>
    <xs:sequence>
      <xs:element name="Time" type="xs:dateTime"/>
      <xs:element minOccurs="0" name="Location_Index" type="xs:integer"/>
      <xs:element minOccurs="0" name="Confidence" type="Probability"/>
    </xs:sequence>
```

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

A.2.11 Minimum_Power_Spectral_Flux_Density Element

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

```
<xs:element minOccurs="0" name="Minimum_Power_Spectral_Flux_Density"
type="Power_Spectral_Flux_Density"/>
```

A.2.12 Protocol_or_Policy Element

The Protocol_or_Policy data structure consists of a name for the protocol or policy and then a list of parameters that further define the protocol or policy. The data structure allows no or multiple parameters of either a string type or 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 minOccurs="0" name="P_or_P_Index" type="xs:integer"/>
         <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>
```

A.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 stand alone.

```
<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>
```

A.4 Receiver Type

The Receiver type is identical to the Transmitter type in that it 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 differs from 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>
```

A.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 minOccurs="0" name="The_Purpose" type="Purpose" />
    <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>
```

A.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>
```

A.7 SCMML Markup

The SCMML Markup consists of the elements at the top of the schema hierarchy and defines the content of? XML files used to communicate system and collection data sets. The file starts with the element Source_ID that identifies the source of the data set. This element is followed by the choice of specifying either a system or a collection. If the markup specifies a collection, there is an additional requirement to select the purpose of the collection: whether to define consumption, give authorization, or specify constraints. The purpose is specified in a data element aptly named "The_Purpose."

```
<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>
```

A.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 specified purpose and each is limited to having a single location element. In addition to a purpose and a single location, a canonical transmitter model must have a total power, 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 for the canonical transmitter model, except that a receiver model must have an underlay mask as opposed to a spectrum mask.

A.9 Full SCMML Schema

The following is the full SCMML schema described above.

```
<?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">
    <xs:simpleContent>
      <xs:extension base="xs:decimal">
        <xs:attribute name="units" use="required">
          <xs:simpleType>
            <xs:restriction base="xs:string">
              <xs:enumeration value="dBW"/>
```

```
            <xs:enumeration value="dBm"/>
          </xs:restriction>
        </xs:simpleType>
      </xs:attribute>
    </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:simpleType name="Zero_to_One">
  <xs:restriction base="xs:decimal">
    <xs:minInclusive value="0"/>
    <xs:maxInclusive value="1.0"/>
  </xs:restriction>
</xs:simpleType>
<xs:complexType name="Likelihood">
  <xs:simpleContent>
    <xs:extension base="Zero_to_One">
      <xs:attribute name="approach" use="optional">
        <xs:simpleType>
          <xs:restriction base="xs:string">
            <xs:enumeration value="alternative"/>
            <xs:enumeration value="cumulative"/>
          </xs:restriction>
        </xs:simpleType>
      </xs:attribute>
      <xs:attribute name="nature" use="optional">
        <xs:simpleType>
          <xs:restriction base="xs:string">
            <xs:enumeration value=" fleeting "/>
            <xs:enumeration value="persistent"/>
          </xs:restriction>
        </xs:simpleType>
      </xs:attribute>
      <xs:attribute name="derivation" use="optional">
```

```
        <xs:simpleType>
          <xs:restriction base="xs:string">
            <xs:enumeration value="judgment"/>
            <xs:enumeration value="measured"/>
            <xs:enumeration value="estimated"/>
          </xs:restriction>
        </xs:simpleType>
      </xs:attribute>
    </xs:extension>
  </xs:simpleContent>
</xs:complexType>
<xs:complexType name="Probability">
  <xs:sequence>
     <xs:element name="Odds" type="Likelihood"/>
     <xs:element minOccurs="0" maxOccurs="1" name="Max_Dwell" type="Short_Time"/>
  </xs:sequence>
</xs:complexType>
<xs:complexType name="Power_Spectral_Flux_Density">
  <xs:simpleContent>
    <xs:extension base="xs:decimal">
      <xs:attribute name="units" use="required">
        <xs:simpleType>
          <xs:restriction base="xs:string">
            <xs:enumeration value="dBW/(kHz(m^2))"/>
            <xs:enumeration value="dBm/(kHz(m^2))"/>
          </xs:restriction>
        </xs:simpleType>
      </xs:attribute>
    </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="Bandwidth">
  <xs:simpleContent>
```

```
    <xs:extension base="xs:decimal">
      <xs:attribute name="units" use="required">
        <xs:simpleType>
          <xs:restriction base="xs:string">
            <xs:enumeration value="Hz"/>
            <xs:enumeration value="kHz"/>
            <xs:enumeration value="MHz"/>
          </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="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="Filter_Mask">
  <xs:sequence>
    <xs:element minOccurs="2" maxOccurs="unbounded" name="Inflection_Point"
      type="Inflection_Point"/>
    <xs:element minOccurs="0" maxOccurs="1" name="Bandwidth_Unit" type="Bandwidth"/>
  </xs:sequence>
</xs:complexType>
<xs:complexType name="Intermediate_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:attribute name="injection" use="required">
        <xs:simpleType>
          <xs:restriction base="xs:string">
```

```
            <xs:enumeration value="high"/>
            <xs:enumeration value="low"/>
          </xs:restriction>
        </xs:simpleType>
      </xs:attribute>
    </xs:extension>
  </xs:simpleContent>
</xs:complexType>
<xs:simpleType name="Power_Margin_Computation">
  <xs:restriction base="xs:string">
    <xs:enumeration value="Total Power"/>
    <xs:enumeration value="Maximum Power Density"/>
  </xs:restriction>
</xs:simpleType>
<xs:complexType name="PDS_Mask">
  <xs:sequence>
    <xs:element minOccurs="2" maxOccurs="unbounded" name="Inflection_Point"
      type="Inflection_Point"/>
    <xs:element name="Bandwidth_Unit" type="Bandwidth"/>
    <xs:element name="Bandwidth_Unit" type="Bandwidth"/>
  </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="Bandwidth"/>
    <xs:element name="Relative_Power" type="Relative_Power"> </xs:element>
```

```xml
  </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="DC_Rating_Values">
  <xs:sequence>
    <xs:element name="Duty_Cycle" type="Zero_to_One"/>
    <xs:element name="Max_Dwell_Time" type="Short_Time"/>
    <xs:element name="Relative_Power" type="Relative_Power"> </xs:element>
  </xs:sequence>
</xs:complexType>
<xs:complexType name="DC_Rating_List">
  <xs:sequence>
    <xs:element maxOccurs="unbounded" name="Rating_Values" type="DC_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="Heading">
  <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="Heading"/>
    <xs:element name="Speed">
      <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" maxOccurs="unbounded" name="Total_Power">
      <xs:complexType>
        <xs:sequence>
          <xs:element name="Power_Level" type="Power"/>
          <xs:element minOccurs="0" name="Confidence" type="Probability"/>
        </xs:sequence>
      </xs:complexType>
    </xs:element>
    <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:choice>
                      <xs:element minOccurs="0" maxOccurs="unbounded" name="Center_Freq"
                     type="Frequency"/>
                    </xs:choice>
                  </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>
```

```xml
   </xs:element>
   <xs:element name="Signal_Mask" type="PDS_Mask"/>
   <xs:element minOccurs="0" name="Confidence" type="Probability"/>
  </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: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:element name="DC_Rating_List" type="DC_Rating_List"/>
     </xs:choice>
    </xs:complexType>
   </xs:element>
   <xs:element name="Mask" type="PDS_Mask"/>
   <xs:element name="PMC_Method" type="Power_Margin_Computation"/>
   <xs:element minOccurs="0" name="Confidence" type="Probability"/>
  </xs:all>
 </xs:complexType>
</xs:element>
<xs:element minOccurs="0" maxOccurs="unbounded" name="Power_Map">
 <xs:complexType>
  <xs:sequence>
   <xs:element name="Orientation">
    <xs:complexType>
     <xs:choice>
      <xs:element name="Surface"/>
      <xs:element name="Relative_to_Platform" type="Orientation"/>
      <xs:element name="Reference_Point" type="Point"/>
     </xs:choice>
    </xs:complexType>
   </xs:element>
   <xs:element minOccurs="0" name="Scanning_Region" type="Map"/>
   <xs:element name="Power_Map_List" type="Map"/>
   <xs:element minOccurs="0" name="Confidence" type="Probability"/>
  </xs:sequence>
 </xs:complexType>
</xs:element>
<xs:element minOccurs="0" maxOccurs="unbounded" name="Propagation_Map">
 <xs:complexType>
  <xs:sequence>
```

```
      <xs:element name="Propagation_Model">
        <xs:complexType>
          <xs:choice>
            <xs:element name="Linear">
              <xs:complexType/>
            </xs:element>
            <xs:element name="Piecewise_Linear">
              <xs:complexType/>
            </xs:element>
          </xs:choice>
        </xs:complexType>
      </xs:element>
      <xs:element name="Propagation_Map_List" type="Map"/>
      <xs:element minOccurs="0" name="Location_Index" type="xs:integer"/>
      <xs:element minOccurs="0" name="Antenna_Height" type="Distance"/>
      <xs:element minOccurs="0" name="Confidence" type="Probability"/>
    </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 minOccurs="0" name="IF" type="Intermediate_Frequency"/>
      <xs:element name="IMCMask" type="Filter_Mask"/>
      <xs:element minOccurs="0" name="IMAMask" type="Filter_Mask"/>
    </xs:sequence>
  </xs:complexType>
</xs:element>
<xs:element minOccurs="0" maxOccurs="unbounded" name="Platform">
  <xs:complexType>
    <xs:sequence>
      <xs:element name="Platform_Name" type="xs:string"/>
      <xs:element minOccurs="0" name="Likelihood" type="Probability"/>
    </xs:sequence>
  </xs:complexType>
</xs:element>
<xs:element minOccurs="0" maxOccurs="unbounded" 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:element minOccurs="0" name="Location_Index" type="xs:integer"/>
      <xs:element minOccurs="0" name="Confidence" type="Probability"/>
    </xs:sequence>
  </xs:complexType>
</xs:element>
<xs:element minOccurs="0" maxOccurs="unbounded" 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:element minOccurs="0" name="Location_Index" type="xs:integer"/>
      <xs:element minOccurs="0" name="Confidence" type="Probability"/>
    </xs:sequence>
  </xs:complexType>
</xs:element>
<xs:element minOccurs="0" maxOccurs="unbounded" name="End_Time">
  <xs:complexType>
    <xs:sequence>
      <xs:element name="Time" type="xs:dateTime"/>
      <xs:element minOccurs="0" name="Location_Index" type="xs:integer"/>
      <xs:element minOccurs="0" name="Confidence" type="Probability"/>
    </xs:sequence>
  </xs:complexType>
</xs:element>
<xs:element minOccurs="0" name="Minimum_Power_Spectral_Flux_Density"
type="Power_Spectral_Flux_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 minOccurs="0" name="The_Purpose" type="Purpose" />
    <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"/>
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Appendix B 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 used as the datum for GPS that approximates the surface of the earth. A WGS 84 coordinate consists of a latitude, φ, and a longitude, λ, that 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 B-1 illustrates a geographic ellipsoid datum demonstrating the meaning of these coordinates and the parameters required to define an ellipsoid. Table B-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, 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

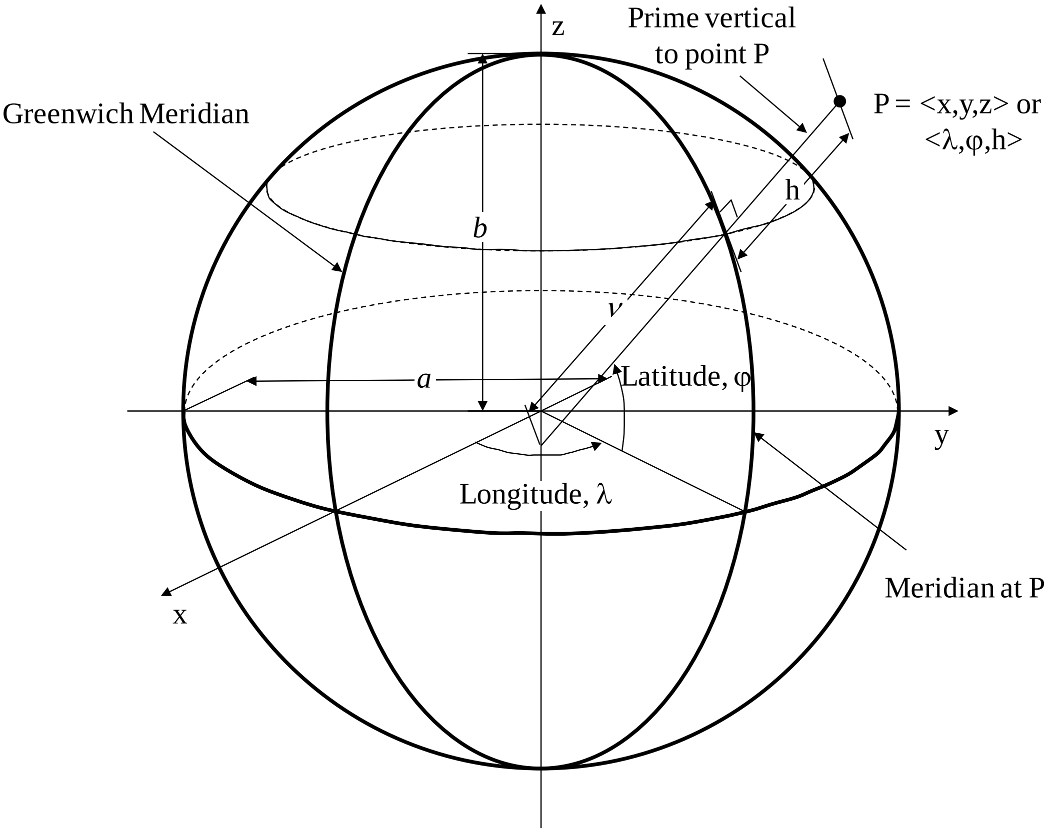


Figure B-1. WGS-84 Ellipsoid

Table B-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 equatorial plane pointing toward the meridian that passes through the Greenwich Observatory. The positive direction of the y axis is chosen to get a right-handed coordinate system. Figure B-1 illustrates the relationship between ellipsoidal and Cartesian coordinates.

Only two parameters 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, 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 is described in [[14]].

Appendix C Criteria for Planar Approximations

The ellipsoidal earth and the associated coordinate systems that follow based on location add a complexity to compatibility computations that modelers should avoid. A preferred option is to assume a planar earth in computing compatibility. In this analysis we seek to establish 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 C-1.

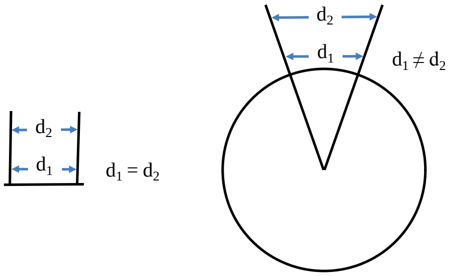
- It results in constant differences in distance on points at the same relative height on different prime verticals that would be different distances on an ellipsoidal earth.
- It allows line-of-sight (LOS) observation of points that would be occluded on a curved earth.
- Directions between points on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

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

C.1 Difference in Distances

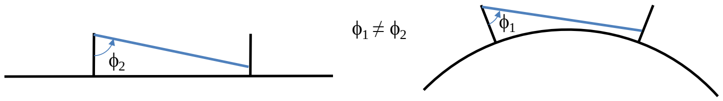
As illustrated in Figure C-1, the distance between points on the prime vertical varies with altitude. These differences in distance affect the strength of propagated signals. A fortunate feature of propagation, however, is that it is proportional to the log of distance, and so differences that are likely to be larger at larger 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 the separation distance on the Earth at which 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 C-1. Significant Differences Between the Planar Approximation of the Ellipsoidal Earth

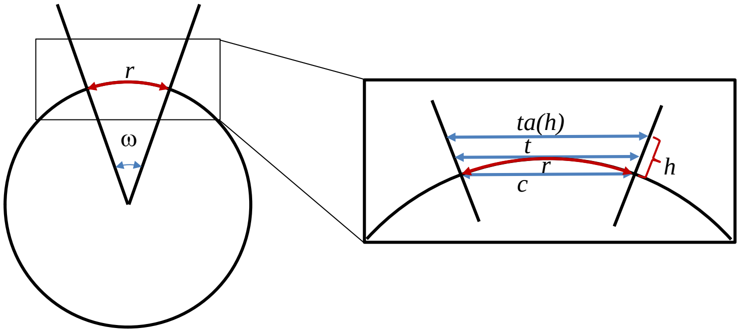


Figure C-2. Analysis Scenario to Assess the Ramification of Distance Differences Between Spherical and Planar Systems on Pathloss Estimates

this analysis we assume a spherical rather than an 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 C-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 distances 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 paragraphs 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:

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

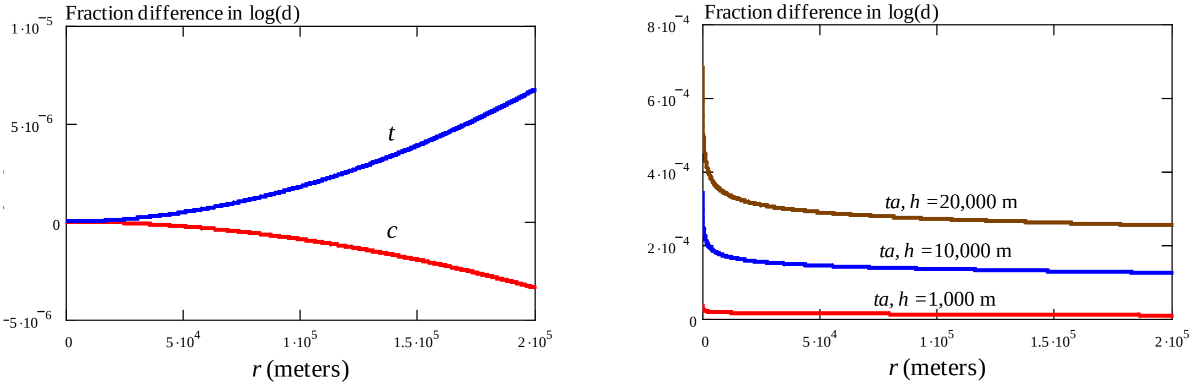
Define a function for the linear distance as a function of the altitudes on the prime verticals of the surface points:

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

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 C-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 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 does not constitute a constraint to using planar approximations.



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 C-3. Fractional Differences in Pathloss Estimates as a Result of Distance Differences Between Planar and Spherical Systems

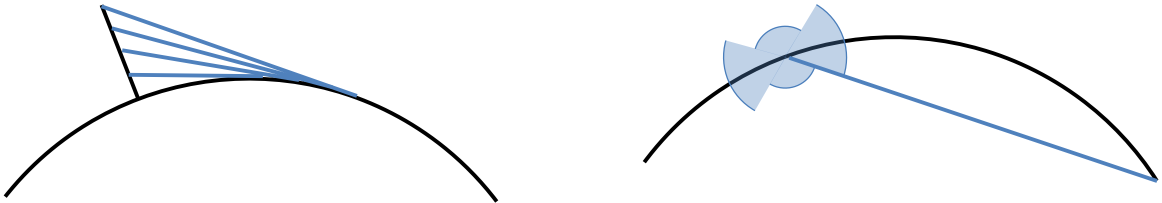
C.2 Occlusion Range

The range to LOS occlusion is a function of antenna height and is illustrated in Figure C-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 depends on how propagation maps and power maps are formed.

Figure C-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 at 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:

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

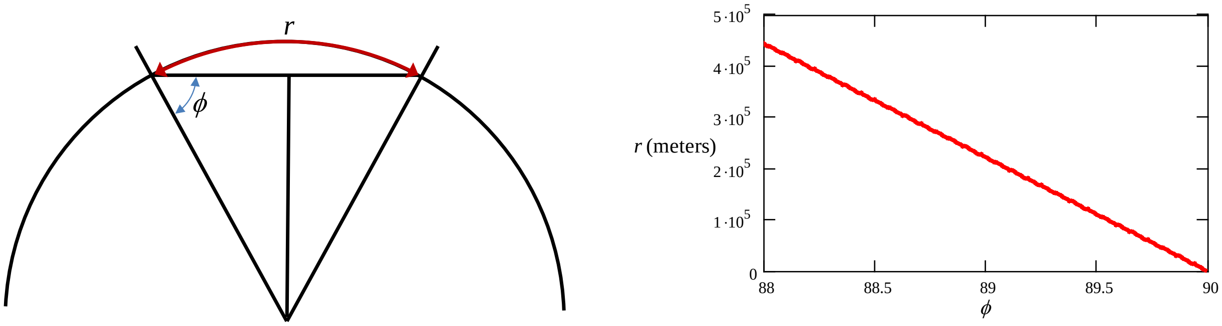
Figure C-5b graphs the range as a function of this elevation and shows that for an elevation as little as 2° below the horizon the planar approximation applies out beyond 400 km. Table C-1 lists the threshold elevations for some benchmark distances. It can be concluded that a planar approximation can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



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 C-4. 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 C-5. Effect of Sector Elevations on the Occurrence of Occlusion by the Earth's Surface

Table C-2. 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°

C.3 Differences in Angular Directions

The final issue in using planar approximations concerns 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 C-6 illustrates a scenario for evaluating the effect. In comparing the two reference systems we assume that the separation of points, *r*, and the relative heights at which an LOS 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 C-7 illustrates the geometry of the problem. Given h_1 and *r* and using the law of sines, the height h_2 is

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

and ϕ_2 follows as

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

where

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

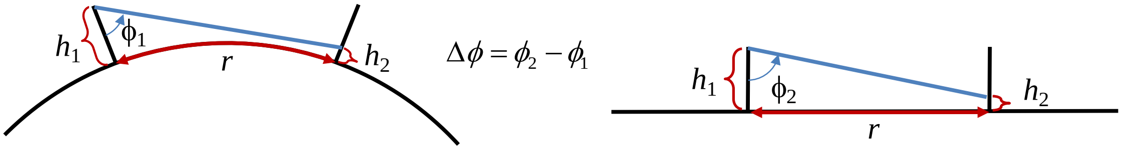


Figure C-6. Scenario for Evaluating the Significance of Angle Discrepancy in Using Planar Approximations

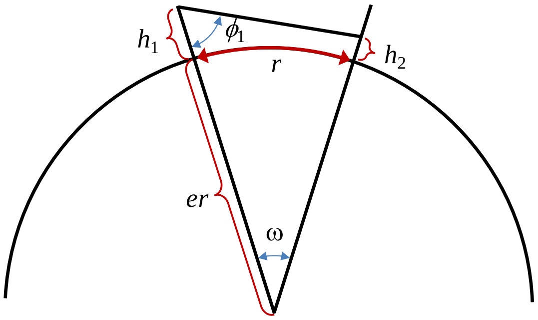


Figure C-7. Geometry of the Spherical Earth Scenario Used to Determine h_2

Figure C-8 illustrates the differences in angles as a function of surface distance and for various elevation 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 C-8 illustrates the effect out to 200 km. The linear trend of these graphs continues out beyond 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 intended to provide a very fine representation of antenna effects then a planar approximation may not be appropriate for large separation distances.

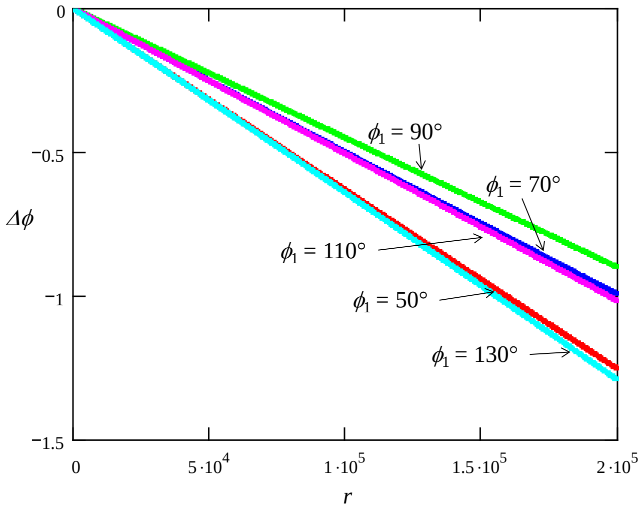


Figure C-8. Angular Discrepancies Between a Spherical Earth and a Planar Earth as a Function of Surface Separation and Elevation Angle

C.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 constitute 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. An elevation of this sector as little as 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 under consideration are not airborne these angles are likely insignificant. Further modeling is likely to be conservative and would thus accommodate these differences in the models.

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

Appendix D Rotation Matrices

The orientation of objects and the directional components of SCMs 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 with antennas which are reference to the platforms on which they are mounted. Thus, converting physical directions to directions for looking up values in the directional model components (i.e., maps and trajectories) requires conversion of the coordinate systems. As discussed later, system-centric coordinate systems are converted by displacing origins and the rotation of axis system. Axis systems are rotated 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

D.1 Coordinate Rotations

D.1.1 Rotation of Earth Surface Coordinates (Propagation Map Coordinates) Relative to Earth-Centric Coordinates

The orientation of an earth surface coordinate system – the same system used for propagation map coordinate systems on the surface of the earth –varies according to 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 that brings the z axis toward the center of the earth. The second is a rotation about the z axis that aligns the x axis with the longitude. The final rotation is again about the y axis; it brings the x axis to an angle tangent to the earth's surface at the latitude φ. The cumulative rotations are obtained by the product

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

and the inverse of these rotations is obtained by the product

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

Appendix E gives further details of this conversion.

D.1.2 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-surface coordinate system to the direction of travel requires two rotations: the first about the z axis by the azimuth of travel, θ, and the second about the y axis by the elevation, ϕ. The cumulative rotation matrix is

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

and the inverse cumulative matrix is

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

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

By convention, the coordinate system of a platform makes the positive x direction point in the 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 point 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

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

The inverse cumulative matrix is

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

D.1.4 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. In some cases the symmetry of the mask structure makes it appropriate to model the antenna as rotated on the platform. By convention, changes in orientation are specified by three values with rotations in the order 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,

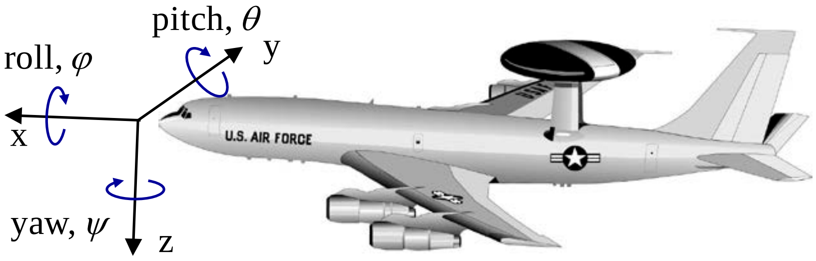


Figure D-1. Platform Coordinate Systems and the Yaw, Pitch, and Roll Rotation Directions

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

and so is its inverse

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

D.2 Directional Computations

D.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:

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

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

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

D.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 E Coordinate Conversions

A conversion between two Cartesian coordinate systems, say from WGS 84 coordinates to platform-centric coordinates, 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 converted. After a translation of the coordinates the coordinate system retains the original orientation. Differences in orientation are calculated by rotating the coordinate system. A coordinate system is rotated about a common origin by using a combination of three rotation matrices that define how the new system was rotated about its axes.

A WGS 84-oriented coordinate system can be converted to a local tangent plane system with an <n,e,d> orientation (that of a propagation map) in three rotations, as illustrated in Figure E-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, and makes 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 with the positive value being down and so labeled the d axis. The rotation matrix from changing orientation from the earth-centric coordinate system to an earth-surface system located at longitude θ and latitude φ is

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

and the inverse rotation is

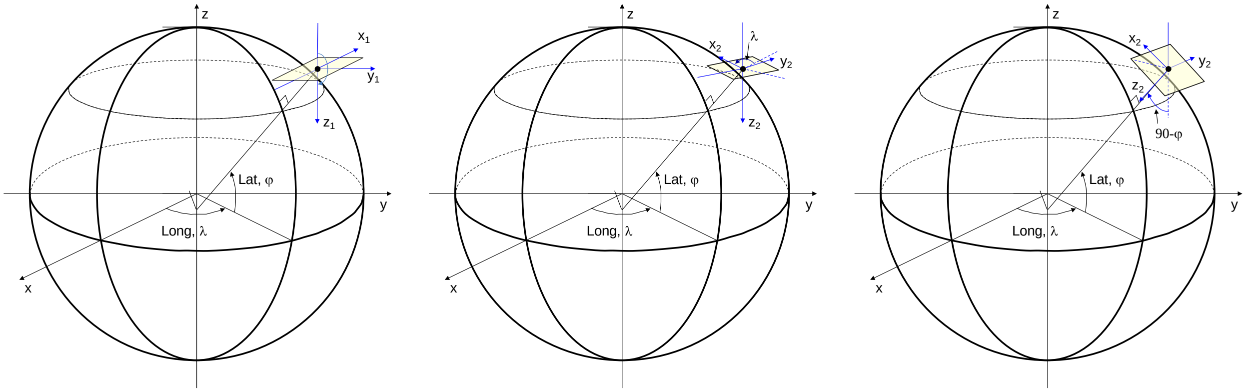
$$R_{S2E}\left(\lambda,\varphi\right) = R_y\left(-180°\right)\cdot R_z\left(\lambda\right)\cdot R_y\left(\varphi-90°\right).$$

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

$$\begin{bmatrix} n \\ e \\ d \end{bmatrix}_{\mathrm{S}} = R_{E2S}\left(\lambda,\varphi\right)\left(\begin{bmatrix} x \\ y \\ z \end{bmatrix}_{\mathrm{WGS84}} - \begin{bmatrix} x_{\mathrm{o}} \\ y_{\mathrm{o}} \\ z_{\mathrm{o}} \end{bmatrix}_{\mathrm{WGS84}}\right).$$

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.

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



a. Rotation about the y axis

b. Rotation about z_1

c. Rotation about y_2

Figure E-1. Axis Rotations to Arrive at the Propagation Map Coordinate System

Appendix F Acronyms

A2P	Antenna to Platform Direction
ACK	Acknowledgement
BAEPSD	Bandwidth-Adjusted Effective Power Spectral Density
BTP	Bandwidth-Time Product
CDMA2000	Code Division Multiple Access 2000
CR	Collision Resolution
CTS	Clear to Send
DC	Duty Cycle
DSA	Dynamic Spectrum Access
DTED	Digital Terrain Elevation Data
DySPAN	Dynamic Spectrum Access Networks
E2S	Earth to Surface Coordinates
EI	Echo Invoke
EIRP	Equivalent Isotropically Radiated Power
EPSD	Effective Power Spectral Density
EW	Electronic Warfare
FCC	Federal Communications Commission
GCS	Ground Control Station
GSM	Global System for Mobile Communications
IEEE	International Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
IM	Intermodulation
IMA	Intermodulation Amplification
IMC	Intermodulation Combining
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
PAWS	Protocol for Access to White Space
PBSM	Policy-Based Spectrum Management
PSD	Power Spectrum Density
RBW	Resolution Bandwidth
RF	Radio Frequency

RTS	Request to Send
S2E	Surface to Earth Coordinates
S2T	Surface to Travel Directions Coordinates
SCM	Spectrum Consumption Modeling
SCMML	Spectrum Consumption Model Markup Language
SCR	Synchronous Collision Resolution
SINR	Signal to Interference and Noise Ratio
SLA	Service Level Agreement
SM	Spectrum Management
SMADEF	Spectrum Management Allied Data Exchange Format
SSRF	Standard Spectrum Resource Formant
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
TV	Television
TVBD	Television Band Device
TVWS	Television White Space
UAS	Unmanned Autonomous System
UAV	Unmanned Autonomous Vehicle
UTC	Coordinated Universal Time
WGS	World Geodetic System
WiMAX	Wireless Interoperability for Microwave Access
WRC	World Radiocommunication Conference
XML	Extensible Markup Language

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