

IEEE Standard for Method for Modeling Spectrum Consumption

IEEE Communications Society

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Dynamic Spectrum Access Networks Standards Committee

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IEEE Standard for Method for Modeling Spectrum Consumption

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Dynamic Spectrum Access Networks Standards Committee
of the
IEEE Communications Society

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Abstract: A vendor-independent generalized method for modeling spectrum consumption of any type of use of radio frequency spectrum and the attendant computations for arbitrating the compatibility among models are defined in this standard. The methods of modeling are chosen to support the development of tractable algorithms for determining the compatibility between models and for performing various spectrum management tasks that operate on a plurality of models. The modeling methods are exclusively focused on capturing spectrum use but are defined in a schema that can be joined with other schemata related to spectrum management.

Keywords: DSA, dynamic spectrum access, IEEE 1900.5.2™, SCM, spectrum consumption model

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Introduction

This introduction is not part of IEEE Std 1900.5.2-2017, IEEE Standard for Method for Modeling Spectrum Consumption.

This document is the first complete standard to define a generalized method for modeling spectrum consumption of any type of use of radio frequency spectrum and the attendant computations for arbitrating the compatibility among models. The methods of modeling are chosen to support the development of tractable algorithms for determining the compatibility between models and for performing various spectrum management tasks that operate on a plurality of models. The modeling methods are exclusively focused on capturing spectrum use to support the determination of compatibility as opposed to being a data standard that seeks to support a particular business process of spectrum management. This standard defines the data requirement for spectrum consumption models. The data elements and their meaning are the critical parts of the modeling and may be expressed by any data schema if content and context are preserved.

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IEEE Standard for Method for Modeling Spectrum Consumption

1. Overview

1.1 Scope

This standard defines a generalized method for modeling spectrum consumption of any type of use of radio frequency (RF) spectrum and the attendant computations for arbitrating the compatibility among models. The methods of modeling are chosen to support the development of tractable algorithms for determining the compatibility between models and for performing various spectrum management tasks that operate on a plurality of models. The modeling methods are exclusively focused on capturing spectrum use to support the determination of compatibility as opposed to being a data standard that seeks to support a particular business process of spectrum management. However, such externally defined spectrum management data standards can beneficially leverage the spectrum consumption modeling defined in this standard.

This standard defines the data requirement for spectrum consumption models (SCMs). The data elements and their meaning are the critical parts of the modeling and may be expressed by any data schema if content and context are preserved.

1.2 Purpose

This standard defines an analytical framework of necessary modeling constructs that can be used to express the boundaries of spectrum consumption by any transmitting or receiving device. These constructs can be combined into a machine readable data exchange schema for the purpose of transferring these SCMs between automated systems. This standard can serve as a loose coupler for the spectrum management enterprise by providing all spectrum communities of interest with a common way to express spectrum consumption. Further, the standard describes algorithms that can rapidly evaluate compatibility among SCMs and enables the creation of algorithms that can quickly perform spectrum management tasks such as finding reuse opportunities or optimizing spectrum assignments to increase spectrum utilization. To achieve this goal, the SCMs must be sufficient in that the algorithms can perform these functions using the models alone without dependence on external information.

The effectiveness of these approaches depends on the quality of the models. The quality of the models depends on the quality of the data on system performance used to build the models and the willingness of the modelers to reveal the true use and vulnerability of the systems to interference. Specifying the required data quality and the accuracy of the models is beyond the scope of the standard.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

None.

3. Definitions, acronyms, and abbreviations

3.1 Word usage

In this document, the word *shall* is used to indicate a mandatory requirement. The word *should* is used to indicate a recommendation. The word *may* is used to indicate a permissible action. The word *can* is used for statements of possibility and capability.

3.2 Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* and IEEE Std 1900.1™ [B3] should be consulted for terms not defined in this clause.^{1,2}

bandwidth-time product (BTP): The product of the bandwidth of a signal and the average time the signal is transmitted per second.

canonical receiver model: A spectrum consumption model of a receiver with all constructs needed to specify spectrum consumption of the receiver located in the receiver definition without referencing model construction from a system or set header.

canonical transmitter model: A spectrum consumption model of a transmitter with all constructs needed to specify spectrum consumption of the transmitter located in the transmitter definition without referencing model constructs from a system or set header.

compatible spectrum consumption models (SCMs): Two or more spectrum consumption models when, together, the collective set of transmitter models do not violate the interference boundaries of any of the receiver models.

incompatible interference: Interference that exceeds the threshold interference limits defined for a receiver model used in model-based spectrum management.

link budget scaled mask: A spectrum mask that has been scaled to account for all sources of attenuation up to the input to a receiver antenna.

local regulating administration: The administration with legal authority to establish policy for the use of spectrum within the local geographic region.

¹ *IEEE Standards Dictionary Online* is available at <http://dictionary.ieee.org>.

² The numbers in brackets correspond to the numbers of the bibliography in Annex A.

model-based spectrum management (MBSM): Spectrum management based on the creation, exchange, and analysis of spectrum consumption models (SCMs).

NOTE—Incumbent and proposed spectrum uses are captured in SCMs. The efficacy of proposed uses is arbitrated based on the compatibility of these models.³

modeler: An entity, person, or machine that builds a model of spectrum use.

receiver model: A part of a spectrum consumption model that defines the threshold boundaries for incompatible interference for a receiving device.

spectrum authorization set: A set of spectrum consumption models (SCMs) that define spectrum that is available for a system to use where an allowed use of spectrum is one that falls within the limits of one or more of the SCMs in this set.

spectrum boundary: The spatial, spectral, and temporal extent of relevance of the spectrum consumption models in a consumption authorization or constraint set.

spectrum constraint set: A set of spectrum consumption models with which a new use must not cause incompatible interference and must accept interference. Spectrum constraint sets are given together with a spectrum authorization set to define spectrum availability.

spectrum consumption model (SCM): A model of spectrum use identifying the key phenomenology and operational use that can be used to determine the extent of radio frequency spectrum effects that prevent others from using it.

NOTE—Use of the SCMs presumes a set of agreed methods for evaluating compatibility between models in support of model-based spectrum management.

spectrum consumption set: A spectrum boundary and set of spectrum consumption models that impact uses of spectrum within that boundary.

spectrum management enterprise: An organization that needs to arbitrate the use of spectrum by its own spectrum-dependent systems and therefore warrants its own spectrum management activity.

spectrum manager: An organization, person, or automated process that arbitrates the access to spectrum.

system manager: A person or automated process that manages the collective set of devices of a system and their use of resources, including the radio frequency spectrum that they use, e.g., a wireless network manager.

system model: A spectrum consumption model with a set of transmitter and receiver models that collectively capture the spectrum use of a spectrum-dependent system.

transmitter model: A part of a spectrum consumption model that bounds the radio frequency emissions of a transmitting device.

3.3 Acronyms and abbreviations

BAEPSD	bandwidth-adjusted effective power spectral density
BTP	bandwidth-time product

³ Notes in text, tables, and figures of a standard are given for information only and do not contain requirements need to implement this standard.

DSA	dynamic spectrum access
EPSD	effective maximum power spectral density
IM	intermodulation
IMA	intermodulation amplification
IMC	intermodulation combining
MBSM	model-based spectrum management
PSD	power spectrum density
PSFD	power spectral flux density
RBW	resolution bandwidth
RF	radio frequency
SCM	spectrum consumption model
SDD	spectrum-dependent device
SLA	service-level agreement
TIREM	terrain integrated rough earth model
UAV	unmanned aerial vehicle
UTC	Coordinated Universal Time
WGS 84	World Geodetic System of 1984

3.4 Symbols

Symbol	Description	Where used
ϕ	Elevation in a map	7.3
θ	Azimuth in a map	7.3
λ	Longitude	8.9, Annex B
φ	Latitude	8.9, Annex B
φ	Yaw	Annex C
θ	Pitch	Annex C
ψ	Roll	Annex C
α	Angle of rotation about the z axis	8.5, Annex C
β	Angle of rotation about the y axis	8.5, Annex C
γ	Angle of rotation about the x axis	8.5, Annex C
μ	Magnetic permeability of free space, 1.26×10^{-6} H/m	Annex F
ε	Electric permittivity of free space, 8.85×10^{-12} F/m	Annex F
a	Altitude	8.9
a	Semi-minor ellipsoid axis	8.9, Annex B

Symbol	Description	Where used
A	Set of fleeting constructs	11.4
ah	Antenna height	8.9
b	Semi-minor ellipsoid axis	8.9, Annex B
b	Coefficient of a linear equation representing a side of a spectrum mask	10.5, Annex F
B	Set of fleeting constructs	11.4
b_R	Attenuation at the boundary of a receiver location	10.4
b_T	Attenuation at the boundary of a transmitter location	10.4
BTP	Bandwidth-time product	8.4
BW	Bandwidth	8.4, 10.5
d	Distance	8.6
d	Down coordinate direction	Annex D
d	A unit of displacement in a lattice	10.10
$d_{breakpoint}$	Distance to a breakpoint	8.6
DC	Duty cycle	8.4
DD	Day	8.10
DT	Dwell time	8.4
e	Eccentricity	Annex B
e	East coordinate direction	Annex D
$\tilde{e}$	Voltage Intensity	Annex F
f	Frequency	8.3, 8.4, 8.7, 10.4, 10.5, 10.6, Annex F
f	Flattening	Annex B
f_c	Center frequency	7.4
g	Gain in a direction from a power map of the device	10.4
gr	Gain from the power map of the local receiver	10.4
gt	Gain from the power map of a distant transmitter	10.4
h	Height of a cylinder or polyhedron	8.9
hh	Hours	8.10
i	Iterator	7.3, 11.4
j	iterator	7.3, 11.4
l	Attenuation or pathloss across a side of a location	8.9
l_B	Attenuation or pathloss across the base of a cylinder or a polyhedron	8.9
l_T	Attenuation or pathloss across the top of a cylinder or a polyhedron	8.9
mm	Minutes	8.10
MM	Month	8.10
n	Exponent for distance based pathloss	8.6
n	North coordinate direction	Annex D
nD	Number of days	8.10
nH	Number of hours	8.10
nM	Number of months or number of minutes base on order of appearance	8.10
nS	Number of seconds	8.10
nY	Number of years	8.10
P	Power (dBW)	4

Symbol	Description	Where used
p	Represents a generic model parameter in a map data structure	7.3
p	Relative power (dB)	8.3, 8.4, 10.5, 10.6, Annex F
p	Probability	11.4
$\mathcal{P}$	Power flux density	Annex F
pl	Pathloss	10.4
pm	Minimum power value in an underlay mask	10.5
PM	Power margin	10.5
ps	Power term from a spectrum mask	10.5
q	Number	7.2
R	3-dimensional space of the location of a receiver	10.9, 10.10
r^*	Potential receiver location	10.10
RBW	Resolution bandwidth	8.3, Annex F
rp	Reference power	10.4
$RP(1m)$	Pathloss at 1 m distance from an antenna	8.6
ρT	Transmitter density	8.9.2.3
s	A signal in a signal set S	10.5
S	A signal set	10.5
S	A signal name	10.6
$ss.s$	Seconds	8.10
t	Time	8.9
T	3-dimensional space of the location of a transmitter	10.9
td	Dwell time	10.5
tr	Average revisit time	10.5
v	Prime vertical	Annex B
x	Coordinate direction	8.9
x_R	X coordinate of a receiver	10.9
x_T	X coordinate off a transmitter	10.9
y	Coordinate direction	8.9
y_R	Y coordinate of a receiver	10.9
y_T	Y coordinate off a transmitter	10.9
YYYY	Year	8.10
z	Coordinate direction	8.9
z_R	Z coordinate of a receiver	10.9
z_T	Z coordinate off a transmitter	10.9

4. Data conventions

The following table shows the formats and units of measure used within this document:

Type	Unit	Description
Power	dBW	Decibel WATT. All power fields are recorded in units of dBW in accordance with ITU treaty procedures, with power in dBW calculated as follows: $P_{dBW} = 10 \log_{10} P_W$ where P_{dBW} = Power in dBW P_W = Power in Watts
Relative power	dB	Decibel. Relative power levels are always recoded in dB.
Power spectral flux density (PSFD)	dBW/(Hz×m ²)	PSFD is always recorded as a decimal number with units of decibel Watt per Hz per square meter (dBW/(Hz×m ²)).
Frequency	MHz	Frequency is always noted in MHz. This specification follows common practice and ITU convention in which a frequency value is normally formatted with between zero to five decimal places. However, fractional Hz values are permitted and a model may employ however many significant digits are required.
Geodetic datum	N/A	All geo-location references are measured and communicated using the World Geodetic System of 1984 (WGS 84) geodetic datum [B11].
Time	Second	All time values are recorded in Seconds. Fractional seconds are permitted and a model may employ however many significant digits are required. For example, one microsecond is noted as 0.000001 s or 0.0000010 s.
Distance	Meter	All distance values are recorded in Meters unless otherwise explicitly declared. Fractional meters are permitted and a model may employ however many significant digits are required.
Time zone	N/A	All date and time values are recorded in Coordinated Universal Time (the UTC time zone). The UTC time zone does not change with the change of seasons and does not observe daylight saving time.

5. Purpose and use of SCMs

5.1 General

The purpose of spectrum consumption models (SCMs) is to convey the extent of the use of spectrum in time, frequency and space, and to reveal what constitutes acceptable reuse. SCMs provide an unambiguous definition of the extent to which a system emits radiation and what the SCM's author would consider harmful interference to that system's operation. These models capture specific uses of spectrum as opposed to being general characteristics of systems. They provide a means to capture and use the judgment of operational planners, RF system users, and spectrum managers.

SCMs provide a means to capture the spectrum consumption of RF devices and RF systems and to arbitrate the compatibility among them. SCMs are self-contained meaning they do not require users to share any external database of environmental data and effects or of device performance data. Sharing SCMs is sufficient for arbitrating compatibility. These features and basic functionality enable distributed and dynamic spectrum management that can lead to better reuse of spectrum. Further, the models, when properly represented in a data exchange format can serve as a means to specify in a machine readable format the availability of spectrum for RF systems to self-select the RF spectrum they use.

5.2 Capturing spectrum use of RF devices

Both transmitters and receivers consume spectrum. Spectrum is consumed by an RF device to the extent that its transmitter precludes the receivers of another RF device from operating and to the extent that its receiver's protection requirements preclude the transmitters of other RF devices from operating. The spatial extent of consumption is determined by identifying the boundary of compatibility beyond which the secondary must operate. SCMs support the definition of these boundaries. Transmitter models within an SCM define the extent of RF emissions. Receiver models within an SCM define what constitutes interference. The computational methods for arbitrating compatibility between transmitters and receivers of different RF devices enable the determination of the separation boundary between those RF devices.

5.3 Capturing spectrum use of RF systems

RF systems generally consist of multiple RF devices that work collaboratively to perform a function. That function is dependent on all devices receiving some level of protection from interfering radiation from external RF devices and systems. SCMs can model the collective use of spectrum by multiple RF devices. These models consist of multiple transmitter and receiver models and/or of transmitter and receiver models that apply to spaces. A system is compatible with an external RF device or RF system if all models across all spaces they apply are compatible. The same methods used for arbitrating compatibility among devices are used for arbitrating compatibility with systems. The lone difference is that multiple transmitter and receiver model pairs and the aggregate effects of multiple transmitters on a single receiver model may need to be evaluated for that determination.

5.4 Model-based spectrum management (MBSM)

5.4.1 General

MBSM is spectrum management based on the creation and exchange of SCMs. These SCMs can be used by all types of spectrum management activities.

- In regulation, SCMs can be used to define a user's spectrum usage rights.
- In operations, SCMs can enable dynamic and flexible management of spectrum resources thus increasing spectrum reuse. Peer spectrum managers and users can collaborate by sharing the models of their spectrum use.
- In technology, SCMs can be used to convey spectrum assignments and spectrum policy to RF systems.
- In commerce, SCMs are a means to capture the quanta of spectrum that are traded.

SCMs serve as a loose coupler for spectrum management. They allow the spectrum management problem to be distributed where users of spectrum can model their own use and then have their models used across the spectrum management enterprise to affect where and when new uses of the same spectrum may occur. Models support this determination because they stand alone from any database of environmental or system data and have well-defined attendant methods for arbitrating pairwise compatibility. These methods use the information in the models only.

5.4.2 Loose coupling spectrum management

A loose coupler is a data exchange specification based on the simple, useful, rough intersection of data sharing needs among many systems. When identified and placed between the layers of complex systems, not only does it engender interoperability, but it also enables the larger system to support innovation. To be effective, the loose coupler must be well defined and broadly adopted. A couple of well-known systems serve as examples. The first is the electrical power system. The loose coupler is the specification for power distribution at the user end, frequency, voltage, and interface definition. This standardized coupler then

allows innovation at two ends, power generation and electrical appliances and devices. There is no constraint to development of means of generating power so long as it can be converted into the frequency and voltage necessary at the end of the distribution. There is no constraint to the development of appliances and devices so long as they can accept power at the specified voltage and frequency. The second example is the Internet. The Internet Protocol (IP) serves as a loose coupler with the two layers being the means of transport and the services of the internet. There can be innovation in the means to enable transport so long as the systems can accept and route IP packets and there can be innovation in the services and applications that ride the network and use the transport so long as they conform their communications to the standards of IP. The loose coupler in these systems is standardized.

Figure 1 illustrates the layering of the anticipated spectrum management system that uses SCMs as its loose coupler. The methods of modeling defined in this standard describe how to specify the boundaries of spectrum use and given a pair of SCMs, how to determine if they are compatible with each other. The SCMs are the loose coupler and are placed at the center of what is referred to as a bowtie diagram. The SCM definition allows disparate spectrum management systems and RF devices to coexist and to collaborate in the activities of spectrum management. Figure 1 illustrates the anticipated interactions. At the top layer it provides a means for systems that collectively perform spectrum management to convey⁴ to each other their vision of spectrum consumption. Thus a diversity of spectrum management systems can interoperate so long as they can articulate spectral quanta in SCMs. Organizations with spectrum management processes that are unique to themselves can create their own tools for management and then convey to peer managers of other organizations their spectrum use and their spectrum requirements using SCMs. At the bottom layer it allows RF systems that use the spectrum to coexist. RF devices adapt their use of spectrum to fit within the boundaries of a model or to avoid violating the boundaries of other users whose models they are given. In the long term, multiple RF systems could autonomously collaborate to share spectrum and use SCMs to arbitrate and manage their spectrum sharing. Moving from layer to layer, SCMs provide a means for spectrum management systems to convey to RF systems what spectrum they can use and the conditions for its use. Finally, SCMs are a means for RF systems to convey the actual spectrum they are using to spectrum management systems.

The SCMs only capture the use of spectrum. In the spirit of defining a loose coupler, this standard deliberately avoids the definition of data that may be required in a spectrum management enterprise for regulatory, business, or security needs. As there are many business cases there can be many different versions of these latter data types. These additional data definitions should be defined as part of creating these enterprises and then may be combined with SCM data in the data exchanges that make the enterprise work. Keeping the SCMs pure allows many different enterprises to interact with each other with their own business related data extensions while the SCMs remain the foundation for the collection of enterprises to arbitrate spectrum compatibility.

⁴ The word “convey” refers to the collection of data in a model to indicate a policy for using spectrum or a definition of a use of spectrum as opposed to the means to transmit such guidance or information.

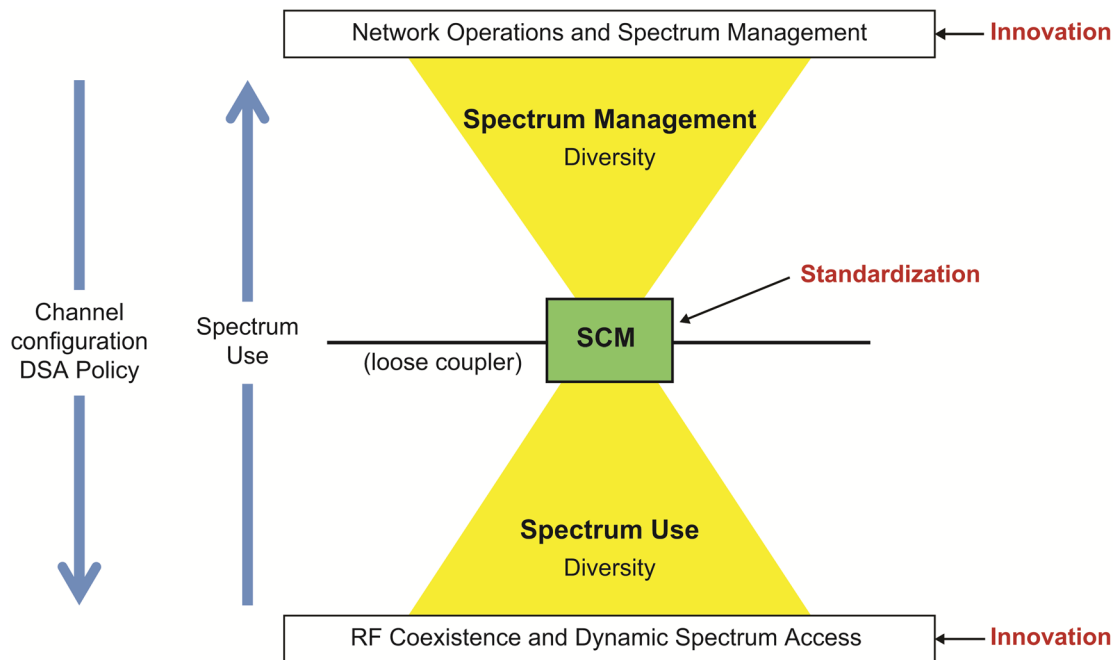


Figure 1—SCM as a loose coupler in spectrum management

5.4.3 Independent modeling of RF systems

Modeling does not require knowledge of peer systems. Users of systems can model their use of spectrum independently and then provide their models to the spectrum management enterprise so their use of spectrum as conveyed in their model is considered in the assignment of spectrum to devices and systems. Knowledge of peer systems, however, is useful. Frequently, knowledge of peer systems allow modelers to call out particular modes of compatibility that are possible with particular peer systems. For example, wideband networking systems may be compatible with low duty cycle signals that are typical of radars. In this case, modelers of the wideband networking system may want to specifically call out in their model the robustness of their system to this type of interference if they know the incumbent system is a radar.

5.4.4 Common methods for arbitrating compatibility of models

Spectrum consumption modeling is complemented with attendant methods of determining compatibility between models. These methods allow any two complete models to be assessed for their compatibility without dependence on any data other than that contained in their models. These computations have the same results anywhere in the spectrum management system. Thus, in modeling, the modeler has a clear understanding of the interpretation of what is included in the model.

5.5 Radio spectrum use policy

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

Spectrum use policy can be conveyed to RF systems in two ways, either as a direct or a dynamic authorization. The dynamic authorization is intended to allow competing systems to interact with each

other's use of spectrum by announcing their use in models that become constraints to their peers. These methods differ in the computations expected at the RF system.

- **Direct Authorization:** The spectrum manager determines the requirements for compatible reuse and creates a set of permissive models of that compatible reuse. These models are given as policy to the dynamic spectrum access (DSA) systems. Components of the DSA system would simply determine where they are and the current time and lookup which models apply and so which channels can be used. If there are choices, they can use other criteria of their own to select which of the choices to use.
- **Dynamic Authorization:** Policy is conveyed using two types of models: *permissive models* (which are broad in scope) that describe the spectrum that might be considered and then *restrictive models* (which are the SCMs of spectrum use of other incumbent systems) that have precedence in spectrum use. The expectation is that the DSA system would make the computations that ensure that a use within the broader permissive model also respects the restrictions of the restrictive models. This approach can provide many more opportunities for reuse. From the spectrum manager's view, creating the models of the incumbent use is equivalent to writing restrictive policies for DSA use. A long-term permissive model can be augmented over time with short-term restrictive models as they are created for new uses.

Generally, SCMs enable location and time based reuse. The Policy and Protocol construct of SCMs may be used to identify well-known behaviors and their operational parameters when a particular policy or protocol is known to be compatible with incumbent use. Modeling does not support the creation of these policies or protocols ad hoc.

6. Spectrum-dependent devices, systems, and sets

6.1 General

This clause gives the bigger picture of spectrum consumption modeling. Spectrum consumption may be modeled for a particular device that uses spectrum, a system that uses spectrum that may consist of multiple devices, or a set of spectrum users that consists of multiple models of system and device use of spectrum. Models may provide the boundaries of what is being used or what may be used.

6.2 Spectrum-dependent devices

6.2.1 General

A spectrum-dependent device (SDD) is a single physical component that emits radiation, receives radiation, or both. Transmitter models capture the emission of radiation and receiver models capture the sensitivity of devices that receive radiation to interference. SDDs that perform both functions are modeled by a combination of transmitter and receiver models.

6.2.2 Transmitter models

A transmitter model captures the RF emissions of a transmitting device. This type of model identifies the possible locations of the device, the time of its operation, the spectral mask and power of its emissions, the directivity of its emissions, and in some cases behavioral information of the device. A proper transmitter SCM is a bound to the use of spectrum by the transmitter, that is the temporal, spatial, and spectral extent of the emission predicted by the model is greater than or equal to that of the actual device.

Details of the data requirements for a transmitter model are found in 9.1.

6.2.3 Receiver models

A receiver model defines the threshold boundaries for incompatible interference to a receiving device. This type of model identifies the possible locations of the device, the time of its operation, the spectral extent that it is sensitive to interference, the power level of interference it can tolerate, the directivity of its reception, its susceptibility to intermodulation (IM) effects, and, in some cases, behavioral information of the device. A proper receiver model SCM provides a limit to the interference that transmitter devices can cause in aggregate to the receiver model, that is a limit to the total interference in the temporal, spatial, and spectral limits of the modeled receiver's operation.

Details of the data requirements for a receiver model are found in 9.2.

6.3 System models

A system model is an SCM with a set of transmitter and receiver models that collectively capture the spectrum use of a spectrum-dependent system. A spectrum-dependent system is any SDD or collection of SDDs. In SCM modeling a system model is used when the modeling of the use of spectrum requires more than what a single transmitter model or a single receiver model can capture. Thus, a system model is a container for multiple transmitter and receiver models that allows the modeler to associate multiple SDDs to a single system. Further, by placing transmitter and receiver models within the same system model, the modelers indicate that they do not constrain each other. For example, an SCM of a transceiver that transmits and receives in the same spectrum would consist of a transmitter model and a receiver model. Since they are part of the same system model, the transmitter and receiver models do not constrain each other.

Details of the data requirements of system models are found in 9.3.

6.4 SCM sets

An SCM set is a collection of system, transmitter, and receiver SCMs. Sets are used for three purposes: (1) to collect all uses of spectrum within some boundary, (2) to provide spectrum that is available for use, and (3) to identify constraints to spectrum use. The heading of a set defines the purpose of the set, i.e., consumption, authorization, or constraint, and the boundary within which it applies. A boundary may be spatial, temporal, and/or spectral. Further there may be an optional transmitter and receiver model in the heading that subsumes all the models within the set. This subsuming model allows for a quick check to determine if a system or device is compatible with the models listed in the set. Not being compatible with the subsuming model does not preclude spectrum use if the new use is compatible with all the individual models within a set. The source of the set defines its scope. For example, a consumption set provided by an enterprise might convey all spectrum used by the enterprise within the specified boundaries while a consumption set provided by a spectrum access system provider might list all spectrum uses it is aware within the boundaries of the set.

Details for the data elements of a set are hinted in 6.5 but are explicitly presented in 9.4.

6.5 SCM messages and data

The transmitter model, receiver model, system model and set are primary data elements of SCM messages. An SCM message has one primary data element. Table 1 lists the primary data elements and in the case of the system model and the set lists the sub-elements. Table 2 lists the header sub-elements of systems and sets and their further breakdown into sub-elements.

Table 1—Primary data elements of SCM messages

Primary data element	Sub-elements	Types	Enumerated values/ unit of measure	Occurrences	Notes
TxModel		Structure		0..1	Sub-elements in Table 27
RxModel		Structure		0..1	Sub-elements in Table 28
SystemModel		Structure		0..1	
	SystemID	String		1	
	Name	String		0..1	
	Purpose	Attribute	AUTHORIZATION, CONSTRAINT, CONSUMPTION	1	
	Boundary	Structure		0..1	Sub-elements in Table 2
	UberModel	Structure		0..1	Sub-elements in Table 2
	TxModel	Structure		0..n	Sub-elements in Table 27
	RxModel	Structure		0..n	Sub-elements in Table 28
SCMSet		Structure		0..1	
	SCMSetID	String		1	
	Name	String		0..1	
	Purpose	Attribute	AUTHORIZATION, CONSTRAINT, CONSUMPTION	1	
	Boundary	Structure		0..1	Sub-elements in Table 2
	UberModel	Structure		0..1	Sub-elements in Table 2
	SystemModel	Structure		0..n	Sub-elements in Table 29
	TxModel	Structure		0..n	Sub-elements in Table 27
	RxModel	Structure		0..n	Sub-elements in Table 28

Table 2—Header data elements for systems and sets

Data element	Sub-elements	Types	Enumerated values/ unit of measure	Occurrences	Notes
ID		String		1	
Name		String		0..1	
Purpose		Attribute	AUTHORIZATION, CONSTRAINT, CONSUMPTION	0..1	
Boundary		Structure		0..1	
	BandList	Structure		0..1	Sub-elements in Table 10
	Schedule	Structure		0..n	Sub-elements in Table 24
	Location	Structure		0..n	Sub-elements in Table 22
UberModel		Structure		0..1	
	TxModel	Structure		0..n	Sub-elements in Table 27
	RxModel	Structure		0..n	Sub-elements in Table 28

7. Special data structures

7.1 General

This clause describes several special data structures used within more than one construct of SCM modeling.

7.2 Specifying confidence

Spectrum consumption modeling is used to convey anticipated use of spectrum. In many cases that use is uncertain and can vary. Modeling to capture the worst case ensures protection but does not fully convey opportunities for reuse and does not allow entities to negotiate spectrum sharing where some level of interference is tolerable. Thus SCM modeling allows the modeler to define multiple boundaries conditioned on some confidence the modeler has that those boundaries contain the full anticipate use of spectrum. The measure of *confidence* is a decimal number q such that that $0 \leq q \leq 1$.

SCMs always convey worst case use. The confidence element allows SCMs to be subdivided into parts that convey boundaries that attempt to define the likelihood that a particular boundary limit is reached. For example, a radio system that uses power adaptation may use something less than the maximum power in most use. The confidence measure could then be assigned to each of multiple power levels to indicate the likely fraction of time each power level is used. In another example, a modeler may not have full confidence that a mobile system will end up where it is planned to go. A confidence measure could be associated with each of multiple location models to indicate that uncertainty.

The causes for differing levels of confidence and the ways one boundary may apply over another can be quite varied. For example, a confidence measure may indicate the likelihood a boundary is reached versus the percent of time a boundary applies. For this purpose, several attributes accompany the likelihood measure when specifying confidence.

- The “approach” attribute identifies whether the confidence measures indicate alternative conditions or a cumulative condition.
 - The *alternative* attribute indicates the confidence that one alternative or another is used. The sum of the confidences of the collection of common construct types using the alternative approach shall be 1.
 - 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 move to a state with some probability and then stay there are *persistent*
 - Phenomena that move freely from state to state, spending some fraction of their time in one state or another, are *fleeting*.
 - The attribute *fleeting*, by itself, is qualitative. To make it quantitative it is accompanied with a value for *maximum dwell time*. The maximum dwell time measure indicates the maximum amount of time that a system is in the state modeled. When used with the cumulative nature attribute, it indicates the time in state space between this state and the next lower probability state.
- 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.

Table 3 provides a summary of the confidence data element.

Table 3—Confidence data element

Data element	Sub-elements	Types	Enumerated values/ unit of measure	Occurrences	Notes
Confidence		Structure			
	Measure	Number	Dimensionless, from 0 to 1	1	
	Approach	Attribute	Cumulative, Alternative	1	
	Nature	Attribute	Persistent, Fleeting	1	
	Derivation	Attribute	Judgment, Estimated, Measured	0..1	
	MaxDwellTime	Number	seconds	0..1	Required with Fleeting nature only

Whenever a model of one of the constructs is divided into multiple constructs with different levels of confidence, then all attributes are required. The attributes are not necessary when only one model construct is used with a confidence of 1.

The computation of compatibility using the confidence measure assumes that the confidence measures within a construct type are independent of those of other construct types.

7.3 Specifying values by direction

The data structures that are used to specify parameters by direction are referred to generally as SCM maps. It is called an SCM map because it assigns values to sectors on a sphere like coloring countries on a map on a globe. The data of an SCM 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 set of model parameters toward all directions. The vector of values starts with elevations (ϕ) from the vertical down direction -90° and reaching to the vertical up direction 90° , 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 the model parameter sets and azimuths that specify different model parameters on that annulus by sector. One or multiple annuluses are defined ultimately to define parameters for all directions. The number and spacing of elevations and azimuths that are listed in the vector is arbitrary and used as necessary to provide resolution. The form of the vector is

$$(-90^\circ, 0^\circ, p_{0,0}, \theta_{0,1}, p_{0,1}, \theta_{0,2}, \dots, 360^\circ, \phi_1, 0^\circ, p_{1,0}, \theta_{1,1}, \dots, 360^\circ, \phi_2, 0^\circ, p_{2,0}, \dots, p_{last}, 360^\circ, 90^\circ)$$

Figure 2 illustrates an interpretation of this vector. The vector starts in the -90° elevation and the 0° azimuth, and an annulus is specified for each pair of elevations and so from -90° 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. In this example, the model parameter set has just one value, p . Each model parameter $p_{i,j}$ applies to the sector that reaches from elevation ϕ_i to ϕ_{i+1} and from azimuth $\theta_{i,y}$ to $\theta_{i,(j+1)}$. For example, in Figure 2, the model parameter $p_{1,0}$ applies from elevation ϕ_1 to ϕ_2 and from azimuth 0° to $\theta_{1,1}$.

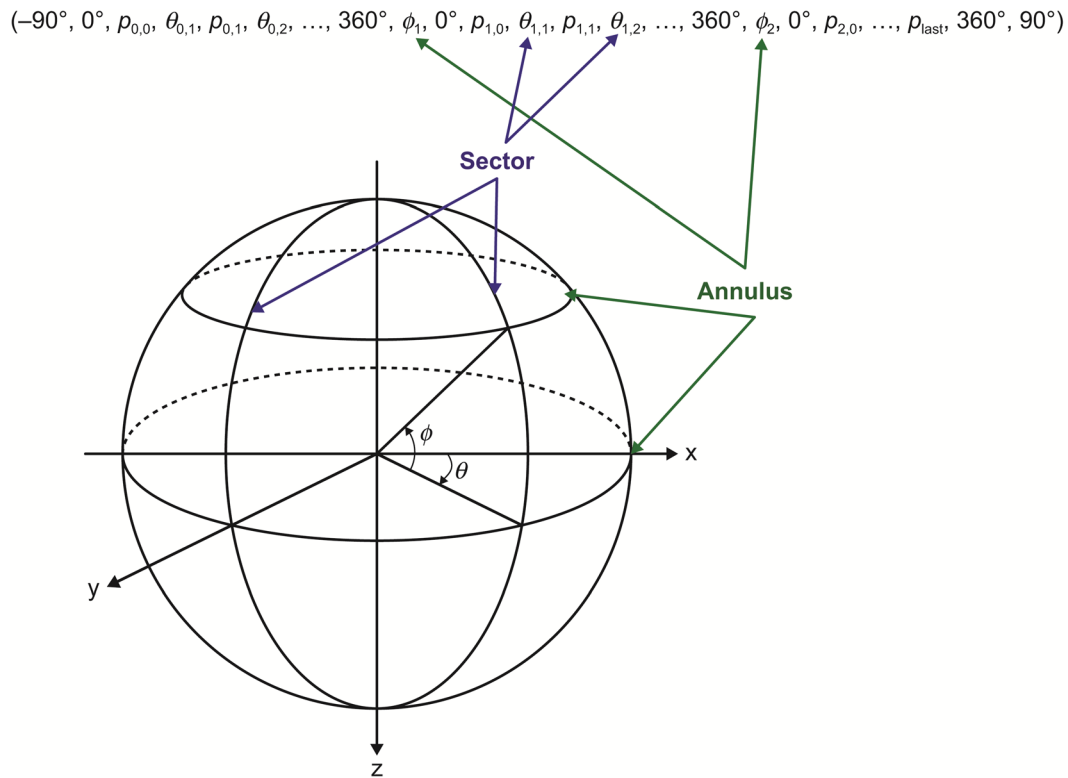


Figure 2—Example of the map vector used in propagation and power modeling

The map vectors are variable in length depending on the resolution desired. When there is just one value specified for all directions, the vector has five values, $(-90^\circ, 0^\circ, p_{0,0}, 360^\circ, 90^\circ)$. By following the order convention of this vector, modelers can ensure a model parameter is assigned to all directions and reduce the size of the data recorded.

Table 4 shows that an SCMMap consists of a vector of values. The attributes for the values qualify their role and the range of possible values. There is not an SCMMap data type but rather an SCMPowerMap or SCMPropagationMap type that are described in 8.5 and 8.6, respectively.

Further, the model parameter above may actually be a structure that consists of multiple parameter values required for a single model. This is the case for the SCMPropagationMap.

Table 4—SCM map data

Data element	Sub-elements	Types	Enumerated values/ unit of measure	Occurrences	Notes
SCMMap		Structure			
	Value	Number		5..n	Attributes may be used to differentiate the role of the value. Units and allowed range of values contingent on the attribute. Order is important to capture the solid angle for the model and may also be used to imply role, units, and allowed values. Refer to 7.2 for better details of values and their order.

7.4 Spectral masks

Masks are used in multiple contexts of spectrum consumption modeling. They are used to articulate the spectral content of transmissions, the spectral sensitivity of receivers, and the susceptibility of both transmitters and receivers to IM effects. A mask consists of a list of tuples consisting of a frequency and a relative power. These tuples are ordered from lowest to highest frequency. The relative power values are either spectral power spectral densities, (dB/bandwidth) in masks for interference and interference susceptibility or just relative power (dB) in IM masks. The number of tuples in a list is arbitrary. There are two versions of a mask, one where the frequencies are explicitly listed and a second where a single center frequency is listed and the mask has frequency values that are relative to that value. For example, here are two versions of the same mask.

[(400 MHz, -60 dB), (401 MHz, 0 dB), (409 MHz, 0 dB), (410 MHz, -60 dB)]

$f_c = 405 \text{ MHz}$, [(-5 MHz, -60 dB), (-4 MHz, 0 dB), (4 MHz, 0 dB), (5 MHz, -60 dB)]

If these masks include a value for resolution bandwidth (RBW), then the power term is applied to that bandwidth for a power spectral density. It is used in all masks except for IM masks. Table 5 lists the data in a mask.

Table 5—SCM mask data element and inflection points

Data element	Sub-elements	Types	Enumerated values/ unit of measure	Occurrences	Notes
SCMMask		Structure			
	RefFrequency	Number	MHz	0..1	If used, the mask is a relative mask
	InflectionPnt	Structure		2..n	In ascending frequency order
InflectionPnt		Structure			
	Frequency	Number	MHz	1	Actual or relative frequency depending if reference frequency provided
	RelativePower	Number	dB	1	Power relative to Reference Power

8. Modeling constructs

8.1 General

The eleven modeling constructs of spectrum modeling are the fundamental building blocks of SCMs. Each construct has a purpose but it is how the multiple constructs are combined and assembled that ultimately makes the SCM. Some constructs may be found in every model such as reference power while other constructs may be used infrequently such as the protocol or policy construct. Some constructs may appear multiple times in the same model.

The particular meaning of the constructs, how each is used to articulate an aspect of spectrum use, how they interact with each other to yield a comprehensive model of use, and how the information contained within the constructs is used to determine compatibility among models is the very the core of spectrum consumption modeling.

This clause serves multiple purposes. It defines the purpose of each construct and the role each construct would play in a model. It describes how the construct interacts with other constructs to capture particular phenomena of spectrum consumption. It defines the particular construct data elements that are in models. It describes some known exemplary best practices of the use of each construct data element.

8.2 Reference Power

8.2.1 General

The reference power is a reference power level for a model. It is the only data element within a model that is a power value, e.g., a value in dBW. Power elements in other constructs are relative to this value and have units of dB.

8.2.2 Purpose and use

The purpose of the reference power term is to provide a reference power level for the emission of a transmitter in a transmitter model or to provide reference power level for the allowed interference in a receiver model. However, the reference power term is modified by multiple other constructs that capture the phenomenology that define how the power is distributed spectrally and spatially. They ultimately convert the total power to a PSFD. Generally, modeling follows the physics so that modeling is natural. In this case, the reference power in a transmitter would be the power level that drives the antenna. The reference power in a receiver could be the total amount of interference that a receiver can tolerate after frequency and time dependent rejection. Modeling, however, is artful and the reference power term can be adjusted with corresponding adjustments in other constructs to yield the same boundaries of use but to obfuscate the specific operating parameters of the modeled system.

Many systems, specifically broadband systems, employ power control. The particular powers used by individual transmitters is managed to achieve reliable reception at a base station while minimizing system wide interference among the plurality of base stations in the system. As a result, power levels may vary with some distribution. The reference power modeling construct provides a means to capture this variability using the confidence data element. The confidence element shall be ignored in computing compatibility unless the receiver model uses multiple reference powers to qualify the underlay masks or there is a peer-wise agreement on how the element shall be considered in spectrum sharing arrangements. The default compatibility computation is to use the highest power in the distribution.

8.2.3 Data elements and their meaning

The data structure consists of two single real numbers, one for the power level and one for the confidence. The use of confidence is optional. If confidence is not used, then there would be a single power term. If confidence is used, the confidence may be alternative or cumulative and persistent or fleeting. If the fleeting attribute is used, then a value for the maximum dwell time of the fleeting event is also required. The model construct will have multiple <power, confidence> tuples. Most models are likely to use the cumulative and fleeting attributes. If the confidence term is used, then all masks shall have the same attributes. The model shall still provide a power bound with confidence 1. By default, the highest power level at transmitters and the lowest power level at receivers are used in compatibility computations. Special arrangement, outside the scope of this standard, must be established to do otherwise.

If a single power level is used, then the data that shall be conveyed is the numerical value of the power in units of dBW. Table 6 lists the data elements of the reference power construct.

Table 6—SCM reference power construct

Data element	Sub-elements	Types	Enumerated values/ unit of measure	Occurrences	Notes
ReferencePower		Structure			
	Value	Number	dBW	1	
	Confidence	Structure		0..1	Used when there is more than one relative values in a model. See Table 3 for description

If multiple power levels with different levels of confidence are used, then there would be multiple power and confidence tuples, e.g., $\langle \text{power}_0, \text{confidence}_0 \rangle$, $\langle \text{power}_1, \text{confidence}_1 \rangle$, ... $\langle \text{power}_n, \text{confidence}_n \rangle$. Expanding the confidence to include attributes, the tuples could be complemented with three attributes and a maximum dwell time value. As an example, assuming the combination $\langle \text{power}, \text{confidence}, \text{approach}, \text{nature}, \text{maximum dwell time}, \text{derivation} \rangle$, consider the following list:

$\langle 0.025 \text{ dBW}, 1, \text{cumulative}, \text{fleeting}, 0.000004 \text{ s}, \text{measured} \rangle$
 $\langle 0.020 \text{ dBW}, 0.9, \text{cumulative}, \text{fleeting}, 0.000004 \text{ s}, \text{measured} \rangle$
 $\langle 0.015 \text{ dBW}, 0.75, \text{cumulative}, \text{fleeting}, 0.000004 \text{ s}, \text{measured} \rangle$
 $\langle 0.010 \text{ dBW}, 0.3, \text{cumulative}, \text{fleeting}, 0.000004 \text{ s}, \text{measured} \rangle$
 $\langle 0.005 \text{ dBW}, 0.1, \text{cumulative}, \text{fleeting}, 0.000004 \text{ s}, \text{measured} \rangle$

This list show that 100% of the time the power is $\leq 0.025 \text{ dBW}$, 90% of the time $\leq 0.020 \text{ dBW}$, 75% of the time $\leq 0.015 \text{ dBW}$, 30% of the time $\leq 0.010 \text{ dBW}$, and 10% of the time $\leq 0.005 \text{ dBW}$. It shows that the maximum dwell of a transmission within the range of 0.020 dBW and 0.025 dBW is 4 ms. The modeler likely means that no transmission last longer than 4 ms and only 10% of the transmissions are within this power range.

8.2.4 Modeling requirement

Every transmitter and receiver model shall have a reference power value. The use of the confidence measure is optional. In order for confidence to affect compatibility computations there shall be a peer-wise agreement how compatibility is to be computed using the confidence measures. Without an agreement, the highest power level in a transmitter model is used and the lowest power level in a receiver model is used in compatibility computations.

8.3 Spectrum mask

8.3.1 Purpose and use

The purpose of the spectrum mask construct is to convey 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 SCM to be used to determine when adjacent band interference occurs.

In a frequency hop system, transmissions are not persistently on a single channel and so offer an opportunity for other systems operating in the same frequency bands of the hopping to coexist. In this case, the spectrum mask captures not only the spectral content of a signal at an instant but also the statistical characteristics of its

hopping. Varying amounts of detail about the hopping can be provided. Subsequent determination of harmful interference on coexisting systems depends on the modeling of the receiver's susceptibility to this interference in its underlay mask. The frequency hopping spectrum mask serves only to capture the nature of the frequency hopping. The basic content is the generic spectral content of a signal, the channels or frequency bands through which these signals hop, the dwell time of a signal at a hop, and then the average period between revisits. In cases where the signal space varies at individual hops or when the dwell time varies, modelers have the choice to use multiple spectrum mask data structures to capture the variation in these characteristics.

8.3.2 Data elements and their meaning

Spectrum masks use the spectral masks described in 7.4 with an RBW to indicate the bandwidth over which the specified power level of the mask is spread. The power term in spectrum masks is a relative power referenced to the reference power of the model. Together, the reference power, the relative power of the mask, and the bandwidth resolution specify the spectral density of power (i.e., power per unit bandwidth) at each frequency covered by the mask. The spectral density power levels for all frequencies outside the frequency band covered by the mask are considered to be less than or equal to those at the closest end of the mask.

If the reference 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 an RBW that is a fraction of the total bandwidth of a signal has only a fraction of the total power. For example, if the bandwidth of a signal is 1 MHz but the RBW is just 10 kHz, then the relative power reduction within the RBW would be determined to be

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

Figure 3 illustrates an example of a spectrum mask and provides the data elements of this mask for the two different approaches of modeling the spectral content of signals as described in 7.4.

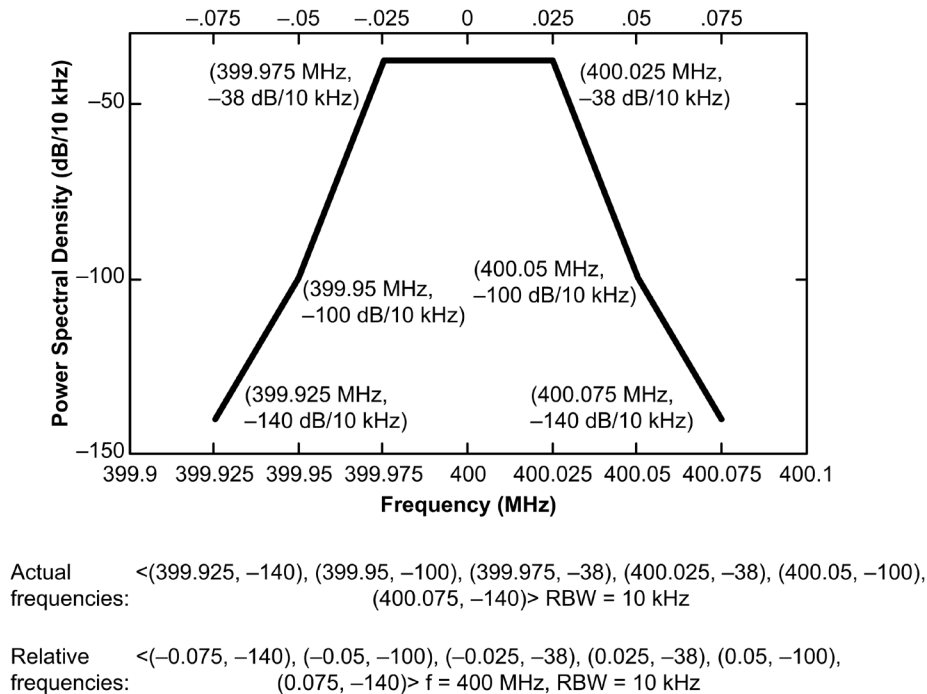


Figure 3—A spectrum mask and the alternative approaches to identify inflection points

Frequency hopping systems require the modeling of the signals that are transmitted and also the characteristics of the frequency hopping. Models of frequency hopping use relative spectrum mask. This type of spectrum mask is then complemented with details on the frequency hopping, specifically, the channels used, the dwell time, and the average period between revisits. There are two options for specifying the frequencies used: a listing of the specific reference frequencies such as $(f_0, f_1, f_2, \dots, f_x)$ or a listing of the end frequencies of the bands that are used. In the second case, the tuple (f_{b1}, f_{e1}) define the beginning frequency and ending frequency of a band. A collection of disjoint bands are specified through a series of frequency pairs such as $\langle (f_{b1}, f_{e1}), (f_{b2}, f_{e2}), \dots, (f_{bx}, f_{ex}) \rangle$. In this modeling the reference frequency for the relative spectrum mask is equally likely anywhere within a specified band. The relative spectrum mask and the frequency specifications are paired with two additional data elements that define the frequency hopping. The first is the dwell time and the second is the average revisit period. In the case of using specific center frequencies, the dwell time refers to the duration of time that a signal dwells on one of the center frequencies before the next hop. The average revisit period specifies the average time between occurrences of a signal on the *same* channel. In the case where bands are specified for the hopping frequencies, the dwell time also specifies the dwell time of a signal as specified by the relative mask at a particular frequency. In this second case, the average revisit period, however, accounts for the fact that individual signals may overlap in spectrum. The revisit period is a function of the bandwidth of the signal conveyed in the relative mask as compared to the bandwidth of the hopping frequency band and the duty cycle for that band. As an example, if the ratio of the bandwidth of the relative mask to the bandwidth for the signal occupancy (the bandwidth between the end frequencies) is 1 to 50 and the duty cycle is 50%, then the revisit period would be

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

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.

Confidence 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 confidence 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 make a difference in whether a secondary would take the risk of using the channel.

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

When used, confidence measures are associated with individual masks. In these cases, transmitter models would have multiple masks. All masks would use the same confidence approach, either alternative or cumulative.

Table 7 lists the data elements in the spectrum mask construct. All masks have the mask itself, SCMMask, and a resolution bandwidth, ResolutionBW. The HoppingData element is added when the spectrum mask is for a frequency hopping or a pulsing type of signal. Table 8 lists the data element of this data object. HoppingData always provides a dwell time, DwellTime, and a revisit period, RevisitPeriod, and then optionally either a frequency list, FrequencyList, which is further defined in Table 9, or a band list, BandList, which is further defined in Table 10. When a frequency or band list is provided, the SCMMask shall be of a relative type.

Table 7—SCM spectrum mask construct

Data element	Sub-elements	Types	Enumerated values/ unit of measure	Occurrences	Notes
SpectrumMask		Structure			
	HoppingData	Structure		0..1	If used, indicates mask is for a frequency hopping or pulsing signal. Sub-elements in Table 8.
	ResolutionBW	Number	MHz	1	The RBW of the mask indicating the bandwidth across which the indicated power is disbursed.
	SCMMask	Structure		1	A spectrum mask. See Table 5.
	Confidence	Structure		0..1	Used in a model with multiple masks showing likelihood of variation in spectral content. See Table 3 for the data description.

Table 8—SCM hopping data

Data element	Sub-elements	Types	Enumerated values/ unit of measure	Occurrences	Notes
HoppingData		Structure			
	DwellTime	Number	Seconds	1	Max duration of a signal
	RevisitPeriod	Number	Seconds	1	Time between signal starts
	FrequencyList	Structure		0..1	Sub-elements in Table 9. If used, replaces reference frequency in the SCM Mask. Not used with BandList.
	BandList	Structure		0..1	Sub-elements in Table 10. If used, the reference frequency of the SCMMask may be anywhere in the listed bands. Not used together with CenterFreqList.

Table 9—SCM frequency list

Data element	Sub-elements	Types	Enumerated values/ unit of measure	Occurrences	Notes
FrequencyList		Structure			
	ReferenceFreq	Number	MHz	1..n	

Table 10—SCM band list and band

Data element	Sub-elements	Types	Enumerated values/ unit of measure	Occurrences	Notes
BandList		Structure			
	Band	Structure		1..n	
Band		Structure			
	StartFrequency	Number	MHz	1	Lower frequency of a band
	EndFrequency	Number	MHz	1	Upper frequency of a band

8.3.3 Modeling requirement

All transmitter models have a spectrum mask. The spectrum mask is used together with the reference power and a power map to specify the PSFD in any direction from a modeled transmitter.

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 are beneath the ambient noise floor at the locations they are considered for compatibility. In cases where the mask does not reach this level, it can only be assumed that the signal outside the mask is something less than that of the end points. For the purposes of compatibility computations the level of the end points are assumed for all frequencies beyond the endpoint for frequencies covered by any overlapping underlay mask.⁵ There is an advantage to specifying frequency content well beyond the channel bandwidth.

The determination of compatibility using the spectrum mask depends on the underlay masks used in models of the systems with which spectrum is shared. The modeling of the details of frequency hopping or short duty cycles allows use of underlay masks that match these characteristics and allow either higher levels of power in the transmitting system or for the receiving system modeled in the underlay to be closer in proximity to the transmitting system. The method for determining compatibility depends on the masks used to model both systems. Subclause 10.5 describes the power margin computations that account for the interaction of spectrum masks with underlay masks.

8.4 Underlay mask

8.4.1 Purpose and use

Underlay masks are the constructs of spectrum consumption modeling that define what is considered incompatible interference. They are selected to provide an interference margin that protects reception in a system. Additionally, underlay masks may be used as a means to define the conditions that a new user must accept in order to use the spectrum. In this case, the underlay mask defines the maximum power level of the anticipated interference as a function of frequency that the new user must accept. The rest of this discussion assumes the masks are used to define incompatible interference.

Underlay masks specify the power spectral density that a receiver can tolerate from a remote interfering transmitter. It conveys both the power level of tolerable interference and the spectral sensitivity to interference. In the latter case, the underlay map conveys the filtering by frequency that the receiver

⁵ This rule attempts to account for the use of masks that were built to show in-band spectrum use only. It is expected 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.

performs. Like the spectrum mask, it is a piecewise linear graph of relative power versus frequency combined with an RBW 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 differentiated by the spectral and temporal nature of interfering transmissions.

An underlay mask may be used in either a receiver model or a transmitter model. When used with a receiver model, relative power in these masks is relative to the reference power in a receiver model for all locations of the receiver model. When used within a transmitter model, the relative power in the underlay mask is assumed to adjust as that of the spectrum mask as a result of antenna directivity and propagation and so it indicates a constant protection margin with the spectrum mask of the transmitter model. In this latter case, when the underlay mask is part of a transmitter model, it is referred to as a *spectrum-mask-referenced* underlay mask or simply a *referenced* model. The use of an underlay mask with a transmitter model can simplify the modeling of broadcast systems where there is a single transmitter. Protection of the receivers is based on the effective range of the broadcast.

Figure 4 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 protection margin relative to the spectrum mask and the constraints of the second are fixed for all locations. The frequency terms of the two are the same but power terms of the mask referenced to a location are much smaller.

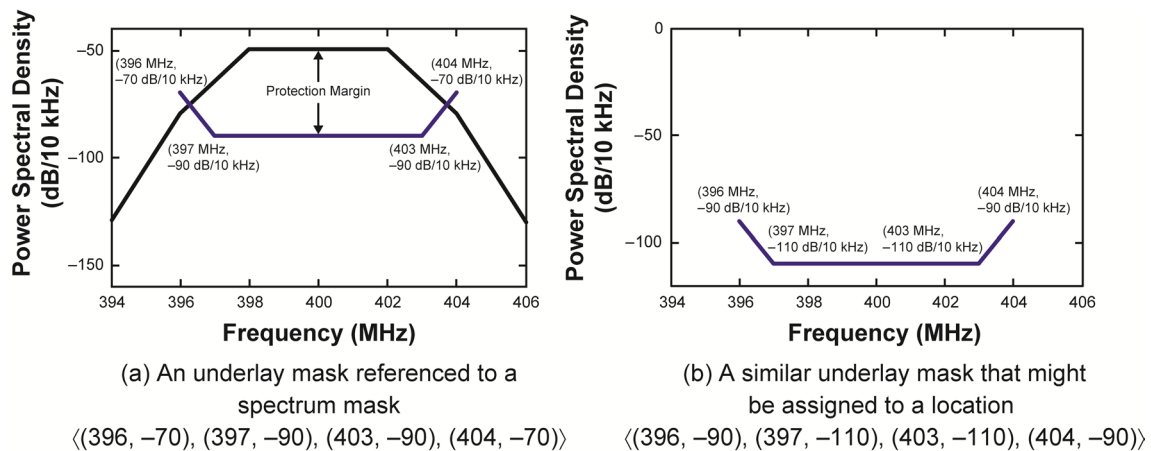


Figure 4—Comparison of underlay masks with alternative references, spectrum mask, and location

A receiver model may use multiple underlay masks to indicate differences in sensitivity based on particular signal spaces or sensitivity to different duty cycles of interference. They are rated for the different conditions.

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 with different bandwidth ratings may be used to account for different scenarios of narrowband interference.

RF systems may be able to coexist in the presence of frequency hopping systems operating in the same bands if the frequency hop systems occupancy in the band is infrequent, brief, low bandwidth, or weak. 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 that capture resilience to interference from frequency hop systems there are also systems that can tolerate interference from certain low duty cycle signals that might be transmitted

from radars and some other low duty cycle frequency hop systems. Rather than a time-bandwidth product, a duty cycle with a maximum dwell time rate each of these masks.

Receivers in a frequency hopping system may be able to tolerate some level of interference if it only affects a portion of the hops the receivers traverse. This assumes the receivers are not staring receivers observing a band but hopping receivers that tune their filters with each hop. Modelers can create underlay masks that convey the susceptibility to interference at each hop where interference is accepted if below a threshold of some number of hops or fraction of time.

A receiver system may be able to coexist with another RF system because of the unique protocols or policies implemented in that system that are effective at preventing interference to the modeled receiver. Examples include medium access control mechanisms that avoid transmitting when the receiver channel is in use, a dynamic frequency selection policy that shifts frequencies to avoid an active use of spectrum, or an adaptive technology such as smart antennas that are effective at nulling emissions in the direction of the receiver. Modelers can indicate greater resilience to these systems by adding underlay masks to receiver models that are matched to the particular Protocols and Policies that a coexisting system may implement.

Modelers use these collections of masks to convey additional opportunities for spectrum reuse. In determining compatibility, the assessment uses the underlay mask with the least restriction for which the interfering transmitter model meets the criteria of its use, e.g., bandwidth, duty cycle, matched protocol.

8.4.2 Data elements and their meaning

Underlay masks use the spectral masks described in 7.4 with an RBW to indicate the bandwidth over which the specified power level of the mask is spread. The power term in spectrum masks is a relative power referenced to the reference power of the model. Together, the reference power, the relative power of the mask, and the RBW specify the spectral density of power (i.e., power per unit bandwidth) at each frequency covered by the mask. The modeler specifies the extent of frequencies that a receiver is sensitive to interference by explicitly modeling that extent. In assessing compatibility there are no assumptions made about the susceptibility to interference outside the frequency limits of the mask.

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 portrayal 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 lower 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.

The computation of the power margin from the interaction of an interfering transmitter spectrum mask and an underlay mask may be of two types: total power or maximum power density. The total power computation uses the underlay mask to assess the quantity of power that would enter the receiver and cause interference. The maximum power density computation assesses whether the maximum power spectral density of a transmitter spectrum mask exceeds any threshold level of the underlay mask. The advantage of the maximum power density method of computation is that it simplifies the assessment of aggregate effects. The assumption is that the power level of the underlay mask has been set in anticipation of the types of aggregate interference that might occur. Compatibility computations and decisions can be made with just the pairwise comparison of the underlay mask with each interferer. The total power method, however, only determines the individual contribution of interference from a single interferer. Admission decisions require the determination of the aggregate interference from all interferers. This aggregate interference must be less than the allowed interference of the receiver model. Thus for a new use to be compatible, its interference in aggregate with all other interference shall be less than the allowed interference conveyed in the receiver model.

An underlay mask that uses the total power method for power margin computation naturally accounts for the difference in interference that results from the bandwidth of an interferer. This is not the case when the

maximum power density method is used. When an underlay mask uses the maximum power density method of power margin computation, the modeler may use multiple masks to indicate the differences in tolerance based on the total bandwidth of the interferers. Individual masks may be rated for the maximum bandwidth (BW) of the interfering signal. When the basic shape of the underlay mask remains the same for the multiple masks being used for different narrowband interference scenarios, then a single underlay mask may be provided followed by a list of bandwidth-rated power level adjustments consisting of a bandwidth and the relative power adjustment pair of the form $\langle(BW_0, p_0), (BW_1, p_1) \cdots (BW_n, p_n)\rangle$ where BW is the rated bandwidth and p is the relative power adjustment of all power levels of the base mask.

Figure 5 illustrates examples of using multiple masks to differentiate tolerance to different bandwidths of interfering signals and compares the two approaches used to specify the values. In the multiple mask approach, the modelers would create multiple masks with each rated by a bandwidth. The difference in interference tolerance is captured in the different power levels of the masks. In the single mask approach, separate lists of bandwidth – power adjustment tuples create the same collection of underlay masks where the adjustment operates on all power levels of the base mask. Note that there is always a base mask that accounts for interfering signals that cannot meet the criteria of any of the bandwidth-rated masks.

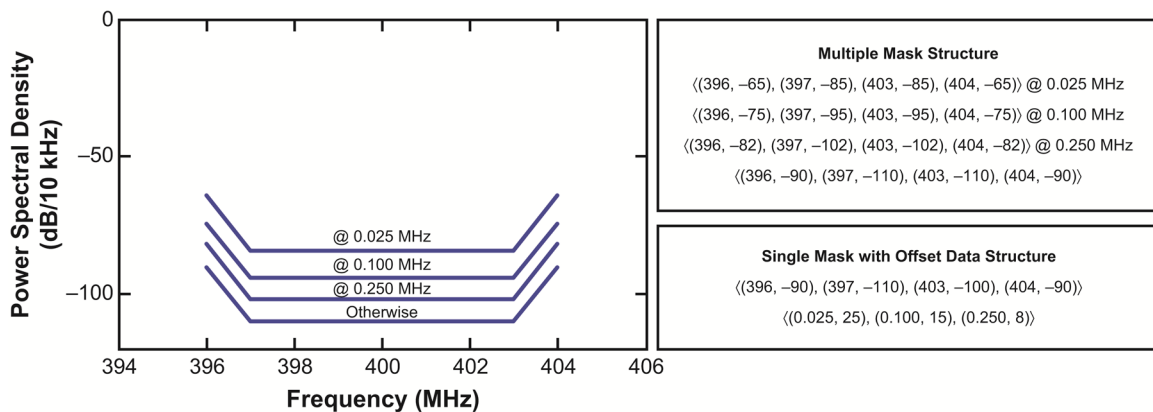


Figure 5—Using multiple masks to specify different interference constraints for different interference bandwidths and a comparison of data structures specifying these masks

Underlay masks that use the maximum power density power margin computation method may be rated for frequency hop interference using a format similar to the underlay masks for narrowband interference. A single mask is given several ratings associating a BTP with a power level of the form $(BTP_0, p_0, BTP_1, p_1, \cdots BTP_i, p_i)$. The BTP is a product of the bandwidth and duration of occupancy of a single signal on average per second within the spectrum covered by the underlay mask. When multiple signals arrive within the spectrum covered by the underlay mask, then the effective BTP is the sum of the individual BTPs.

Figure 6 illustrates examples of using multiple masks to differentiate tolerance to different occupancy of frequency hopped interfering signals and compares the two approaches used to specify the values. In the multiple mask approach, the modelers would create multiple masks with each rated by a BTP. The difference in interference tolerance is captured in the different power levels of the masks. In the single mask approach, separate lists of BTP – power adjustment tuples create the same collection of underlay masks where the adjustment operates on all power levels of the base mask. Note that there is always a base mask that accounts for interfering signals that cannot meet the criteria of any of the BTP-rated masks.

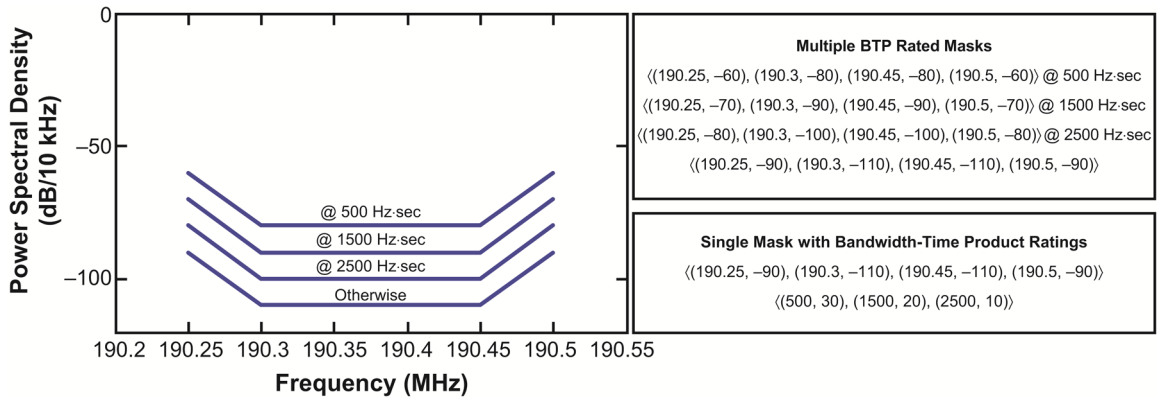


Figure 6—Using underlay masks to specify ratings for frequency hopping interference

Underlay masks may be rated for low duty cycle interference similar to the previous two mask but using only the single mask method. It may be used with either underlay masks that use either the maximum power density or total power methods for power-margin computations. The single mask is given several ratings that combine duty cycle, maximum dwell time and a power level adjustment of the form $\langle (DC_0, DT_0, p_0), (DC_1, DT_1, p_1), \dots, (DC_n, DT_n, p_n) \rangle$. These masks identify two constraints that define the duty cycle limitation. The duty cycle (DC in Figure 7) identifies the total fraction of time the interferer is present and dwell time (DT in Figure 7), the maximum dwell time, identifies the maximum continuous period of time that an interfering signal is on. When multiple low duty signals arrive from distant interferers, margin computations add their duty cycles and add their dwell times in order to select the correct mask.

Figure 7 illustrates examples of rating masks for a duty cycle using a single mask approach. A mask is provided with lists of duty cycle, – maximum dwell time, – power adjustment, three-tuples that create a collection of underlay masks where the adjustment operates on all power levels of the base mask. Note that there is always a base mask that accounts for interfering signals that cannot meet the criteria of any of the duty-cycle-rated masks.

The HopRated type underlay mask allows modelers to describe frequency hop systems that may tolerate the loss of some number of their hops to interference. The SCMMask in the UnderlayMask construct shall be a relative mask and the HoppingData in the HopRated structure defines how that masks moves in frequency and the time it dwells at each hop. This is the same as used in defining spectrum masks with the same meanings concerning spectrum occupancy, see 8.3.2. The Threshold element describes the tolerable fraction of hops that can suffer interference.

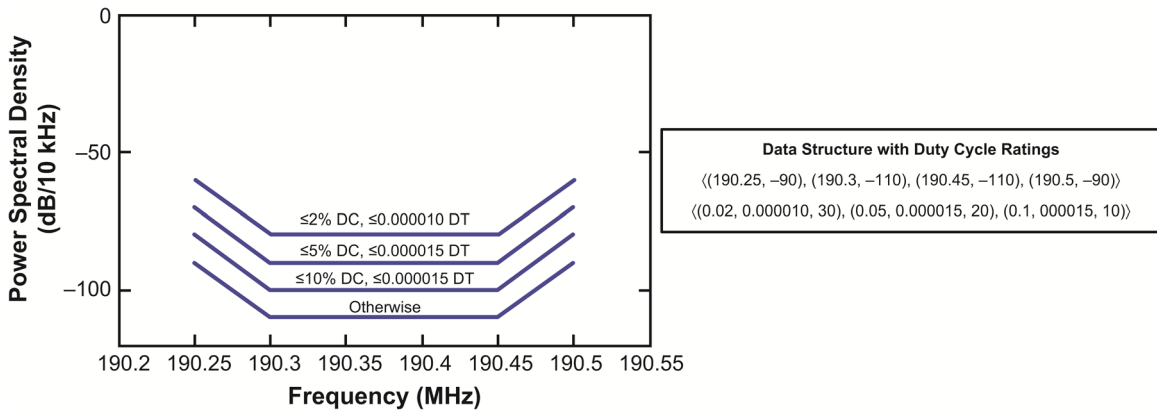


Figure 7—Using underlay masks to specify ratings for low duty cycle interference

The last type of rating for masks is one associated with a particular protocol or policy. In modeling, a mask is defined and an index number in the mask data that associates it with a particular protocol or policy modeled using the Protocol or Policy Construct, see 8.12.

An underlay masks may be given a confidence rating. A collection of masks with confidence ratings indicate the distribution of interference that a receiver can tolerate. A description and example of using the confidence element with underlay masks appears in 11.4.4.2.

Table 11 lists the data elements in the underlay mask construct. All masks have the mask itself, SCMMask, a resolution bandwidth, ResolutionBW, and the power margin computation method, MaskPowerMarginMethod. The Rating element is added when the underlay mask has ratings for either narrowband, frequency hopped, or low duty cycle signals. Table 12 list the data element of this structure. There are six possible types of ratings, only one is used. The RatingBW is single bandwidth rating indicating the bandwidth rating for the mask. The BWRatedList is a data structure that provides a list of ratings for different interferer bandwidths. Each rating in the list consists of the bandwidth rating and a power level adjustment for the base mask. Table 13 defines this type of list and the data elements of the bandwidth ratings. The RatedBTP is a single BTP rating indicating the BTP rating of the mask. The BTPRatedList is a data structure that provides a list of the BTP ratings and a power level adjustment for the base mask. Table 14 defines this type of list and the data elements of the BTP ratings. The DCRatedList is a data structure that provides a list of the duty cycle ratings. Each rating in the list includes the three-tuple of a duty cycle, maximum dwell time, and power level adjustment. Table 15 defines this type of list and the data elements used for each duty cycle rating in the list. Finally, there is the PorPIndex which is an integer that allows an underlay mask to be matched with a Protocol or Policy Construct. The matching instance of the Protocol or Policy Construct has the same index value.

Table 11—SCM underlay mask construct

Data element	Sub-elements	Types	Enumerated values/ unit of measure	Occurrences	Notes
Underlay Mask		Structure			
	Rating	Structure		0..1	If used, indicates the mask is rated for particular conditions. Sub-elements in Table 12.
	ResolutionBW	Number	MHz	1	The RBW of the mask indicating the bandwidth across which the indicated power is disbursed.
	SCMMask	Structure		1	An underlay mask. See Table 5.
	MaskPowerMarginMethod	String/ Attribute	TotalPower, MaximumPowerDensity	1	Method used to compute compatibility
	Confidence	Structure		0..1	Used in a model with multiple masks showing a distribution of allowed interference. See Table 3 for the data description.

Table 12—SCM underlay mask rating data

Data element	Sub-elements	Types	Enumerated values/ unit of measure	Occurrences	Notes
Rating		Structure			Choose of one of the following:
	RatedBW	Number	MHz	1	Cumulative bandwidth of interferers.
	BWRatedList	Structure		1	List of adjustments to the relative level of a mask based on cumulative bandwidth of the interferers. Sub-elements in Table 13.
	RatedBTP	Number	MHz × seconds, (cycles/10 ⁶)	1	Cumulative BTP of interferers.
	BTPRatedList	Structure		1	List of adjustments to the relative level of a mask based on cumulative BTP of the interferers. Sub-elements in Table 14.
	DCRatedList	Structure		1	List of adjustments to the relative level of a mask based on cumulative duty cycle of the interferers. Sub-elements in Table 15.
	HopRated	Structure		1	Describes how the mask moves in frequency. Sub-elements in Table 16.
	PorPIndex	Integer		1	Used to associate the mask with a particular Protocol or Policy Construct.

Table 13—SCM bandwidth-rated list and rating adjustments

Data element	Sub-elements	Types	Enumerated values/ unit of measure	Occurrences	Notes
BWRatedList		Structure			
	BWRating	Structure		1..n	
BWRating		Structure			
	RatedBW	Number	MHz	1	Cumulative bandwidth of interferers
	Adjustment	Number	dB	1	Relative power adjustment of the mask

Table 14—SCM BTP-rated list and rating adjustments

Data element	Sub-elements	Types	Enumerated values/ unit of measure	Occurrences	Notes
BTPRatedList		Structure			
	BTPRating	Structure		1..n	
BTPRating		Structure			
	BTP	Number	MHz × seconds, (cycles/10 ⁶)	1	Cumulative bandwidth of interferers
	Adjustment	Number	dB	1	Relative power adjustment of the mask

Table 15—SCM duty-cycle-rated list and rating adjustments

Data element	Sub-elements	Types	Enumerated values/ unit of measure	Occurrences	Notes
DCRatedList		Structure			
	DCRating	Structure		1..n	
DCRating		Structure			
	DC	Number		1	Fraction of time interferers are transmitting
	MaxDwellTime	Number	seconds	1	Maximum duration of a contiguous transmission
	Adjustment	Number	dB	1	Relative power adjustment of the mask

Table 16—SCM Underlay Mask Hop Rating Adjustment

Data element	Sub-elements	Types	Enumerated values/ unit of measure	Occurrences	Notes
HopRated		Structure			
	HoppingData	Structure		1	Sub-elements in Table 8.
	ToleranceThreshhold	number		1	Fraction of hops in which the interference threshold may be violated.

8.4.3 Modeling requirement

All receiver models have at least one underlay mask. Broadcast transmitter models may optionally provide a spectrum-mask-referenced underlay mask to indicate the receiver model for the broadcast. When a spectrum mask reference underlay mask is used in a broadcaster transmitter model, that model shall also have a Minimum PSFD Construct. The role of this construct in the model is to define the limits of protection to these receivers. Subclause 8.11 describes this construct and greater detail of its role.

The main role of the underlay mask is to identify the spectral and small scale temporal limits to interference. The underlay 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 indicating the attenuation necessary through the other constructs to assess their spectrum use compatible. The computation of this power margin is described in 10.5. There are two methods to compute the margin, the total power method and the maximum power density method. The modeler of the underlay mask specifies the method that is used with each modeled mask. The link budget computations and the determination of compatibility between models are described in Clause 10 and Clause 11. Modelers build underlay masks with the understanding of how the models will be used to compute compatibility. The methods in Clause 10 and Clause 11 are very important not only to understand the specific meaning of underlay masks but also to understand how to build underlay masks.

Modelers may model a receiver with multiple underlay masks to reveal that the receiver is more tolerant to particular types of interference. Bandwidth-rated and BTP-rated masks are used with the maximum power density methods of power margin computation only. The duty-cycle-rated and protocol- or policy-rated underlay masks may be used with either power margin computation method. The power margin of the system is computed using the least restrictive underlay mask for which the interfering transmitter model meets all the use criteria of the underlay mask. When a modeler uses multiple underlay masks for a receiver, there shall still

be one general mask that would cover all potential types of interference for transmitter models that cannot meet the specialized criteria of any of the other underlay masks of the receiver model.

8.5 Power map

8.5.1 Purpose and use

The power map captures the dispersion of electromagnetic energy that is transmitted from antennas and the concentration of electromagnetic energy that is received by antennas. These effects may be the result of antenna gain or result from the environment and its interaction with the antennas.

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

Power maps individually specify a relative power flux density by direction that is relative to the reference power of the model, typically the power level that drives the antenna in transmitters and the interference threshold power level after the antenna in receivers. The relative power flux density is added to the power spectral density that are defined by the reference power and spectrum masks constructs of transmitters to convey PSFD by direction. It is the reciprocal for receivers where signals with a PSFD arrive at the antenna from a direction and the relative power flux density of the power map is added to determine the power spectral density of the signal that has arrived at the receiver.

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 local structures (e.g., a building that is close to the antenna). Structures can affect directional gain in both several ways. They can serve as obstacles that block signals in their direction or may also give the perception of higher gain in a direction because they reflect signals arriving from 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 these types of 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 out from the point of transmission or reception at a 1 m distance. This term takes into account the losses that occur when the transmission first leaves the antennas because of the transition from the antenna to the propagation media

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

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 1 m radius:

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

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

Antennas have 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 provide methods to capture the more deliberate behaviors such as scanning and tracking but at best can assign a probability to the success of adaptation. In cases where particular pairs of systems are known to be compatible based on the adaptation methods used, the protocol and policy construct is the more applicable means to capture that compatibility in a model.

The intent of the SCM is to capture the geospatial limit of a use of spectrum. So constraints to transmit power are defined as the effective PSFD at a particular frequency at a specified distance away from the antenna rather than the power driving an antenna. Transmitters with high gain antennas shall still conform to the PSFD constraints. Users cannot switch to a higher gain antenna using the same driving power and assume they can remain compliant to a use approved for the previous antenna at that driving power.

8.5.2 Data elements and their meaning

8.5.2.1 General

The SCM power map has five elements, an orientation, a scanning region, a gain map, a location index, and a confidence. The required elements are the orientation and gain map. The orientation specifies the reference coordinate system for the gain map and the gain map uses the SCM map approach described in 7.3 for specifying directional power flux density. The optional scanning region also uses the SCM map but there are only two directional values, 1 and 0, where 1 identifies in what directions the z-direction (elevation = -90°) of the gain map is scanned. When a scanning region is part of the model, the orientation defines the scanning region map orientation. The location index allows the modeler to create multiple power maps and assign them to different locations of the model. The confidence element allows the modeler to identify the probability that one of multiple power maps is used at any particular time. The following subclauses provide additional details about these elements. Table 17 lists the data elements of the SCM power map construct.

Table 17—SCM power map construct

Data element	Sub-elements	Types	Enumerated values/ unit of measure	Occurrences	Notes
SCMPowerMap		Structure			
	Orientation	Structure		1	
	ScanningRegion	Structure		0..1	
	GainMap	Structure		1	
	LocationIndex	Integer		0..1	Associates multiple constructs to a location and/or time.
	Confidence	Structure		0..1	See Table 3.
Orientation		Structure			Choice of one of the following options.
	Surface	Boolean		1	Set true when used.
	RelativeToPlatform	Structure		1	
	TowardReferencePoint	Structure		1	
RelativeToPlatform		Structure			Platform orientation shall be specified using location.
	ZRotation	Number	degrees	1	
	YRotation	Number	degrees	1	
	XRotation	Number	degrees	1	

Table 17—SCM power map construct (*continued*)

Data element	Sub-elements	Types	Enumerated values/ unit of measure	Occurrences	Notes
TowardReferencePoint		Structure			
	Point	Structure		1	Sub-elements in Table 23.
ScanningRegion		Structure			
	ScanValue	Structure		5..n	Order shall follow convention of a map as described in 7.3.
ScanValue					Choice of one of the following options.
	Elevation	Number	−90° to +90°	1	
	Azimuth	Number	0° to 360°	1	
	ActiveDirection	Boolean		1	
GainMap		Structure			
	GainMapValue	Structure		5..n	Order shall follow convention of a map as described in 7.3.
GainMapValue		Structure			Choice of one of the following options.
	Elevation	Number	−90° to +90°	1	
	Azimuth	Number	0° to 360°	1	
	Gain	Number	dB/m ²	1	

8.5.2.2 Map orientation

Using maps in SCMs require that they have a reference location and an orientation to the physical environment. There are three orientations, surface, relative to the platform, or toward a reference point.

The default orientation of a power map is the surface orientation which 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 is similar to measuring directional azimuths in land navigation. The elevations are also similar to those used in navigation and are measured from the horizon with the skyward direction being positive.

The surface orientation is the best for computational simplicity since it has the same orientation as that of the propagation map of the model. The surface orientation is likely to be used most since the other orientations exist to accommodate mobility and require a detail understanding of the operational scenario.

There are specific scenarios where the orientation is best referenced to that of a platform. In this case, assume that the starting reference matches that coordinate system of the platform and then coordinate rotations are used to reorient the antenna from that reference. Figure 8 illustrates the standard platform coordinate system where the x axis is coincident with the normal direction of travel of a platform (e.g., coincident to the fuselage of an aircraft) that the y axis is perpendicular to and to the right of that direction and generally parallel to the horizon (e.g., parallel to the wings of an aircraft) and that the z axis points towards the Earth. The antenna may then be displaced from this orientation by rotating the axis first about the z axis by an angle of rotation α , then the y axis by an angle of rotation β , and finally the x axis by an angle of rotation γ . Thus the orientation of the power map is conveyed in the 3-tuple $\langle \alpha, \beta, \gamma \rangle$.