SPECTRUM CONSUMPTION MODEL BUILDER: A SOFTWARE TOOL TO ENHANCE SPECTRUM SHARING

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ABSTRACT

Regulatory changes related to spectrum management in the U.S. and worldwide are promoting the use of dynamic spectrum access (DSA) and spectrum sharing mechanisms. Wireless service environments that use these mechanisms will rely heavily on radio interference control and management techniques to coordinate the boundaries of spectrum use for devices owned/managed by different entities. To communicate the characteristics and limits of spectrum use of an RF transmitter, receiver, system or collection of systems a common data structure to represent this information must be in place. Spectrum consumption models attempt to capture this information. They are currently being standardized within the IEEE DySPAN-SC 1900.5.2 workgroup. This paper presents our results and ongoing efforts in developing an open source tool for the construction and analysis of SCMs as a means to promote their use and showcase their potential for enhancing spectrum sharing and DSA interactions.

1. INTRODUCTION

The growing demand for Radio Frequency (RF) spectrum resources for commercial and government use has motivated changes to spectrum management regulatory frameworks. Many of these changes focus on moving away from rigid spectrum management policies and embracing dynamic spectrum access and spectrum sharing mechanisms [1, 2]. Spectrum sharing refers to "the use of automated techniques to facilitate the coexistence of disparate unaffiliated spectrum dependent systems that would conventionally require separate bands to avoid interference" [1]. Thus, radio interference control and management will be a key requirement for the successful operation of future RF spectrum sharing environments. To satisfy this requirement, there must be an effective means of communicating the spectral, spatial, and temporal characteristics, and boundaries of the consumption of spectrum of an RF transmitter, receiver, system or collection of RF systems. Spectrum consumption models (SCMs) attempt to capture this information.

The structure and characteristics of SCMs are being standardized by the 1900.5.2 working group of the IEEE Dynamic Spectrum Access Networks Standardization Committee (DySPAN-SC). The standard will also define tractable procedures to assess compatibility of spectrum uses specified via SCMs. Thus, the information contained in the models and the related algorithms to verify non-interference (compatibility of SCMs) will enable better RF spectrum management practices and allow for the identification of spectrum reuse opportunities.

This paper presents our results and ongoing efforts in developing an open source tool for the construction and analysis of SCMs: *The Spectrum Consumption Model Builder*. Among its main functions, the tool provides a means for the construction of standard compliant SCMs and for the analysis of compatibility between systems and/or devices in which an SCM describes the boundaries of spectrum use. The tool is intended to promote the use of SCMs and educate radio engineers, wireless service providers, researchers and regulators on their benefits. The tool also serves as a mechanism to test the viability of using SCMs in scenarios of interest to industry and regulators.

This paper is structured as follows: Section 2 provides a brief description on the structure of SCMs, further details can be obtained from [3] and [4]. Section 3 describes the creation of SCMs with the Spectrum Consumption Model Builder tool. Section 4 provides an overview of how to perform SCM compatibility calculations with the tool. Section 5 provides information on future perspectives for the tool and our conclusions.

2. SPECTRUM CONSUMPTION MODELS

As a data model for spectrum consumption modeling, the SCM aims to be minimal and effective at providing the means for spectrum managers to use their judgment and tools to capture relevant spectrum consumption details of their devices/systems and express them in a standardized way [3]. For the characterization of spectrum consumption by an RF device, it should be understood that both transmitters and receivers consume spectrum. Spectrum is consumed by an RF device to the extent that its transmissions prevent another RF device from getting adequate reception of desired signals. There is also spectrum consumption from an RF device based on its receiver's protection requirements which prevent the transmissions of other RF devices from taking place [4]. The use and interpretation of the information captured in an SCM is defined in such a way that it is not dependent on any external database or specific device architecture parameters. The IEEE 1900.5.2 standard seeks to standardize the data model for SCMs and the mechanisms/algorithms to arbitrate compatibility among combinations of transmitter/receiver devices. RF devices and/or systems are compatible if they can operate under the spectrum use boundaries detailed by their respective SCMs. The standard also aims to provide the means to generate machine-readable SCMs, which together with the standardized compatibility calculation mechanisms would provide the means to automate the identification of spectrum reuse opportunities and coordinate spectrum access.

Overall, SCMs attempt to capture spectral, spatial, and temporal characteristics, and boundaries of the consumption of spectrum by any specific transmitter or receiver device or RF system through a series of basic data constructs and a hierarchical structure for model aggregation. The constructs for an SCM are the following:

- *Total Power*: The power at the transceiver to which values of the spectrum mask, underlay mask, and power map reference.
- *Spectrum mask*: A variable sized data structure that defines the relative spectral power density of emissions by frequency.
- *Underlay mask*: A variable sized data structure that defines the relative spectral power density of allowable interference by frequency.
- *Power map*: A variable sized data structure that defines a relative power flux density per solid angle. Power maps capture antenna effects and some environmental effects.
- *Propagation map*: A variable sized data structure that defines a path loss model per solid angle.
- *Intermodulation mask*: A variable sized data structure that defines the propensity of co-located signals to combine in nonlinear components of an RF system, and be emitted by a transmitter or be received in the later stages of a receiver.
- *Platform Name*: This construct is used to identify devices, facilities, or platforms on which individual transceivers or receivers of a system are placed
- *Location*: The location where an RF component may be used. A location may be a point, a volume, a trajectory, or an orbit.
- *Schedule*: This construct specifies the time in which the model applies. It allows for the specification of a start time and end time for the model. Periodic cycles (on / off) can also be defined.
- *Minimum power spectral flux density*: A power spectral flux density that when used as part of a transmitter model, implies the geographical extent in which receivers in the system are protected.
- *Policy or protocol*: A named protocol or policy with parameters that define behaviors that allow different systems to be co-located and to coexist in the same spectrum.

The constructs allow for the modeling of a spectrum dependent device (transmitter and receiver models), a system that uses spectrum and is composed of multiple devices (a system model), or a set built from the combination of spectrum uses of multiple systems and devices (a set model). For the purposes of our work, we focus on transmitter and receiver models. Transmitter SCMs attempt to capture the characteristics and extent of RF emissions from a transmitting device by specifying the location(s), time of operation, spectral mask, transmission power and direction of its emissions. The required constructs for transmitter models are: total power, spectrum mask, power map, propagation map, schedule and location. Receiver models define the threshold limits for interference to a receiving device by specifying its possible locations, time of operation, range of spectrum subject to interference, tolerable interference power level, directivity of reception and impact of intermodulation effects. The required constructs for receiver models are total power, underlay mask, power map, propagation map, schedule and location [3, 4].

Probability values can be associated with several of the constructs of an SCM and are used to specify confidence in the spectrum consumption boundaries inferred by a model. With these capabilities SCMs and the systems that are built around them would provide sufficient information to enable dynamic and flexible spectrum management decisions that can increase spectrum reuse (i.e. spectrum sharing, spectrum trading and policy-based spectrum management interactions) [4, 5]. Thus, SCMs are well in line with moving forward the goals of many regulators for modernizing spectrum management.

3. THE SCM BUILDER TOOL

The 1900.5. Workgroup of the IEEE Dynamic Spectrum Access Networks Standards Committee (DySPAN-SC) has a charter to work on policy language and policy architectures for managing cognitive radio for dynamic spectrum access applications. Since 2012, the workgroup started work on project P1900.5.2 - Standard Method for Modeling Spectrum Consumption - with the goal of producing a standard that defines the necessary modeling constructs and tractable algorithms for determining compatibility between SCMs. Work on the IEEE 1900.5.2 standard is expected to be completed in 2016.

We have built a software tool - *The Spectrum Consumption Model Builder* - for the construction of SCMs and the analysis of compatibility between transmitters and receivers for which an SCM describes their boundaries of spectrum use. The tool is intended to promote the use of SCMs across different groups such as radio engineers, wireless service providers, researchers and regulators. The tool also serves as a mechanism to gather feedback on the use of SCMs and test the completeness of the standard and the viability of using SCMs in scenarios of interest to industry and regulators.

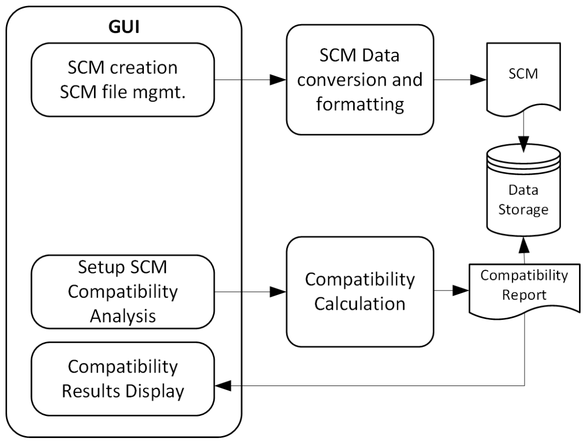

Figure 1: Main software modules of the SCM Builder tool

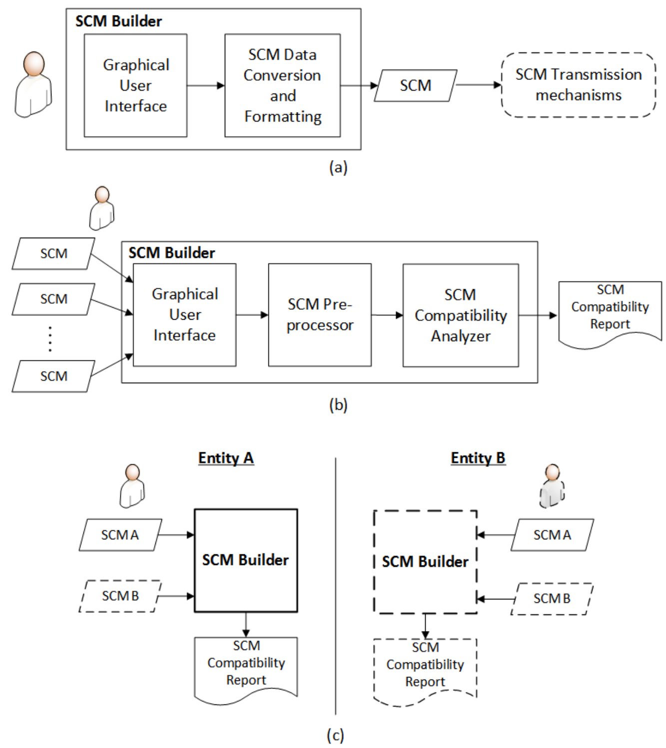

Figure 2: SCM Builder use case scenarios

Software development efforts for the tool mirror closely the activities of the IEEE 1900.5.2 workgroup. Once the standard and the tool are stable, the software tool will be released to the public via an open source license. Figure 1 presents the architecture of the tool indicating its main software modules. The first version of the tool is expected to be released in the first semester of 2016.

3.1. Use case scenarios

Figure 2 shows the main use scenarios for the tool. Part a) of the figure shows the software tool functions that will be involved in the construction of SCMs by a spectrum user/manager (most likely a radio/telecommunications engineer with knowledge of the RF operational characteristics of the radio devices that need to be modeled). The GUI lets the user select the SCM constructs that he/she determines need to be included in an SCM. For each construct, the tool provides adequate input elements and guidance to complete the input of information relevant to the construct. Once the SCM is finalized, the information provided via the GUI will be processed and formatted to structure a SCM that follows the content and format specifications defined in the IEEE 1900.5.2 standard. The fully structured and standard compliant SCM will be stored in a data file which can also be sent to a spectrum management system or a spectrum manager entity via a previously agreed transmission mechanism. The details of such mechanisms are outside the scope of this work.

Part b) of figure 2 shows the software functions that will be involved in the determination of compatibility across a set of SCMs taken as input. In the information flow shown in the figure, the GUI enables a user to input into the tool the SCMs of two or more devices. The information in each of the SCMs is pre-processed to verify their compliance to the format and structure of the IEEE 1900.5.2 standard and to deliver the spectrum consumption information contained in the SCMs to the compatibility analyzer. This last component, produces a compatibility report based on the execution of the algorithms and procedures mentioned in the IEEE 1900.5.2 standard to determine compatibility of spectrum use across the SCMs. The report mentions if the set of SCMs leads to compatible (non-interfering) spectrum use or if there is incompatible use.

Part c) of figure 2 depicts a scenario where two different entities that manage spectrum dependent devices want to verify if they will be able to operate their devices in a spectrum sharing environment. The entities after having shared their respective SCMs with each other verify that spectrum sharing is feasible or not feasible by using the SCM builder tool to determine if the SCMs are compatible or not. Since the tool implements the algorithms for compatibility calculations defined in the IEEE 1900.5.2 standard , and since these algorithms produce only one result when run with the same input information, the compatibility reports obtained by each entity will be identical and both entities can decide to move forward with sharing spectrum and operate their devices under the limits mentioned in their SCMs or make additional arrangements/adjustments to the operation of the devices if needed.

3.2. Creating SCMs

The main (home) screen of the tool shown in figure 3. It provides links for the user to create a new SCM model, open an existing SCM model or execute a compatibility computation between two or more SCM models. To create a new SCM, the user must specify the model name and its type: transmitter or re-

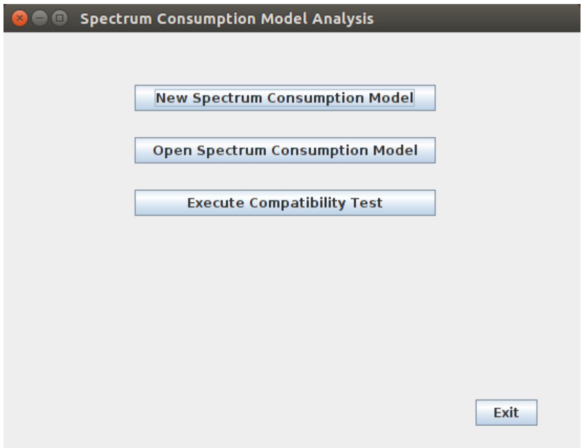

Figure 3: Home page window

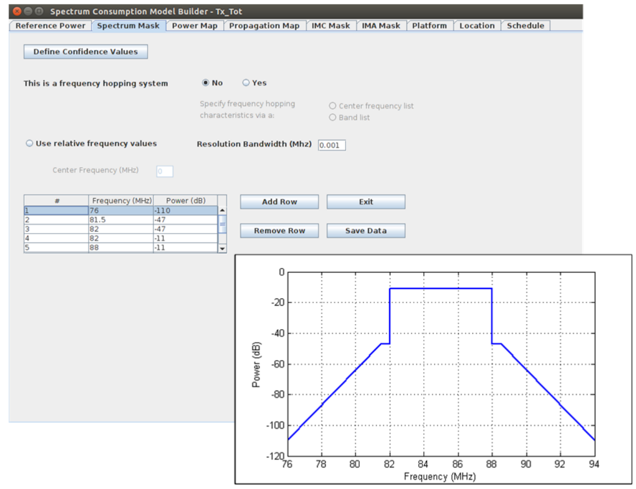

Figure 4: Spectrum mask example

ceiver. The current version of the tool supports the creation and compatibility calculation operations between transmitter and receiver models only. Support for system and set models will be added in future versions. On creating a new model a new GUI window pops up containing a series of tabs that enable the user to enter the values and details for required and optional SCM constructs. We describe the information capture and operation for some of the constructs in the following paragraphs. In our description, we include a screen capture of the actual GUI environment of the SCM builder tool and a graph of the data being entered into the tool. It should be understood that the graph is not currently produced within the SCM builder environment and is provided for illustrative purposes only (graphing capabilities may be introduced in future versions of the tool).

The spectrum mask tab shown in figure 4 is active when a transmitter model is being built and allows for the use of a table structure to list the frequencies and relative power levels necessary to specify the shape of a spectrum mask. Power levels are relative to the value of the Reference Power construct (which can be provided in the first tab provided in the GUI). Frequencies can be absolute or relative to a reference frequency. Probability / confidence levels for the spectrum mask and the capacity to specify frequency hopping behavior are also available but not shown in the figure.

When the model of a receiver is being built, the spectrum mask tab becomes the underlay mask tab and displays a similar table structure for the modeler/user to define the underlay mask of the receiver. An example of an underlay mask definition is shown in figure 5.

The power map is a construct for specifying the dispersion of RF energy transmitted by antennas or the concentration of RF energy received by an antenna. The power map tab shown in figure 6 allows the modeler to specify a relative power flux density for any particular direction. Using the values in the power map, the total power construct and the power spectral density of the spectrum mask, a power spectral flux density at one meter from an antenna can be computed which is later used for far field computations of signal strength by incorporating the information provided in the propagation map construct. The user may also define the orientation of the map, i.e. relative to the surface, relative to the platform or towards a reference point. An antenna scanning region can also be defined in terms of azimuth and elevation limits.

The propagation map construct is used to specify the rate of RF power attenuation by direction. This rate is specified by a single pathloss exponent in the case of a linear model or by three parameters (pathloss exponent, a distance, and a second path loss exponent) for a piecewise linear model. Both cases are variants of a log-distance pathloss model. Figure 7 shows the Propagation Map tab for the input of information of a piecewise linear propagation map. The propagation map can be referenced with respect to a given antenna height.

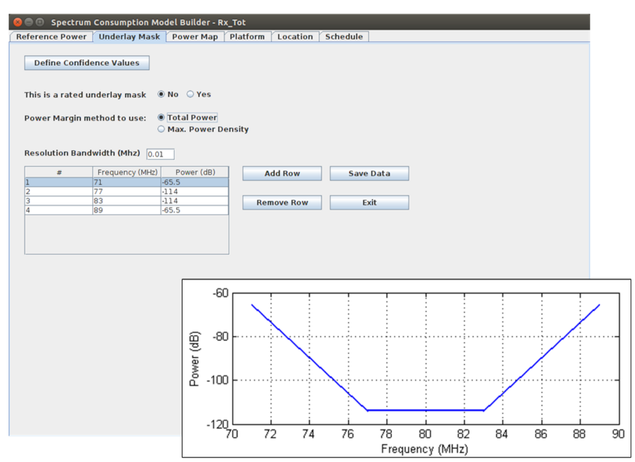

Figure 5: Underlay Mask example

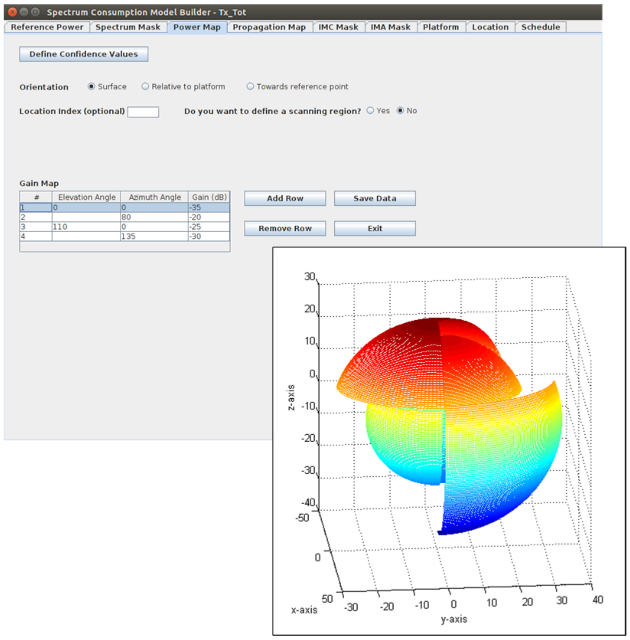

Figure 6: Power map example

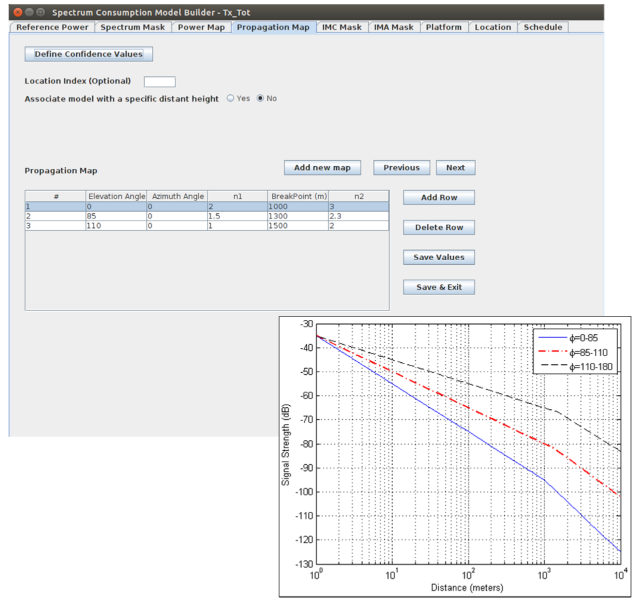

Figure 7: Propagation map example

4. SPECTRUM USE COMPATIBILITY CALCULATION WITH THE SCM BUILDER SOFTWARE TOOL

The calculation of non-interfering spectrum use (compatibility calculations) between systems that have expressed their spectrum use by SCMs involve determining the transmitter and receiver locations where there would be the most interference between a transmitter and receiver pair while taking into account the directional effects of antenna gain and pathloss conveyed in their SCMs. For a single transmitter and a single receiver case this can be done rather efficiently but as the number of transmitters, receivers and potential locations increases it becomes a non-trivial task[4].

From the data contained in the SCM constructs, calculations can be performed to determine a bound to by how much power could the spectrum mask be adjusted to be at the threshold of compatibility (non-interference) with the underlay mask, this is known as the power margin computation and its result can be used to assess the potential for further spectrum reuse and/or sharing opportunities. This computation is detailed in [3] and included in the IEEE 1900.5.2 standard.

In the calculation of compatibility between the SCMs of a transmitter and receiver, the software tool produces several plots as part of the generation of a compatibility result report. Figure 8 shows a transmitter spectrum mask before and after link budget adjustment as shown in a report for a specific scenario. The adjusted spectrum mask takes into account the total transmitter power value, the effects of the gain described in the power map construct and the pathloss predicted by the power map in the direction and distance of interest in a given scenario. Figure 9 illustrates an example of the structure of an underlay mask (of a receiver) and the structure of the adjusted spectrum mask (of a transmitter) which is used to compute the amount of interference (RF energy) that the transmitter generates on the receiver in a spectrum sharing scenario to determine if the systems are compatible, that is, if they can operate under the spectrum use boundaries detailed by their respective SCMs. In addition to the plots, the result of the compatibility calculation (compatible or not compatible) and the calculated power margin values are provided in the compatibility report.

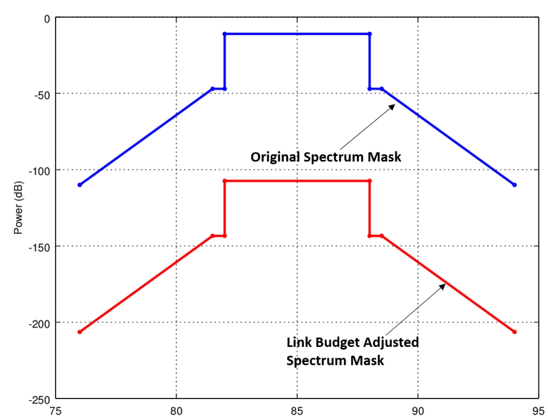

Figure 8: Example of a transmitter spectrum mask, before and after link budget adjustment

In addition to single transmitter vs. single receiver compatibility calculation scenarios. The tool can also compute compatibility for multiple transmitter vs. a single or a group of under-

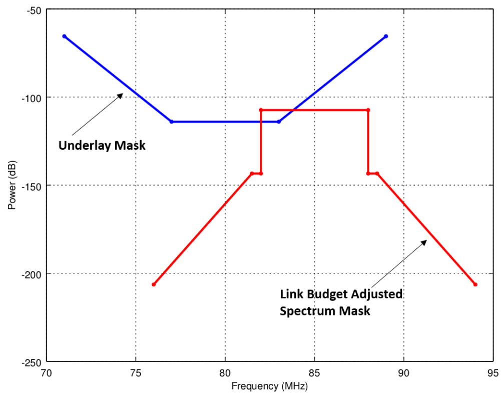

Figure 9: Receiver Underlay Mask vs. Transmitter Spectrum Mask

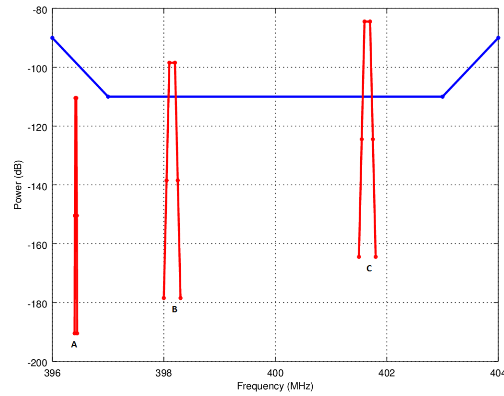

Figure 11: Example of a multiple transmitter vs. a single receiver scenario

lay masks. Figure 10 shows a table that provides a description of the spectrum masks for three transmitters that are operating in the same area of a receiver. The power values shown indicate the adjusted values for each of the masks at the point where interference is being calculated. The structure of the adjusted spectrum masks for this scenario is shown in figure 11. In this scenario, only transmitter A is compatible with the receiver. It is worth mentioning that the tool can also compute the compatibility of the different combinations of transmitters being active at the same time and the effect of their combined interference towards the receiver.

Transmitter (Spectrum Mask)						Receiver (Underlay mask)	
A		B		C			
Freq. (MHz)	Power (dB)	Freq. (MHz)	Power (dB)	Freq. (MHz)	Power (dB)	Freq. (MHz)	Power (dB)
396.4	-173	398	-185	401.5	-167	396	-90
396.405	-133	398.05	-141	401.55	-127	397	-110
396.415	-93	398.1	-101	401.6	-87	403	-110
396.43	-93	398.2	-101	401.7	-87	404	-90
396.44	-133	398.25	-141	401.75	-127		
396.445	-173	398.3	-181	401.8	-167		

Figure 10: Spectrum mask data for an example of a multiple transmitter vs. a single receiver scenario

5. CONCLUSION

Access and provision of wireless services in environments that support spectrum sharing will require the automation of processes that enable dynamic spectrum access interactions. SCMs aim to be minimal and effective at providing a means to capture the essential information required by spectrum dependent systems to express the boundaries of spectrum use and to arbitrate the compatibility of spectrum uses amongst several devices and/or systems. Overall, SCMs provide a common way to express spectrum use and determining compatible spectrum use for collaborative interactions in spectrum sharing environments without requiring the sharing of any external database of environmental data or device performance data. The Spectrum Consumption Model Builder tool aims to incentivize the use of SCMs, uncover the potential benefits of their use, collect feedback for their improvement and contribute to the development of spectrum sharing techniques. We expect the first versions of the tool to be released in 2016 as an open source tool and to generate a community of interested parties from the spectrum management community that can participate and contribute in growing the capabilities of the tool as an open source project.

ACKNOWLEDGMENT

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