SPECTRUM USAGE MEASUREMENT AND DECONFLICTION

Peraton Labs Team – PoC Phiroz H. Madon

ABSTRACT[1] [2]

DoD test ranges have expanding needs for air-to-ground telemetry bandwidth and are under pressure to manage the spectrum resource efficiently. In addition, DoD spectrum reserved for T&E is subject to encroachment by commercial entities. The T&E community needs tools to address both challenges at once: spectrum defense and spectral efficiency.

The Spectrum Usage Measurement System (SUMS) measures and records the use of spectrum at test ranges on a daily basis. The system imports mission planning data from range systems as a base-line, then uses networked sensors and telemetry receivers to verify this usage over-the-air.

The Spectrum Access Manager (SAM) is a set of features designed to expand the deconfliction capabilities of the currently-deployed IFDS system. Advanced features provided by the SAM library will dramatically increase frequency reuse, reduce fragmentation of the allocated spectrum, and support inter-range collaborative frequency deconfliction.

I. INTRODUCTION: SUMS AND SAM OVERVIEW

DoD flight test and training ranges are faced with the twin challenges of ever-increasing demand for test data throughput, and continuing encroachment by commercial entities on the RF spectrum traditionally reserved for them. In such a congested RF environment, the ranges need to be able to defend their use of the current telemetry spectrum. One of the main impediments to achieving this capability is the unavailability of data on planned and actual use of spectrum at ranges. To address this gap, Perspecta Labs and partners have developed a Spectrum Usage Measurement System (SUMS), which will:

- Create a knowledge base that combines range mission planning data with frequencies sensed over-the-air by sensors, to produce an accurate representation of spectrum usage.
- Provide analytics on usage measurements that will, among other things, help forecast future spectrum requirements and improve spectral efficiency by providing insights into current and future operations.

At the same time, there is a need for test range operations personnel to be able to plan and manage the use of the current telemetry spectrum in the most efficient manner possible. The Spectrum Access Manager (SAM) is a set of features designed to expand and evolve the deconfliction capabilities of the currently-deployed Integrated Frequency Deconfliction System (IFDS).

Advanced deconfliction features provided by SAM include:

- Spatially-Aware Frequency Deconfliction. Currently, a conflict between two frequency assignments is determined by a time-frequency overlap. This feature will also take

[1] [DISTRIBUTION STATEMENT A. Approved for public release; Distribution is unlimited XXXXXXXXX].

[2] These projects are funded by the National Spectrum Consortium (NSC) through Advanced Technology International (ATI) under Contract NSC-19-RPP-05, Spectrum Base Agreement No. 2017-318.

space into account and permit frequency reuse if there is enough spatial separation between two assignments, enabling a significant increase in the effective availability of spectrum.

- Inter-Range Deconfliction. Missions sometimes fly through the flight areas belonging to neighboring ranges. This is true, for example between Edwards Air Force Base and China Lake. Currently coordination of frequency assignments over the flight areas of neighboring ranges is handled manually over the phone. This feature will facilitate the viewing of conflicts with neighboring ranges on the SAM Time Frequency Chart, and enable on-line automated deconfliction.
- The SAM Time Freq Chart enables GUI-assisted frequency deconfliction by allowing the user to drag frequency assignment blocks across a time-frequency scale.
- Auto-Assign and Auto-Resolve. These features provide automated frequency deconfliction by SAM, while minimizing spectrum fragmentation and making optimal use of the available spectrum.
- Coverage Maps of Frequency Assignments. These map overlays predict the performance of frequency assignments by displaying the SINR experienced at the mission's ground stations for each position of the aircraft within the mission's flight areas. In addition to providing a display to users of the predicted performance of the air-to-ground RF link, coverage maps are used by the Spatially-Aware Frequency Deconfliction feature.
- The SAM<->ASAM API. With its knowledge of planned frequency assignments and current RF emissions at the test range and surrounding area, SAM is able to support an API for dynamic spectrum sharing with Adaptive Spectrum Aggregation and Management (ASAM) radios.

II. SUMS, SAM, AND COMMON PLATFORM ARCHITECTURE

Figure 1 shows an overview of the common platform which supports both the SUMS and the SAM systems. The platform is essentially a web container, which supports SUMS and SAM web servers. Each web server is supported by its own object oriented database. The web servers support the common web browser-based SUMS/SAM GUI.

The platform supports an interface with one or more range resource management and scheduling systems. Instances of these systems are Test Resources Management System (TRMS) or Central Scheduling Enterprise (CSE). The platform periodically downloads the latest update of mission planning data over this interface. The data is modeled as Mission objects, each of which is associated with multiple FreqAssignment objects. Each FreqAssignment object characterizes a planned frequency assignment and has the attributes startTime, endTime, minFreq, maxFreq.

To determine and store RF Emissions actually occurring at the range and its flight areas, the SUMS system supports a sensing network, which primarily consists of:

- General purpose frequency scanning sensors.
- Interfaces to telemetry receivers within ground stations at the range. This interface focuses on recording Emissions by capturing the startTime, endTime, and the frequency range of the telemetry signal being received.

To verify that planned FreqAssignments were actually used, SUMS supports a Correlation Function, which wakes up periodically and attempts to correlate planned FreqAssignments with recently-discovered Emissions. When successfully correlated to an Emission, a FreqAssignment's use is said to have been verified.

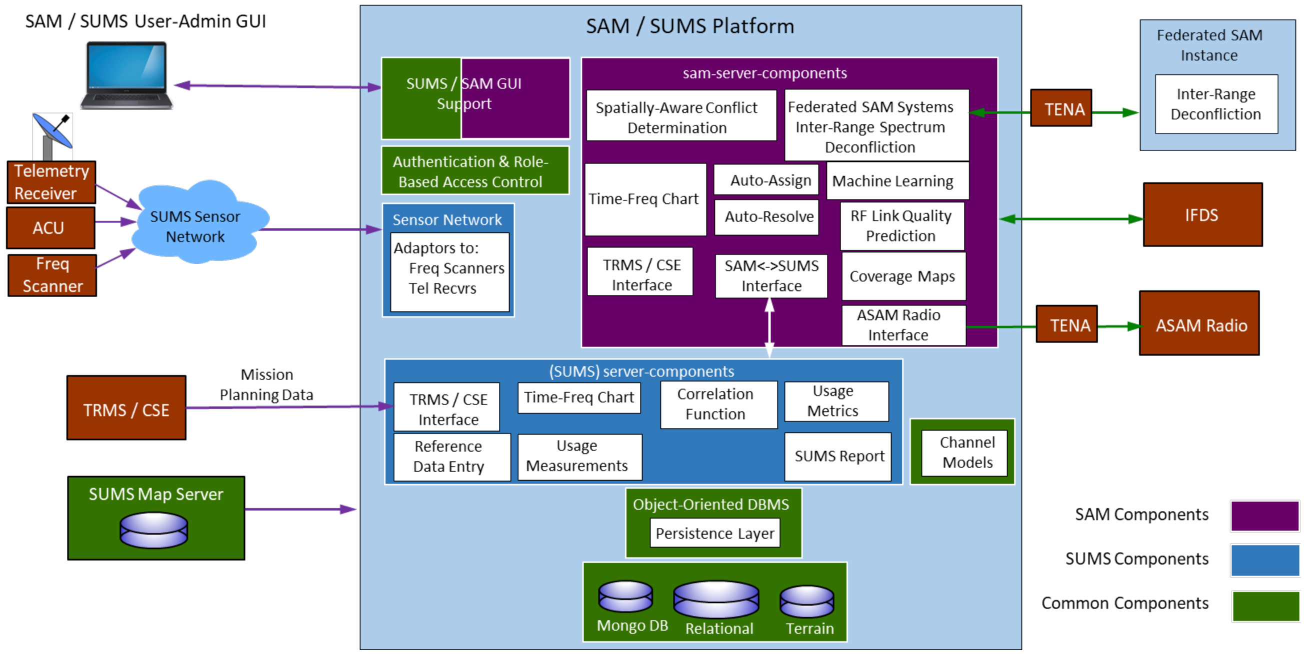

Figure 1. SUMS and SAM Common Platform Architecture.

SUMS performs data analytics on the captured FreqAssignments and Emissions in its database and generates spectrum usage metrics for the frequency manager. These usage metrics are based on the "Spectrum Management Metrics Standard (RCC 707-14)". They are accessible to the user via a query screen, and via the SUMS Report function.

The SAM functions reside inside a module called sam-server-components. This module piggy-backs on the SUMS<->TRMS/CSE Interface to acquire mission planning downloads.

The primary SAM display is the SAM Time Frequency Chart. This allows users to deconflict planned FreqAssignments by constrained movement of FreqAssignments blocks on a chart where the X axis is time and the Y axis is frequency. The chart displays conflicts via time-frequency overlaps between two conflicting frequency assignments. The overlap area is colored black. The Chart invokes the Spatially-Aware Frequency Assignment feature to determine if an overlap is in fact not a conflict and the frequency can be reused due to spatial separation. In that case the Chart colors the overlap area white. The Time Frequency Chart also has the ability to invoke the SAM Auto-Assign and Auto-Resolve functions.

The Spatially Aware Frequency Deconfliction feature requires the generation of CoverageMaps, characterizing interference between pairs of FlightAreas, associated with Missions. Generation of the CoverageMaps is computationally intensive. The sam-server-components module continuously runs a CoverageMap generation function in the background. At the time of frequency deconfliction, SAM conducts a search to match the attributes of these previously-generated CoverageMaps with the frequencies being spatially deconflicted.

To support the Inter-Range Deconfliction feature, SAM instances at neighboring ranges support interfaces with one another, over which they run an Inter-Range Frequency Request protocol. To support the SAM<->ASAM radio API, sam-server-components supports a broadcast TENA (Test and Training Enabling Architecture) interface for this purpose.

III. SUMS – MAJOR FUNCTIONS AND CAPABILITIES

Verification of Spectrum Usage

In the past the ranges have relied on archives of past mission planning data to provide a report on spectrum usage. This approach has not worked well for spectrum defense, raising the question of the gap between planned usage and actual usage of spectrum. The discrepancy between planned and actual may be caused by cancelled or delayed flights, excessive time buffering in assignment requests by test engineers, the lack of demarcation of the space in which the spectrum is used, and potential illegal use of spectrum by unscheduled transmitters. To correct this problem, SUMS supports a sensing network, whereby it detects telemetry RF signals over-the-air at the time of Mission execution, and attempts to correlate them with planned FreqAssignments.

The SUMS sensor network consists of two types of sensing devices: telemetry receivers and scanning sensors. SUMS has the capability to support a passive interface to each of the telemetry receivers used by ground stations at the test range. The SUMS interface does not read the actual telemetry data feed. Rather, it monitors the receiver for requests to receive, capturing the center frequency and bandwidth in each request. Further, it monitors for an indication from the receiver that telemetry data is actually being received. Typically, this attribute is the automatic gain control (AGC) value.

When the AGC value goes from low to high, the interface software notes the current time, as the startTime of an **Emission**. When the AGC value goes from high back to low, the interface notes the current time, as the endTime of the Emission. The interface stores the Emission as an object in the SUMS database.

Figure 2: Telemetry Receiver Used by Ground Stations.

Likewise, SUMS takes advantage of the scanning sensors, currently being deployed experimentally at some ranges, for over-the-air verification. Unlike the telemetry receivers, the scanning sensors may be tasked to scan a variety of frequencies at the same time. The advantage of this is that the scanning sensors may be able to detect unauthorized uses of the telemetry spectrum. Like the telemetry receiver interface, the scanning sensor interface notes the startTime, centerFreq, bandwidth, and endTime of any Emission it detects over-the-air, and stores the resultant Emission object in the database.

The Correlation Function

The SUMS Correlation Function attempts to match each Emission with a planned FreqAssignment. The Function runs periodically as a daemon. Each Emission object has a correlation status (corrStatus) attribute, which reports the state of attempting to correlate the Emission object. To begin with the corrStatus for each Emission object is PENDING. When the Correlation Function runs, it sweeps up all the Emission objects in the database with a corrStatus of PENDING, and attempts to correlate each one. Once an attempt to correlate an Emission has been made the corrStatus is changed to CORRELATED or NOT_CORRELATED. In the latter case, the Correlation Function was unable to find a matching FreqAssignment. The relationship between planned FreqAssignments and observed Emissions is fuzzy, and the Correlation Function has to develop a set of rules and heuristics from experience, over time.

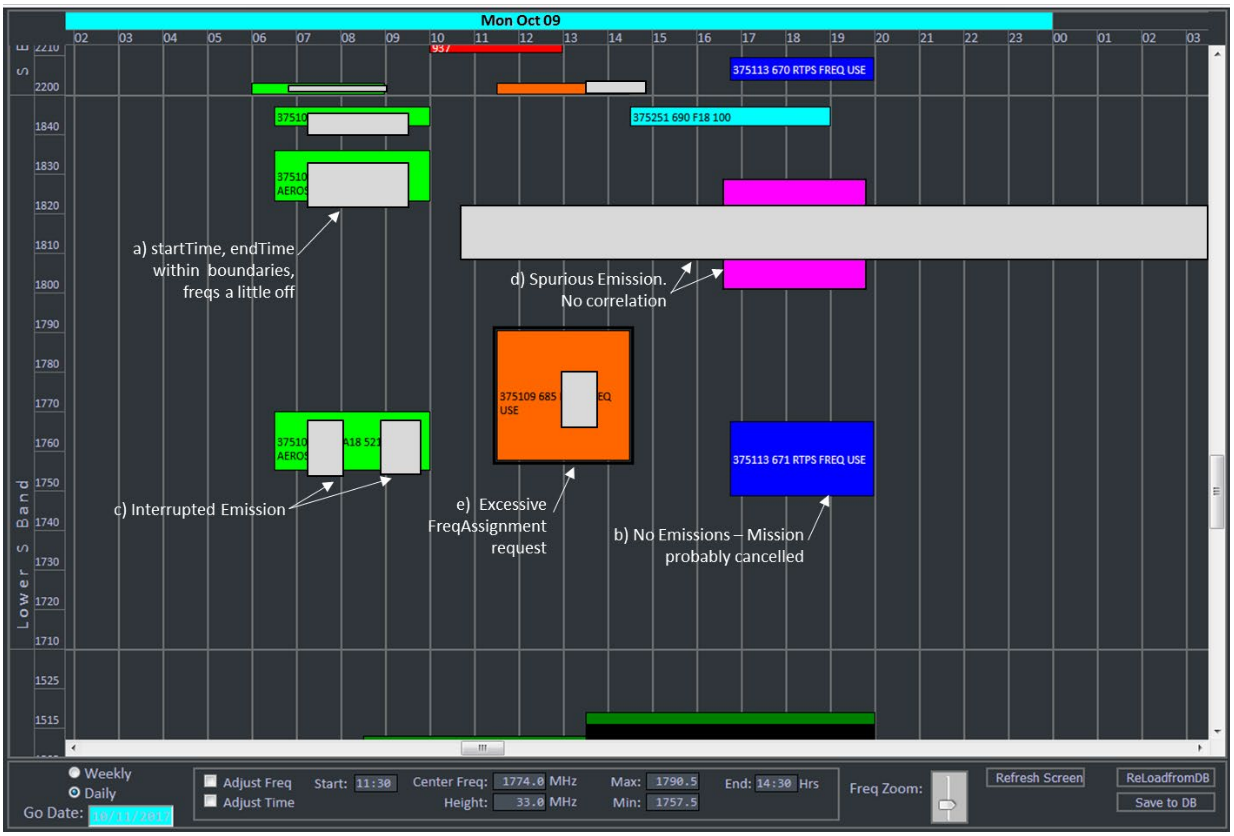

Figure 3: Time Frequency Chart, Planned FreqAssignments vs Actual Emissions.

Figure 3 is an example of a SUMS **Time Frequency Chart**, showing planned FreqAssignments, overlaid with Emissions. The X axis shows time, spanning a single day in the recent past. The Y axis represents the telemetry spectrum allocation for a test range. Each of the colored blocks represents a FreqAssignment. Blocks of the same color represent FreqAssignments belonging to a particular Mission. The Emissions discovered in actuality by the sensor network are overlaid as grey blocks. The baseline algorithm for the Correlation Function is as follows:

A query is run on the database to discover all Emissions with a corrStatus of PENDING. For each such Emission object, SUMS searches the database for a FreqAssignment object which overlaps with the Emission object in time and frequency. If multiple FreqAssignments overlap, the one with the largest overlap is chosen as being correlated with the Emission. However, there are a number of use cases, that the Correlation Function has to support in addition. The use cases are marked in Figure 3 as a), b), c), d).

For each Emission object, the Correlation Function creates a result, which is stored in attributes of FreqAssignment. These are: verFlag, and verText. The verFlag is a Boolean which indicates if the FreqAssignment has been verified. This occurs when it is positively correlated with an actual

Emission over-the-air. The verText attribute provides a reason string for the verification (or lack of verification). Example values of the verText are:

- TEL_RECVR_VERIFIED – Verified by telemetry receiver.
- SCAN_SENSOR_VERIFIED – Verified by sensor.
- OPS_STAFF_VERIFIED – Verified by operational staff.
- UNVERIFIED – Could not be verified by the Correlation Function.

The SUMS Query and Reports Capabilities

Having collected archived FreqAssignments and Emissions in its data repositories, SUMS supports Query and Reports features, which provide usage metrics on the data collected thus far.

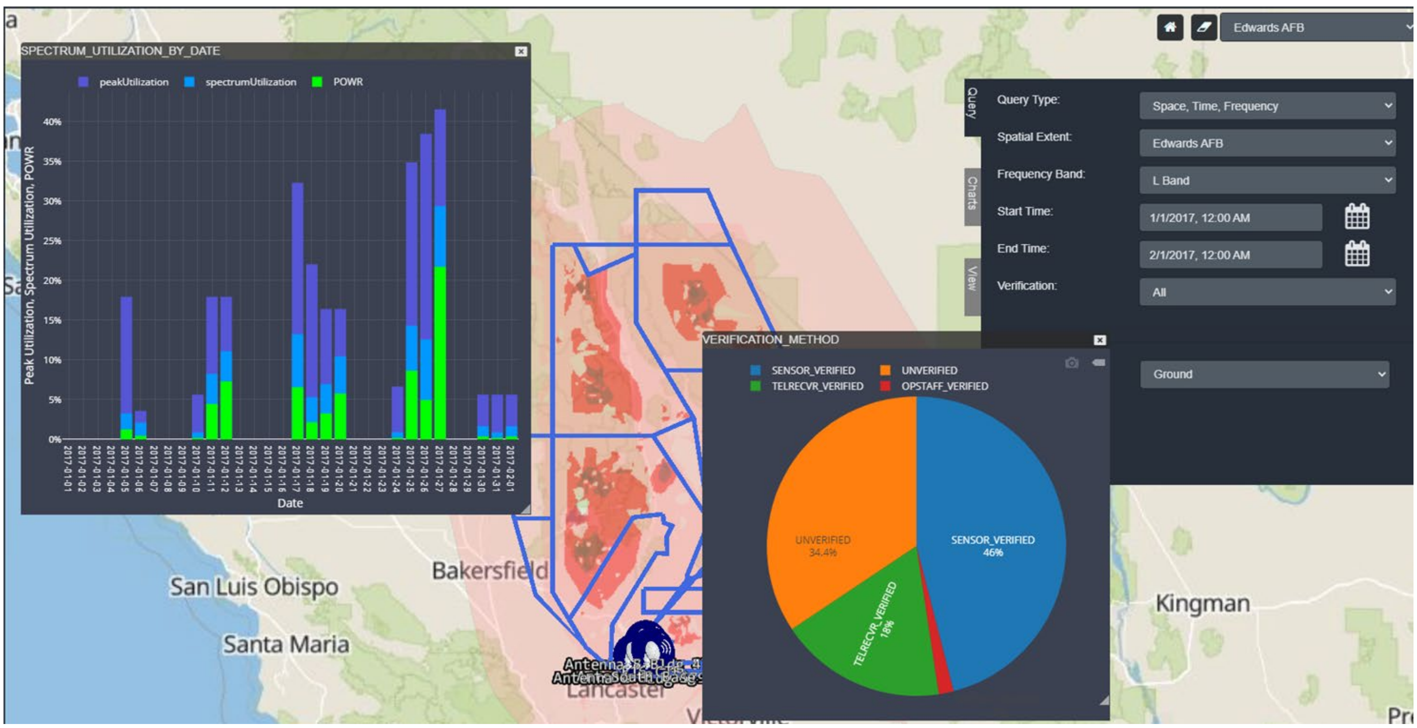

Figure 4. The SUMS Query Screen, Displaying Two Usage Metrics and the Spatial Occupancy.

SUMS supports the displaying and reporting of ~30 different usage metrics. These metrics are based on the Spectrum Management Metrics Standard [5]. In the course of the SUMS project we extended this set to include metrics which take verification into account.

Figure 4 shows a screen print of the SUMS query screen, displaying the spatial occupancy of the queried spectrum in the background and two usage metrics: Spectrum Utilization by Date and Verification Method. The Spectrum Utilization by Date metric shows 3 different measures of the percentage of available spectrum used each day, extending over the period of a month. The Verification Method chart shows the percentage of FreqAssignments that could be successfully verified by SUMS, with each verification method. It also the shows the percentage of FreqAssignments that were unverified. The side-panel on the right of the screen allows the user to enter the parameters of the spectrum usage query. These are startTime, endTime, band name, and a spatial extent.

The SUMS **Reports** capability generates a printable PDF report of spectrum usage over a query period. As before, a retractable side-panel allows the user to select the time-interval of the Report, along with the bands and the usage metrics that are to be presented. The Report is designed to be what a frequency manager would like to see on her desk on a monthly basis.

Band	Frequency Range (MHz)	Full / Part	Average Daily Spectrum Utilization	Average Daily Peak Utilization	Average Daily Percent Occupancy	Average Daily Percent Verified
L Band	1435.0 - 1535.0	Full	**4.56 %**	8.28 %	1.8 %	66.07 %
Lower S Band	1755.0 - 1850.0	Full	**54.92 %**	56.28 %	25.16 %	57.64 %
S Band	2200.0 - 2290.0	Full	**36.65 %**	46.47 %	13.71 %	56.88 %
Upper S Band	2310.0 - 2395.0	Full	**37.77 %**	38.85 %	15.9 %	63.48 %
Lower C Band	4400.0 - 4940.0	Full	**0.28 %**	0.37 %	0.03 %	0 %
Middle C Band	5091.0 - 5150.0	Full	**0 %**	0 %	0 %	0 %

Figure 5. SUMS Report Summary Table.

Figure 5 shows the Report Summary Table. The key column is the Average Daily Spectrum Utilization. This provides the monthly average of the percentage of the spectrum that was occupied over the course of the day, taking into account expected spectrum fragmentation. The Peak Utilization provides the monthly average of the percentage of the spectrum occupied at the time of peak traffic each day, taking spectrum fragmentation into account.

IV. SAM – MAJOR FUNCTIONS AND CAPABILITIES

The SAM Time Frequency Chart

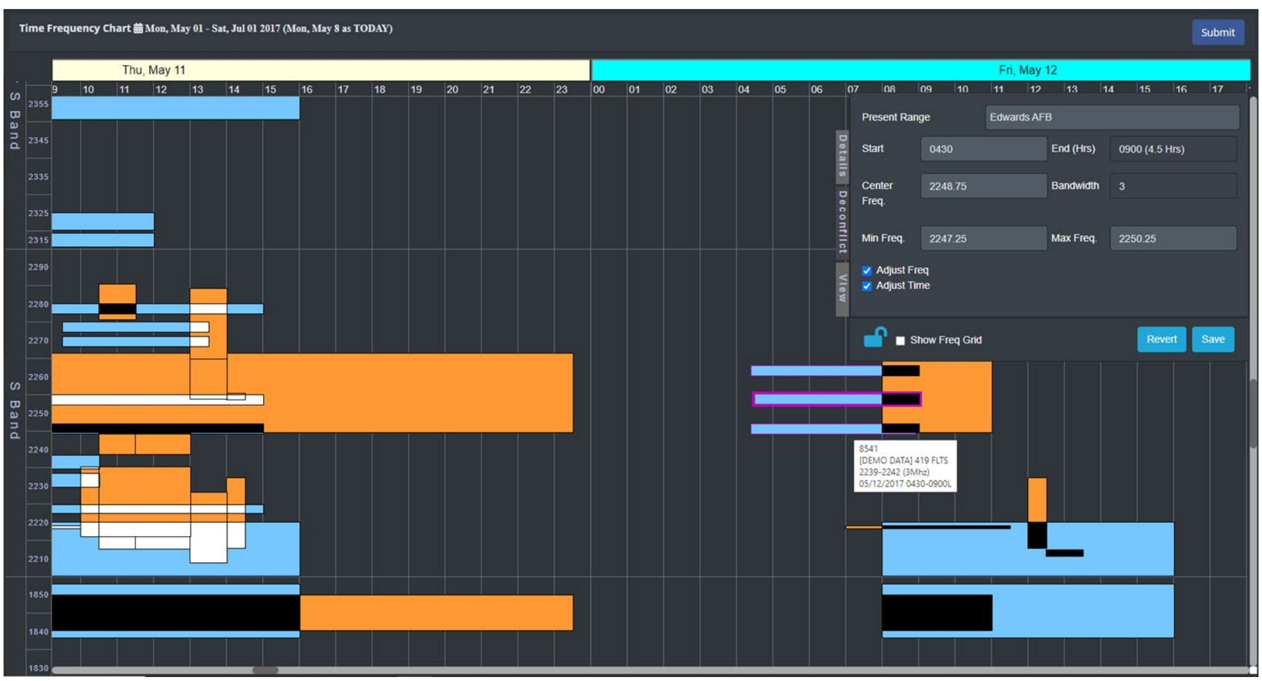

Figure 6. The SAM Time Frequency Chart.

The primary purpose of the SAM system is to allow the user to deconflict planned FreqAssignments. Figure 6 shows a screen shot of the SAM Time Frequency Chart, which is the primary panel for deconflicting.

The X axis of the Chart is a dynamic time scale. The Y axis is a frequency scale, covering the spectrum band allocations of the test range. Each rectangular block represents a FreqAssignment. By hovering the mouse over a block the user can get a quick summary of the FreqAssignment. A block is also selectable. In that case all the attributes of the FreqAssignment are displayed in the Deconflict and Details tabs of the retractable side-panel on the right.

The Chart displays FreqAssignments of the present test range as well as FreqAssignments of neighboring ranges if that data is available. The View tab on the retractable side-panel allows the user to select a particular view of the assignments. Example views are:

- The Present Range View. This shows FreqAssignments belonging to the present range in a blue color. In the event of a time-frequency overlap with a FreqAssignment of another range, it shows the FreqAssignment of the other range (in beige) and the time-freq overlap. The view filters out all non-conflicting FreqAssignments from other ranges, allowing the frequency manager to focus on deconflicting her own range.
- The All Ranges View. This view simply shows the FreqAssignments of the present range in blue and the FreqAssignments of all other ranges in beige.

An overlap between two FreqAssignments is colored black if the assignments conflict. It is colored white if the assignments do not conflict for a particular reason, although they overlap in time-frequency. Examples of such reasons are:

- Enough spatial separation between the two sets of mission flight areas, that interference, over the course of the missions, is tolerably low.
- Non-adjacent ranges.
- An eventuality that the missions can tolerate co-interference for certain combinations of flight areas.

SAM enables the frequency manager to manually deconflict by appropriately selecting a conflicting FreqAssignment and dragging it to a new location on the Time Freq Chart. The movement of a time-freq box is constrained as follows:

- The time-freq boxes are locked in place, until the “Adj Freq” or “Adj Time” check-boxes are checked.
- A box cannot be dragged outside its spectrum band allocation.
- To enable neat stacking of FreqAssignments, the boxes will dock with each other, along a frequency or time edge.
- When a FreqAssignment box is moved in time, its sibling FreqAssignments, belonging to the same mission, also move, to maintain the same time offset.
- If a FreqAssignment is dragged over another, a black conflict rectangle appears.

The Time Freq Chart also supports **Auto-Resolve** and **Auto Assign** buttons. If a conflicting FreqAssignment is selected and the Auto-Resolve button is clicked, SAM will automatically move the FreqAssignment to a deconflicted time-freq position. In doing so, it seeks to minimize fragmentation, making optimal use of the allocated spectrum. Likewise, the Auto Assign button selects an optimal time-frequency position for a potential FreqAssignment when the user specifies a desired band and bandwidth, via the retractable side-panels.

Frequency Assignment Optimizations

SAM uses a constraints and heuristics-based rack-and-stack algorithm to address the NP-hard problem of making optimal frequency assignments.

One possibility would be to conduct an exhaustive search of all N factorial permutations of the channel set to be assigned. For each permutation the channels would be assigned in the order specified by the permutation, checking against the search constraints. The optimal permutation would be selected, based on all (or most) assignments successfully deconflicted, and the least fragmentation of the telemetry spectrum. This approach is impractical from a computing perspective because of the potential number of permutations. A busy test range may have as many as 50 assignments in a single day.

In an easier approach, SAM seeks to arrive at the first "good" set of assignments, rather than the optimal set. Criteria for a good set require no conflicts and a low level of spectrum defragmentation. The search constraints themselves are used in a preliminary filtering process to eliminate vast numbers of channel permutations. In the end, only a small number of permutations are compared with one another, to arrive at a functional rack-and-stack solution, which minimizes fragmentation of the spectrum.

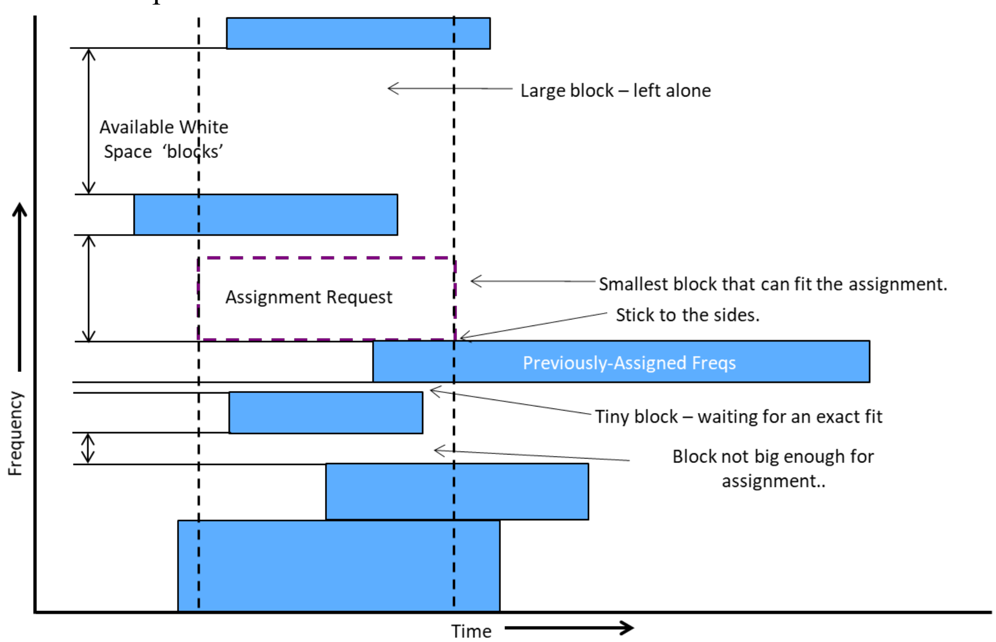

Figure 7. Insertion of a Frequency for the Least Spectrum Fragmentation.

The constraints used to filter and reduce the search possibilities include the following:

- Assignments must respect tests that cannot be re-scheduled vs those that can.
- Assignments must respect frequencies that cannot be moved vs those that can.
- …must be from within test range allocated spectrum.
- …must conform to frequency ranges supported by respective RF devices.
- …must result in minimum disruption – moves – of previous assignments.
- …when re-scheduling, must move missions forward in time as little as possible.

- RF channels from the same test article should be assigned as far apart as possible to minimize the effects of interference from spatial adjacency on the same test article.

Figure 7 shows how a current assignment is inserted into a time-frequency space containing previously-determined assignments, such that the insertion results in the least amount of spectrum fragmentation.

Coverage Maps and Calculating Air-to-Ground RF Channel Quality

To support its RF channel quality prediction feature, SAM makes use of the concept of a spectrum 'bin'. A bin is a quantization of space. It represents a cube of airspace at a fixed location above the Earth. Typical dimensions are (1 minute of latitude) x (1 minute of longitude) x 2000 meters. From a RF perspective, the mid-point of each bin represents all the points within the bin.

To create a coverage map for a flight area, SAM calculates the RSSI and the SINR for a RF emission from each bin in the flight area to the ground station. To calculate RF propagation pathloss, SMS uses an algorithm based on the Johnson-Gierhart and Longley-Rice Channel Models [1] [2] [3].

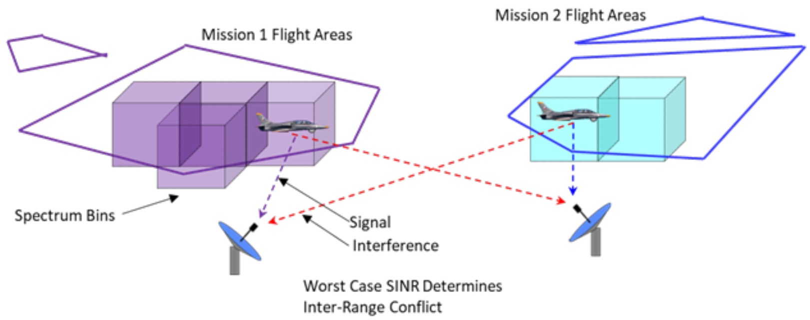

Figure 8. Determining Interference with Spatial Separation of Flight Areas.

For each bin in the mission flight plan, there is a non-zero probability that the test article will traverse the bin in the course of its mission. Having determined the path-loss, the RSSI at the ground station is calculated as:

RSSI = (Test article xmit power (dBm)) + (xmit antenna gain (dB) + receive antenna gain (dB)

o (pathloss (dBm)) – (system losses (dBm))

Figure 8 shows a scenario where there are two time- and frequency-coincident missions. SINR is calculated for each bin in the flight area of Mission 1. For the 'signal', the RSSI from the bin to the ground station is calculated, as described above. To determine worst-case interference, SAM computes the maximum of the RSSIs from each bin in the flight plan of Mission 2 to the ground station of Mission 1. Then,

(SINR for bin 1) = (signal from bin 1) – (worst-case interference from Mission 2) – (noise floor)

V. REFERENCES

[1] Triolo, Anthony, Report on Channel Models, Telcordia, March 2011.

[2] Spectrum Management Metrics Standard, Frequency Management Group (FMG) – Range Commanders Council (RCC) 707-14, Apr 2014.