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SPECTRUM MANAGEMENT SYSTEM – FREQUENCY ASSIGNMENT DE-CONFLICTION AND RF LINK QUALITY PREDICTION

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DoD test ranges are experiencing ever-expanding needs for air-to-ground telemetry bandwidth, and hence are under pressure to manage the telemetry spectrum resource with high efficiency. The Spectrum Management System (SMS) provides test range operations staff with advanced tools for frequency de-confliction and air-to-ground RF link quality prediction for upcoming test flights. Additional features of the system include: automated, algorithm-based frequency de-confliction and assignment; record-keeping and automated archiving of frequency assignments, to be used for spectrum defense; 3-D GIS terrain-based coverage maps, displaying predicted air-to-ground link quality in each part of upcoming flights; determination of opportunities for frequencies reuse.

Innovations include: addressing the combinatorial NP-hard problem of frequency assignment by applying multiple real-world constraints in a specified order; using a spectrum white space closest-fit algorithm to minimize spectrum fragmentation; creating space-time-frequency quanta in the database to store RF emissions for rapidly-moving aircraft.

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SPECTRUM MANAGEMENT SYSTEM – FREQUENCY ASSIGNMENT DE-CONFLICTION AND RF LINK QUALITY PREDICTION [1]

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Abstract

DoD test ranges are experiencing ever-expanding needs for air-to-ground telemetry bandwidth, and hence are under pressure to manage the telemetry spectrum resource with high efficiency. The Spectrum Management System (SMS) provides test range operations staff with advanced tools for frequency de-confliction and air-to-ground RF link quality prediction for upcoming test flights. Additional features of the system include: automated, algorithm-based frequency de-confliction and assignment; record-keeping and automated archiving of frequency assignments, to be used for spectrum defense; 3-D GIS terrain-based coverage maps, displaying predicted air-to-ground link quality in each part of upcoming flights; determination of opportunities for frequencies reuse.

Innovations include: addressing the combinatorial NP-hard problem of frequency assignment by applying multiple real-world constraints in a specified order; using a spectrum white space closest-fit algorithm to minimize spectrum fragmentation; creating space-time-frequency quanta in the database to store RF emissions for rapidly-moving aircraft.

Introduction

Test ranges are experiencing increasing numbers of requests for tests and dramatically higher bandwidth needs for each test. Further, commercial interests in the telemetry spectrum bands prompt the lucrative sell-offs of parts of the spectrum, as exemplified by the recent AWS – III sale. These pressures create a need for test range operations personnel to be able to plan and manage the use of the available spectrum in the most efficient manner possible. The Spectrum Efficient Technology (SET) Spectrum Management System (SMS) project is intended to deploy advanced capabilities in a tool that may be used to assist test range personnel with managing the spectrum resource with improved efficiency.

SMS Features

To aid efficient management of telemetry frequency assignments at a test range, SMS supports the following features.

Frequency Assignment and De-Confliction

SMS periodically downloads mission plans for upcoming test flights from test range resource management and scheduling systems. These plans include preliminary frequency assignments

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for upcoming test flights. In a sense, the assignments represent frequency requirements for upcoming missions, and often contain conflicts.

SMS provides a GUI-based tool to de-conflict individual these assignments on a **Time-Frequency Chart**.
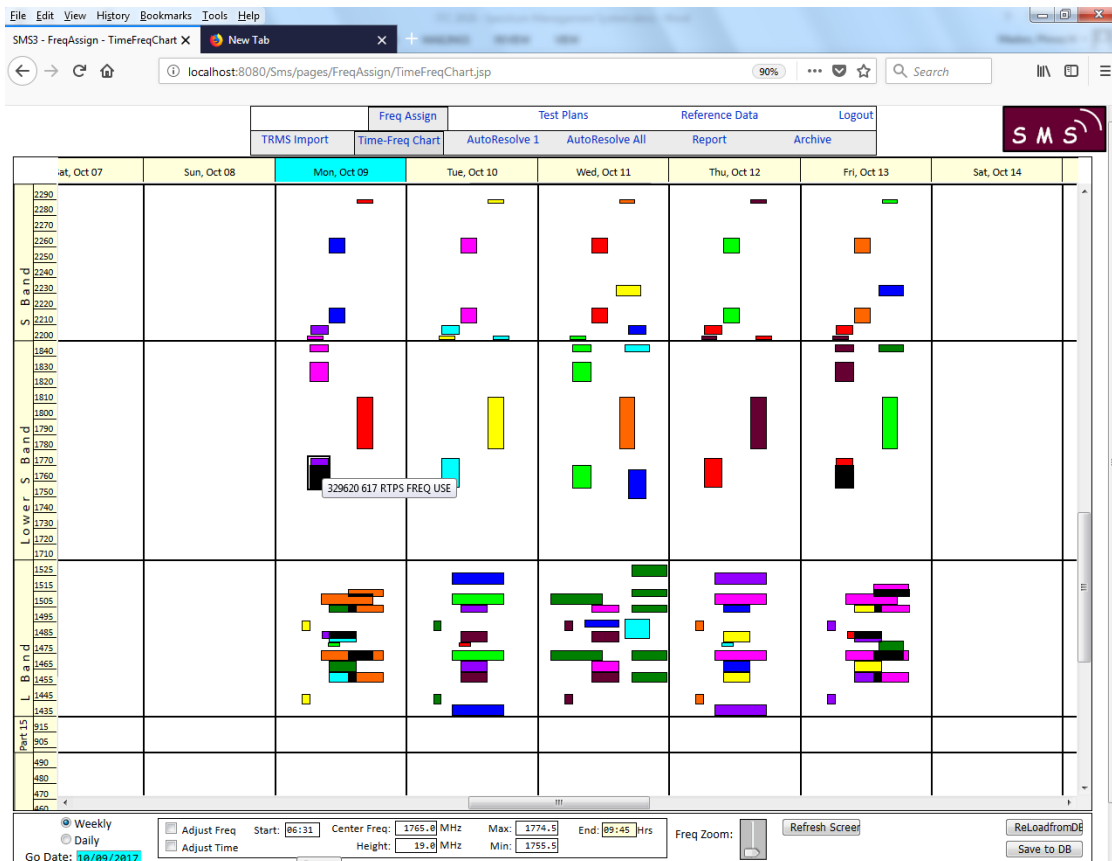

Figure 1. Time-Frequency Chart

Manual De-Confliction

Figure 1 shows an example chart. The X-axis spans time on an infinite scale, typically displaying assignments 2 weeks in the past and 4 weeks into the future around the currently-selected date. The Y-axis displays the bands of the telemetry spectrum. Each colored block represents a frequency assignment. Hovering the mouse over an assignment displays the operation number, mission title and other details. Frequency assignment blocks of the same color represent frequencies belonging to the same mission. When two assignments conflict, the overlapping areas are colored in black.

Figure 2 shows how assignments may be manually de-conflicted. The Time-Frequency Chart is switched to the 'daily' view, for greater ease in manipulating the assignment blocks. Selecting an assignment causes its details to appear in the bottom panel. Checking 'Adjust Freq' allows the assignment to be moved only in frequency. Checking 'Adjust Time' enables it to be moved in the time scale. Checking both allows the assignment to be moved in both domains. When an assignment is moved in time, the other assignments in the mission move with it, because the mission's start time is, in effect, being changed. A docking feature allows assignments to be aligned next to each other, if necessary. Clicking the button 'Save to DB' makes the de-confliction changes permanent.

Automated De-Confliction

The Automated De-Confliction feature allows the user to de-conflict a large number of frequency assignments with a single operation.
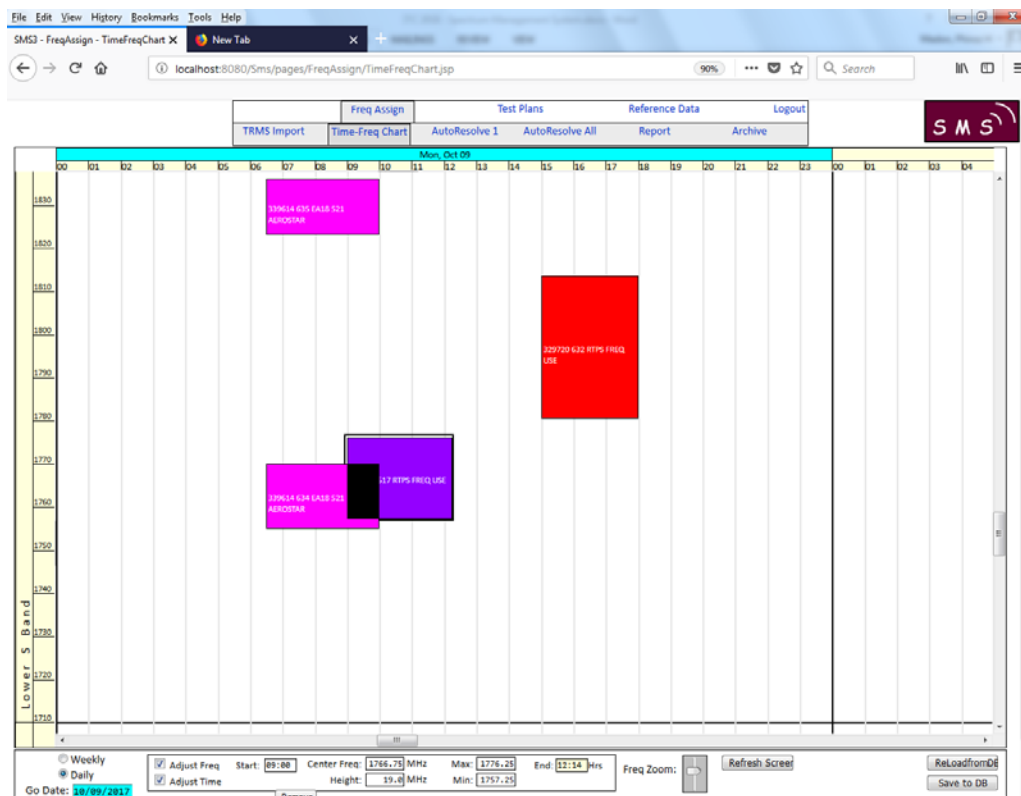

Figure 2. Manually De-Conflicting Two Assignments

Missions with conflicts are listed in a table. The user has the ability to specify whether individual assignments can be moved in time or frequency. SMS uses an optimization algorithm that resolves all the conflicts in the set while incurring minimum fragmentation of the allocated spectrum.

Automated Assignment

Often, in test range CONOPS, there is a need to request a set of frequency assignments, based on the requirements of a particular mission. Whereas de-confliction acts after the fact, automated assignment requests a set of frequencies that are not conflicting to begin with.

The request typically takes the form of a specified fixed or movable mission start time, in conjunction with requested frequency widths in specified bands. The automated assignment feature determines the center frequency for each assignment, such that there is no conflict.

Time-Frequency Rack-and-Stack

For the automated de-confliction and assignment features, SMS uses a constraints and heuristics-based algorithm to address the NP-hard problem of making optimal frequency assignments with the least fragmentation of the telemetry spectrum. This time-frequency rack-and-stack algorithm is described below in the section on 'Design Topics'.

Reports for Dissemination of Frequency Assignments

The Reports feature allows the user to query SMS for de-conflicted assignments. Queries may retrieve the assignments for a single mission or a set of missions. The query response consists of a file that may be distributed to appropriate stakeholders, or back into the test range resource management or scheduling system.

Archiving Past Assignments

Past frequency assignment data is valuable for performing data analytics and obtaining insights on how to manage the telemetry spectrum efficiently. SMS has an automated archiving feature, which periodically archives assignments data and purges it from the database, once it becomes a specified number of weeks old. The feature allows historical spectrum assignments data to be retrieved from the archive, viewed on the Time-Frequency Chart, and made the subject of queries and reports.

RF Channel Quality Prediction

With this feature, SMS calculates the predicted air-to-ground RF channel quality for a given mission. The mission's flight plan is described in terms of test range flight areas. The overall RF channel quality is provided in terms of average received signal strength indication (RSSI) and signal-to-interference-and-noise ratio (SINR).

SMS also generates a 3-D geographical terrain-based coverage map, showing the RF channel quality for every part of the flight plan. To characterize each part of a flight plan on a coverage map, SMS divides up the airspace into spatial quanta, termed 'bins'. A bin is a fixed quantum of airspace above the earth, typified by the latitude, longitude and elevation of its bottom south-west corner. A bin's dimensions are 1 minute of latitude x 1 minute of longitude x 2,000 meters elevation.

The RF Channel Quality Prediction feature helps to qualify upcoming tests and provides a soft alarm if the predicted RF channel quality is below the desired threshold. It is also useful for visually assessing the impact of frequency reuse with spatial separation in hypothetical flight test plans.
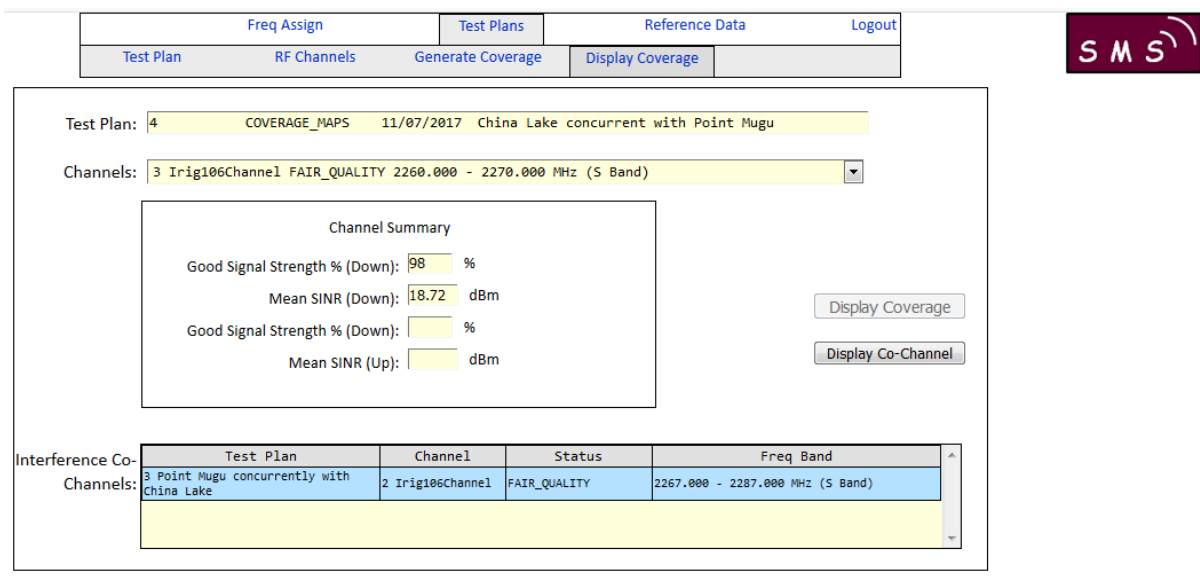

Figure 3. Overall Signal Strength and SINR for an RF Channel in a Mission.

Figure 3 shows an example SMS display of overall predicted RF link quality. The overall quality of the channel is described as FAIR_QUALITY. 'Good Signal Strength' is the percentage of bins

in the test article's flight plan, where the telemetry signal reaching the ground station has sufficient signal strength. In this case, it is 98%.
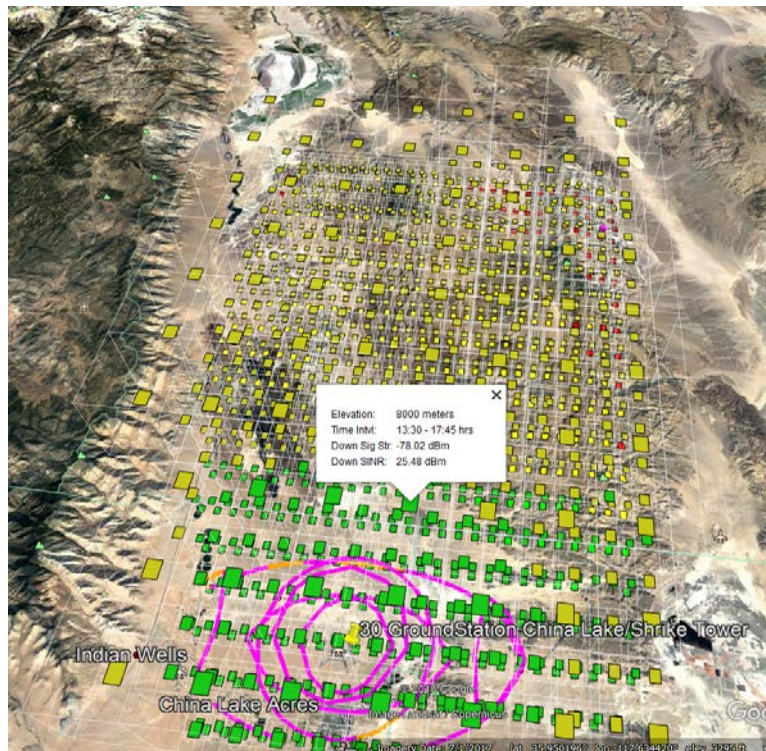

Figure 4. Coverage Map Showing Predicted RF Link Quality over a Flight Area

The mean SINR value across the entire flight is provided. The screen also indicates that there is a time- and frequency-conflicting assignment at a neighboring test range.

Figure 4 shows an example of a coverage map. In each bin, the colored swatch indicates the quality of the signal reaching the ground station (shown by the pin), when the test article is traversing the airspace in the bin. The red swatches, for example show bad link quality, where the bins are close to the ground and the RF signal is blocked by terrain. Clicking a bin provides a pop-up with the RSSI and SINR for the selected bin.
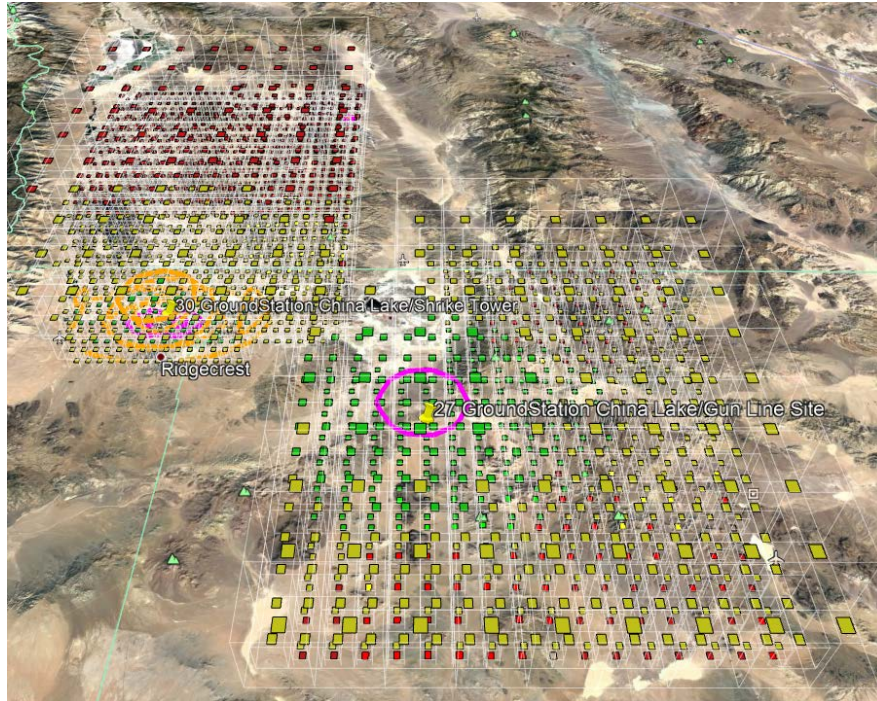
Figure 5. Coverage Maps of Two Interfering Missions.

In this example, although there is an interfering RF channel at a neighboring test range, there is enough spatial separation, that the overall quality is not significantly degraded.

In Figure 5, the flight area of Figure 4 is towards the upper left. There is a hypothetical flight with a conflicting frequency assignment in a neighboring area. We see that there is a great deal more red in the coverage map, indicating that the RF link quality is significantly degraded by interference.

Discovering Flight Plans that Permit Frequency Reuse

SMS enables a planner to run hypothetical scenarios, testing the effects of frequency reuse with spatial separation. The system enables the planner to enter missions in which the frequency assignments conflict. Each mission is assigned one of the flight areas that is being tested.

Generating a coverage map for an RF channel in each mission provides an overall summary of the RF Channel quality, as shown in Figure 3. Using thresholds, SMS summarizes the quality of each channel as: EXCELLENT_QUALITY, FAIR_QUALITY, PROPAGATION_PROBLEMS, HAS_INTERFERENCE. If two time-frequency-coincident channels have FAIR_QUALITY or better, then there is a potential to use the associated flight areas without significant degradation. A visual inspection of the coverage maps further indicates if there is potential for frequency reuse.

Frequency reuse in certain flight situations can double the available frequencies, and hence is a significant mechanism for improving spectral efficiency.
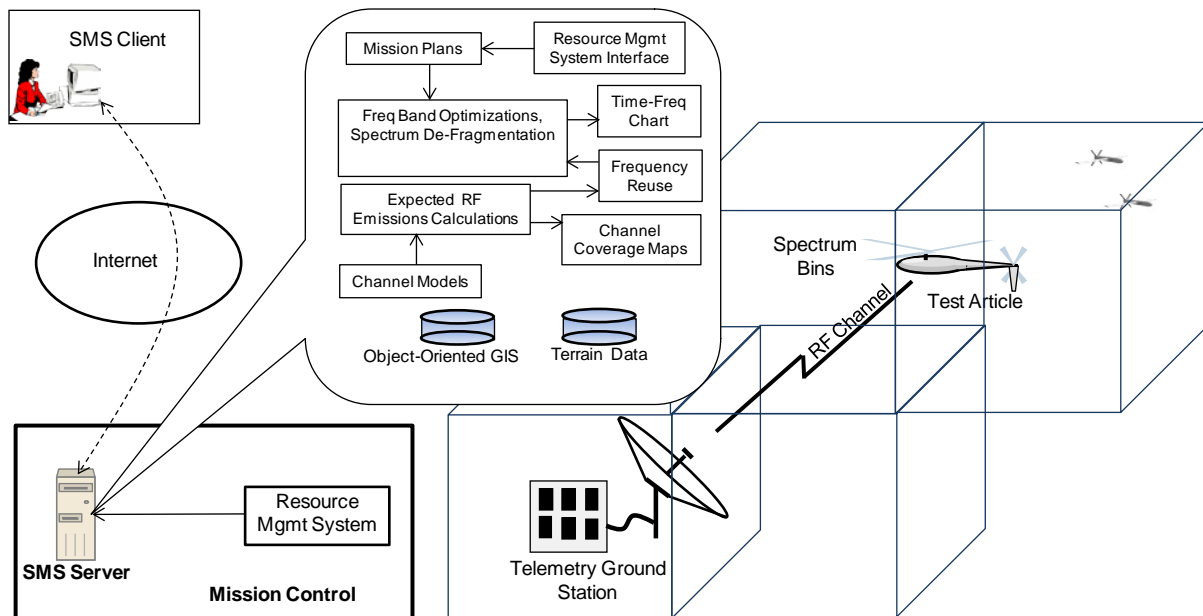
SMS Architecture

Figure 6. SMS Architecture

Figure 6 illustrates the SMS architecture. A SMS server may be located anywhere at a test range. Clients may log in remotely and get a common view of upcoming missions, frequency band assignments, spectrum occupancy, RF link quality predictions and RF channel coverage maps.

The SMS server is equipped with an object-oriented database, which models and tracks the evolving spectrum-related scenario at the test range. Major functions implemented by SMS algorithms include:

- An interface to the test range resource management system, which allows automatic download of upcoming test plans.
- A SMS GUI interface that allows entry and update by a user of planned missions. Elements of a mission include: a description, the start date/time, test articles and ground stations involved in the test, their RF transmitting and receiving devices and their spectrum capabilities, antennas and antenna patterns, the flight plan for each test article, and the required RF channels.
- A frequency band assignments optimization algorithm that follows a desired set of constraints to resolves conflicts, and makes frequency band assignment recommendations.
- A time-frequency chart that displays the current planned occupancy of the spectrum.
- RF channel quality prediction calculations. Generation of coverage maps, computing channel quality for each bin in the mission's flight plan.
- Display of this data on a 3-D terrain-based channel coverage map.
- Channel models, to provide RF propagation for the channel quality prediction calculations. Two models employed are: the Johnson-Gierhart and the Longley-Rice model [1] [2] [3].

The Longley-Rice channel model requires the support of a GIS terrain database. SMS uses the National Elevation Dataset, provided by the United States Geological Survey (USGS) [4].

Design Topics

Frequency Assignment Optimizations

For the Automated De-Confliction and Automated Assignment features discussed above, SMS uses a constraints and heuristics-based rack-and-stack algorithm to address the NP-hard problem of making optimal frequency assignments. When the user selects a set of missions and makes a request for automated de-confliction the two driving requirements are:

– Resolve assignment conflicts.
– Minimize fragmentation of the available telemetry spectrum.

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 de-conflicted, 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, the SMS 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.

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:

All the white-space blocks of time-frequency into which the current assignment might fit are enumerated. Out of these the smallest white-space block – the one with the least frequency range – is selected. The current frequency assignment is docked with either the upper or lower boundary of the white-space block. (This is subject to any constraint that may require a guard-band between assignments.)
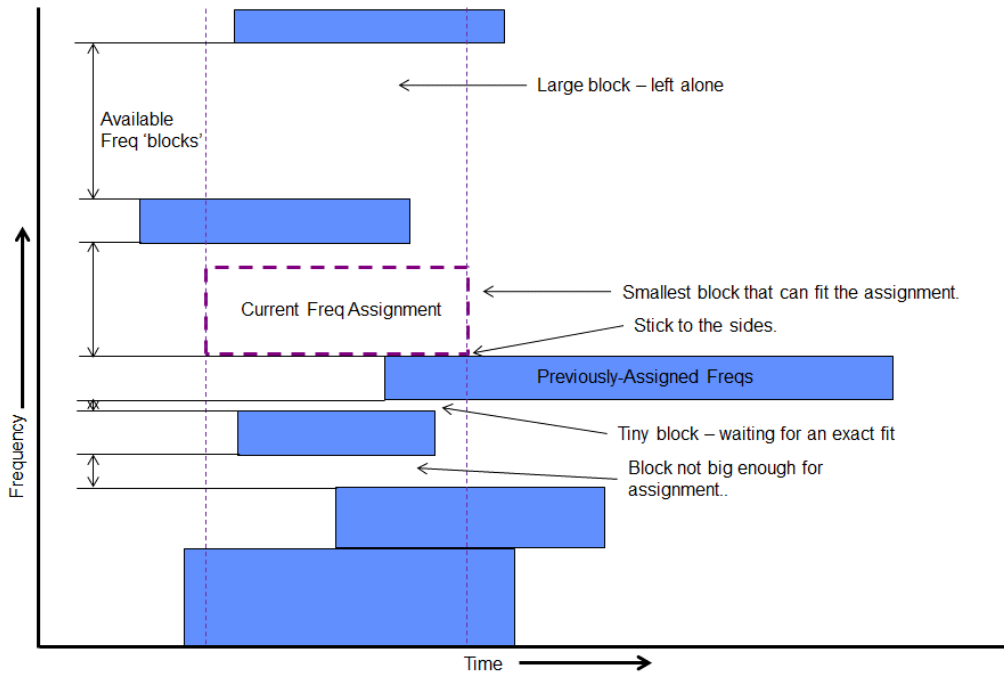
Figure 7. Insertion of a Frequency for the Least Spectrum Fragmentation.

Calculating Air-to-Ground RF Channel Quality

To support its RF channel quality prediction feature, the SMS calculates the RSSI and the SINR for an emission from each bin in the flight plan 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].

The Johnson-Gierhart model addresses pathloss for radio waves traveling through airspace, without obstruction. The Longley-Rice model provides pathloss when the waves are skimming the surface of the earth, and terrain needs to be taken into account. To support Longley-Rice, SMS includes a terrain database

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. When the angle with the horizon from the bin to the ground station is > 12°, SMS uses the Johnson-Gierhart model. When this angle is < 12°, it uses the Longley-Rice model. Having determined the path-loss, the RSSI at the ground station is:

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

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

For a measure of overall signal strength for a mission, SMS uses the notion of 'percent good signal strength'. This is the percentage of bins across the entire mission where the RSSI exceeds a pre-determined threshold.

Figure 8 shows a scenario where there are two time- and frequency-coincident missions. SINR is calculated for each bin in the flight plan 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, SMS 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)
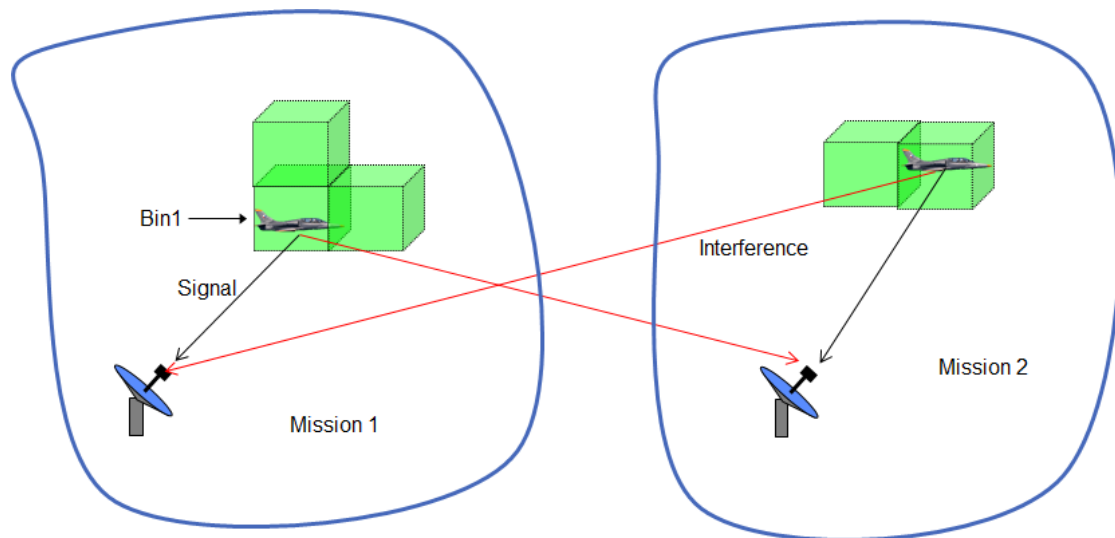
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Figure 8. Calculating Interference with Frequency Reuse

SMS Calibration

The SMS is dependent on being able to calculate RF propagation through the airspace. A number of unknowns have to be accounted for in the propagation algorithm. These include:

- Model-specific antenna patterns for the test articles and ground stations.
- System loss, for the path from the antenna to the transmitter/receiver/transceiver.
- Building and other clutter. Building data may be added in future to the SMS, but notwithstanding this, variables such as tree growth and parked vehicles may cause errors in propagation calculations, while the aircraft is standing or taxiing.
- Test article orientation during flight. This can only be roughly estimated, and may introduce significant error into the calculation.
- Ambient RF noise. This may vary from test range to test range, and even within the airspace of a single test range.

The SMS was calibrated in one exercise using Time-Space Position Information (TSPI) data at a test range.
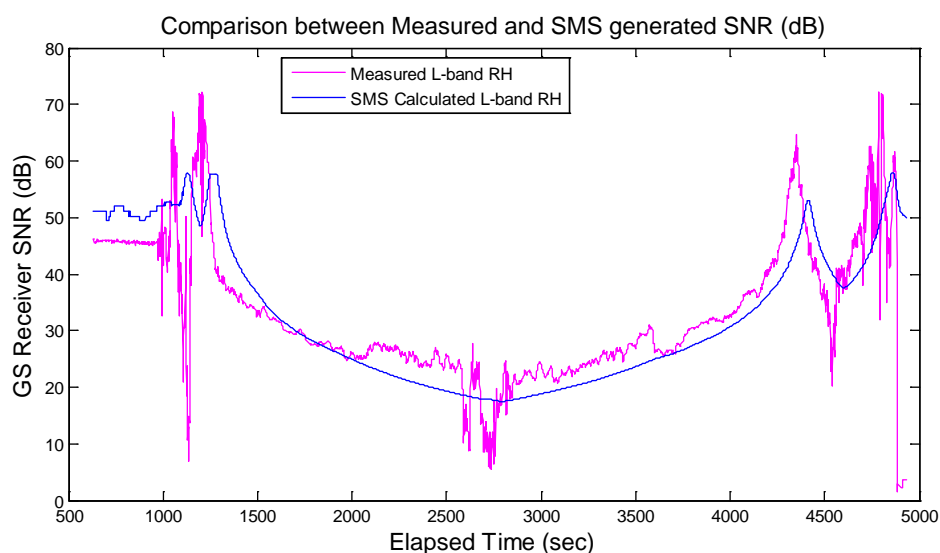

Figure 9. Calibration Curves – TSPI Data vs Actual.

Figure 9 shows the results. The jagged curve plots the measured TSPI SNR data. The smooth curve plots SNR values calculated by the SMS using its channel models. The unknowns listed

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above were adjusted as constants to make the curves as close to each other as possible. The most variations in the TSPI SNR curve occur while the aircraft is taking off and landing, and near the middle of the flight. Land-based clutter and changes in the aircraft's orientation are good explanations for these variations. The time-shift in the SMS-calculated curve is attributed to the fact that the aircraft's position, after being measured on the aircraft, took some time to make its way to the ground station, where the position data was paired with the current time. In the comparison, 89.7% of the calculated values proved to be within $\pm$ 10 dB of the TSPI SNR   values. [2]

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