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Item Type	text; Proceedings
Authors	Painter, Mike K.; Fernandes, Ronald; Ramachandran, Satheesh; Verma, Ajay; Jones, Charles H.
Publisher	International Foundation for Telemetering
Journal	International Telemetering Conference Proceedings
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Download date	25/08/2022 18:50:14
Link to Item	http://hdl.handle.net/10150/606132

STRATEGIES FOR OPTIMIZED SPECTRUM ALLOCATION AND MANAGEMENT

Mike K. Painter
Ronald Fernandes, Ph.D.
Satheesh Ramachandran, Ph.D.
Ajay Verma, Ph.D.
Knowledge Based Systems, Inc.
1408 University Drive East
College Station, TX 77840

Charles H. Jones, Ph.D
812TSS/ENTI
Edwards AFB, CA

ABSTRACT

This paper describes research aimed at investigating how to help decision makers devise optimized frequency scheduling and management strategies, both for advanced planning and real-time metrics adjustment. Part of these investigations include research to (i) define the metrics, objectives, and constraints involved in optimal frequency allocation decision-making; (ii) harmonize competing, orthogonal goals when devising candidate solutions; and (iii) devise an architectural strategy for dynamic spectrum allocation and management.

KEYWORDS

Dynamic frequency allocation, optimization, electronic spectrum, telemetry, iNET

INTRODUCTION

Effective spectrum and frequency management is essential to the success of U.S. military operations. Military operations, both now and in the future, increasingly rely on the ability to maintain full access and reliable control of the radio frequency (RF) spectrum for communications (including satellite communications), radar, electronic warfare, remote fires, avionics, global positioning, logistics, medical support, and signals intelligence use. Information dominance cannot be achieved without it.

Meanwhile, historical notions of spectrum allocation and management are changing dramatically. What was once a static, one-dimensional property is now beginning to be viewed as a dynamic, multifaceted commodity. Spectrum allocation and management has long been based on the idea of owning parts of the spectrum for a predefined purpose. More recently, the notion of spectrum ownership has shifted in response to recent developments in software-programmable radios and radars, spread-spectrum waveforms, digital signals, spectrum-sharing technology, and dynamically allocated frequency that allow users to share common spectrum, separated by frequency, location, time and waveform under the control of supervisory systems. In addition, the Department of Defense is finding this resource increasingly scarce, largely due to economic pressures arising through the increased commercial uses of the electronic spectrum.

The test and evaluation (T&E) community is not immune to these challenges. It is not unusual for test missions to include multiple aircraft, thereby requiring multiple telemetry links. Imagine a test involving four aircraft attacking six intruder targets. Each aircraft could be operating two telemetry links. Each missile and target may have its own telemetry link. Therefore, it would not be unusual for one test to involve 14 or more telemetry links and multiple frequency ranges. Depending on the missile types and test requirements, there could be aggregates of 70-plus megabits per second (MBPS) passing over the communications links.

In the T&E environment, contention for bandwidth is most often the main challenge in mission scheduling. Multiple systems may need to broadcast simultaneously using different frequencies at different power levels and in different directions. There are other complications as well. Frequency requirements must often be determined dynamically, in real-time. Hence, each system must be able to communicate its changing requirements to a controller function, which must, in turn, communicate its allocations to all involved parties [1].

In classical optimization, frequency scheduling in this domain would be characterized as a dynamic bin-packing problem. These problems are by their very nature NP-hard, which means that arriving at a solution can be computationally intractable [2]. Yet, increasing demands make it evident that there is a need to provide more efficient frequency management.

SPECTRUM ALLOCATION ALGORITHM DESIGN CONSIDERATIONS

It is unlikely that one allocation algorithm will work well for the various frequency scheduling scenarios encountered. For example, real-time requests for a change in bit rate and/or modulation schemes will require almost immediate response. Simple conflict assessment or satisfying methods may be all that is needed in this case. Weekly planning and negotiation processes, however, could explore multiple options, thereby expanding algorithm options. One goal of this research is to test alternative scheduling optimization strategies to determine which are the most appropriate for the various scenarios involved in frequency scheduling.

Our initial efforts in this area focused on two predominant frequency-scheduling scenarios, which we refer to as *off-line* scheduling and *real-time* frequency scheduling. In both scenarios, the goal is to optimally allocate spectrum to individual missions to maximize the *availability* of the remaining or leftover spectrum. The off-line scheduling scenario involves creating a schedule from a clean slate once you've received all known frequency scheduling requests for that scheduling period. In the real-time scheduling scenario, there are scheduled missions one needs to work around, often with insufficient time to make changes to those commitments. The goal in this case is to schedule new missions in a way that minimizes disruption to already scheduled missions while simultaneously maximizing the availability of the leftover spectrum.

FORMULATION FOR DYNAMIC SPECTRUM ALLOCATION

We now provide an initial problem formulation for the frequency management problem. First, we provide a general formulation. We then illustrate its application for a spectrum assignment problem involving two dimensions—time and frequency.

Our general formulation reflects the goal of optimally making frequency assignments to satisfy a set of time-indexed requests. Let $\Phi(t_k)$ define the frequency assignment at a time instant t_k. Let $M(t_k) = \{m_i(t_k)\}$ be the set of mission requests at time t_k. These missions are situated in a multi-dimensional decision space consisting of time, frequency, a discrete set of multiplexing options, and spatial dimensions. Among these may be missions that have active spectrum assignments while others are not yet serviced. Let $D(M(t_k))$ define the frequency demand at time t_k based on the mission set $M(t_k)$. The goal is to find an optimal $\Phi^*(t_k)$ that maximizes an objective function *f* while satisfying a set of equality constraints *g* (e.g., two missions that have to start simultaneously) and inequality constraints *h* (e.g., allocation needed no later than some specified time). The resulting constraint equations reflect spectrum requirements (i.e., demand) and previously made allocation decisions. The objective function is structured to embody goals relative to mission priorities, costs, quality of service, etc. Formally stated:

Find $\Phi^*(t_{k+1})$, such that

$$\max_{\Phi^*} f\left(S_{M(t_{k+1}),\phi^*(t_{k+1})}\right), \tag{1}$$

where

$$g\left(S_{M(t_{k+1}),\Phi^*(t_{k+1})}\right) = 0 \tag{2}$$

$$h\left(S_{M(t_{k+1}),\Phi^*(t_{k+1})}\right) < H \tag{3}$$

$$D(M(t_{k+1})), \Phi(t_k) \rightarrow g\left(S_{M(t_{k+1}),\Phi(t_{k+1})}, t_{k+1}\right), h\left(S_{M(t_{k+1}),\Phi(t_{k+1})}, t_{k+1}\right) \tag{4}$$

The goal of this dynamic assignment model is to optimally allocate spectrum so as to maximize the utility of the solution to the enterprise relative to some set of objectives *f*. This general formulation can be focused toward optimally allocating spectrum so as to maximize the remaining usable spectrum, measured in terms of "*availability*", while accommodating as many missions as possible.

Figure 1 shows a simplistic visual representation of this optimization problem. It shows four preexisting missions, with a new mission that has to be scheduled within certain time and frequency constraints. The goal is allocate it in a way that maximizes the objective function.

Missions that have spectrum allocated to them fragment the time-frequency space, which leads to deterioration of this space in terms of its ability to accommodate additional missions. In making those assignments, the objective thus becomes one to maximize certain availability metrics that reflect the *goodness* of the left over spectrum. There are multiple ways to measure this *availability*. One prominent way to evaluate the true availability of the leftover spectrum is by quantifying the largest mission profile that can be accommodated. Some prominent availability metrics from literature [2] include:

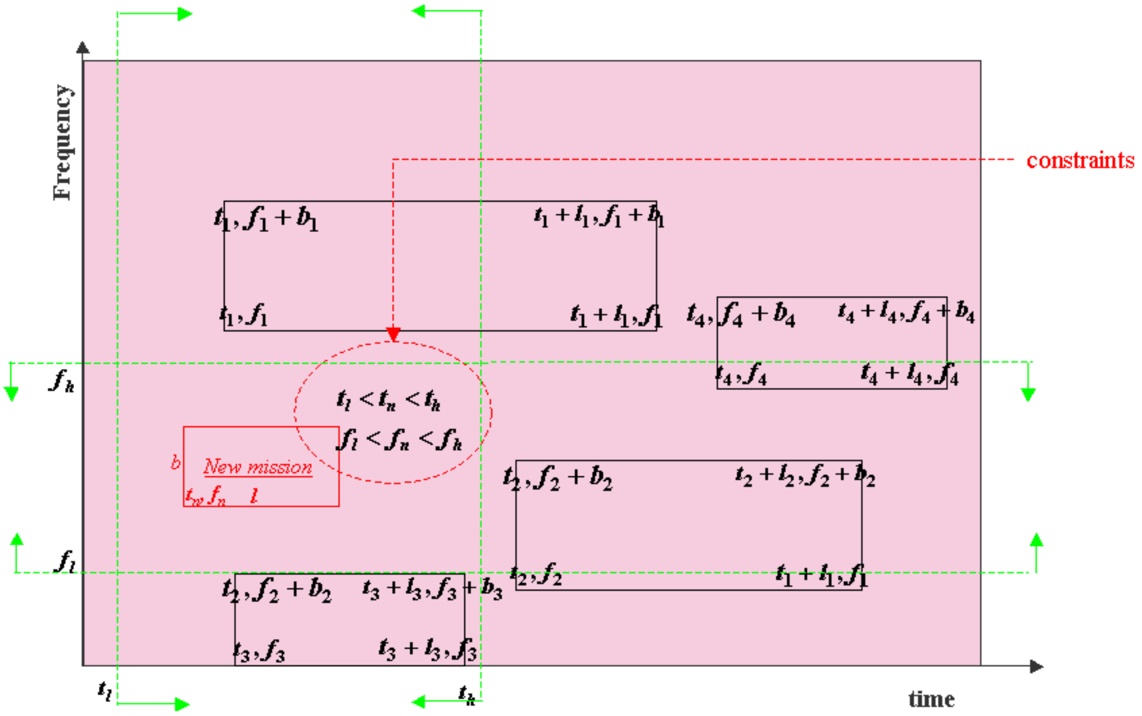

Figure 1. Conceptual Overview of the Optimization Problem

- Maximum Available Duration (MAD) – the longest possible duration a mission that can be scheduled for a given start time and required bandwidth.
- Maximum Available Bandwidth (MAB) - the largest possible bandwidth that mission can be scheduled for a given start time and required duration.
- Maximum Available Mission Occupancy (MAMO) – the largest mission occupancy that can be scheduled for a given start time and frequency (where mission occupancy could be defined as the largest *time-frequency* block).
- Maximum MAMO – The maximum MAMO that can be achieved over the feasible set of start times and frequencies.

The first three metrics are specific to a particular start time or frequency. To achieve a global performance objective, one could take the averages or maximum of these local metrics over the entire set of feasible start times and frequencies to create global metrics. The focus of our recent work in formulation, algorithm design, test and evaluation was based on the Maximum MAMO metric. While undertaking this work, we sought to extend current metrics to more accurately reflect domain requirements while ensuring that the resulting algorithm was extensible.

The formulation and algorithms are explained with the help of simple examples. First, a few definitions are provided. All of the definitions are based on the 2-dimensional time-frequency (***t*, *f***) plane with the origin **0,0** located at lower left corner. Note that an empty rectangle in time-frequency means that the space inside the rectangle is free and available for any mission assignment.

Definition 1 – *Maximal Empty Rectangle*: *An empty rectangle that cannot be further extended.*

By corollary, each edge of the maximal empty rectangle is either (i) at the border of the available spectrum, or (ii) a part of the edge forms the boundary of an already scheduled mission, or (iii) the edge contains an anchored corner of the rectangle. It is obvious that for any maximal empty rectangle, there is no other empty rectangle subsuming the maximal rectangle and satisfying any constraint on anchoring of rectangle corner.

Definition 2 – *Maximal Empty Rectangle at point (t, f)*: *A maximal empty rectangle with its lower left corner anchored at point (t, f).*

Definition 3 – *AMO (t, f) (Available Mission Occupancy) – AMO at a point (t, f) can be defined as the maximal empty rectangle with left bottom corner anchored at the given point (t, f).*

Observe that all the rectangles with lower left corner anchored at a point *(t, f)* have the following properties - the rectangles are lying in the positive quadrant from *(t, f)*, and any larger rectangle subsuming these rectangles would intersect an existing mission. For the example shown in the Figure 2 containing the two time-frequency blocks, for the point X, there are two AMO's represented by the dashed rectangles. One of the AMO's is maximal along the f direction, and the other along the *t* direction.

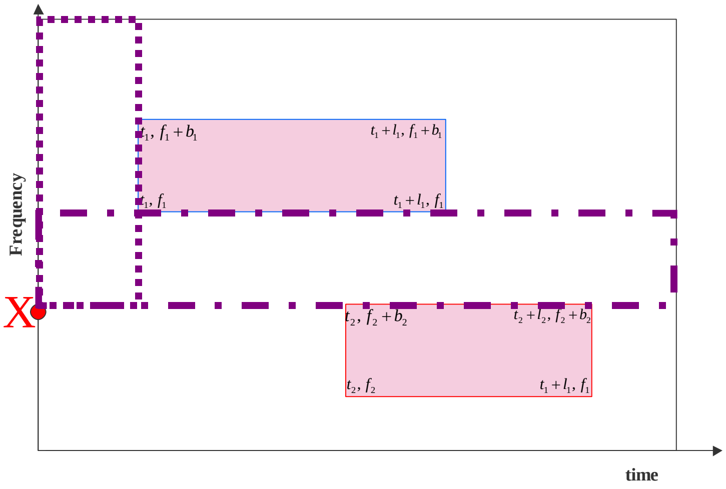

Figure 2. Two AMOs at Point X

Definition 4 - *Corner Points (CP)*: *A CP is the lower left corner of any maximal empty rectangle.*

The corner points of the given spectrum, include the following set of points: (a) the origin (0, 0) if no mission is scheduled at the origin, (b) the projections of the top or right edge of the mission onto the edges of other missions,., and (d) the projections of the top or right edge onto the or spectrum boundary or axis.

As a general Lemma, for *n* rectangular missions, there are 2*n*+1 CPs. For the example containing two time-frequency mission blocks, Figure 3 shows all the CPs for the assigned missions.

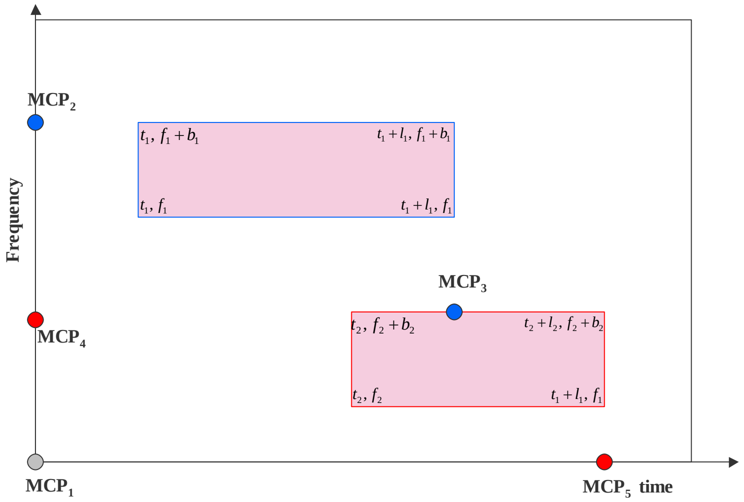

Figure 3: 2n+1 CP's for the Example Mission Schedules

With the definition for CP, we describe the algorithm for determining Max-MAMO for a certain configuration. As stated earlier, Max MAMO represents a global measure for availability of the left over spectrum, and represents the objective function for the optimization problem.

- Step 1: Identify all the Corner Points (CP)
  - Lemma 1: For N blocks, there are maximum 2N+1 corner points
  - Lemma 2: Max MAMO has to lie at a CP
- Step 2: Determine MAMO’s for all CP’s
- Step 3: Find maximal MAMO among these.

While allocating a new mission, another observation that can be made here is that for a feasible allocation, the new mission must fit within a MAMO for some CP. Note that as new missions are scheduled, the space gets more fragmented and the probability of scheduling new mission decreases. The goal of optimal placing of the given mission is to maximize the probability of scheduling a future mission. This objective is equivalent to maximizing the available spectrum in large size MAMOs. For optimal mission scheduling, a minimum MAMO must be determined that is big enough to for the given mission. With this fact, the following algorithm enables the allocating a new mission in a way that preserves the best MAMO properties.

- Find the smallest of the MAMO’s associated with the 2n+1 CP’s.
- Evaluate the 4 corners for this MAMO.
- Pick the corner that leaves the maximum sub-MAMO within the MAMO

AVAILABILITY METRIC EXTENSIONS

The allocation solutions provided by an optimization formulation are largely driven by the choice of an availability metric. There are many potential availability metrics, as described above. One limitation of these metrics is that they assume a uniform usability (or desirability) across the entire time-frequency spectrum. This uniformity assumption does not hold since certain regions of the spectrum are likely to be in greater demand. Ideally, spectrum allocation strategies should be derived so as to maximize the availability of more desirable regions of the spectral real estate. This concept can be elaborated through a simple, one-dimensional illustration.

Given a set of pre-assigned blocks as shown in Figure 4(a), the best place to assign an additional block is in the narrowest available space since this maximizes the overall MAMO. However, with a demand distribution for the real estate as shown in Figure 4(b), a better allocation for the block is as shown since this maximizes the availability of the high-demand region.

Thus, having availability metrics that take into account the regional demand or desirability within the time-frequency spectrum is important in deriving a truly optimal allocation process. The desirability for a particular region can be represented by a demand distribution. The demand-weighted area is computed as the volume under the two-dimensional demand probability density function (the 1-d representation shown in Figure 4(b). Reconfiguring availability metrics such as Maximum MAMO to this new demand-weighted area enables establishing allocations that truly maximize the usability of the remaining spectrum.

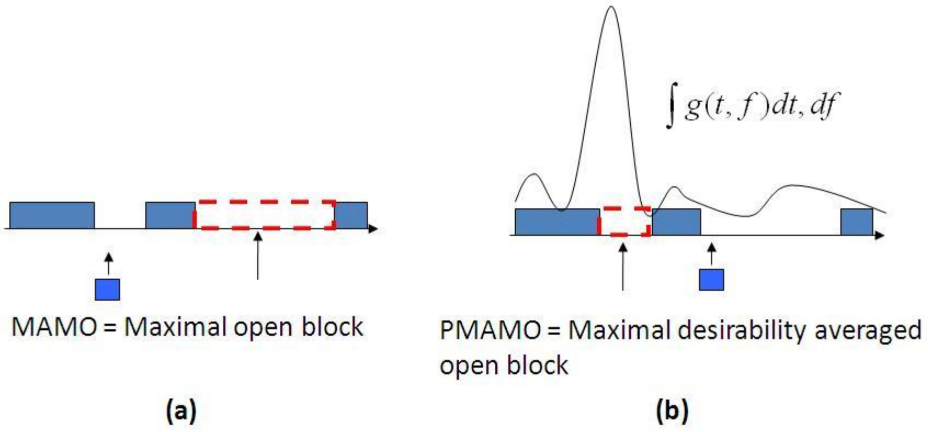

Figure 4: Illustration of Desirability-driven Allocation

ADDITIONAL CONSIDERATIONS

Feasible spectrum allocation solutions involve more than just central frequency and bandwidth constraints. Among the additional constraints to be considered are the following:

- Mission priorities and timing constraints
- Multiple test article mission groupings and relative timings
- Equipment capability constraints (e.g., transmitter tunability and range, digitization rate, on-board memory, multiplexing schemes supported)
- Mission flexibility constraints (e.g., sufficient fuel for extended flight)
- Cost constraints
- Environmental constraints (e.g., weather)
- Truly available frequency (e.g., moving out of Upper S-Band between 2330-2360)
- Multiple access strategy physics

With regard to multiple access constraints, consider a situation where Asset 1 requests 1MBPS for downlink telemetry and 256 kilobits per second (KBPS) for downlink video. Asset 2 requests 750 KBPS for telemetry. Assume that what's available is one contiguous band of 2MBPS equivalent capacity. In this situation, there are at least five choices, depending on the capability of the assets and the ground station(s) as shown in Figure 5.

Note that the second and third solutions require common frequency tuning capacity by both assets and time division multiple access (TDMA)-capable transmission (i.e., each asset needs to know when to shout and when to be quiet).

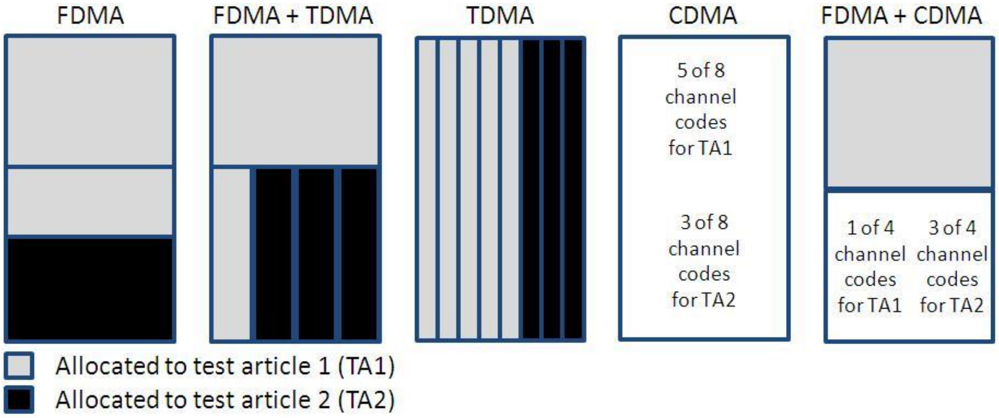

Figure 5. Options Available to Satisfy Spectrum Requests

HARMONIZING DIFFERENT OBJECTIVES

Usually, frequency scheduling problems involve more than a single objective criterion. For example, one objective may be to pack as many missions into the available spectrum with the aim of maximizing spectrum occupancy. Another might be to maximize the frequency-time domain separation among scheduled missions to maximize schedule adjustment flexibility. Other goals may be expressed in terms that have less to do with frequency management, per se, such as minimizing cost or maximizing on-time performance for critical T&E milestones. Objectives of interest may fall into one or more of the following categories:

- Spectrum utilization-related objectives (e.g., maximize utilization of available spectrum)
- Priority-related objectives (e.g., maximize high priority missions serviced)

- Service-related objectives (e.g., maximize ratio of actual versus scheduled tests)
- Time-related metrics (e.g,. maximize on-time test completion rate, minimize test queuing time)
- Cost-related metrics (e.g., minimize ratio of actual cost per test versus infinite spectrum-based cost)

Most often, when multiple objectives are simultaneously applied to a problem they may work at cross-purposes with each other. That is, while one objective improves, another one becomes worse. The major difficulty with these problems is the non-existence of a feasible solution that simultaneously optimizes the conflicting objective functions. A feasible single-objective optimization problem does not have such difficulty. For this reason, it is very difficult to deal with a multi-criteria optimization (MCO) problem practically or theoretically although it is one of the most realistic problems faced by decision makers.

The most difficult aspect of this problem is to determine tradeoffs among values of the objectives with diverse measuring units. That is, solution performance relative to each objective is often measured in different units (e.g., on-time performance may be measured in percentage values, costs are measured in dollars, throughput may be measured in test missions generated per month, efficiency may be measured in terms of percent utilization per month).

The current effort includes research of a metrics harmonization approach that first elicits decision maker judgments of value for each key objective in terms of a utility function, and then uses those value judgments to determine the overall merits of competing options. This kind of utility function-based framework simplifies the MCO problem by making it easy to characterize and simultaneously consider orthogonal objectives using a single measure of merit.

CONTRIBUTIONS TO THE INET ARCHITECTURE

Ultimately, a key goal of this work is to provide a foundation for the Spectrum Assignment Management function within the iNET architecture (Figure 6). This goal is supported through efforts to develop a pre-production prototype spectrum allocation advisor (SAA). The prototype will target a “typical” iNET scenario that one would expect to encounter two to three years down the road wherein an operator calls up an advisor to propose how to best respond to a metric adjustment request.

The primary role of the SAA is to provide a test environment to dynamically visualize different assignment algorithms and analyze their effectiveness. The prototype takes a set of requests as input, applies an assignment algorithm to allocate frequency, records the request and the result of the request in a scrolling text window, and maintains an updated map of all active frequency assignments.

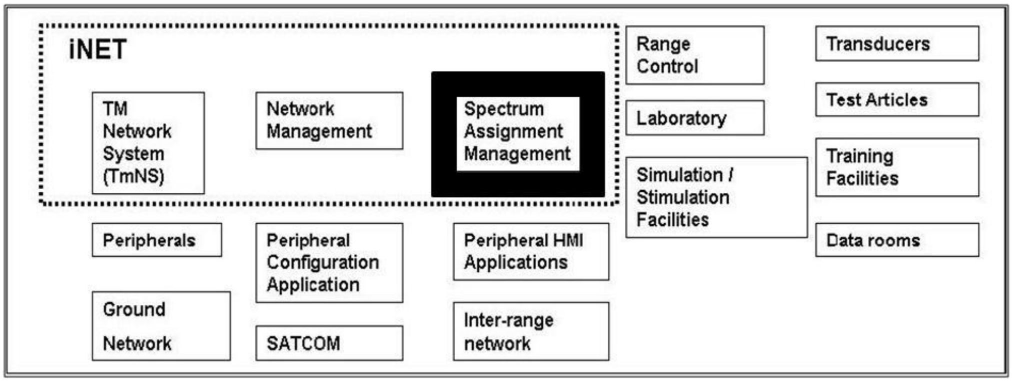

Figure 6. Potential SAA Role in iNET Architecture

SUMMARY

Novel and efficient methods are needed to better manage the available spectrum and increase data transfer throughput capacity. The research described in this paper is targeted at (i) defining the metrics, objectives, and constraints involved in optimal frequency allocation decision-making; (ii) harmonize competing, orthogonal goals when devising candidate solutions; and (iii) devising an architectural strategy for dynamic spectrum allocation and management. An initial formulation for the optimization problem has been developed. This process served to help identify additional extensions that will be needed to support an iNET environment. Among these was the recognition that different segments of the spectrum must be treated differently, just as the location of real estate determines its value. There is also a need to recognize and deal with competing objectives and complex constraints. These developments will provide foundational insights regarding how to evolve a key function of the iNET architecture—Spectrum Assignment Management.

ACKNOWLEDGEMENTS

This research is funded through Small Business Innovation Research (SBIR) contract FA9302-08-C-0003 sponsored by the Air Force Flight Test Center (AFFTC) at Edwards Air Force Base, California.

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