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Linear optimization of frequency spectrum assignments across systems

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NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

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LINEAR OPTIMIZATION OF FREQUENCY SPECTRUM ASSIGNMENTS ACROSS SYSTEMS

by

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March 2016

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Development and acquisition of naval communication, data, and radar systems for ships is an almost entirely modular process. For this reason, virtually all existing systems have separate controllers, antennas, and transmitters. However, future systems could use existing planar antennas that operate across a range of frequencies and create a variety of complex waveforms, eliminating the need to develop separate antennas and transmitters. Additionally, frequency use plans are expensive in terms of time and effort to develop and change. The "Integrated Topside (InTop) joint Navy industry open architecture study" published in 2010 described the need for an integrated sensor and communication system that is modular, scalable, and capable of performing multiple functions. Such a system requires a scheduling and frequency deconfliction tool that is capable of representing the current antenna configuration and matches those capabilities with requests for frequency space and time. This thesis describes SPECTRA, an integer linear program that can prioritize and optimize the scheduling of available antennas to deconflict time, frequencies, systems and capabilities. It can be uniquely tailored to any platform including naval warships, aircraft, and ground sites.

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LINEAR OPTIMIZATION OF FREQUENCY SPECTRUM ASSIGNMENTS ACROSS SYSTEMS

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Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

Development and acquisition of naval communication, data, and radar systems for ships is an almost entirely modular process. For this reason, virtually all existing systems have separate controllers, antennas, and transmitters. However, future systems could use existing planar antennas that operate across a range of frequencies and create a variety of complex waveforms, eliminating the need to develop separate antennas and transmitters. Additionally, frequency use plans are expensive in terms of time and effort to develop and change. The "Integrated Topside (InTop) joint Navy industry open architecture study" published in 2010 described the need for an integrated sensor and communication system that is modular, scalable, and capable of performing multiple functions. Such a system requires a scheduling and frequency deconfliction tool that is capable of representing the current antenna configuration and matches those capabilities with requests for frequency space and time. This thesis describes SPECTRA, an integer linear program that can prioritize and optimize the scheduling of available antennas to deconflict time, frequencies, systems and capabilities. It can be uniquely tailored to any platform including naval warships, aircraft, and ground sites.

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LIST OF ACRONYMS AND ABBREVIATIONS

ADM	advanced development model
AMRF-C	advanced multifunction radio frequency concept
AW	air warfare
CM	communications
CNO	Chief of Naval Operations
DT	data transmission
EA	electronic attack
EME	electromagnetic environment
EMI	electromagnetic interference
EMS	electromagnetic spectrum
EMW	electromagnetic maneuver warfare
EP	electronic protect
ES	electronic surveillance
EW	early warning
GAMS	general algebraic modeling system
GHz	gigahertz
IDE	integrated development environment
ILP	integer linear program
InTop	Integrated Topside Antenna
LPD	low probability of detection
LPI	low probability of intercept
MHz	megahertz
NRL	Navy Research Laboratory
ONR	Office of Naval Research
RF	radio frequency
SDS	spectrum-dependent system
SS	surface search
TACAN	tactical air navigation system
UHF	ultra high frequency
VHF	very high frequency

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EXECUTIVE SUMMARY

Development and acquisition of naval communication, data, and radar systems for warships is an almost entirely modular process. Virtually all new communication, data, and radar systems have separate controllers, antennas, and transmitters (Office of Naval Research 2002). However, new systems could use planar arrays that can operate across a range of frequencies and create a variety of complex waveforms, eliminating the need to develop unique antennas and transmitters for future systems.

Frequency use plans are expensive to develop and change in terms of time and effort. This is due in part to the inability of warships' electromagnetic systems to operate dynamically across the spectrum (Carter 2013). Bureaucratic and administrative spectrum allocations further restrict warships to the parts of the spectrum allowed by agreement and law, and each warship's unique equipment configuration further restricts where it can operate inside that framework. During peacetime operations, this rigidity is deceptively workable. During wartime, however, movement across the spectrum may be a necessity. An ability to adapt quickly to changing demands would likely result in increased survivability and lethality.

The InTop (Integrated Topside) program has resulted in a number of smaller multi-function arrays that are capable of performing the same tasks currently performed by many different antennas. Adopting a single multifunction array would change operational and system development paradigms. Operationally, an electronically controlled antenna would have the ability to maneuver rapidly within the spectrum. Developmentally, new capabilities could be introduced in the form of a software updates or modular central processing units (CPU) that contain the logic for new capabilities. This shift in design requires a scheduling program that is capable of optimizing the use of the antenna. This scheduling software can be used to deconflict all electronic emissions from both onboard and offboard assets. This includes, but is not be limited to, communications, data, electronic support, electronic attack, and radar signals.

This thesis describes SPECTRA, a mixed integer linear model capable of performing the function of frequency and time deconfliction in a multifunction system and multiple legacy systems.

SPECTRA is capable of managing prioritized missions and requests and matching them with available antenna resources. SPECTRA provides frequency deconfliction, if desired, and ensures that antenna resources are utilized efficiently. SPECTRA is capable of scheduling complicated large-scale spectrum use plans, but SPECTRA can also be used to rapidly schedule smaller warship operations. Fast schedule generation is a vital step toward rapid, dynamic frequency management. Maneuverability across the spectrum is necessary for the efficient use of the available spectrum space and is a vital component of electromagnetic protection (EP) and electromagnetic attack (EA). The model is also capable of allocating unused resources to fulfill additional requests from external sources after completing its primary tasks. This expanded capability opens up the reality of radio frequency task sharing across platforms or around the world.

SPECTRA also has the ability to perform dynamic frequency deconfliction that might be required because of friendly, neutral, or adversarial interference. New frequency usage plans can be generated that move or shift frequencies that have become unavailable for use dynamically. Such plans can be shared across platforms for a more efficient use of the electromagnetic spectrum.

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It is impossible to imagine that this could have been accomplished without extensive help from a long list of advisors, professors, classmates, sponsors, and other interested parties. It is my hope that this thesis can help to propel a needed capability a little bit closer to reality.

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I. PROBLEM AND BACKGROUND

A. PROBLEM

The Integrated Topside (InTop) program integrates a series of antenna designs allowing for transmissions over a wide frequency spectrum. The particular InTop antenna that served as the focus for this thesis is composed of several larger arrays divided into smaller sub-arrays. These sub-arrays increase the number of tasks that could be performed by a single aperture. The Office of Naval Research (ONR) working with the Navy Research Laboratory (NRL) as part of the InTop program is exploring the feasibility of placing a series of antennas with these characteristics on U.S. Naval warships. Logically, multifunction antennas capable of performing more than one task must have a means to schedule and prioritize tasks. A multifunction antenna needs a program that rapidly optimizes scheduling of the antenna's resources, one capable of taking multiple requests from multiple missions and prioritizing them according to a commander's intent. A program is required to take advantage of such multifunction systems.

This thesis describes SPECTRA, a linear optimization model designed to work with a ship's multifunction antenna, which possesses the capability to schedule legacy antenna systems. The benefits of SPECTRA include the ability to prioritize tasks, to facilitate rapid switching between tasks, and to maximize the use of available radio frequency systems to enhance the overall effectiveness of warship capabilities.

B. BACKGROUND

Antennas for radio frequency (RF) systems on warships are typically designed for a single purpose. Individual antennas are normally optimized for frequency, radiation pattern, polarity, and power requirements. In 2002, ONR highlighted the increases in the numbers of antennas and the negative effects that they have on warships.

> [A]part from the continuously increasing procurement and maintenance costs of individual "stovepipe" antenna types—has increased ships' radar cross-sections. The need for new antennas also has required extensive

> modifications in ship design to manage the added weight, as well as complex restrictions on use to minimize dangerous electronics interference. (Office of Naval Research 2002)

Additionally, warships' superstructures are cluttered with single purpose antennas. The superstructures of ships are metal and antenna transmission patterns change because of the presence of metal and other antennas. This typically results in three undesirable conditions. First, antenna patterns are unpredictable for both transmission and reception. Antennas mounted on metal structures are subject to interference from that same structure. In some cases, null zones are created where transmission or reception is not possible or severely degraded. Unobscured space on a warship's superstructure is limited. Since these physical limitations are permanent and are harder to design away, warships are at times required to execute course corrections to compensate for transmission or reception nulls created by their own masts.

Second, antennas that have similar operational frequencies can receive energy from other antennas and often require shielding or filters to remove the extraneous signals. In some cases, large portions of the frequency spectrum become unusable due to mutual interference between similar systems. Large systems with very high power requirements can create interference with other receivers located at higher or lower multiples of the larger system's transmission frequency. These frequencies may become unusable unless a system can be retuned to avoid this interference.

Third, energy is wasted by using increased power for transmissions to compensate for the lack of directionality and signal sidelobes. Some antennas are omnidirectional, while others are directional. Omnidirectional antennas provide a wider area of transmission and reception; in most cases, they are used for large area communication. The use of an omnidirectional antenna is inefficient if the direction of the intended recipient is known. Using an omnidirectional antenna in this case wastes energy transmitting away from the intended recipient.

C. CURRENT METHODS

Changing radio frequencies of systems using existing processes is usually labor intensive. First, a new frequency assignment must be administratively deconflicted from frequencies used locally by other entities. Second, the new frequency must be deconflicted from other frequencies already in use by other systems onboard the warship. Finally, the new frequency must be selected on the equipment itself. This process may require a significant amount of time. The additional time and effort required to make adjustments sometimes results in the systems becoming, in essence, fixed over time and predictable. Occasionally, interfering systems are simply turned off and not used when they might otherwise be available if the frequency could be changed quickly. When a ship operates all of its systems on set frequencies for long periods of time, the ship becomes predictable and vulnerable to electronic surveillance and attack.

D. PROPOSED SOLUTION

The InTop program includes a multifunction antenna designed to fit on the superstructure of a warship in a multiple sector configuration similar to a SPY-1 array. Transmission beams are steered electronically and are not as susceptible to unpredictable antenna patterns as legacy systems. Mutual interference between similar antennas is reduced by the ability to transmit and receive in different sectors. Two similar frequencies transmitted in two different sectors can be separated physically and directionally. The beams of the antenna are also steerable, which may further reduce the system’s susceptibility to stray energy from other transmissions. Signals can be steered toward the intended recipient and the energy transmitted in other sectors is reduced. This ability not only protects the signal from being intercepted by unintended recipients, but also reduces a receiver’s susceptibility to jamming.

The InTop system is capable of performing a wide range of functions, but it requires a scheduling tool to manage antenna resources. SPECTRA is an optimization-based decision support tool that allows planners to organize and group *requests* for frequency and time intervals into prioritized *missions*. These requests are paired to available *systems* while simultaneously ensuring that no frequency overlaps occur between missions or against unavailable frequencies. SPECTRA allows a more efficient use of systems onboard a warship by attempting to match high priority requests with available antennas. SPECTRA can regenerate schedules rapidly in response to changes in spectrum availability, changing priorities, mission adjustments, or even system failures, and allow warships to shift frequencies rapidly, greatly enhancing maneuverability within the spectrum.

II. DEPARTMENT OF DEFENSE EFFORTS

A. ELECTROMAGNETIC MANEUVER WARFARE

Summarizing a speech given to the Association of Old Crows in 2013, Julianne Metzger reported that then Chief of Naval Operations (CNO) Admiral Jonathan Greenert, "stressed the importance of agility in regards to the electromagnetic spectrum and … developing radars that can use alternate frequencies" (Metzger 2013). This need for agility in the electromagnetic spectrum requires systems that are capable of operating across a range of frequencies and have the ability to adjust to a rapidly changing RF environment.

In 2014, Admiral Greenert testified before the House Armed Services Committee about the Navy's need to modernize and enhance its ability to maneuver in the electromagnetic spectrum (Greenert 2014). The ability to maneuver in the electromagnetic spectrum is a vital part of electromagnetic maneuver warfare (EMW). It assumes three basic system capabilities. First, the system must be able to operate on more than one frequency. The inability to transmit across a wider range of frequencies is a limit that is imposed on many systems, often by the physical limits of the systems design or bureaucratic limitations. The second capability required for maneuvering in the spectrum is the ability to change frequencies quickly. When it becomes necessary to make adjustments, a system must be capable of doing so with minimum delay. Finally, the new frequency selected must be deconflicted from other frequency assignments. Transmission frequencies need to be chosen that do not overlap with other frequencies and avoid restricted frequencies. This process is generally time consuming, and would benefit from automation.

True electromagnetic maneuverability should provide a warship with the ability to transmit across a larger range of possible frequencies. Systems would have the ability to transmit outside of fixed ranges complicating the identification, classification, and jamming of signals (Greenert 2014).

B. THE SPECTRUM AS THE NEWEST DOMAIN

Late in 2015, the Department of Defense Chief Information Officer (CIO) spoke to a reporter about a draft proposal to recognize the electromagnetic spectrum (EMS) as a warfighting domain. Terry Halverson also confirmed that the CIO office is investigating "the potential recognition of the EMS as a domain" (Freedberg Jr 2015a). If the EMS is designated as a domain, it will be the first new domain since cyberspace was declared a domain in 2006. The Deputy Secretary of Defense, Robert Work announced the creation of a new council that will direct all of the Pentagon's electronic warfare (EW) programs. He stressed the reasons behind the new focus in an interview.

> EW is often regarded as a combat enabler. … electronic jamming and deception are traditionally [seen] as adjuncts to physical weaponry rather as weapons in their own right. Our adversaries don't think so, …. For relatively small investments, you get an extremely high potential payoff. …and our competitors are trying to win in the EW competition….Now, we still have a lead—I think—[but] that lead is diminishing rapidly. (Freedberg Jr 2015b)

In the 2013 "Electromagnetic Spectrum Strategy" released by then Deputy Secretary of Defense Ashton Carter highlighted the government's goals and objectives with regard to the use of the spectrum-dependent systems (SDS). Four of the objectives listed in that report are directly supported by work done in this thesis.

- "Expedite development of technologies that increase an SDS's ability to: access wider frequency ranges; exploit spectrum efficiency gains; utilize less congested bands; and adapt rapidly to changing EMEs [Electromagnetic Environments]"
- "Accelerate the fielding of technologies that enable spectrum sharing and improve access opportunities"
- "Develop the ability to perform near-real-time spectrum operations"
- "Advance the ability to identify, predict, and mitigate harmful interference" (Carter 2013)

The Department of Defense leadership is emphasizing electromagnetic warfare and is considering giving it the same importance as cyberspace. The InTop program is designed to achieve the first goal to "Expedite the Development of SDS Capabilities with Increased Spectrum Efficiency, Flexibility, and Adaptability" (Carter 2013). The design of the antenna provides the ability to perform the tasks listed. A scheduling program enhances the capabilities of the overall system.

C. A FULL SPECTRUM OF NEEDS

At their heart, antennas are a means by which information is transferred from one medium to another. Antennas are the single point where information is broadcast into or received from airspace. As the amount of information that needs to be exchanged increases, the numbers and types of antennas may also tend to increase.

1. Networks Need Antennas

In 2002, ONR identified the focus on what was then referred to as “network-centric warfare” (Office of Naval Research 2002) and the need to enhance the ability to exchange data. They recognized the burden that this places on the electromagnetic spectrum and the increases in “antennas, transmitters, receivers, and the accompanying complexities of operating and supporting new RF systems. The Navy has met each new functional requirement for use of the RF spectrum with a new antenna, each needing new auxiliary equipment, operator training, and maintenance and logistics support.” They continued to highlight that “apertures also will integrate electronic warfare systems, which detect, jam, or deceive enemy radars and weapons.”

Their solution at the time was the advanced multifunction radio frequency concept (AMRF-C). ONR’s surveillance, communications, and electronic combat division, director Joe Lawrence stated that the AMRF-C program:

> aims at overcoming the antenna-proliferation crisis, with all the cost, ship-design, and operational problems it creates. Instead of separate transmit and receive apertures for each of the multiple radar, communications, and electronic warfare systems, a few pairs of AMRF-C apertures would handle most microwave RF functions. (Office of Naval Research 2002)

An example of the “antenna-proliferation crisis” is shown in Figure 1. It depicts both the abundance of antennas and the irregular shape of a warships superstructure. The multifunction antenna concept is a driving force for the reduction of procurement costs. It will enable the ability to introduce new capabilities and functions with simple software changes instead of the lengthy procurement of new systems.

Figure 1. Superstructure of a Ticonderoga Class Cruiser

Source: Keller J (2014) Navy to pour more time and money into shipboard antenna project to cut RF cross interference. (12 June), Military & Aerospace Electronics, http://www.militaryaerospace.com/articles/2014/06/navy-extends-intop.html.

2. Breaking Communications Stovepipes

In 2003, the Office of Naval Research released a press statement drawing attention to the desire for radios to have the ability to find clear channels to communicate in. They also recognize the need to have multifunction communication devices that combine a variety of waveforms that will only require software updates to enhance the capabilities of the system (Huergo 2003).

3. InTop As a Solution

The Naval Research Laboratory published a report in 2010 titled “Integrated Topside (InTop) Joint Navy-Industry Open Architecture Study” outlining the benefits of an open architecture. In that report, they outlined the fundamental characteristics of open architecture as:

- “Modular, open RF architecture”
- “Synchronized RF functions for mission support and [Electromagnetic Interference] EMI mitigation”
- “Reduced life-cycle costs”
- “More RF functions optimally sited topside”
- “Rapid adaptability to new threats/requirements through software upgrades”
- “Integrated antenna/array topside designs that are seamlessly compatible with the associated platform architecture and design” (Tavik et al. 2010)

The open design architecture allows multiple subsystems to place demands on a multifunction antenna. However, it also creates the need for a means to schedule which subsystem is allowed to use the antenna and when. Scheduler logic can be paired with the ability to automatically change frequencies and thus provide a complete system that can couple prioritized demands with resources and send the necessary data to a switching device that is capable of making rapid adjustments.

The concept of InTop program follows the train of thought used by smartphone manufacturers. By designing and building an antenna that is capable of generating a variety of waveforms across a wider frequency range, new signal types can be generated by simply changing the software that is installed in the system. In effect, the change is like an application for a smart phone that is downloaded onto the device to provide new capabilities. The InTop program is already capable of generating the waveforms and frequencies necessary and SPECTRA is capable of scheduling and deconflicting frequency assignments while maximizing the use of the antennas onboard the platform.

The result is that many users will be able to request transactions on an antenna. The system is designed such that any antenna that is available at the required time and frequency can be scheduled for use. No longer will systems be limited to one particular antenna that is taking up space on the superstructure utilized for a single need. InTop could handle multiple requests for a variety of locations efficiently and direct them to a multifunction antenna that can be used for a variety of purposes.

D. SEIZING THE OPPORTUNITY

In 2015, the Center for Strategic and Budgetary Assessments released a report titled “Winning the Airwaves: Regaining America’s Dominance in the Electromagnetic Spectrum” in which they highlight the importance of the electromagnetic spectrum. They acknowledge its use for everything from communications, navigation, identification, and location of both enemy and friendly units. They also assert that a lack of funding over the last 10 years means that the United States has “failed to keep pace” with our adversaries (Clark and Gunzinger 2015).

In their report, they assert that “the U.S. military has an opportunity to make another such leap ahead, one that will allow it to regain and maintain an enduring advantage in the EMS warfare competition” (Clark and Gunzinger 2015). They believe that the following capabilities should be developed:

- “Networked: able to communicate and coordinate operations with neighboring EMS warfare systems using Low Probability of Intercept [LPI]/ Low Probability of Detection [LPD] data links;”
- “Agile: able to maneuver in power, frequency, space, and time to remain undetected, target enemy networks, and avoid enemy countermeasures;”
- “Multifunctional: able to perform multiple EMS warfare functions such as communications, active and passive sensing, jamming, deception, or decoying;”
- “Small and affordable: can be procured and deployed in large numbers on small unmanned vehicles and systems or large platforms to enable diverse EMS warfare networks; and”
- “Adaptive: able to characterize the EMS, including previously unknown emitters, and respond to exploit opportunities or counter enemy EMS operations” (Clark and Gunzinger 2015).

In order to accomplish these capabilities, SPECTRA’s features included the need to integrate other antenna systems. SPECTRA assumes that networking of systems is possible within the warship, and that requests for antenna use can include communication, radar, electronic support, electronic attack, and external sources. The model is designed to generate new frequency assignments if areas of the spectrum are input as unusable.

E. MULTIFUNCTION SYSTEMS NEED A SCHEDULING TOOL

In 2009, Knowledge Based Systems, Inc. published a report titled “Advanced Spectrum Allocation, Frequency Deconfliction, and Scheduling Optimization decision Support,” highlighted six topics of further interest that are ready to be explored.

- “Baseline and develop a simulation capability reflecting frequency demands for both normal and combat operations, thereby providing the foundation for defining performance requirements for emerging spectrum allocation optimization models and tools.”
- “Define more relevant measures of effectiveness (MOEs) and measures of performance (MOPs) for spectrum allocation and use.”
- “Develop the mechanisms to measure the parameters that will yield the chosen MOEs and MOPs and force critical examination of the cost and practical feasibility of those metrics.”
- “Compile body of knowledge of rule sets for frequency allocation.”
- “Experiment with the different architectural strategies identified through this effort to employ the mechanisms of spectrum allocation and management.”
- “Leverage and extend project developments in solution concept development, algorithm research, solution architecture definition, and dynamic frequency allocation tool development targeting deployment through the InTop initiative.” (Painter et al. 2009)

This highlights the need for the exploration of strategies for spectrum allocation and management. Spectrum management and allocation can be achieved using a variety of techniques. The most common, but perhaps not the most efficient, is a line-by-line logical algorithm that mimics the thought process that a human scheduler would follow.

Knowledge Based Systems Incorporated’s report further describes the requirements for a scheduling solution. The report contains a description of a framework for a scheduling algorithm and listed eight objectives.

- “Maximize number of requests satisfied”
- “Maximize the number of high priority requests serviced”

- “Maximize flexibility to rapidly accommodate new tasks or to change parameters for current assignments.”
- “Maximize on-time task completion rate”
- “Minimize queuing time awaiting spectrum”
- “Maximize the efficient use of spectrum”
- “Minimize interference / data loss”
- “Minimize cost” (Painter et al. 2009)

We present an Integer Linear Programing (ILP) model for assignment of missions and requests to shipboard systems to achieve very similar goals as these.

III. SPECTRA PLANNING MODEL

A. GENERAL APPROACH

The basic unit for planning in the SPECTRA model is the *request*, which represents a particular tasking for an antenna on a warship. The basic resource is a *system*, which is a piece of equipment (i.e., a radio) that provides access to an antenna for transmission, reception, or both. In order for a request to be fulfilled, it must be matched with an available compatible system. A *mission* is a collection of requests that fulfill a function of the warship. We specify a priority for each mission: priority 1 missions must be completed, or the model is infeasible. Likewise, each request has an associated priority, and all priority 1 requests in a mission must be completed for that mission to be considered complete. Every completed mission and request has an associated reward value.

Requests must be deconflicted in time on each system. No system is capable of performing more than one request at a time. The user specifies whether a request tolerates other transmissions on the same frequency. If a request can allow an overlap in frequency to occur it is considered *transmit tolerant.*

B. ASSUMPTIONS

We assumed that all antennas are omnidirectional, each system can perform one task at a time, and systems cannot share requests. We also require that requests cannot be partially competed, but missions can be. The allocation of partial missions allows systems to be utilized for lower priority requests when the alternative is to remain idle.

C. PARAMETERS

The model divides standard antenna characteristics and request requirements into a set of parameters. Requests for antenna space contain the following parameters: mission code, mission priority, request priority, lower bound of frequency, upper bound of frequency, bandwidth, lower bound of start time, upper bound of end time, and duration of transmission.

The system capabilities are presented to the optimization model using the following parameters: lowest system frequency, highest system frequency, lower time available and upper time available. The range of the frequency is included but it is simply the lowest system frequency subtracted from the highest system frequency. Likewise, the total time horizon is calculated by subtracting the earliest time available from the latest time available. These fields allow the optimization model to handle a variety of system types. They also allow the optimization model to be used with a combination of multifunction antennas and legacy antennas.

D. FORMULATION

This section shows the formulation of the SPECTRA model using a linear program.

1. Sets and Indices

$m \in M$	missions linked to requests
$r \in R$	requests (alias *r*, *nr*)
$s \in S$	systems available
$p \in P$	request priorities
$(m,r) \in D \subseteq M \times R$	link between mission and requests
$(m,p) \in C \subseteq M \times P$	link between mission and priority
$(r,p) \in B \subseteq R \times P$	link between request and priority

2. Data

pri_r	priority of request *r*
m_reward_m	reward of mission *m*

p_reward_p	reward of request of priority *p*
$transmit_r$	transmission required Boolean for request *r*
$receive_r$	receive required Boolean for request *r*
$tx\_tolerant_r$	transmission tolerant Boolean for request *r*
lf_r	lower bound on frequency for request *r*
uf_r	upper bound on frequency for request *r*
bw_r	frequency bandwidth for request *r*
lt_r	lower bound on start time for request *r*
ut_r	upper bound on end time for request *r*
dur_r	transmission duration for request *r*
tx_s	transmission capable Boolean for system *s*
rx_s	transmission capable Boolean for system *s*
lf_s	lower bound on frequency for system *s*
uf_s	upper bound on frequency for system *s*
$range_s$	frequency range available from system resource
lt_s	lower bound on start time for system *s*
ut_s	upper bound on end time for system *s*
$horizon_s$	time horizon for system resources
ms	large value equal to $\max(uf_s) - \min(lf_s)$

3. Variables

a. Non-negative Variables

$FREQ_r$	lower frequency for request *r*
$START_r$	start time for request r on system *s*

b. Binary Variables

$EARLY_{r,nr}$	request *r* completes transmission before request *nr* starts
$LOWER_{r,nr}$	request *r* frequency range completely below request *nr* range
$ALLOC_{r,s}$	request *r* is allocated to system *s*
MC_m	all priority 1 requests from mission *m* are completely assigned
RC_r	request *r* is assigned

4. Formulation

$$\max \quad \sum_{m} MC_m m\_reward_m + \sum_{r,p \in B} RC_r\, p\_reward_p \tag{S0}$$

$$s.t. \quad FREQ_{nr} - FREQ_r \ge bw_r - ms(1 - LOWER_{r,nr}) \qquad \forall r \ne nr \tag{S1}$$

$$START_{nr} - START_r \ge dur_r - ms(1 - EARLY_{r,nr}) \qquad \forall r \ne nr \tag{S2}$$

$$EARLY_{r,nr} + EARLY_{nr,r} + LOWER_{r,nr} + LOWER_{nr,r} \ge RC_r + RC_{nr} - 1 \qquad \forall \neg tx\_tolerant_r, transmit_{nr} \tag{S3}$$

$$EARLY_{r,nr} + EARLY_{nr,r} - ALLOC_{r,s} - ALLOC_{nr,s} \ge -1 \qquad \forall s, r \ne nr, \neg(tx_s + rx_s \ge 1) \tag{S4}$$

$$-ms(1 - RC_r) + lt_r \le START_r \le ut_r - dur_r + ms(1 - RC_r) \qquad \forall r \in R \tag{S5}$$

$$-ms(1 - RC_r) + lf_r \le FREQ_r \le uf_r - bw_r + ms(1 - RC_r) \qquad \forall r \in R \tag{S6}$$

$$START_r \ge lt_s - ms(1 - ALLOC_{r,s}) \qquad \forall r, s \tag{S7}$$

$$FREQ_r \ge lf_s - ms(1 - ALLOC_{r,s}) \qquad \forall r, s \tag{S8}$$

$$START_r \le ut_s - dur_r + ms(1 - ALLOC_{r,s}) + 1 \qquad \forall r, s \tag{S9}$$

$$FREQ_r \le uf_s - bw_r + ms(1 - ALLOC_{r,s}) \qquad \forall r, s \tag{S10}$$

$$RC_r - MC_m \ge 0 \qquad \forall (m, r) \in D : pri_r = 1 \tag{S11}$$

$$\sum_{s: tx_s \vee rx_s} ALLOC_{r,s} \le 1\Big|_{transmit_r} + 1\Big|_{receive_r} \qquad \forall r, s \tag{S12}$$

$$\sum_{s} ALLOC_{r,s} \ge RC_r \qquad \forall r, s \tag{S13}$$

$$\sum_{s: tx_s} ALLOC_{r,s} \ge RC_r \qquad \forall r, s, transmit_r \tag{S14}$$

$$\sum_{s: rx_s} ALLOC_{r,s} \ge RC_r \qquad \forall r, s, receive_r \tag{S15}$$

5. Explanation of Equations

Equation (S0) is the objective function for the SPECTRA model and calculates a large reward for mission completion and a smaller reward for additional assignments made. The structure of the reward system is such that the reward for mission completion is the greater than the reward for all of the individual requests contained in the mission. Each mission reward is also greater than the entire mission rewards at a lower priority level. Thus, higher priority missions have the highest rewards available and the model is biased toward filling the required requests for each mission over all lower priority missions.

Equation (S1) requires that the frequencies for all assignments to a system do not overlap. This is the most basic form of deconfliction and it ensures that transmissions do not interfere with each other. Even transmissions from other antennas on different parts of the ship may cause interference due to the sensitivity required for most receivers.

Equation (S2) requires that the start and stop times of the assignments for a system do not overlap. This part of the scheduling observes the physical limits of the transmitters.

Equation (S3) requires that all assignments to a system be deconflicted in time or frequency. In the event that a request is transmit tolerant this equation will allow for overlap of either a transmit assignment or a receive assignment on another system.

Equation (S4) requires all frequencies to be deconflicted in time or frequency on each system. Since each system can only make one assignment at a time this equation ensures that all assignments are separated in time on each system.

Equation (S5) requires all start times to be within the request lower and upper time. It works in conjunction with Equation (S6) and ensures that the requested upper and lower frequencies are honored.

Equation (S7) requires the start time to be after the lower time limit of the system. Equation (S9) ensures the system is not scheduled after the upper time limit. These two equations ensure that the lower and upper time limits of the system are adhered to by all assignments.

Equation (S8) requires the frequency of all assigned requests to be at or above the lowest frequency of the system. Equation (S10) ensures that the frequency is within the upper frequency limit of the system.

Equation (S11) requires all of the requests be complete for a mission to be completed. Each mission is defined by the priorities of the requests assigned to the mission. Each request that is required for the mission to be completed is listed as a priority 1. When all priority 1 assignments are completed the mission is flagged as complete.

Equation (S12) allows for requests, which are both transmit and receive, to be allocated to two systems. Some assignments are listed as both transmit and receive, while some systems are capable of both and some are only capable of either transmit or receive. This equation allows for a request to be allocated to two systems if required.

Equation (S13) sets RC equal to 1 if required transmit Equation (S14) and receive Equation (S15) requirements are completed. In the event that a request is flagged as transmit and receive this flag will not change until both parts are satisfied. This will not prevent a system that is capable of transmit and receive from fulfilling both parts of the request. The model favors using systems that are capable of both transmit and receive since it allows for more requests to be allocated to other systems.

E. INPUTS

The SPECTRA model has two sets of inputs. The mission requests represent demands and the systems represent available resources.

1. Requests

Requests contain the parameters for a desired event. Since the model is a scheduling tool, basic information regarding the frequency and time of the event are necessary. The frequency may be a specific frequency or a range of potential values bounded by a lowest possible frequency and a highest possible frequency. The size of the bandwidth tells the model how much of the frequency space is required for the request. By making the range of the allowable frequencies the same as the bandwidth of a request, we can essentially fix that request in frequency.

Likewise, time may be a specific time or a range of values bounded by the lower time limit and the upper time limit. The length of the duration for the request, shown in a separate field, tells the model how much time is required for the request. By making the range of the allowable time the same as the duration of a request, we can essentially fix that request in time. The time units in this thesis are whole numbers of an arbitrary time unit.

The request also needs to specify whether it requires a transmitter, a receiver, or both and whether or not the assignment is tolerant of other transmissions on the same frequency. Possible combinations for the Boolean logic flags and the types of request that each could represent are shown in Table 1. Since the fields can be populated using any combination of 1’s and 0’s each request can be tailored to the specific need of the requester. For example, a two-way radio request will normally require the ability to transmit and receive, and does not want any other systems to overlap in frequency. A user would use the same logical flags as the first line of the table. If some frequency overlap is acceptable then the request will be flagged as transmit tolerant and assignments may be made that overlap in frequency, as shown in line 2 of Table 1.

Do Not Transmit frequencies will be unavailable for any transmissions and these will be represented using the three logical flags on the bottom line.

Table 1. Possible Values for Transmit, Receive, and Transmit Tolerant Booleans and Potential Uses

Transmit Boolean	Receive Boolean	Transmit tolerant Boolean	Possible types of request
1	1	0	communication / data link / radar
1	1	1	ES and EA / high power radar
0	1	0	ES / data link receive / satellite or broadcast downlink
1	0	0	EA / datalink transmit / satellite or broadcast uplink
0	1	1	ES
1	0	1	EA
0	0	0	Do Not Transmit / restricted frequencies

Electronic Surveillance (ES) and Electronic Attack (EA)

Inputs for a request are shown in Table 2. For each request, the required fields include transmit Boolean, receive Boolean, transmit tolerant Boolean, lower frequency, upper frequency, bandwidth, lower time, upper time and duration of assignment. The sample request in Table 2 shows that the request is transmit only and is not transmit tolerant. Since the space between the lower frequency limit and the upper frequency limit is equal to the bandwidth, the request is not flexible in frequency. The upper time minus the lower time is 199; since this value is larger than the duration, the start time is flexible up to the 150th time unit.

Table 2. Request Fields with Sample Data for a Communications Request

Transmit	Receive	Transmit Tolerant	Lower Frequency	Upper Frequency	Bandwidth	Lower Time	Upper Time	Duration
1	0	0	1010.25	1010.75	0.5	1	200	50

2. Available Systems

The model schedules several different types of shipboard antennas. These antennas make up the resources that the requests are required to share. In the SPECTRA model, systems are antennas available for use. The minimum required system data is shown in Table 3, and includes the lower frequency, upper frequency, the range of the frequency block, the lower time, and the time horizon. The time horizon represents the total block of time that the system is available to be scheduled. Finally, the system also has transmit and receive Boolean flags that indicate whether the system is capable of transmitting, receiving, or both.

Table 3. Sample System Data

Lower Frequency	Upper Frequency	Range	Transmit	Receive	Lower Time	Upper Time	Time Horizon
1000	2000	1000	1	1	1	200	199

The transmit and receive Boolean flags account for a variety of antenna functions. Antennas are capable of transmitting, receiving, or both based on their unique characteristics. The model is able to schedule several different types of shipboard antennas including the InTop and other legacy antenna systems. The possible variations of transmit and receive, and the types of antennas that could be represented to the model, are shown in Table 4.

Table 4. Modeling System Capabilities

Transmit Boolean	Receive Boolean	Types of Systems or Antenna
0	0	Do Not Transmit System
0	1	ES / satellite dish/ data link / communication / GPS
1	0	EA / data link / satellite dish / communication
1	1	voice communications / radar / two way data

The Do Not Transmit system is a notional system and accepts an unlimited number of requests. The Do Not Transmit requests are deconflicted from all other assigned requests. The user lists sub-dividable antennas as separate systems. Each system can only fulfill one request at a time.

3. Building a Mission

A mission is an assortment of requests grouped together and assigned a priority. The request priorities are numbered 1 through 4. If a request has a priority of 1 then it must be completed along with all other priority 1 requests in order for the mission to be counted as complete. All lower priority requests 2, 3, and 4 are treated as having a value that is based on their priority, but are not considered to be required for the mission to be completed. If a request is required for a mission then it must have a priority of 1 or it will be given the same weight as all of the other requests of that same priority.

Two sample missions are shown in Table 5. Mission EX1 has five requests. Requests r1 and r2 are priority 1; therefore, they are required for the completion of mission EX1. Requests r3, r4, and r5 are not required for mission completion. Requests r3 and r4 will have priority over request r5. Mission EX1 is given an overall priority of 1 and will be given priority over all non-priority 1 missions.

Table 5. Two Missions with Mission Priorities and Request Priorities

Mission Name	Mission Priority	Request Number	Request Priority
EX1	1	r1	1
		r2	1
		r3	2
		r4	2
		r5	3
EX2	2	r6	1
		r7	1
		r8	2
		r9	3
		r10	4
		r11	4

A more complete list of request data for a separate mission set is shown in Table 6. Each request will contain all of the fields shown. The table shows two missions. The first mission is composed of two requests, but only the first request is required for completion of the mission. The request r3 is part of another mission EX4 and has a lower reward value than the required assignments from the priority 1 missions.

Table 6. Full Table of Request Data Including Mission Name, Mission Priority, Request Number, and Request Priority

Mission Name	Mission Priority	Request Number	Request Priority	Transmit	Receive	Transmit Tolerant	Lower Frequency	Upper Frequency	Bandwidth	Lower Time	Upper Time	Duration
EX3	1	r1	1	1	0	0	1010.25	1010.75	0.5	1	200	50
EX3	1	r2	2	1	0	0	1010.25	1010.75	0.5	1	200	50
EX4	2	r3	1	1	0	0	1010.25	1010.75	0.5	1	200	50

4. Reward Function Values

The reward value for individual requests is shown in Table 7. These are the starting reward levels for each request if an assignment is made to a system. A reward value of 4 is rewarded to a priority 1 request, 3 to a priority 2 request, 2 to a priority 3 request, and 1 to a priority 4 request. This value is divided by 2.5, the midpoint between 1 and 4.

Table 7. Reward Values by Request Priority

Request Priority	Reward Value	Number Required to Equal Priority 1
1	1.6	1
2	1.2	1+
3	0.8	2
4	0.4	4

Scoring is designed such that an accumulation of requests will always have a lesser reward than the completion of any single mission and is described as follows. After the complete list of missions is constructed the reward values for the missions are constructed. The request reward values are the basis for the creation of the mission completion reward values. The total reward value for the lowest priority missions is set at the sum of all of the requests for the lowest mission priority increased by a value of 10.

$$EX5 = r21 + r22 + r23 + r24 + 10 = 13.6$$

The next highest priority missions are the summation of all of the mission completion values of the lower tier missions added to the sum of the request values in the current tier with an additional 10 points added.

$$EX4 = EX3 = EX5 + r12 + r13 + r14 + r15 + r16 + r17 + r18 + r19 + r20 + 10 = 34.4$$

This process continues until the reward value for mission priority 1 is set.

$$EX2 = EX3 + EX4 + EX5 + r6 + r7 + r8 + r9 + r10 + r11 + 10 = 98.4$$
$$EX1 = EX2 + EX3 + EX4 + EX5 + r1 + r2 + r3 + r4 + r5 + 10 = 183.6$$

A sample reward table is shown in Table 8. The highlighted requests indicate the required requests for the mission completion reward to be assessed.

Table 8. Sample Reward Table

Mission Name	Mission Priority	Mission Reward	Request Number	Request Priority	Request Reward
EX1	1	183.6	r1	1	1.6
			r2	1	1.6
			r3	2	1.2
			r4	2	1.2
			r5	3	0.8
EX2	2	98.4	r6	1	1.6
			r7	1	1.6
			r8	2	1.2
			r9	3	0.8
			r10	4	0.4
			r11	4	0.4
EX3	3	34.4	r12	1	1.6
			r13	1	1.6
			r14	3	0.8
			r15	4	0.4
			r16	4	0.4
EX4	3	34.4	r17	1	1.6
			r18	1	1.6
			r19	1	1.6
			r20	2	1.2
EX5	4	13.6	r21	1	1.6
			r22	3	0.8
			r23	4	0.4
			r24	3	0.8

Two missions at the same mission priority will be awarded the same number of points for completion. The reward for mission completion will be awarded if all of the priority one requests for that mission are assigned. Resultantly, the optimization may squeeze out equally scored missions with a higher number of requirements in lieu of achieving multiple missions with the same systems. Individual rewards for other lower priority requests will be available for assignment, but will never exceed the value for the required requests for mission completion.

This reward structure prevents any combination of reward from lower tiers from becoming larger than the reward for the completion of a higher tier mission. It also allows additional requests to be assigned if additional systems are available only after the required assignments are made for each mission. If any systems are available after missions are completed, they will be assigned to requests with the highest request priority without regard to mission association.

The model is designed to perform each of the tasks listed in Table 9 and was tested using a series of small tests designed to verify that each of the goals listed was accomplished. The results of these tests are listed in the last column. The model testing criteria will show the ability of the model to organize and prioritize the requests according to a prioritization and reward scheme that allows commanders to ensure that missions and elements of a mission that are required are fulfilled before the model attempts to fulfill lower priority missions and requests.

Table 9. List of Tests for SPECTRA

SPECTRA Model Goal	Test Conditions	Expected Output	Result
Deconflict frequency	Two requests at the same time with same frequency window	Make both assignments on non-overlapping frequencies	Success
Deconflict frequency	Two requests at the same time with limited systems	Make the assignment to the request with highest priority	Success
Deconflict time	Two requests on same frequency with flexible time and limited duration	Shift starting time to accommodate both requests	Success
Deconflict time	Two requests on same frequency with flexible time and limited duration and limited systems	Make the assignment with highest priority	Success
Assign transmit request to transmit capable system	Transmit request and transmit capable system	Make assignment to system	Success
Assign receive request to receive capable system	Assign receive request to system capable of receiving	Make assignment to system	Success
Assign transcieve request correctly	Transcieve request with whip antenna	Make 1 transcieve assignment to whip system	Success
Assign transcieve request correctly	Transcieve request with InTop antenna	Make two assignments to InTop-one; transmit and one receive	Success
Prevent transmit assignment to restricted frequencies	One transmit request and one Do Not Transmit request on same frequency	Only allow the Do Not Transmit assignment	Success
Allow receive assignment to restricted frequencies	One receive request and one Do Not Transmit request on same frequency	Allow both assignments to be made	Success
Prioritize missions correctly	Two missions with different priorities and only enough systems to accomplish one of them	Assign the higher priority mission	Success
Prioritize missions and requests correctly	Two missions with different priorities and all secondary requests from the lower priority mission set higher than the secondary requests from primary mission	Assign all of the required from the higher priority mission and all secondary from lower priority mission	Success
Prioritize missions over requests	Two missions with only enough systems to accomplish the required requests from each	No assignments made to secondary requests	Success

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IV. MODEL TESTING

We developed a sample mission set for SPECTRA with 16 missions with 6 restricted frequencies. These 16 missions have various numbers of requests associated with them and are intended to model a typical schedule for a surface ship over ten hours, with 600 time units one minute in duration.

A. BUILDING REQUESTS

The list of requests was generated using frequencies and ranges from the data shown in Table 10. In practice requests would be generated by a user utilizing an interface that started with a broad list of missions areas and would progress through functions and down to the request level. The user could then add or subtract individual requests as required.

Table 10. Request Characteristics Modeled

Function	Unique Characteristics	Frequency Ranges Modeled
navigation and search	wide bandwidth	2700–3100 MHz/ 8500–10550 MHz [1]
air search and surveillance	wide bandwidth	3100–3650 MHz [1]
data link TACAN satellite communications	narrow frequency requirements	full range of frequencies
voice or data transmissions	narrow frequency requirements	117.975–150.8 MHz vhf[2] 328.6–456 MHz uhf[2] satellite systems – full range
electronic surveillance and monitoring	wide frequency requirements/ adversary dependent	full range of frequencies
electronic attack or other transmissions	wide or narrow frequency requirements/ adversary dependent	full range of frequencies
Do Not Transmit restricted frequencies	can be fixed or flexible frequency and time	full range of frequencies

Adapted from: Frequency ranges for radars derived from U.S. Department of Commerce Document Federal Radar Spectrum Requirements (Camacho 2000)[1], Radio frequencies for UHF/VHF are taken from the FCC Online table of Frequency Allocations (2015)[2]

The list of requests is intended to be a demonstration of the model’s capability to handle a wide variety of mission scenarios and system capabilities. The flexibility of the model and its ability to accommodate larger and more complicated applications will be demonstrated by this problem.

B. MODELING ANTENNAS

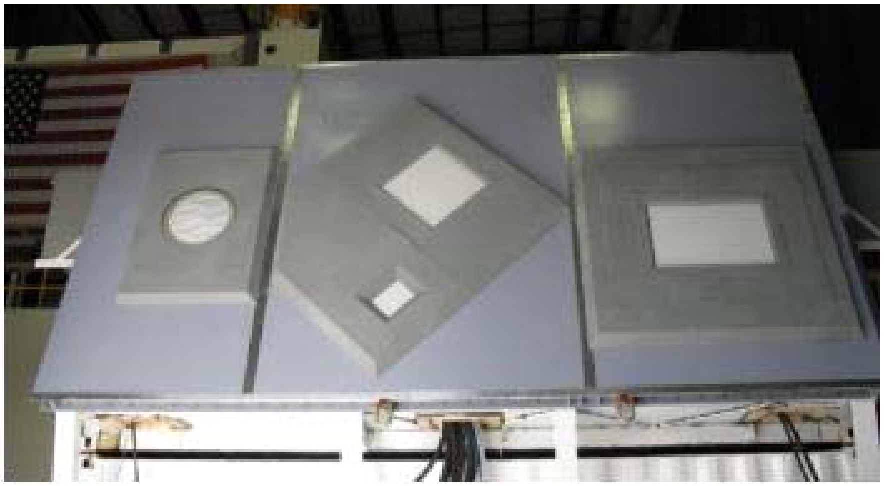
The model is generalizable to include several types of antenna systems including those that have wide frequency ranges and multiple sub-transmitters and receivers; however, the model is also able to schedule tasks for existing systems. Even systems that are not able to be reprogrammed rapidly can be deconflicted in frequency from the transmissions from other systems that are readily reprogrammable.

1. InTop Multifunction Antenna

The InTop program contains a variety of multifunction antennas. The Figure 2 is a picture of the Advanced Development Model (ADM) prototype of the antenna configuration that was used for this model. Each array is capable of only transmitting or receiving; therefore, each subsystem is capable of only transmitting or receiving. If a request requires transmission and reception then it must be assigned to two sub-arrays one located on the transmission sub-array and one on the receiving sub-array.

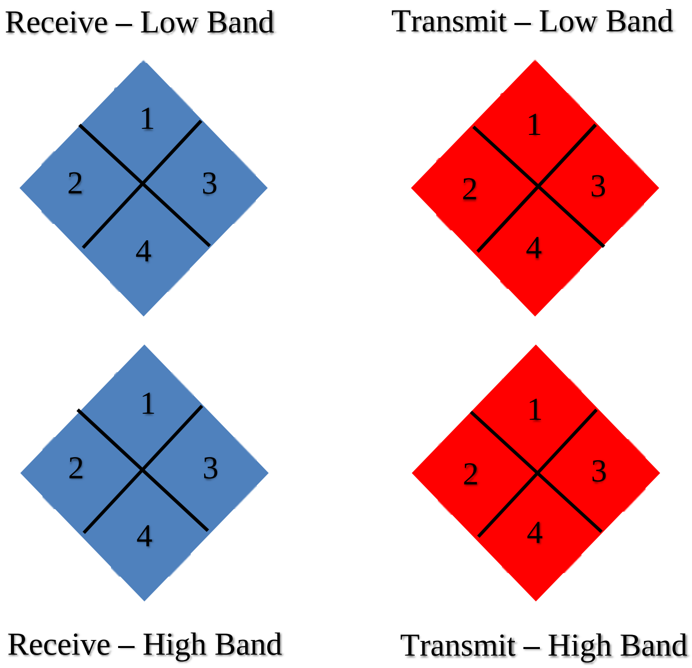
For the purpose of this thesis, a simplified proof of concept model is used that consists of four arrays, two transmit and two receive that operate over an arbitrary frequency range of 1–8 GHz. The four arrays are further divided into two low band (1–4 GHz) and two high band (4–8 GHz) units. Each band has a separate transmit and receive array. Each array is further divided into four sub-arrays that are individually assignable. Conveniently, the number of sub-arrays and frequency ranges can be represented in the SPECTRA model to accommodate any actual system specifications. This simplified model is depicted in Figure 3.

Figure 2. Prototype of InTop Multifunction Advanced Development Model (ADM) Antenna



Source: Office of Naval Research. 2015. Integrated Topside (InTop) & Electromagnetic Maneuver Warfare Command & Control (EMC^2). Power Point Brief, 5 May.

Figure 3. Simplified Model of InTop ADM Antennas with Sub-arrays



2. Legacy Systems

The model is capable of scheduling services for existing antennas. These include radio communication, radar, and satellite antennas. A wire whip antenna is designed primarily for voice communications and is capable of both transmitting and receiving. The transmission and receiving assignments for traditional voice communications are not intended to be conducted simultaneously they normally default to receive and switch to transmit only when it is required. Thus, one transcieve voice communication assignment can be accomplished by one whip antenna, by two sub-arrays using the InTop antenna, or a combination of whip and InTop. If a communication system is full duplex and requires separate dedicated transmit and receive frequencies it can be represented to the model as two requests—one transmit request and one receive request—which would preclude the assignment to a single whip antenna. The full table of antennas and characteristics are listed in Table 11.

Table 11. Antenna Systems Modeled, Number of Systems and Capabilities

System	Abbreviation	Number of Arrays	Number of Sub-arrays	Transmit	Receive
InTop Antenna Transmit Low	TX_LOW	1	4	Yes	No
InTop Antenna Receive Low	RX_LOW	1	4	No	Yes
InTop Antenna Transmit High	TX_HIGH	1	4	Yes	No
InTop Antenna Receive High	RX_HIGH	1	4	No	Yes
Whip Antenna	WHIP	11	1	Yes	Yes
Satellite Dish	SAT	4	1	No	Yes
Radar Navigation	RAD_LOW	1	1	Yes	Yes
Do Not Transmit	DNT	1	Infinite	No	No
Total Systems Available		33			

Systems included in test case.

C. COMPILING MISSIONS

The missions are composed of two parts the first part is a two letter abbreviation followed by a number. The categories selected for this sample problem were surface search (SS), air warfare (AW), data transmission (DT), communications (CM), electronic surveillance (ES), electronic attack (EA), and restricted frequencies (RF). The model is capable of handling any naming convention and there is no limit to the number of names or types of missions.

The frequency ranges of the requests are based on the ranges of real systems, but the model is flexible and works within the limits of each system and the limits presented by the request. The systems modeled and the frequency ranges used in the sample problem are shown in Table 12. Missions CM6, CM7, and DT3 demonstrate that frequencies can be deconflicted from all ships missions and used by other assets operating around the warship.

Table 12. Composition of Mission Types, Requests Per Mission and Priorities of Missions

Mission	Mission Code	Number of requests	Modeled After	Mission Priority
Communication	CM1	1	Bridge to bridge radio	1
Communication	CM2	6	Single aircraft radio	1
Communication	CM3	4	Helicopter radio	1
Data Transmission	DT1	2	Separate transmit and receive data signals	1
Communication	CM6	4	Air-to-air and air-to-ship data link*	1
Communication	CM7	2	Air to air communications*	1
Data Transmission	DT3	2	Two data transmissions*	1
Restricted Frequencies	RF1	6	Do not transmit radio frequencies*	1
Air Warfare	AW1	3	Air search radar	2
Surface Search	SS1	1	Surface search radar	2
Communication	CM4	8	Multiple aircraft radios	2
Communication	CM5	5	Helicopters with data-link	3
Data Transmission	DT2	3	Three data signals	3
Air Warfare	AW2	1	Aeronautical radio navigation signal (TACAN)	3
Electronic Surveillance	ES1	1	Electronic surveillance	4
Electronic Attack	EA1	1	Electronic attack	4
Total Requests		50	Total Missions by Priority	8 / 3 / 3 / 2 = 16 Total

*Missions include Do Not Transmit frequencies.

D. TEST RESULTS

The test case included 50 requests (full listing in the Appendix). Thirty-three systems from Table 11 and the missions listed in Table 12 were scheduled using a laptop using General Algebraic Modeling System (GAMS) Integrated Development Environment (IDE) Release 24.5.6 r55090 WEX-WEI x86 for a 64bit processor with a Windows 10 operating system on with a 2.40 GHz Intel Core i7-4700HQ processor with 12 GB of RAM. The total solve time using a CPLEX solver to reach an optimal solution was 17.94 seconds. The solve time for most of the test cases was less than 1 second using the same setup. The standard solve time for a simple mission with few restrictions demonstrates that an emergency switch of assignments due to a change in priorities from low to high can be accomplished in a very short period of time. The model can recommend frequencies quickly should the need arise.

The calculated reward values for this mission set are listed in Table 13. Table 14 is a summary of the output from the model, which lists the schedule of completed requests, antenna, frequency, and start time of all of the accomplished requests. All of the eight priority 1 missions were completed, while two of the three priority 2 missions were completed: one priority 2 mission was not completed due to lack of systems available or higher priority missions. Half of the priority 3 and half of the priority 4 missions were completed; those not completed were also due to lack of resources available or higher priority missions taking precedence.

Table 13. Mission Reward Values for Missions

Mission Priority	Reward
1	734.4
2	228.8
3	50.4
4	13.2

Table 14. Final Output of SPECTRA

Request Number	Antenna	Frequency	Start Time	Request Number	Antenna	Frequency	Start Time
r1	TX_LOW_1_1	1010.25	1	r27	TX_LOW_1_3	1289	66
r2	WHIP_5_1	455	1	r27	RX_LOW_2_4		
r3	WHIP_4_1	455	150	r28	TX_LOW_1_3	1289	140
r4	WHIP_10_1	149.8	1	r28	RX_LOW_2_4		
r5	WHIP_6_1	149.8	180	r31	TX_LOW_1_2	1800	570
r6	WHIP_4_1	149.8	1	r31	RX_LOW_2_3		
r8	WHIP_1_1	450	1	r32	TX_LOW_1_3	1011.25	1
r9	WHIP_9_1	402	1	r32	RX_LOW_2_4		
r10	WHIP_11_1	402	56	r33	TX_LOW_1_3	1011.25	170
r11	SAT_12_1	402	170	r33	RX_LOW_2_4		
r12	WHIP_2_1	402	1	r37	TX_LOW_1_3	1011.25	105
r13	TX_LOW_1_3	1231	11	r37	RX_LOW_2_4		
r14	DNT_0_0	1299	170	r38	RX_LOW_2_4	1290	110
r15	DNT_0_0	1200	1	r42	TX_LOW_1_4	1101	1
r16	DNT_0_0	1200	1	r42	RX_LOW_2_2		
r17	DNT_0_0	1200	1	r43	DNT_0_0	1000	1
r18	DNT_0_0	1200	1	r44	DNT_0_0	1200	1
r19	DNT_0_0	1200	1	r45	DNT_0_0	1400	1
r20	RAD_LOW	3050	1	r46	DNT_0_0	1600	1
r21	TX_LOW_1_2	1201	1	r47	DNT_0_0	1603	1
r21	RX_LOW_2_1			r48	DNT_0_0	1100	1
r23	RX_LOW_2_3	1126	1	r49	WHIP_3_1	150	1

Incomplete requests: r7, r22, r24, r25, r26, r29, r30, r34, r35, r36, r39, r40, r41, and r50.

E. SPECIAL REQUESTS

The model is capable of handling requests from both internal and external entities. A mission can be generated at a remote location as easily as onboard the ship. The user inputs the mission into the request queue with a mission priority and then runs SPECTRA to evaluate if the new mission can be accommodated. The model produces a schedule according to the mission priority assigned and also makes additional allocations if resources are available. This process deconflicts externally produced missions from internally generated missions.

The request text is shown in Table 15 and can be reduced to approximately 520 bytes of information. It contains a list of 10 requests of mission priority 4, with request priority of 1—meaning that individual requests would compete well for “scraps” of available resources. Using this structure high priority requests can be accomplished without interfering with the resources necessary for the completion of the ship’s regular missions.

Table 15. Sample Special Mission

Mission	Request	Mission Priority	Request Priority	Transmit	Receive	Transmit Tolerant	Lower Frequency	Upper Frequency	Bandwidth	Lower Time	Upper Time	Duration
SP1	r1	4	1	0	1	1	103.1	103.2	0.1	1	200	199
SP1	r2	4	1	0	1	1	100.2	100.3	0.1	1	200	199
SP1	r3	4	1	0	1	1	96.3	96.4	0.1	1	200	199
SP1	r4	4	1	0	1	1	90.5	90.6	0.1	1	200	199
SP1	r5	4	1	0	1	1	99.8	99.9	0.1	1	200	199
SP1	r6	4	1	0	1	1	92.6	92.7	0.1	1	200	199
SP1	r7	4	1	0	1	1	101.7	101.8	0.1	1	200	199
SP1	r8	4	1	0	1	1	95.5	95.6	0.1	1	200	199
SP1	r9	4	1	0	1	1	97.9	98.0	0.1	1	200	199
SP1	r10	4	1	0	1	1	92.4	92.5	0.1	1	200	199

The special requests were added to the test mission and the model was rerun to see if any of the special requests could be accomplished. The model completed in 20.47 seconds and was able to schedule 3 of the 10 requests on resources that were previously assigned to lower priority requests. Each of the required requests from each mission were completed and the list of completed missions did not change from the previous iteration. These higher priority requests were accomplished without compromising the set of required missions.

V. EXTENSIONS, FUTURE WORK, AND CONCLUSION

A. MULTI-SHIP FREQUENCY DECONFLICTION

The model is capable of providing a frequency deconfliction plan for large groups of ships conducting coordinated operations or within close proximity of one another. The process of ensuring that the correct numbers and types of requests are fulfilled is a matter of presenting the data to the model using included features.

When an aircraft carrier is working with another smaller ship, the aircraft carrier is almost always the highest priority platform and has priority in frequency choices over other US ships operating in its area. The mission planners on the aircraft carrier build missions that allocate all required requests between the carrier and the smaller ships. For example, data links, bridge to bridge radio, and helicopter inflight frequencies could all be set as required requests for a battle group (BG1) mission. The carrier would then run the SPECTRA model and the required frequencies would be allocated to systems that the carrier had onboard.

The carrier would then transmit these same shared frequency allocations from BG1 to the other ship along with all of the other frequencies allocated to the carrier that are not transmit tolerant. The mission BG1 would be imported to the smaller ships SPECTRA model with an appropriate mission priority. The remaining assignments would be imported as Do Not Transmit requests. The smaller ships SPECTRA model would then allocate missions that it needed to perform along with the carrier coordination mission BG1 and the output would produce a frequency deconflicted schedule that accommodated the coordination mission with the carrier and the commander’s other missions.

B. AIRBORNE PLATFORMS

The model is generalizable to airborne platforms as well. Missions, requests, and systems available can be presented to the model using the same format and the output will provide a frequency deconflicted schedule for onboard systems in addition to providing allocations for onboard antennas.

C. LAND-BASED FREQUENCY SCHEDULING SYSTEM

The model is also capable of deconflicting frequencies at shore facilities. The basic structure of the inputs to the model would remain the same. Requests are demands for frequencies and the systems, whether real or notional, would represent the number of available allocations. Missions can be used to prioritize groups of requests or all missions and requests can be set at the same priority. The available system queue can be expanded to contain a list of actual systems available or notional systems with the correct parameters.

If a spectrum controlling authority required 10 frequencies that are deconflicted from each other they could be presented to the model as 10 Do Not Transmit frequencies with the full lower frequency to upper frequency range and an appropriate bandwidth size. The model will produce a list of 10 frequencies that do not interfere with each other or any other frequencies already allocated in their area. Those 10 frequencies would be available for distribution to whomever the controlling authority desires.

D. FUTURE WORK

The model could be made to prioritize persistence of frequencies after it has already provided a solution. In many cases it would be advantageous to be able to make adjustments while minimizing the number of changes to frequency allocations from a previous iteration. The reward function and formulation can be adjusted so that only systems that can be rapidly changed are allowed to move while systems that are more time consuming to adjust are not moved. In many cases there will be frequencies that cannot be changed without a great deal of coordination. This might make changes infeasible and once a schedule is set it should not be changed. The format of the request can accommodate inflexible frequencies or could be adjusted to heavily penalize any changes.

The formulation of the model can be expanded to accommodate detailed technical requirements. Requests can specify transmission polarity, power requirements, direction, beam elevation, relative azimuth, and antenna separation rules. For example, an antenna with multiple sub-arrays might be designed to allocate to arrays 1, 3, 2, and then 4 in order to perform optimally. These details would take advantage of the more complex capabilities of a beam steering multifunction antenna with multiple sub-arrays. The system resources will also contain these additional fields of information so that requests are matched to systems that are capable of performing the exact functions required. They would also account for the differences in polarity between a communication antenna and a radar antenna for example and be able to take advantage of low power transmissions to avoid interference or minimize own ship's electronic signature.

Mounting planar arrays in quadrants allows them to transmit 360 degrees; however, the formulation would change if requests were limited to particular sectors. The ability to add directionality will increase the numbers of requests completed and reduce the total amount of energy transmitted. It could also prevent signals from being intercepted by anyone other than the intended recipient.

E. CONCLUSION

The goals expressed in the Knowledge Based Systems, Inc. study conducted in 2009 could be achieved by integrating SPECTRA with antennas in the InTop program. The integer linear program discussed in this thesis is capable of optimizing across all of the available resources and demands simultaneously. SPECTRA has the ability to include priorities by using a reward system that places a high value on high priority missions. This reward system was able to maximize the amount of requests accomplished. SPECTRA is also capable of providing provable optimal solutions. SPECTRA is able to leverage the speed of simplex solvers and, in most cases, to produce solutions in a few seconds. This speed can be leveraged to minimize the time required to maneuver in the spectrum which, when matched with a capability to rapidly switch frequencies, will reduce the overall time it takes to react to a changing electromagnetic environment. SPECTRA is able to provide management for the entire spectrum and can accept administrative restrictions from external and internal sources. SPECTRA has the ability to make allocations across the entire spectrum resulting in the ability to efficiently schedule the spectrums use.

SPECTRA accomplishes these goals at minimum cost to the government. The basic features of the model can be expanded to include additional rules that are particular to any naval platform including warships, airships, and ground sites. Any application that requires the management of the electromagnetic spectrum and requires frequency deconfliction, a rapid solve time, and the ability to find new solutions to a changing environment can utilize the basic features in this model as a starting point for the development of a platform or mission specific program. The model could be greatly enhanced if the inputs were automated or near real time data was available as an input to the program.

APPENDIX

The complete request data set is shown in Table 16. It includes a combination of all four types of fixed and flexible requests. It also contains more realistic frequency ranges although the total range of the model is only limited by the frequency ranges of the systems available. The data set for systems available is shown in Table 17 and includes a multifunction InTop antenna, several whip antennas, satellite dish antennas, and a super high frequency radar antenna. Table 18 provides a list of the missions that were completed and Table 19 lists the requests that were filled.

Table 16. Request Data

Mission	Request	Mission Priority	Request Priority	Transmit	Receive	Transmit Tolerant	Lower Frequency	Upper Frequency	Bandwidth	Lower Time	Upper Time	Duration
CM1	R1	1	1	1	0	0	1010.25	1010.75	0.5	1	200	199
CM2	R2	1	1	1	1	1	117.975	456	1	1	200	20
CM2	R3	1	2	1	1	1	117.975	456	1	1	200	20
CM2	R4	1	2	1	1	1	117.975	150.8	1	1	200	20
CM2	R5	1	2	1	1	1	117.975	150.8	1	1	200	20
CM2	R6	1	2	1	1	1	117.975	150.8	1	1	200	20
CM2	R7	1	2	0	1	0	9000	9001	1	1	600	600
CM3	R8	1	1	0	1	1	100	500	50	1	600	599
CM3	R9	1	2	1	0	1	402	403	1	1	200	5
CM3	R10	1	2	1	0	1	402	403	1	1	200	10
CM3	R11	1	2	1	0	1	402	403	1	1	200	30
DT1	R12	1	1	1	0	1	402	403	1	1	200	10
DT1	R13	1	2	1	0	0	1100	1300	5	1	200	55
RF1	R14	1	1	0	0	0	1280	1300	1	1	200	30
RF1	R15	1	1	0	0	0	1200	1300	1	1	200	199
RF1	R16	1	1	0	0	0	1200	1300	1	1	200	199
RF1	R17	1	1	0	0	0	1200	1300	1	1	200	199
RF1	R18	1	1	0	0	0	1200	1300	1	1	200	199
RF1	R19	1	1	0	0	0	1200	1300	1	1	200	199
SS1	R20	2	1	1	1	1	3050	3070	20	1	600	599
AW1	R21	2	1	1	1	1	1100	1300	30	1	200	199
AW1	R22	2	2	1	1	1	1100	1300	5	1	200	199
AW1	R23	2	3	0	1	0	1100	1300	5	1	200	199

CM4	R24	2	1	1	0	1	1500	1800	20	1	600	599
CM4	R25	2	1	1	0	1	1700	1900	50	1	600	599
CM4	R26	2	1	1	0	1	1700	1900	50	1	600	599
CM4	R27	2	1	1	1	1	1280	1300	10	1	200	30
CM4	R28	2	1	1	1	1	1280	1300	10	1	200	30
CM4	R29	2	1	1	1	1	1100	1300	1	1	200	199
CM4	R30	2	2	1	1	1	1100	1300	1	1	200	199
CM4	R31	2	3	1	1	1	1800	1900	100	530	600	30
CM5	R32	3	1	1	1	1	1011.25	1011.5	0.25	1	200	10
CM5	R33	3	1	1	1	1	1011.25	1012.5	0.25	1	200	30
CM5	R34	3	2	1	1	1	1100	1300	1	1	200	199
CM5	R35	3	2	1	1	1	1100	1300	1	1	200	199
CM5	R36	3	2	1	1	1	1100	1300	1	1	200	199
DT2	R37	3	1	1	1	1	1011.25	1011.5	0.25	1	200	5
DT2	R38	3	4	0	1	0	1280	1300	10	1	200	30
DT2	R39	3	3	1	0	1	1010.25	1010.75	0.5	1	200	199
AW2	R40	3	1	1	0	1	1500	1800	20	1	600	599
CM6	R41	1	2	1	1	1	1500	1800	20	1	600	599
CM6	R42	1	1	1	1	1	1100	1150	25	1	200	199
CM6	R43	1	1	0	0	0	1000	1001	1	1	200	199
CM6	R44	1	1	0	0	0	1200	1201	1	1	200	199
CM7	R45	1	1	0	0	0	1400	1401	1	1	200	199
CM7	R46	1	1	0	0	0	1600	1601	1	1	200	199
DT3	R47	1	1	0	0	0	1603	1604	1	1	200	199
DT3	R48	1	1	0	0	0	1100	1101	1	1	200	199
ES1	R49	4	1	0	1	1	150	350	200	1	200	199
EA1	R50	4	1	1	0	1	9040	9060	20	1	200	199

Table 17. Systems Available

System	Lower Frequency	Upper Frequency	Range	Transmit	Receive	Lower Time	Upper Time	Horizon
DNT_0_0	100	10000	9900	0	0	1	600	600
TX_LOW_1_1	1000	4000	3000	1	0	1	600	600
TX_LOW_1_2	1000	4000	3000	1	0	1	600	600
TX_LOW_1_3	1000	4000	3000	1	0	1	600	600
TX_LOW_1_4	1000	4000	3000	1	0	1	600	600
RX_LOW_2_1	1000	4000	3000	0	1	1	600	600
RX_LOW_2_2	1000	4000	3000	0	1	1	600	600
RX_LOW_2_3	1000	4000	3000	0	1	1	600	600
RX_LOW_2_4	1000	4000	3000	0	1	1	600	600
TX_HIGH_3_1	4000	8000	4000	1	0	1	600	600
TX_HIGH_3_2	4000	8000	4000	1	0	1	600	600
TX_HIGH_3_3	4000	8000	4000	1	0	1	600	600
TX_HIGH_3_4	4000	8000	4000	1	0	1	600	600
RX_HIGH_4_1	4000	8000	4000	0	1	1	600	600
RX_HIGH_4_2	4000	8000	4000	0	1	1	600	600
RX_HIGH_4_3	4000	8000	4000	0	1	1	600	600
RX_HIGH_4_4	4000	8000	4000	0	1	1	600	600
WHIP_1_1	100	500	400	1	1	1	600	600
WHIP_2_1	100	500	400	1	1	1	600	600
WHIP_3_1	100	500	400	1	1	1	600	600
WHIP_4_1	100	500	400	1	1	1	600	600
WHIP_5_1	100	500	400	1	1	1	600	600
WHIP_6_1	100	500	400	1	1	1	600	600
WHIP_7_1	100	500	400	1	1	1	600	600
WHIP_8_1	100	500	400	1	1	1	600	600
WHIP_9_1	100	500	400	1	1	1	600	600
WHIP_10_1	100	500	400	1	1	1	600	600
WHIP_11_1	100	500	400	1	1	1	600	600
SAT_12_1	402	403	1	1	0	1	300	300
SAT_13_1	9000	9001	1	0	1	1	600	600
SAT_14_1	402	403	1	1	0	300	600	300
SAT_15_1	9000	9001	1	0	1	300	600	300
RAD_LOW	3050	3070	20	1	1	1	600	600

Table 18. Missions Completed

CM1	1
CM2	1
CM3	1
DT1	1
RF1	1
SS1	1
AW1	1
CM5	1
DT2	1
CM6	1
CM7	1
DT3	1
ES1	1

Table 19. List of Requests Completed

r1	1
r2	1
r3	1
r4	1
r5	1
r6	1
r8	1
r9	1
r10	1
r11	1
r12	1
r13	1
r14	1
r15	1
r16	1
r17	1
r18	1
r19	1
r20	1
r21	1
r23	1
r27	1
r28	1
r31	1
r32	1
r33	1
r37	1
r38	1
r42	1
r43	1
r44	1
r45	1
r46	1
r47	1
r48	1
r49	1

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