AUTOMATED SPECTRUM PLAN ADVISOR FOR ON-THE-MOVE NETWORKS

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ABSTRACT

Warfighters today face new challenges in accessing the electromagnetic spectrum. These challenges are due to the significant growth in spectrum demands for deployed spectrum dependent systems, increased demand for information and advanced C2 concepts associated with net-centricity and increased competition for spectrum resources from commercial and civil interests. This adds up to near complete spectrum saturation in areas of potential DoD deployment. In addition, the rapid pace of future Net Centric Warfare requires spectrum plans for mission specific demands to be reduced from weeks/days to hours/minutes. The Coalition Joint Spectrum Management Planning Tool (CJSMPT) Program is developing a system for assessing and planning at-the-halt (ATH) and on-the-move (OTM) spectrum use that will give warfighters the ability to rapidly predict conflicts and optimize spectrum utilization for mission success. This paper will describe the technical details of the CJSMPT system and its architecture. Details of the CJSMPT automated spectrum de-confliction algorithms will also be presented. Finally, this paper will discuss the current project status and the current transition plan into military operations.

OBJECTIVES AND APPROACH

CJSMPT is a 27-month Joint Concept Technology Development (JCTD) managed by the U.S. Army CERDEC that began in May 2005. Lockheed Martin Advanced Technology Laboratories (LM ATL) is the prime contractor, working in cooperation with Alion Science, SYColeman, Battle Command Battle Lab (BCBL), Fort Gordon, Joint Spectrum Center (JSC) and Penn State University. During the first 11 months of the Program, CJSMPT is developing spectrum management and planning capability to mitigate the effects of Electronic Warfare (EW) operations on Blue military systems during maneuver operations. Developing the capability to perform efficient spectrum management through an automated spectrum management-planning tool is the long-term objective. Although CJSMPT is adaptable to multiple communications programs, present and future, early insertion opportunities include Warfighter's Information Network-Tactical (WIN-T).

The spectrum for battlefield networks is currently managed by a number of software tools including: Spectrum XXI, Joint Automated CEOI System (JACS), Automated Communications Engineering Software (ACES), and Battlefield Spectrum Management (BSM). According to the Army Spectrum Management Office (ASMO), these tools do not support current requirements. These tools are suited to an era when systems were less flexible, took longer to configure and operations had a slower operating tempo (OPTEMPO). A critical example, which illustrates the difficulties that now result from these processes, is occurring in combat operations today. Electronic Countermeasures (ECM) missions are planned on a short time scale compared to that used for spectrum management/planning of communications systems. This creates instances of interference to friendly systems from ECM devices. The centralized spectrum management database, Spectrum XXI, is not designed to handle the movement of these ECM (or any other) systems.

As systems become more flexible, more mobile and used in increasing OPTEMPOs, the integration of spectrum management with sophisticated OTM analysis, advanced visualization and spectrum optimization tools is needed to speed the spectrum planning processes to significantly reduce communications interference in the field. Both joint and coalition requirements and constraints must be factored into the planning process. In addition to the tactical challenge, new technology is needed for strategic spectrum planning to determine future spectrum requirements, develop spectrum policy and ensure spectrum supportability and acquisitions throughout the network centric transformation.

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14. ABSTRACT
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The approach taken by CJSMPT addresses the challenges in spectrum planning and management by automating the spectrum planning process, mitigating the problem of spectrum saturation through conflict detection and resolution to maximize spectral reuse. Currently, no tools exist for automatically establishing a conflict free spectrum plan for OTM forces. In addition, current tools do not address the larger problem of allotment and assignment of spectrum throughout and between elements of equipment hierarchy, at the theatre, force levels and component levels. These problems have been attacked by CJSMPT through the use of faster-than-real-time simulation of the environment and mission using a Communications Effects Simulator (CES) to take into account radio and propagation effects like terrain and coupling this with graph theoretic algorithms to enable automated synthesis of a conflict free or near conflict free spectrum plan for the mission duration.

ARCHITECTURAL AND COMPONENT DESCRIPTION

The CJSMPT architecture (Figure 1) is comprised of five key components that coordinate to perform the spectrum management planning and RF de-confliction processes:

- *Spectrum Manager (SM)* coordinates overall operation of the system and executes de-confliction algorithms.
- *Communication Effects Simulator (CES)* simulates anticipated missions to predict conflicts. CES is based on LM ATL CSIM Simulator [1]
- *Visualizor (VIZ)* visualizes spectrum use including EW effects.
- *Spectrum Knowledge Repository (SKR)* contains key scenario data to support simulation of mission (force structure, emitter characteristics, spectrum usage, etc.).
- *Framework* provides open service oriented architecture with mechanisms for component data exchange.

LM ATL is also leading the Army's Communications Planner for Operational and Simulation Effects with Realism (COMPOSER), a CERDEC ATO developing capabilities for the warfighter to enable effects-based communication planning of equipment configuration for forces OTM. As part of this capability, COMPOSER is developing a Communications Effects Simulator (CES), a Visualizor (VIZ), and Spectrum Manager (SM). This technology is being leveraged directly into CJSMPT.

The top-level CJSMPT Spectrum planning and maintenance functions supported by the architecture include: (1) spectrum allotment and assignment; 2) interference prediction and de-confliction; and (3) data base maintenance. The planning process (Figure 2) begins when the operator specifies the Area of Interest (AOI). Information is automatically gathered by the system for the AOI, from the SKR including force structure equipment characteristics, terrain data and the accompanying spectrum requirements of assets that comprise the overall network (i.e., ground, air, space). Other aspects of the scenario involving movement, such as convoy route trajectories, not contained in the SKR are entered manually through the CES scenario generator element. The operator makes a request to Spectrum XXI (via API provided by the SKR) for an allotment of frequencies and attempts to match these available resources to requirements, which formulate a preliminary plan. A preliminary candidate spectrum plan is entered manually or generated based on static approximation and analysis using Spectrum XXI's de-confliction module. The system is required to operate on a common PC Laptop in either standalone mode or distributed mode. In distributed mode, the SM component performs collaboration with other spectrum users and distributes frequency information. The interference prediction function analyzes the plan to determine if, when, and where conflicts occur.

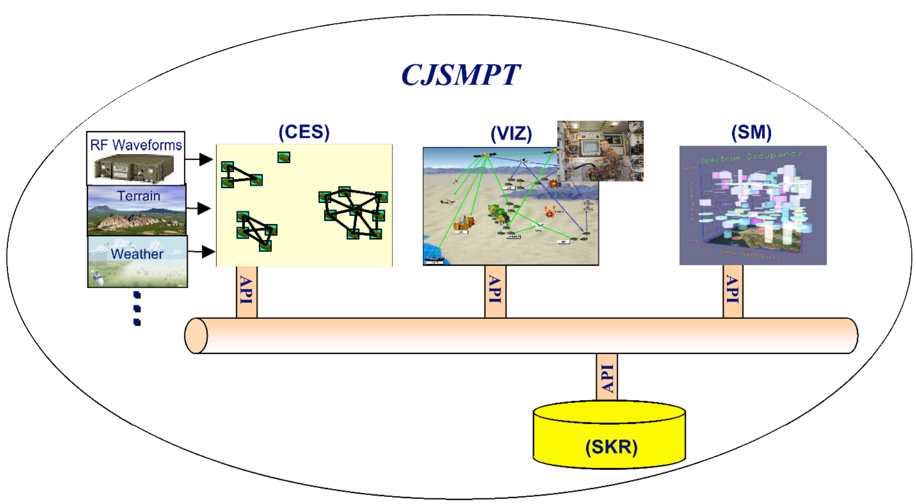

Figure 1. CJSMP Architecture

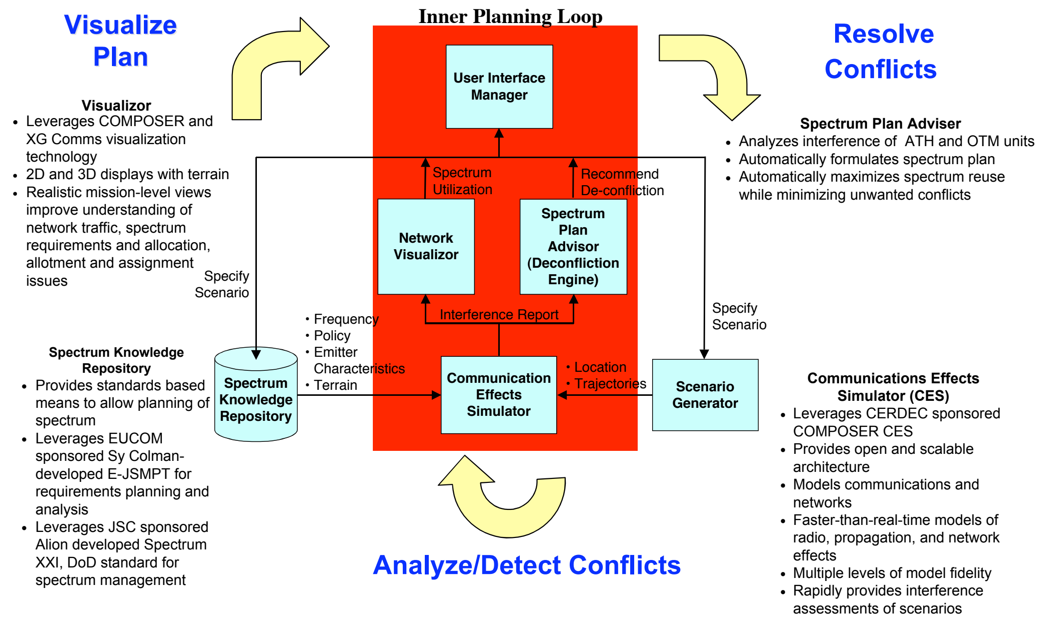

Figure 2. Iterative Simulation-based Deconfliction Process: (1) Define Scenario from Spectrum Knowledge Repository, (2) Analyze Scenario via CES and Visualize Interference Report, (3) Resolve Conflicts via Spectrum Plan Advisor, (4) Re-run CES with Revised Plan and Visualize Results, and (5) Refine Plan as necessary through repeated iterations

This function is performed within the CES. Uncertainty in location is also accounted for within the CES when making the interference predictions. The Spectrum Plan Advisor (SPA) element of the SM performs de-confliction and optimization based on the interference report output by the CES, accounting for anticipated movement (including EW missions) and propagation effects to produce a usable plan. The VIZ displays spectrum use predicted by the CES and assists the operator in the automated spectrum planning and management process. The database maintenance function performs the management of the frequency assignment records.

SPECTRUM PLAN ADVISOR (SPA)

The SPA is at the heart of the CJSMPT Spectrum Planner Tool. Spectrum planning is a multi-dimensional optimization problem, which involves space, time frequency, modulation-code and other dimensions. The SPA contains a suite of algorithms to solve for conflict free (or near conflict free) spectrum plans. The SPA can be used to perform automated allotment or assignment. The rules generated by the SPA specify which nodes can share frequencies and which cannot. If nodes represent individual subnets operating in the same band then the rules degenerate to a vector of indices to lookup frequencies from a list that ensure conflict free operation. However, if nodes represent multiple logical units each containing multiple subnets the rules specify pools of frequencies, which can be then allotted to these logical entities to ensure conflict free operation. Conceptually it is simpler to speak about frequencies rather than rules so in the discussions that follow we consider the degenerate case.

The mathematical field of graph theory provides a useful model of the frequency de-confliction problem. A "graph" is a set of points (called vertices) connected by lines (called edges). We can represent the interference as a graph, in which every vertex represents one node, and every line represents interference causing conflicts between those nodes, where a node represents a communication subnet. The algorithms developed leverage heavily from the field of fixed network spectrum planning (i.e. commercial cellular systems). There is a major difference between the approach being used by CJSMPT and previous work to automatically develop frequency plans for fixed networks. Specifically, the approach being used integrates the occurrence of conflicts over time as nodes move. This requires simulation of the entire mission to gather the interference measures to detect conflicts and produce and an integrated interference graph. The algorithms explored solve the graph-coloring problem. The graph-coloring problem is the problem of assigning a label to each vertex in such a way that no vertex is connected to another vertex with the same label, while minimizing the number of labels. If the edges represent conflicts caused by interference and the labels represent frequencies, then clearly a minimum coloring of an integrated interference graph represents a way to assign a minimum number of frequencies to avoid interference.

The problem of finding an optimum coloring for a graph is computationally hard (NP-hard, meaning no algorithm is known which scales as a polynomial in the number of nodes). We adapted several algorithms, including a known heuristic algorithm from graph theory, and have used them to develop good coloring solutions in a reasonable amount of time to be practical. We also used a mixed-integer linear-programming (MILP) algorithm and ran it long enough on some of the smaller problems to find optimal solutions, to compare with the heuristic approaches. Graph coloring is an example of a constrained optimization problem: the problem is to minimize some objective (the total number of labels or colors) subject to constraints (no two connected nodes should have the same label). The algorithms we studied included general-purpose optimization algorithms as well as some specific to graph coloring:

- *Mixed Integer Linear Program (MILP):* The graph-coloring problem can be formulated as a MILP, a problem where the objectives and constraints are linear in the variables and in which some of the variables are constrained to be integers.
- *Particle Swarm Optimization (PSO):* Particle swarm optimization is inspired by biological models such as swarming insects or birds. Many individual agents "fly" randomly through the search space, with a bias toward whichever member of the swarm currently has the best solution. PSO is an unconstrained optimization algorithm, so the different-coloring requirement (no neighbors the same color) was represented as a penalty term in the fitness function rather than a hard constraint.

In addition we used several graph-theoretic "greedy" (largest-first) heuristics:

- *Single-pass Greedy:* First the nodes are sorted in terms of decreasing number of connections to other nodes (i.e. decreasing amount of interference experienced). The nodes are colored in this order. At each step, all the neighbors are examined. The node is assigned the lowest available color. For example, if there were three neighbors with assigned colors of 0, 1, 2, then the current node would be assigned color 3. (If the neighbors have not been colored, they are not considered). This heuristic is very fast since it takes only a single pass through the nodes.
- *Stochastic Greedy Algorithm, Variant 1:* In this variant, there is a maximum allowed color number. When deciding the color of each node, first the set of numbers from 0 to the maximum are generated, and then those colors already used by a neighbor are deleted. A color is picked at random from the remaining list. The basic greedy algorithm is used on the first pass to set the initial maximum color. At the end of each pass if the total number of colors is less than the previous best coloring, that is taken as the new maximum. Typically the one-pass greedy algorithm solution can be reduced by about a factor of two by 1000 passes.
- *Stochastic Greedy Algorithm, Variant 2:* The coloring algorithm is the same as variant number 1, with new colors chosen randomly from unused colors for each node. However, a different strategy is used to set the maximum color. The user sets a low target and the algorithm runs a number of passes attempting to find a coloring meeting that target. If none is found, the target is relaxed and the search restarted. Early versions of this algorithm did not succeed in finding solutions better than those found with variant 1, and so it was not used for separate tests during the benchmarking runs. However, an improvement was later made and the improved version can find significantly better results in the same amount of time.

An import variant of the basic problem studied was the over constrained assignment problem. This is the most common case expected. In this problem, there is a predetermined maximum color set by the user, so there will probably be some violations (adjacent nodes will have the same color) because there are not enough frequencies to ensure conflict free operation. The idea is to minimize the cost of the violations. The approach in this case is to sort the nodes by the total amount of received interference at each node (this is equivalent to the amount of transmitted interference the node causes other nodes). Stochastic Greedy Algorithm 2 is applied with the user target (no relaxation). If the target is not met, the first node is disconnected from the graph. That is, the interference from the least-interfering node is deleted from consideration. The greedy algorithm is then reattempted. This continues until success is achieved. (There is guaranteed to be a solution eventually. In a worst-case scenario, all of the edges would be erased and then all the nodes could be assigned the same color. In actuality, nowhere near this many edges have to be deleted before a solution is found).

To test the algorithms, a set of benchmark scenarios was created. Each scenario consists of a set of fixed nodes and an interference graph calculated from the initial node positions representing the integrated interference graph. Ten scenarios were generated for each size at 5, 50, 500, and 5000 nodes. The results were averaged. The benchmarks indicate that the stochastic greedy algorithm offers the best combination of good solution, fast runtime and scalability. Given a 5000-node problem the stochastic greedy algorithm finds a conflict free plan in less than 10 minutes. It also produces good quality solutions for smaller problems (on the order of 20-30 seconds for 50 nodes) and can handle arbitrarily large scenarios. Based on the performance results, the Stochastic Greedy algorithm was chosen for use in the baseline SPA. In the future, the SPA could use a combination of algorithms. Simulated results from a typical planning scenario using the SPA (Figure 3) demonstrate the ability to plan for conflict free operation using the developed approach.

SUMMARY AND CONCLUSION

Warfighters today face severe limitations in accessing the electromagnetic spectrum. These limitations are due to the significant growth in spectrum demands for deployed spectrum dependent systems. The challenge to reuse frequencies, minimize interference, and maximize available spectrum is difficult, especially with OTM forces. The CJSMPT program is developing capability for joint and coalition forces to enable optimization of this scarce resource. The CJSMPT architecture being built will address these issues. The core Spectrum Planner Tool comprised of the CES and SM performs simulation-based analysis of the scenario under study. The SM, which contains the SPA, can suggest an optimized plan to minimize conflicts and maximize reuse. The CJSMPT process for conflict detection and de-confliction over a user specified mission duration was presented. The process works for hierarchical architectures, the radio subnets can be comprised of multiple subnets. In addition, a suite of efficient algorithms within the SPA has been assembled to solve the de-confliction problem for on-the-move networks. The SPA has been exercised in simulated scenarios. A summary of test results from the SPA algorithm evaluation scenarios are presented. The SPA has successfully processed a 5000 mobile node scenario and generated a conflict free spectrum plan in less than 10 minutes. Currently de-confliction can take days or weeks for fixed installations and is non-existent for mobile forces. Thus, CJSMPT with the SPA offers the potential for significant improvements over current approaches and will fill an important void in DoD's spectrum transformation capability.

REFERENCES

[1] Lockheed Martin ATL CSIM http://www.atl.lmco.com/proj/csim.

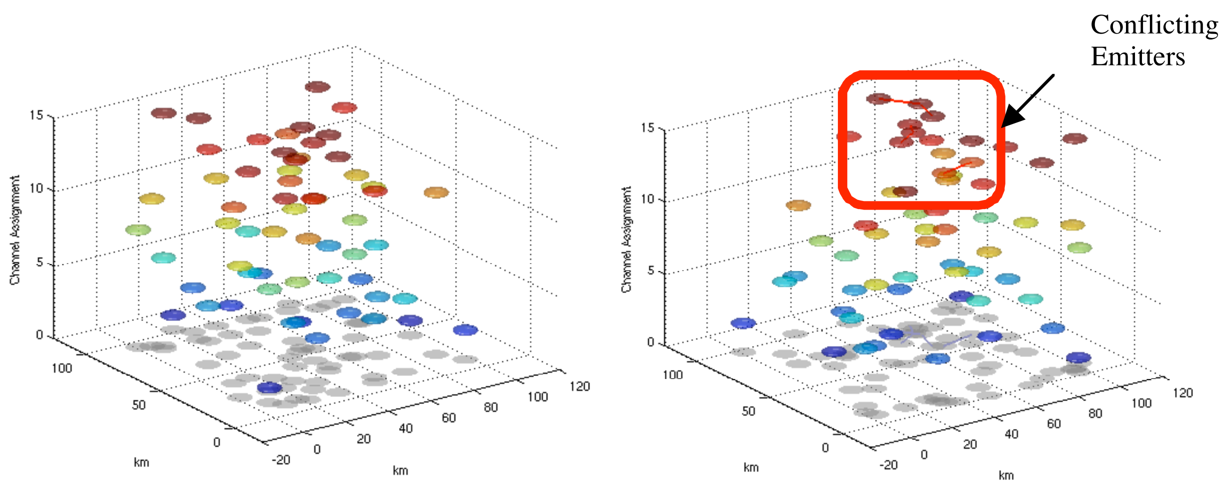

Figure 3. Results from Planning Scenario - show spectrum utilization vs. time-varying location for an automatically generated plan using the SPA (plan generated for 48-hour period, area of operation, 100 x 100km, ~50 mobile nodes representing subnets). The simulation run included time beyond the 48-hour period. The plot (left) shows conflict free operation within the planned 48-hour period showing no conflicts. The plot (right) shows conflicts (red lines) occurring between nodes for the network beyond the 48-hour window due to interference from new movement patterns.