APPLYING COGNITIVE RADIO CONCEPTS TO NEXT GENERATION ELECTRONIC WARFARE

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ABSTRACT

The vision and technological aims of software defined radio (SDR) in general and cognitive radio (CR) in particular are not that dissimilar from those of next generation electronic warfare (EW). CR is about autonomously and cooperatively establishing a specific communication link, while next generation EW is about autonomously observing communication links in order to autonomously and uncooperatively degrade specific communication links of interest. The US Army's Intelligence and Information Warfare Directorate (I2WD) has recently developed and tested an SDR-based prototype system that will go a long way toward providing this capability. Providing next generation capabilities, especially advanced surgical EW techniques, requires advanced autonomous control and scheduling algorithms that can optimize the utilization of available resources, while complying with user defined policies such as target priority and threat level listings. Zeta has developed next generation EW planning and scheduling algorithms for I2WD's platform and validated them with a simulation framework of sufficient fidelity to assess the efficacy of the algorithms. Cognitive radio notions were a key element in creating and developing these algorithms.

1. INTRODUCTION

The vision and technological aims of software defined radio (SDR) in general and cognitive radio (CR) in particular are not that dissimilar from those of modern electronic warfare (EW). SDR is all about a flexible platform that can intelligently manage its own resources. CR has been defined by the SDR Forum as "radio in which communication systems are aware of their environment and internal state and can make decisions about their radio operating behavior based on that information and predefined objectives" [1]. This could just as easily define next generation EW, which will be explained in the next section.

In this paper, we will first lay the groundwork by looking at how the DOD is pursuing SDR and CR for tactical communications as well as establish the basic notions of EW. With this understanding, the motivation for modern EW and the potential for CR inspired notions can be appreciated by considering a recent applied R&D effort of the US Army's Intelligence and Information Warfare Directorate (I2WD). I2WD has developed a system architecture that provides the capability to perform the required EW technique necessary to remove a threat efficiently and improve spectrum management. The author and his team have developed a CR inspired EW "Scheduler" (high level task planning and low level scheduling) as well as a simulation framework for testing the Scheduler and the system. The simulation framework produces measures of effectiveness for both the Scheduler in particular and the system in general. This paper will discuss the overall system hardware (HW) and software (SW) architecture, resource and system awareness, how user policy constrains the autonomous high-level planning and low-level scheduling, the families of algorithms developed, and a brief overview of their performance.

2. YIN YANG OF TACTICAL COMMUNICATIONS

Effective command and control (C2) depends on reliable tactical communications (comms). The goal of EW is to protect friendly C2 and deny the adversary their C2. This is what is called Electromagnetic Spectrum (EMS) Control (EMC), which is to "achieve effective management and coordination of friendly systems while countering adversary systems" [2]. SDR and CR can play key roles in this.

2.1. SDR & CR in Military Tactical Communications

The inflexibility and cost of upgrading tactical radios were the big drivers in SDR for tactical comms over the last couple of decades (cf. Ch. 2 in [3]). The development of SDR in this application domain is well documented in [4] (cf. Ch. 9). The most widely deployed SDR is the Joint Tactical Radio System (JTRS) [5].

While there are many lofty goals for CR (cf. [6, 7]), the initial and key element of CR is dynamic spectrum access (DSA), which is defined by the SDRF as "allowing the systems to select the frequency spectrum in which they will operate at a given location and over a given period of time to optimize the use of available spectrum and avoid interference with other radios or other systems" [8]. Bringing CR into tactical comms has been led largely by a couple of DARPA programs, the neXt Generation (XG) and the Wireless Network After Next (WNAN). The goal of XG was to develop a radio that could adapt and select the environments in which it works best and bring other similar radios into its network. WNAN goes further in creating a flexible architecture for military comms. The key aspect of WNAN is to develop and test an inexpensive handheld SDR that is capable of selecting its own frequencies and forming small networks within a larger battlefield network. [9]

CR notions are making their way into existing military SDRs. Harris has demonstrated DSA capabilities in its Falcon III, which is a fielded JTRS approved hand-held tactical radio system supporting a variety of waveforms [10]. It is interesting to note that at this time there are two non-JTRS military radios challenging the JTRS radio, the WNAN radio by Cobham and Raytheon's BBN Technologies and the SideHat developed by ITT, a unit that can be plugged into the SINCGARS radio to make them compatible with the JTRS Soldier Radio Waveform. This unit was made necessary since the JTRS has been late. The SideHat enables a SINCGARS radio to be compatible with the JTRS network. [11]

2.1. Electronic Warfare & Current Cognitive EW R&D

There are essentially three "pillars" of EW under the overarching EMC introduced in §2 (cf. [2]):

- Electronic Support (ES)—Search for, intercept, identify and locate emitters for the purpose of immediate threat recognition, targeting, planning and conducting of future operations
- Electronic Attack (EA)—Prevent or reduce an enemy's use of the EMS, both non-kinetic (e.g., jamming & EM deception) and kinetic (e.g., anti-radiation missiles); includes both offensive and defensive activities
- Electronic Protection (EP)—Protect personnel, facilities & equipment from effects of friendly or enemy use of the EMS that degrade, neutralize or destroy friendly combat capability; includes EMS management, EM hardening, emission control, etc.

More on each of these topics can be readily obtained from open source technical literature, e.g., titles from Artech House that include [12-15] for comms EW in particular.

Interest in applying CR to EW can be seen in advanced R&D efforts recently undertaken by different military organizations:

- NRL—researching cognitive jamming techniques through the use of an experimental system for automating the search and optimization of comms EA waveforms [16] and now currently working on a DSA vulnerability test bed
- AFRL—recently offered a BAA to develop a "multi-functional, flexible first-generation Cognitive Jammer (CJ) architecture that can be applied towards both near-term and futuristic EW needs" [17]
- DARPA—IPTO just released a CJ program BAA (DARPA-BAA-10-79, "BLADE") and STO released an anti-CJ program BAA (DARPA-BAA-10-74, "CommEx"); these two programs may be used to test each other

2.3. The Yin Yang of Modern Comms & EW

Whereas CR is about autonomously and cooperatively establishing a specific communication link, modern EW is about autonomously observing communication links in order to autonomously and uncooperatively degrade specific communication links of interest. The purposes of CR and EW are in opposition, but when considering the fundamental tenets of CR vis à vis EW in Table 1, it is interesting to see how much they actually have in common. It is clear that CR and EW fundamentally have a lot in common and that using CR notions in EW systems could enable these systems to provide more effective jamming.

Table 1. Comparing CR and EW tenets

CR	EW
Where is there a hole in the spectrum?	Where is there NOT a hole in the spectrum? Is it a signal of interest (SOI)?
Do NOT transmit if a Primary User is in the spectrum	DO transmit if the Primary User is a SOI on a target list
Use the best waveform to MINIMIZE interference	Use the best waveform to MAXIMIZE interference

3. I2WD'S NEXT GENERATION EW PLATFORM

A significant shortfall of legacy and modern EW systems in use today is an inability to execute simultaneous ES and EA missions against a diverse and rich target battlespace such as is instantiated by existing legacy and modern communication systems. The US Army's Intelligence and Information Warfare Directorate (I2WD) recently developed and tested a prototype system that should go a long way toward providing this capability, centered on software (SW) control of dynamically allocated distributed hardware (HW). Such a SW-based architecture, especially when implementing advanced surgical EW techniques in a dynamic RF environment, requires advanced autonomous control and scheduling algorithms that can optimize the utilization of available HW resources, while complying with user defined policies such as target priority and threat level listings. EW tasks are handled as schedulable jobs within the system that are generated dynamically during system execution as new target signals are identified. The Scheduler and Controller must support a background of ES search for situation and target awareness, simultaneous with a foreground of EA tasks. This will need to be performed continuously and on a recurring basis.

4. EW PLATFORM ARCHITECTURE

The logical architecture of I2WD's next generation EW platform is illustrated in Figure 1 (adapted from Figure 2 in [18]). This is a fairly standard tiered architecture, but has been adapted for a platform that has co-located ES (receivers) and EA (transmitters) resources. It is important to understand the perimeter of the Scheduler in order to know what information it will possess to accomplish autonomous planning and scheduling. Managing granularity by abstraction is a key feature of architectures; i.e., layers in the I2WD notional architecture insulate higher level services from the detailed signaling at the lower levels. It allows the creation of complex behaviors at the user or logical layer from having to manage the minutiae at the physical layer.

In this logical architecture, the Scheduler's purview (both input & output) is limited as it should be; it relies on the Controller for situation awareness and resource availability. Because of this principle, the Scheduler does not need to account for the physical layer details, only the sensor and effector services at layer 3 via the Controller.

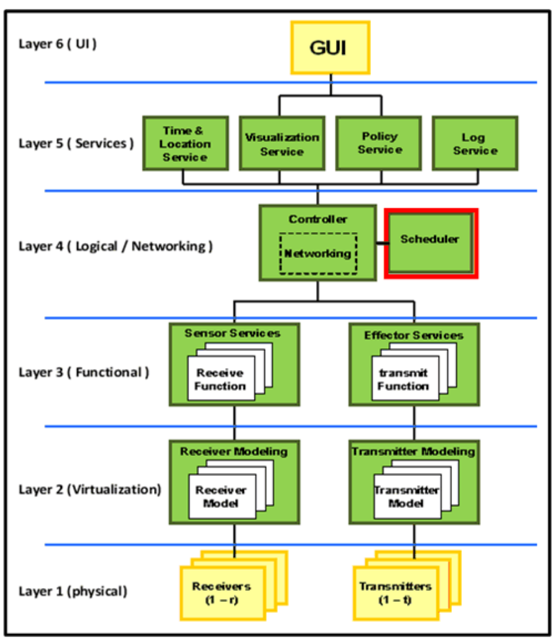

Figure 1. The I2WD architecture with the Scheduler in red

5. SCHEDULER INTERFACES

Understanding where in the I2WD logical architecture the Scheduler resides and its purview, we can expand the interface between the Controller and the Scheduler to highlight the information flow between these two central elements, which is shown in Figure 2.

EW Policy is determined pre-mission and includes the target list and descriptions of the EA techniques along with their efficacy and the scope of their impact. The scope of techniques varies; i.e., some are very intrusive, affecting all users in a given bandwidth, just one user, or something in between. The mission of the user may be stealthy or not, or somewhere in between; hence, techniques are also quantified as to which level of stealth they may be used. Resource Pool (RP) status describes the health and availability of the EA and ES resources. The Situation Awareness (SA) is a report provided by the ES resources as to what is present in the RF environment. The Scheduler consumes these inputs and based on these inputs, plans and schedules EA. The EA schedule is a list of EA tasks along with what EA resource will execute each task and when.

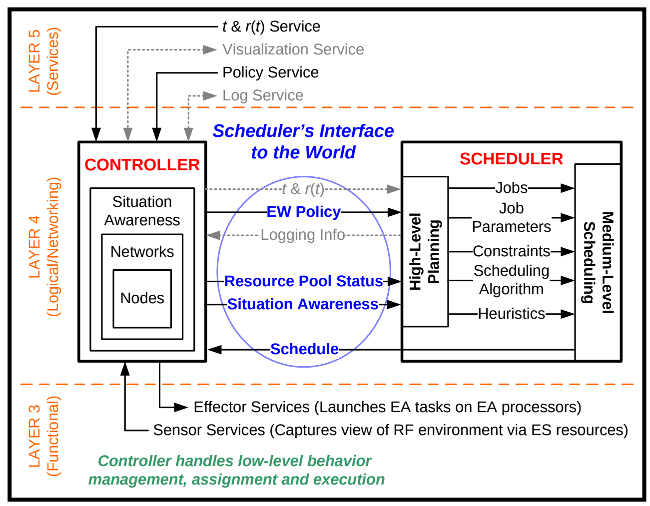

Figure 2. Information flow for the Scheduler

6. PLANNING & SCHEDULING ALGORITHMS

The I2WD next generation EW problem requires a Scheduler that can optimize the mission, i.e., the optimal prosecution of signals of interest (SOIs). Zeta developed two algorithm families, based on a recently published pragmatic approach and one that is based on integrating two theoretic based approaches. The former pragmatic algorithm family is known as "Best Effort" (BE) and is actually an adaptation of the more general HBSS algorithm, which has been effectively deployed and used by NASA with a problem very similar to ours, i.e., oversubscription of sensor services [19-23]. The latter theoretic algorithm family ("AIOR") integrates pragmatic artificial intelligence (AI) based planning with operations research (OR) based scheduling techniques [24-27]. The HBSS has already been used in ad hoc satellite networks by NASA. These algorithm families have been modeled and simulated as described in the following sections. The AIOR performed better than the BE algorithm and comparable to an optimized version of the BE algorithm. Given this and that AIOR offers more flexibility, it will be the focus of the rest of this paper.

The potential space of planning and scheduling states can grow very large quite quickly, depending on how dense the RF battlespace is and the frequency of obtaining SA and launching EA based on same. Frankly, real-world problems quickly overwhelm standard search algorithms, even informed searches. Good heuristics are critical, but hard to find. The key to being able to manage the problem is to take advantage of decomposition, i.e., independent subgoals, which require good insight into the problem domain. For problems of greater complexity than the 8-queens problem, i.e., the I2WD problem, the following AI-based planning concepts proved to be the most effective, i.e., *"Plan first, schedule later"*:

- Plan—Actions are selected and perhaps partially ordered to meet the goals of the problem; i.e., determine which set of EA tasks are optimal for mission success based on the SA and RP
- Schedule—Temporal information is added to ensure that the plan meets resource & deadline constraints; i.e., assign tasks to EA assets in an order that maximizes success, knowing that the plan may exceed the EW "dwell period"

The logic varies somewhat between the variations of each of the two algorithm families, but the essential AI-based cognitive planning and OR-based scheduling logic is illustrated in the flowchart shown in Figure 3. Details on planning and scheduling are provided in Sections 5.1 and 5.2 that follow.

6.1. Planning

Two AI concepts were leveraged to provide the Scheduler with cognitive planning capabilities, hierarchical task planning (HTN) and partial order planning (POP). HTN planning is the most popular way of dealing with complexity because *it works*; it is very tractable and efficient. Plans are refined by "action decompositions," which is to reduce high-level action to partially ordered set of lower-level actions, i.e., a "plan library". EA techniques are developed in the community and can be stored in a library, which can be encapsulated by the Scheduler as an EA POP library where the partial plans are EA techniques pre-loaded in the EW system with known characteristics (execution time, probability of success, resources required, etc.)

ES assets obtain SA after an EA plan has completed. If a given SOI remains, then the Scheduler can use the next EA technique in its POP with the same stealth constraints, having learned that the preceding EA technique was not effective. The planning tends to be aggressive; i.e., the POPs are ordered such that within a given level of stealth the planning algorithm uses the most effective techniques possible, such that the overall attack plan has maximum impact, i.e., the maximum number of SOIs and the most important targets are attacked with the highest probability of success.

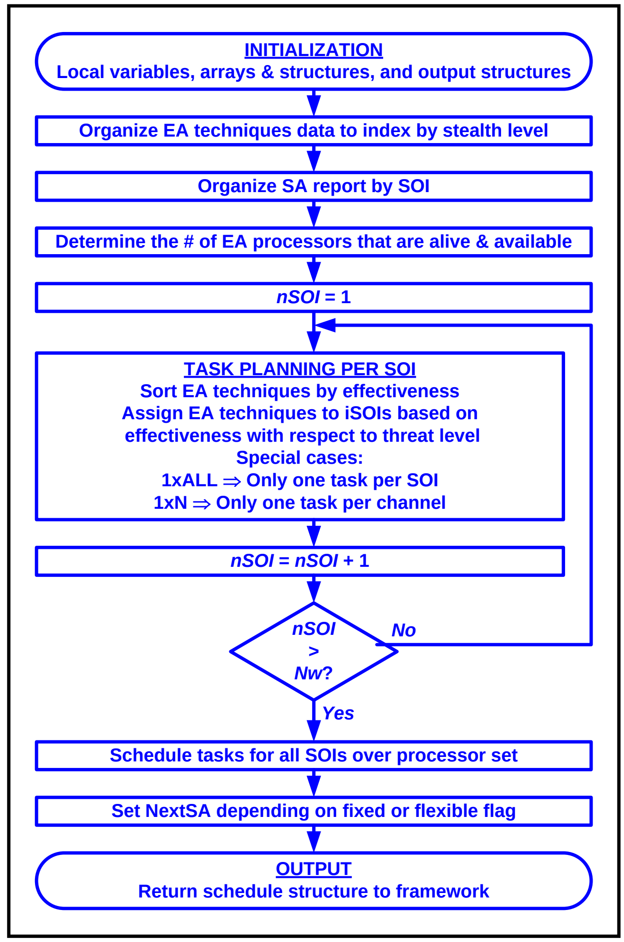

Figure 3. Conceptual flowchart of algorithms

6.2. Scheduling

Planning is determining the selection and ordering of actions to accomplish a goal, while scheduling is determining the sequencing of those actions with respect to time. There are two approaches to solving the scheduling problem:

- Theoretic options—Given a collection of tasks in a given processor environment, sequence those tasks subject to given constraint(s), doing so to optimize some performance criterion(ia); i.e., objective function(s)
- Real world options—Pragmatic approaches that are typically domain specific and heuristic
    - o Composite dispatching rules are heuristically driven rules to determine which jobs run on which processors

- Multi-tiered approaches that decompose scheduling into subschedules
- Reformulative re-scheduling acknowledges that change happens, so deal with it; i.e., be prepared to re-schedule

We ended up integrating these two approaches.

There are three basic elements in the scheduling problem:

- Resources—e.g., EA digital signal generators (DSGs)
- Tasks—e.g., EA jamming waveforms
- Objective—e.g., minimizing last task completion time

Scheduling problem descriptions reduce to three of the same form but with different objective functions and heuristics. Problem descriptions use the standard form of the scheduling problem canon: $\alpha \mid \beta \mid \gamma$, where

- α = "Machine environment"; i.e., the target platform
- β = Processing characteristics & constraints; e.g., precedence, preemption, etc.
- γ = Objective to be optimized

Given the architecture presented in Section 4, our scheduling problem is of the form $Pm \mid \mid \gamma$:

- Pm = *m* processors of the same kind; i.e., a homogeneous suite of EA DSGs
- $\mid \mid$ = no constraints (see following caveat)
- γ = objective to be optimized (explained below)

There actually are some constraints such as setup times, but these can be rolled into the execution time, thus simplifying the problem without loss of efficacy. Relevant objective functions include the following:

- C_{max} = "makespan," which is approximately the completion time of the last EA task; a minimum C_{max} implies good EA resource utilization
- ΣC_j = total completion time, kept preferably to the time when the ES resources must be released to obtain the next SA report
- $\Sigma\, w_j C_j$ = total weighted completion time, where higher priority tasks have a heavier weight to assure they are scheduled

The family of problem descriptions and heuristic strategies used in our Scheduler were the following:

- $Pm \mid \mid C_{max}$ using SPT, WSPT & LPT
- $Pm \mid \mid \Sigma C_j$ using ECT & EST
- $Pm \mid \mid \Sigma w_j C_j$ using ECT & EST

where the heuristics are as follows for the planned tasks to be scheduled:

- SPT = shortest processing time first
- WSPT = weighted SPT; tasks with higher priorities have a heavier weight to assure they are scheduled
- LPT = longest processing time first
- ECT = earliest completion time first
- EST = earliest starting time first

For implementation, list scheduling (LS) was used for computing the schedules for a number of reasons. It is a simple combinatorial algorithm; i.e., it is *robust*. More sophisticated algorithms suffered from instability issues for reasons that are beyond the scope of this paper. LS is also computationally efficient, which is important for a real-time Scheduler. LS is well-proven; i.e., it is mature, having been around for almost half a century. LS has great value because any optimal schedule can be constructed by LS with an appropriately chosen list. The basic operation of LS follows:

1. The list of EA tasks to be scheduled is created (i.e., passed in from the Planner)
2. The EA tasks are assigned in list order to an EA processor in the SOI's set of EA processors as it becomes available
3. After assignment, EA tasks are removed from the list

7. SIMULATION FRAMEWORK & RESULTS

The simulation framework is illustrated in Figure 4. It has a user's front end and a simulation engine "under the hood." The front end consists of an Excel "EW Workbook" and a MATLAB GUI. The EW Workbook serves as the database for SOI and EA techniques data as well as system and simulation parameters. The MATLAB GUI is where the user selects the EW Workbook of interest, destination for the results data file, scheduling algorithm and run time. The user starts the simulation by pressing the GUI's execute button, launching the Simulink model, which consists of components built from Stateflow, SimEvents and Embedded MATLAB. When the simulation completes, a summary of metrics are plotted with respect to time in the MATLAB GUI.

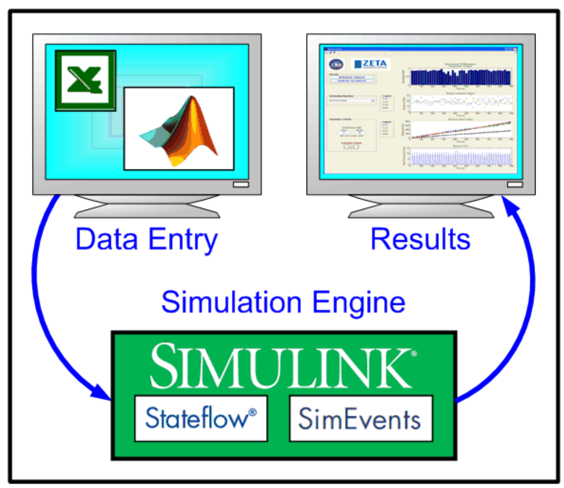

Figure 4. High level view of the next generation EW scheduling algorithm simulation framework

An overview of the methodology is presented here. A methodology is the "tools and rules" used to solve a complex problem, especially in the domain of system design and simulation [28]. The "tools" used in the analysis of electronic warfare schedulers include the following:

- EW Workbook (EW WB)—the analyst's starting place, where the EW WB is an Excel-based repository of signal and techniques parameters and the place where the EW platform is configured and mission parameters defined

- Simulation Engine—the analysis workhorse, which is a MATLAB/Simulink model that creates the Scheduler's environment as well as measures how well a Scheduler performs
- Post-simulation analysis tool—capability to evaluate results and examine different results after a simulation completes, including being able to compare different results side by side

The "rules" are the workflow of how the tools are used:

1. Collect signal parameters and techniques parameters into the EW Workbook
2. Configure the EW platform by deciding on processor count and target SOIs for each EA processor
3. Set mission parameters by defining a signal mix of SOI types and number of SOIs to be generated periodically
4. Set other simulation parameters
5. Select scheduling algorithm and run time
6. Run the simulation
7. Review the simulation results and compare different results data as necessary

Performance of the algorithms has been measured using a measure of effectiveness (MOE) for the Scheduler and a Battle Damage Assessment (BDA) for the platform in the presence of varying and dynamic simulated RF environments that stressed the framework and algorithms in multiple dimensions, testing both performance and stability.

8. CONCLUSION

Next generation EW can leverage SDR and CR notions for accomplishing its mission. I2WD has required planning and scheduling algorithms for their next generation EW SDR-based platform, which we have created using CR notions that deliver autonomous optimizing performance. We have validated them with a simulation framework of sufficient fidelity to assess the efficacy of the nine different algorithms. CR notions were a key element in creating and developing the higher order planner side of the Scheduler.

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