XG DSA Radio System

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***Abstract*— This paper describes the Dynamic Spectrum Access radio system that was built as part of the DARPA XG Program [1]. The DSA system's architecture four principal components (the DSA engine; the environmental sensing (i.e., detection) subsystem; the communications (i.e., radio) subsystem; and a policy module/enforcer) are described. The DSA system's 802.16-based radio hardware is described. One of the field tests related to Group Sensing is described. A companion paper describes the XG DSA Policy software design and field test.**

I. Introduction

On August 15 – 17, 2006, the U.S. Department of Defense (DoD) Advanced Research Projects Agency (DARPA) demonstrated, for the first time, a six-node network of neXt Generation (XG) radios capable of using spectrum over a wide range of frequencies on a secondary basis [5, 6]. Since these initial large scale DSA field tests, we have made significant progress in developing dynamic spectrum access hardware and software.

The 2006 DSA hardware was based on off-the-shelf desktop computers, an 802.16 development kit, a stand alone spectrum sensing unit, and large RF hardware. Our current DSA hardware is fully integrated, rugged, small, low cost and suitable for deployable. It utilizes the radio's signal path for detection and doesn't require a standalone spectrum sensing unit. Our current DSA hardware supports almost all spectrum from 174 MHz to 3000 MHz.

The 2006 DSA software supported a single DSA mode: Listen-Before-Talk [4]. Our current DSA software supports two additional modes: Group Behavior and Policy Control [7, 8]. Group Behavior provides increased transmit power levels at a fixed level on unintended interference by combining multiple measurements to extend the system's detection distance. Policy Control enables multiple controlling authorities to provide spectrum access policies to any DSA radio. This minimizes international certification problems and enables a flat spectrum management control arrangement that is fully automated. This above functionality was implemented in a low cost, general purpose processor suitable for a deployed radio system.

The current DSA system has been extensively tested in both laboratory and field testing so that the above new hardware and software can be evaluated. These trials were live and were witnessed by over fifty U.S. Government and industry representatives. This permitted DARPA to receive instant feedback after our demonstration tests regarding XG's desirability for technology insertion into funded DoD radio communications projects.

This document provides a detailed description of Shared Spectrum Company's (SSC's) Dynamic Spectrum Access (DSA) solution. The current implementations of the solution are described and key system components are outlined.

II. System Functional Overview

SSC's DSA technology enables RF radios to continually and autonomously assess the radio spectrum environment; and automatically (i.e., without human intervention) and swiftly adjust frequencies to changing capacity/interference conditions. Radios are able to do this without interfering with "non-cooperative" radios, and in accordance with user-defined policies. This is all accomplished via an elegant/novel combination of RF, signal processing, networking, and detection technologies coupled with SSC-developed algorithms. The system is depicted in Fig. 1 below.

The DSA system's architecture consists of four principal components: the DSA engine; the environmental sensing (i.e., detection) subsystem; the communications (i.e., radio) subsystem; and a policy module/enforcer.

The DSA Engine forms the heart of SSC's DSA system. As a result, it's the area where much of the company's innovation has occurred. The engine can be broken into three principal subcomponents: spectrum manager; rendezvous-related functions; and the high-level scheduler. At each node, the scheduler manages the operation of the detectors; spectrum manager maintains a list of candidate channels; and the rendezvous process uses channels ranked by the spectrum manager (in the channel manager) for network discovery and frequency negotiation with other network nodes.

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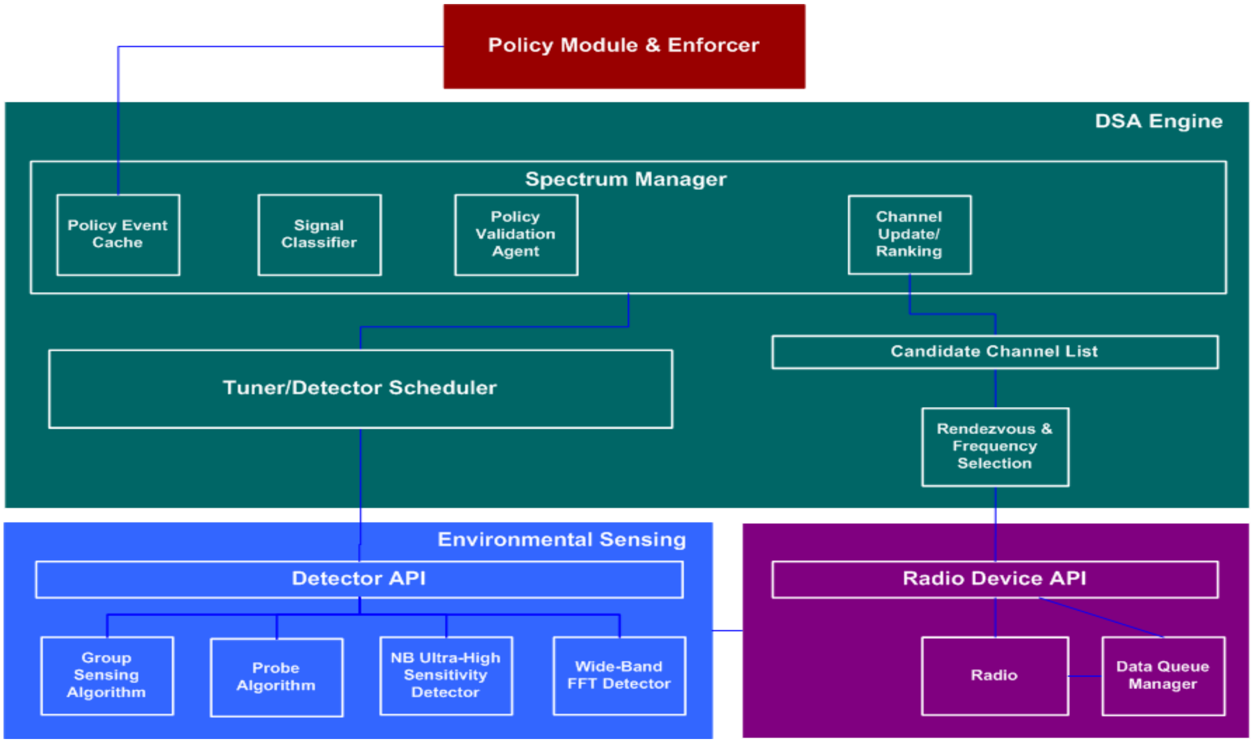

Figure 1. DSA Functional Architecture

The operation of DSA system components and subsystems is described below.

A. *Waterwheel Analogy*

It may be helpful to look at the DSA architecture in terms of "waterwheels" (i.e., threads). The original vision for the system architecture was that of a motorized waterwheel. The waterwheel turns and scoops up water (i.e., sensor data). Next, it operates on the data as it turns sequentially (i.e., it characterizes, reacts, and adapts to the data). Once data is adapted to, the waterwheel dumps the "water" and starts over with new sensor data. Stopping the waterwheel would allow immediate verification of the state of water in each bucket (i.e., detection timeslot).

In reality, the architecture has multiple waterwheels which operate asynchronously (i.e., independently from one another). One wheel rotates and collects sensor data that it drops into a sleuth (channel storage vector), while another wheel rotates and performs the rendezvous process. Based on entries in the channel storage vector, an event can be triggered that starts up another water wheel. The rendezvous waterwheel can trigger a branch off to a "network adapt" waterwheel (i.e., join the network or switch channels).

The rendezvous and detector threads asynchronously trigger events in a common water trench (i.e., the radio). The waves in this trench have a period of an 802.16 frame (for the SSC DSA implementation, which is based on 802.16). All waterwheels, while asynchronous to each other, are bound to the wave pattern (i.e., frame structure) of the trench. Stopping a waterwheel does not determine the state of water in other waterwheels. Time scales are generally not longer than the frame boundary. The logical map is a vector, not an array of elements stacked in time (depth). The logical map moves from detector to rendezvous, not backwards.

The following Fig. 2 pictorially represents the high level process flow. The loops represent the independent threads. (Only two types of detectors out of many possible types are shown.)

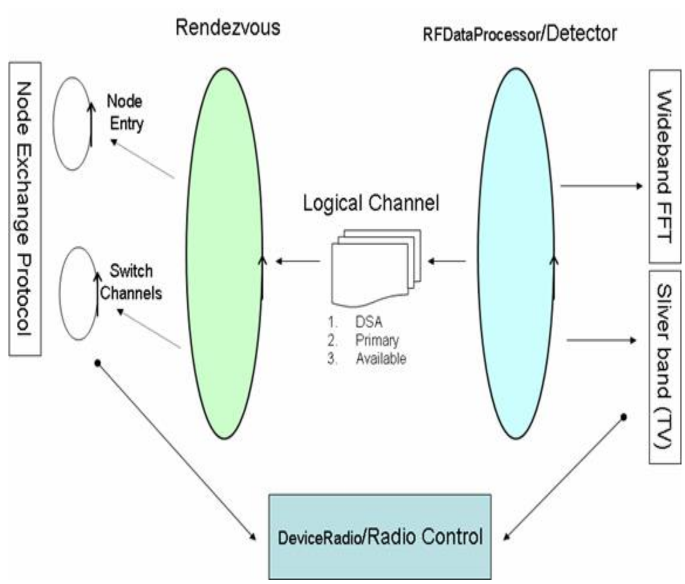

Figure 2. High-Level DSA Process Flow

B. *Example High Level Flow*

Fig. 3 is a depiction of the flow of events in DSA Cold Start mode (i.e., when a DSA node turns on and attempts to join a DSA network). The Policy Module loads the spectrum access policies to the Policy Validation Agent. The Tuner/Detector collect spectrum measurements. The Signal Classifier determines if the measurements are related to Non-cooperative signals (where spectrum policy is applied) or other DSA signals (spectrum policy is not applied). The measurements and the policies re used to rank the channels. The allowed channels are sent to the Rendezvous and Frequency Selection modules. These modules communicate with the other DSA radios in the area and start communications.

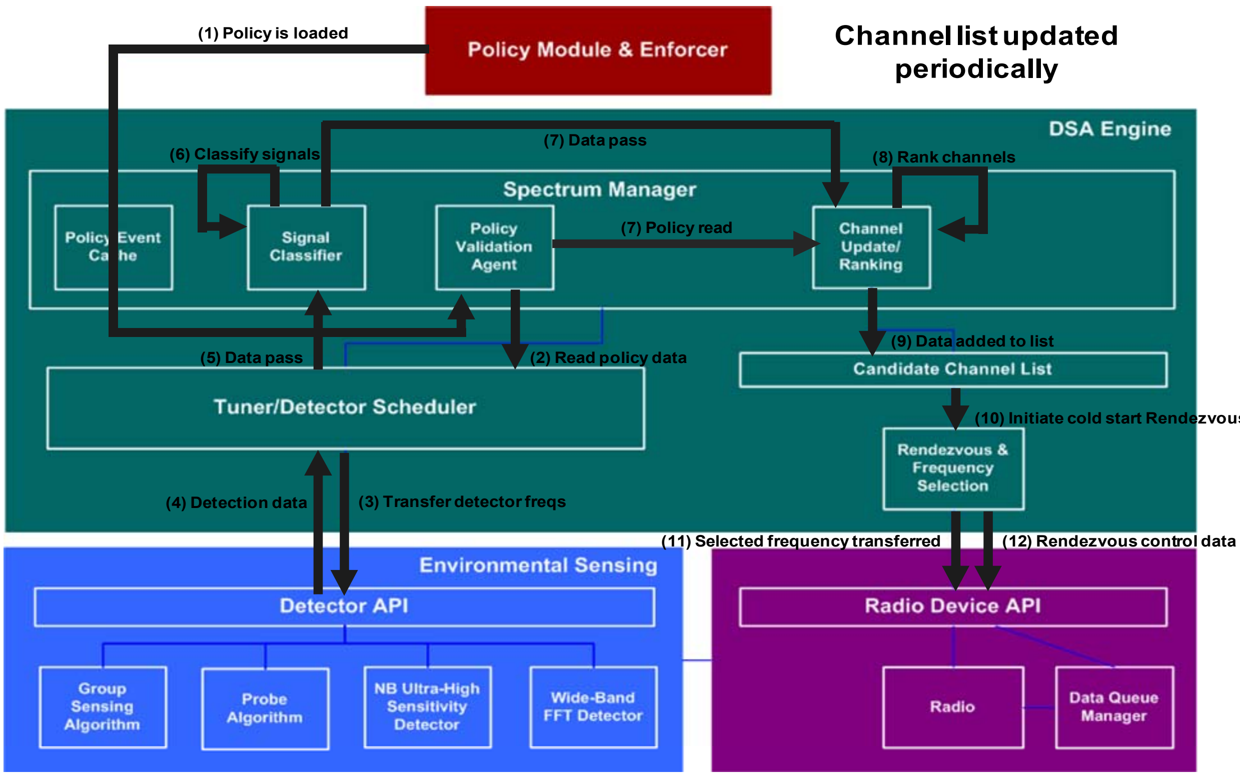

Figure 3. DSA Cold Start Flow

C. *Frequency/Channel Perspective*

The following Fig. 4 shows how the DSA system operates to reduce the entire spectrum being scanned at a node down to a small candidate list of high quality channels to be used in the rendezvous process.

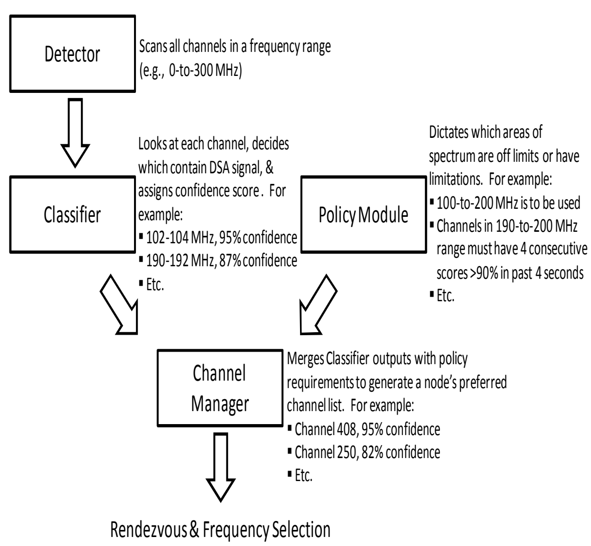

Figure 4. DSA Channel Funneling

III. Detailed Software Functional Description

This section breaks down the DSA Software Design into its major components, describing each in terms of its functional behavior and its interaction with other components.

A. Major Software Functional Component Breakdown

The DSA software framework can be represented by Fig. 5 below.

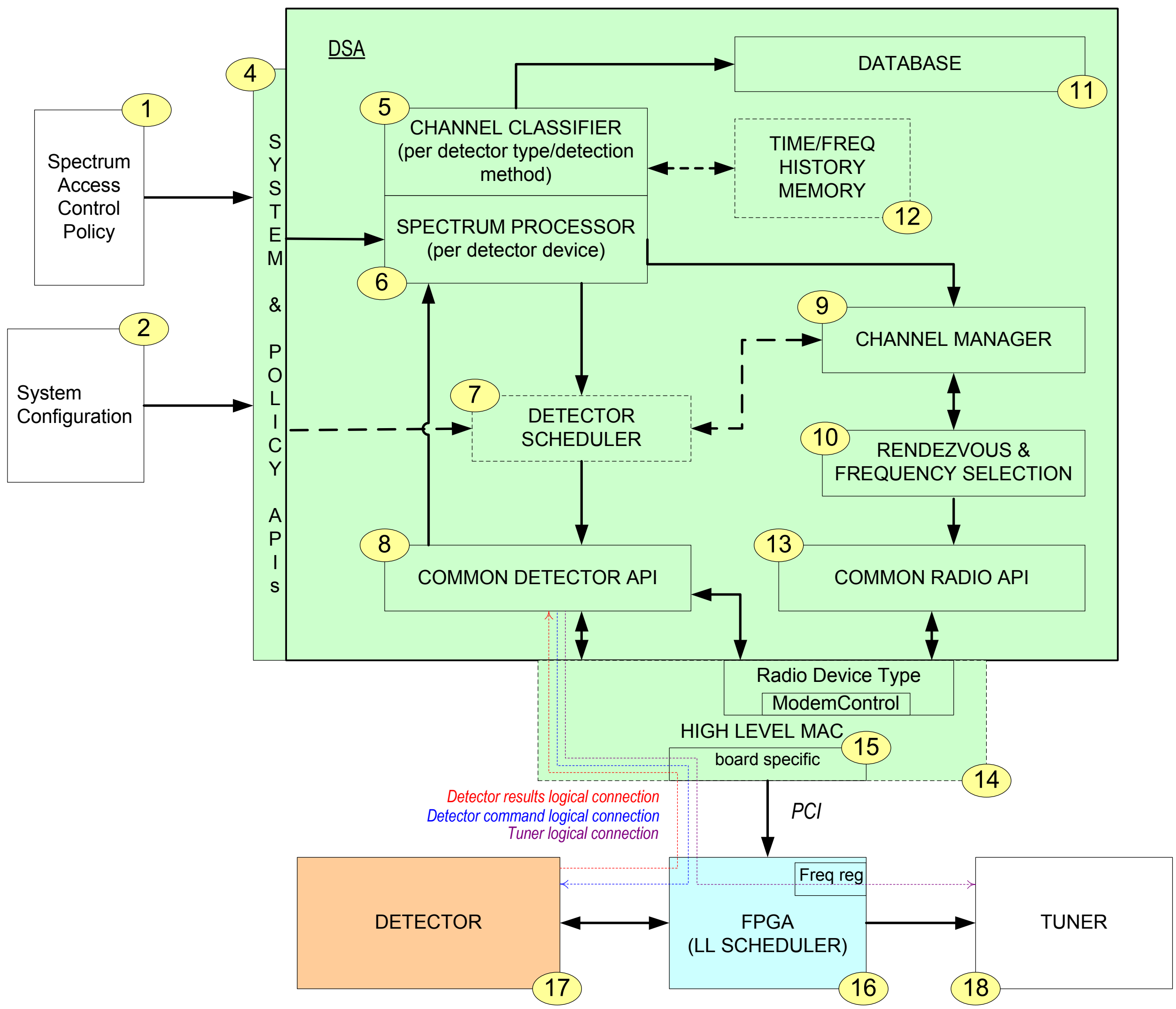

Figure 5. DSA Software Framework

The following functional blocks are implemented in the general purpose processor (GPP) – shown in green.

TABLE I. DSA Software Framework Components

ID	Block	Functionality
4	System & Policy APIs	Application programming interfaces. Component configuration based on Policy, INI files, and Web interface inputs. (A Web interface was developed for the March, 2008 XG demonstrations)
5	Channel Classifier	(Per detector device type/detection method) Implements channel classification algorithms
6	Spectrum Processor	This is basically a utility module (i.e., it doesn't do any major operations). It formats the detector data into something that can be used by the Classifier (e.g., it calculates the Max Hold array).
7	Detector Scheduler	Controls detectors' time schedule and configuration. This is implemented as a standalone block in the WAND system only
8	Common Detector API	Provides interface with detector devices
9	Channel Manager	A.k.a. Channel Update/Ranking. Maintains all available logical channel information. Supports conformance with Spectrum Access Control Policies. This is called a "manager" because it maintains a data structure.
10	Rendezvous	Implements DSA network maintenance

ID	Block	Functionality
		procedures including communications protocols, connect, disconnect, and channel switching procedures.
11	Database	Provides storage for detector results and other information
13	Common Radio API	(Radio device specific) Provides interface with radio devices

IV. DETAILED HARDWARE FUNCTIONAL DESCRIPTION

A. Introduction

This section describes the current DSA hardware. The DSA radio is a high performance, 802.16-2004 based radio that covers a wide frequency range. It is designed for video and high bandwidth data transmission (i.e., data rates range from approximately 500 kbps to 30 Mbps) over long ranges (1 km to 30 km). It has adaptive TDMA frames and OFDM modulation. The radio is software controlled using practical sized (i.e., low-to-moderate cost) DSP, FPGA and general purpose processors. Software developed for this DSA radio using these standard processors can be readily ported to other radios; hence the DSA radio is an excellent software development platform. Because the SSC radio is low cost and physically robust it is well-suited as a test platform for software development and field testing.

The 10 W transmit power level enables the radio to send video and voice data over several kilometers, which is the link range requirement related to vehicle convoys. The 12 VDC prime power facilitates testing using vehicles or with batteries.

B. RF Transceiver Module

Fig. 6 below shows the RF transceiver module (DSA 1000). It is the first low cost, high performance, multi-band cognitive radio. It consists of four circuit boards: (1) The RF Board, (2) the IF Board, (3) the Digital Processing Board, and (4) the single board computer. The transceiver's size is 6" x 4" x 4". The transceiver's power consumption is less than 15 W.

Figure 6. RF Transceiver Module (DSA 1000)

C. RF Board

Four different RF boards can be used in this radio. A list of each of the RF Board frequencies is provided in Table II below. A continuous 30 MHz-to-3000 MHz RF board was considered, but was found to be too expensive for commercially viable applications. For most of the DSA software development, the DoD RF board was used. This RF board covers all DoD-controlled spectrum between 225 MHz and 3000 MHz.

TABLE II. THE DSA RADIO SUPPORTS FOUR DIFFERENT RF CARDS COVERING THE SPECTRUM BANDS AVAILABLE TO DIFFERENT CLASSES OF USERS

DoD RF Board (MHz)	Public Safety RF Board (MHz)	Wireless (TV) RF Board (MHz)	Commercial RF Board (MHz)
225 – 512 1215 – 1390 1435 – 1525 1755 – 1850 2200 – 2290	138 – 174 220 – 512 764 – 869	174 – 216 516 – 806	698 – 941 1390 – 1435 1670 – 2680

The RF Board's front-end has high filter selectivity and input intercept points, which is required for operation in an intentional interference environment. In contrast, most radios have poor selectivity and will not operate well in a high signal environment.

D. IF Board

The IF board converts the IF signal at 1250 MHz or 850 MHz (depending on the RF Board type) to 140 MHz, filters the signal, and samples the 140 MHz signal. This digital data is sent to the Digital Processing Board.

E. Digital Processing Board (DPB)

The DPB is a custom circuit board containing an FPGA, a DSP, and the 802.16-2004 DM256 modem ASIC as shown in Fig. 7 below. This board is tailored to DSA requirements and is significantly different than the digital boards of conventional radios. It supports the DM 256 mode, DSP-based DSA detection (on board), and the use of an external DSA detector (Rockwell Collins XG Sensor), and it controls the transceiver.

The DPB FPGA contains many functions that are shown in Fig. 8 below. This includes digitally down converting the data signal using a mixer and low pass filter (LPF). There is an automatic gain control (AGC) and an automatic level control (ALC) that set the gain in the RF transceiver and the transmit power levels. Different AGC loops are maintained for the modem and for the detector, which is required when the DSA transceiver is close together. The FPGA MAC function supports the 802.16 chipset. The DSA detector reads data from the digital processor board memory, which is controlled by the FPGA.

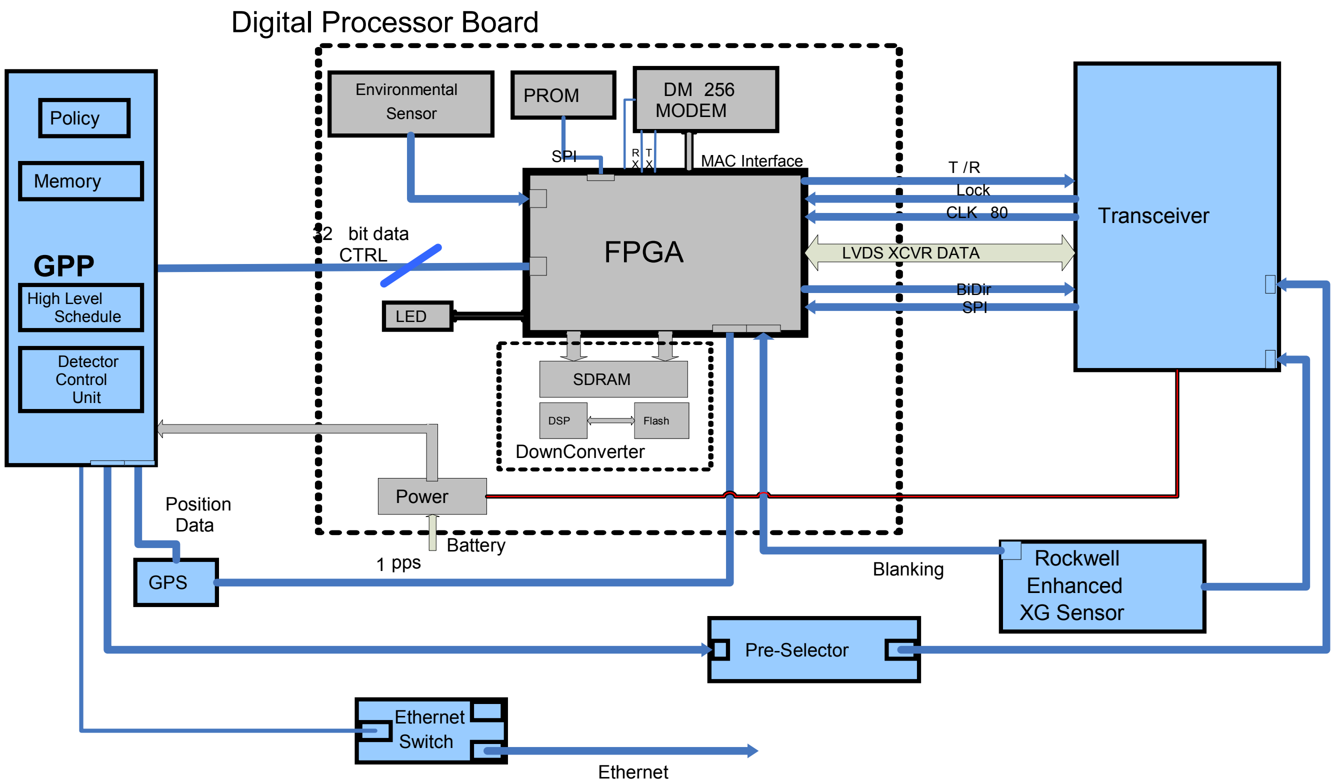

Figure 7. Digital Processing Board Architecture

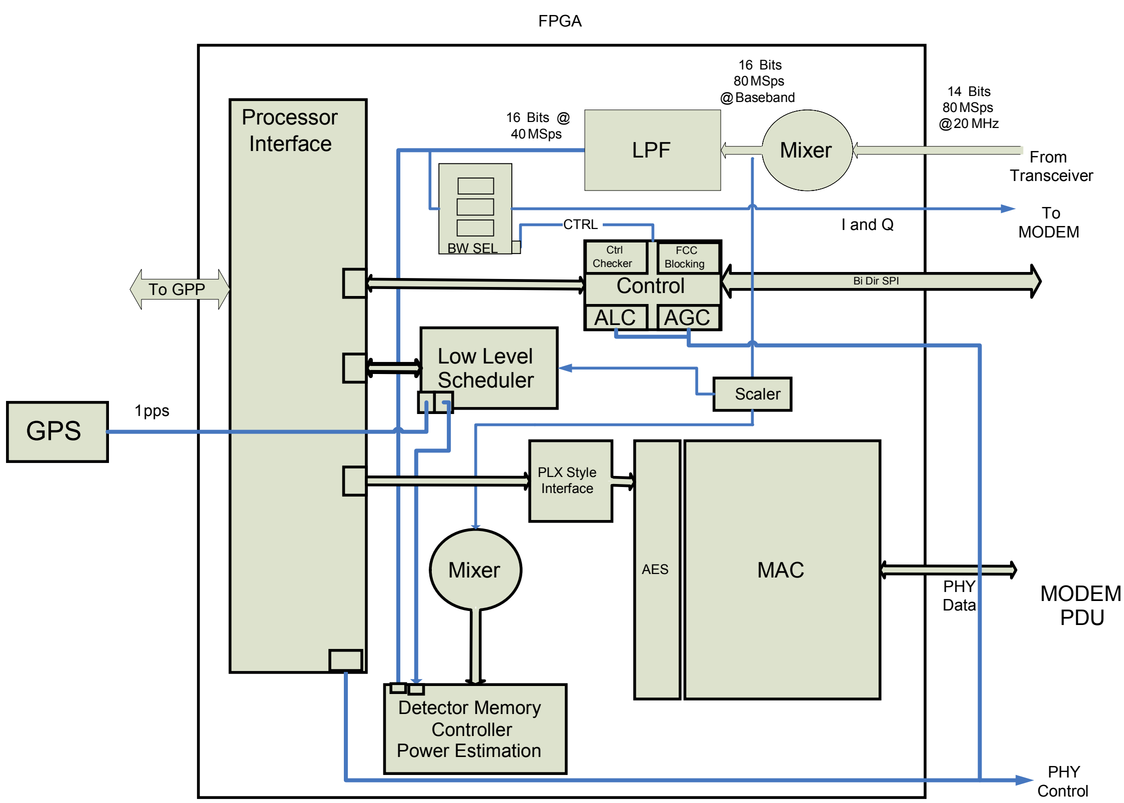

Figure 8. FPGA Architecture Contains Multiple Functions

The DPB uses a DSP to host the DSA detection algorithms. The DSP was used to enable the DSA detection algorithms to be easily tailored to the specific non-cooperative signal types. This DSP is a low cost (<$20), integer math engine with limited processing power so that commercially viable (low hardware cost) detection algorithms could be demonstrated. To meet both the performance and cost goals, the DSA detector implementations were designed around these fixed point and processing limitations.

The DSP contains a variety of detectors that are selected based on the signal of interest. The Wide Band Detector is an FFT-based detector that was optimized for execution speed and has limited dynamic range. It most cases, high dynamic range is needed since the spectrum measurements are usually made of empty spectrum or of very low level signals. There is no requirement to measure high level signals. The PolyPhase FIR filter is a building block used by the Cyclostationary Detector and the TV detector [2].

The 802.16-2004 compliant modem is based on an ASIC made by Wavesat. It is a high bit-rate modem intended to be used in static environments as a wireless local loop modem. Modulation is orthogonal frequency division multiplex (OFDM). OFDM subcarrier modulation types include BPSK, QPSK, 16-QAM, and 64-QAM. The 802.16-2004 air interface protocol is intended to transport voice as well as data. The IF bandwidth is variable, between 1.75 MHz and 10 MHz. Baseband interface is Ethernet.

The time division multiple access (TDMA) frame structure is variable frame length of between 1 and 20 msec, with distinct uplink and downlink burst time periods within each frame. Each frame has order wire slots which can be used by new network members to request time slots. The frame is very flexible: Uplink and downlink burst time slots depend on traffic loading. Users will be granted more time for their time slots depending upon the amount of data in their MAC queues (which depends on traffic loading) [9].

F. General Purpose Processor (GPP)

The General Purpose Processor (GPP) contains most of the DSA algorithms and provides an external interface for control and data. The GPP is an x86-based with a PCI, CompactPCI, or PC104/Plus interface that operates with Windows or Linux operating systems.

G. Complete Radio (DSA 2100)

The complete radio (DSA 2100) is shown in the following figure. It contains the Transceiver Modules, the RF power amplifier and a power supply.

The radio architecture is shown. The DSA DSP detector is integrated with the 802.16/802.16 modem. The transceiver also supports an external detector such as the Rockwell Sensor. The GPP is a separate COTS single board computer that support multiple standard I/O interfaces. Most of the DSA software is on the GPP. The FPGA provides many modem functions.

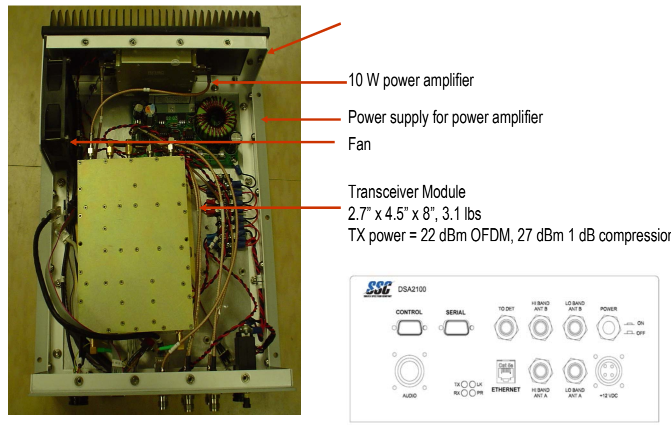

Figure 9. Complete DSA Radio w/Power Amplifier

V. Group Behavior Software Demonstration

Group Behavior (GB) is a method to enable the DSA radios to learn where spectrum holes in their vicinity are located, and to share this information amongst themselves, the better to avoid interfering with NC radio communications. The objective is to find the highest power level each DSA node can transmit at without interfering with the NC radios—maximizing DSA communication range, while protecting NC radios from interference. At maximum interference free transmit power (MIFTP) [4], DSA’s signal is at a specified INR value at the NC radio.

A. Scenarios When Group Behavior is Required

Group Behavior is required in many operational scenarios because the single detector, Listen-Before-Talk approach doesn’t work because of insufficient detection sensitivity. The required DSA detector sensitivity for several sample cases is shown in Table III. They are listed in order of difficulty considering “Threshold Relative to Thermal Noise” (SNR) and MDS (hardware spurs).

TABLE III. SAMPLE REQUIRED DSA DETECTOR SENSITIVITIES

Case	Spectrum Band/Scenario	TX/RX Factor (dB)	P_{PRI} (dBm)	P_{DSA} (dBm)	BW_{PRI} (kHz)	BW_{DSA} (kHz)	NF (dB)	I/N (dB)	Threshold (dBm/Hz)	Threshold Relative to Thermal Noise (dB)	Minimum Detectable Signal Level (dBm)
1	DoD Voice Bands, low power DSA	0	30	20	25	1,750	5	0	-140.5	28.5	-96.6
2	Radar Bands	0	60	40	2000	1,750	5	-6	-155.6	13.4	-92.6
3	DoD VHF/UHF Bands, Public Safety	0	30	40	25	1,750	5	0	-160.5	8.5	-116.6
4	Broadcast TV	-60	70	40	0.01	1,750	5	0	-146.6	22.4	-136.6
5	Cellular	0	30	40	1250	1,750	5	0	-177.5	-8.5	-116.6
6	TDMA Point-to-Point Microwave	0	30	40	10000	1,750	5	0	-186.6	-17.6	-116.6
7	FDMA Point-to-Point Microwave	-10	30	40	10000	1,750	5	0	-196.6	-27.6	-126.6
8	Wireless Mic	-10	20	40	100	1,750	5	0	-186.6	-17.6	-136.6
9	Unlicensed Band	0	20	40	20000	1,750	5	0	-199.6	-30.6	-126.6

Case 1 – This is the case in the 2006 XG AP Hill DSA field tests . The Non-cooperative signals had narrow bandwidth and the DSA system had low transmit power levels. The required detector sensitivity was high (33.5 dB SNR), and thus was easy to achieve.

Case 2 – This case is for operation in the radar bands, which has high Non-cooperative transmit power levels, a wider Non-cooperative signal bandwidth and low I/N requirements. This is similar to the DFS case except that the DSA transmit power is 20 dB higher. Operation in this case can be achieved with the Listen-Before-Talk approach because of the high SNR values.

Case 3 – The same as Case 1 except that the DSA system uses a 10 W transmit power level. This high transmit power level is required in many applications to obtain high link range. The required detector sensitivity is harder to obtain because low SNR and low MDS.

Case 4 – This case is for operation in the TV bands. The TX/RX factor is a critical issue and is being investigated in the recent TV White Space measurements SSC is performing. The small detector bandwidth is required to reject man-made noise signals and not for SNR reasons. The small bandwidth [2] is used to detect the ATSC pilot, which has approximately 10 dB less power than the total TV signal level, hence, the P_{NC} power level must be 10 dB less than the FCC database value.

Case 5 – This case is for operation in the cellular bands. Because of the large Non-cooperative signal bandwidth and low Non-cooperative transmit power levels, Listen-Before-Talk approaches are not practical.

Case 6 – This case is for operation in the point-to-point microwave bands in TDMA mode. Because of the large Non-cooperative signal bandwidth and low Non-cooperative transmit power levels, Listen-Before-Talk approaches are not practical.

Case 7 – This case is for operation in the point-to-point microwave bands in FDMA mode. The TX/RX factor is a critical issue. SSC has not investigated this, and the 10 dB value is assumed. Because of the large Non-cooperative signal bandwidth and low Non-cooperative transmit power levels, Listen-Before-Talk approaches are not practical.

Case 8 – This case is for operation in the TV band where the Non-cooperative signal is a wireless mic. The TX/RX factor is a critical issue. SSC has not investigated this, and the 10 dB value is assumed. Because of the large Non-cooperative signal bandwidth and low Non-cooperative transmit power levels, Listen-Before-Talk approaches are not practical.

Case 9 – This case is for operation in the Unlicensed bands. Because of the large Non-cooperative signal bandwidth and low Non-cooperative transmit power levels, Listen-Before-Talk approaches are not practical.

Fig. 10 shows that the required detector performance is reduced when the DSA transmit level is reduced from 40 dBm to 10 to 20 dBm. If these lower power levels are acceptable to users, then the Listen-Before-Talk access method will work in a majority of cases.

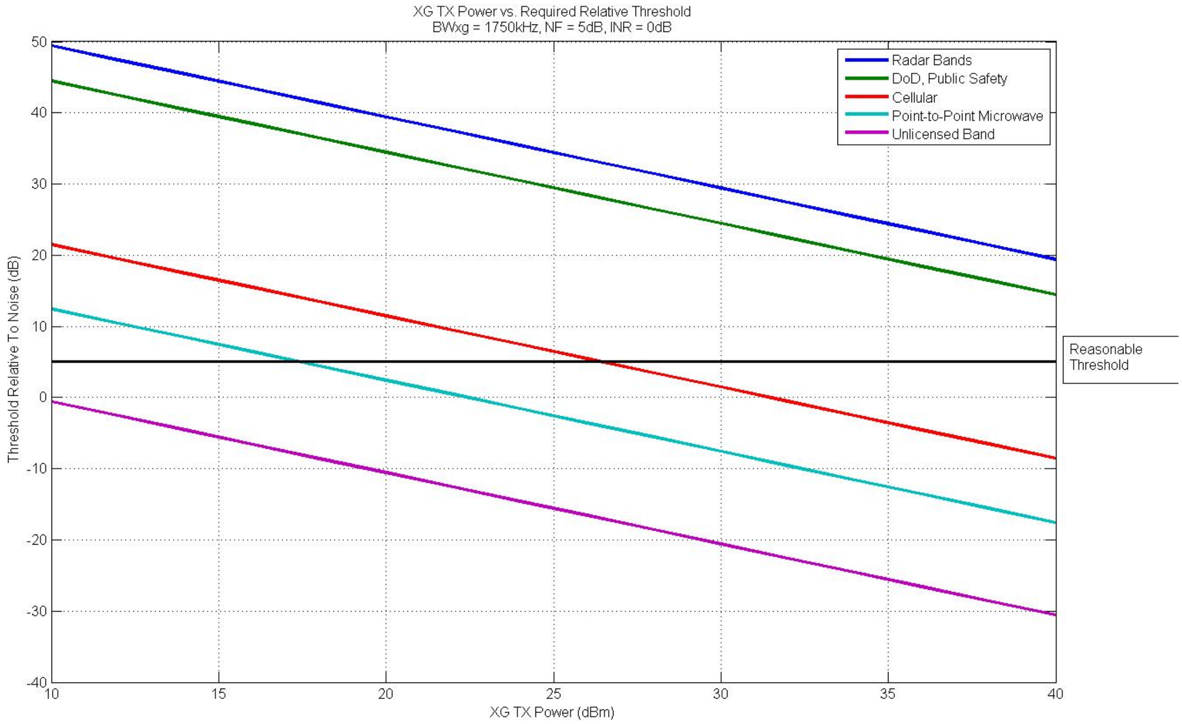

Figure 10. Required detector performance versus DSA transmit power level for different use cases.

B. *Group Behavior Algorithm Description*

The main components of the Group Behavior Algorithm are:

Maximum Interference-Free Transmit Power (MIFTP): a power level at which the DSA radio can transmit, such that its signal is effectively out of range of the NC receiver, and so cannot interfere.

Interference-to-Noise Ratio (INR): an objective measure of interference caused by a DSA node at the NC receiving point, referenced to the local RF noise floor. MIFTP is calculated to keep INR at the NC receiver below a value that noticeably degrades the NC's radio signal. INR = (I + N) / N where I = interference attributable to the DSA node and N is the noise floor. Actual interference suffered, measured in digital systems as an error rate, is a function of (I + N) and the NC's modulation type.

Spectrum hole location estimate: Enables DSA to calculate MIFTP and adjust output power based on location of discovered and remembered spectrum holes, rather than up-to-the-moment signal strength received from one or more non-cooperative transmitters, that can potentially emit signals with various duty-cycle levels.

GPS (the Global Positioning System): used by GB for geo-location of DSA nodes and mapping of NC transmitter locations.

Dempster-Shafer Data Fusion: Statistical inference method used to locate NC transmitters, without need for specialized radio direction-finding (RDF) hardware.

Group Sensing: sharing of Dempster-Shafer NC location maps among DSA nodes. Enables Group Behavior; extends sensing range, in effect.

C. *Group Behavior Demonstration*

This demonstration was designed to evaluate Group Behavior's merits relative to the LBT (Listen-Before-Talk) spectrum access method. In its current implementation GB is complementary to the fundamental DSA technology of LBT, in the sense that it enables continued use of a channel where an NC transmitter is encountered, by adjusting the DSA node's transmit power, rather than turning power off altogether and vacating the channel.

The experimental scenarios reported here were designed to enable comparison across experimental conditions. Therefore in these scenarios, DSA mobile vans drove a fixed, identical path in each case NC nodes were placed in a fixed position relative to this path in each case, and so performance when different algorithms were applied (GB with single BDI map, GB with dual BDI-maps, and LBT) could be readily compared. The scenarios all used a setup summarized in Fig. 11.

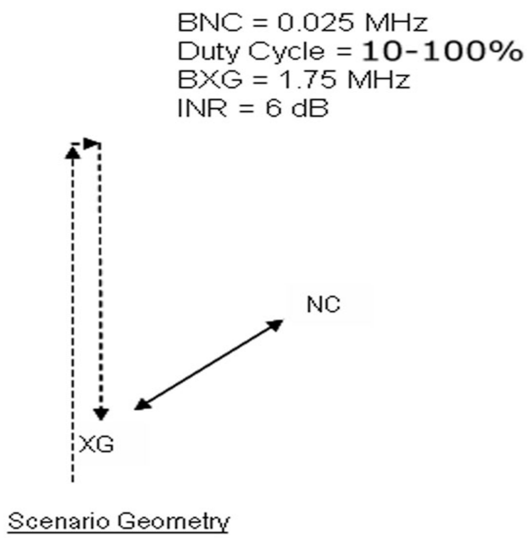

Figure 11. GB vs. LBT test scenario, conditions and drive path.

Fig. 12 charts DSA transmission power alongside distance from the DSA node to the NC transmitter and Interference-to-Noise Ratio (INR) measured at the NC radio. Here, the NC bandwidth is 25 kHz, DSA's bandwidth is 1.75 MHz, allowed INR is 6 dB, and the NC duty cycle is 100% (continuous transmission).

The upper left graph shows distance to between DSA radio and NC. At the upper right, the DSA radio's detection of NCs can be seen (note that it correlates with the DSA node's proximity to the NC, upper left).

The lower left graph shows DSA transmit power under GB and LBT control (blue and red, respectively). This graph demonstrates that GB enables enhanced DSA transmit power over most of the test course, as compared with LBT.

The resulting Interference-to-Noise Ratio (INR) at the NC receiver is given at lower right. NC bandwidth in these graphs is 0.025 MHz; NC duty cycle = 1 (100%); DSA bandwidth = 1.75 MHz; and the allowed INR criterion is 6 dB.

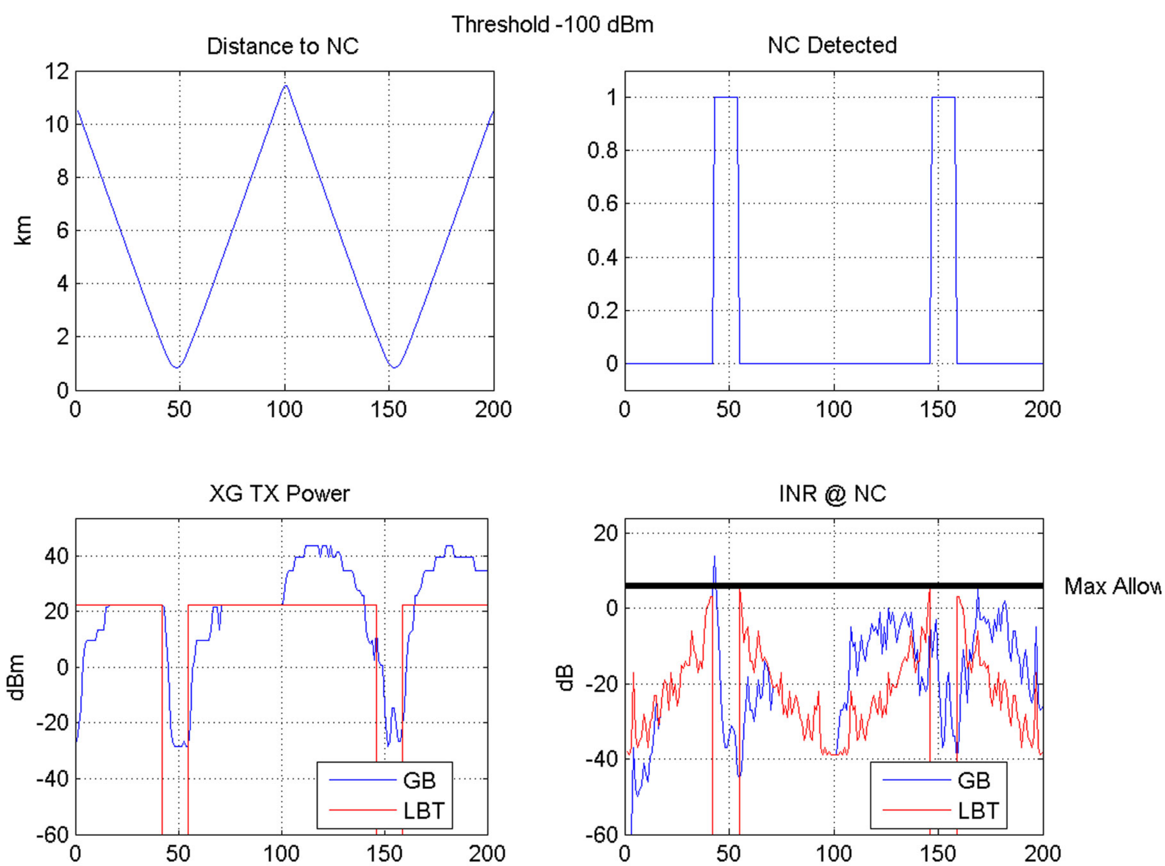

Figure 12. Group Behavior algorithm vs. LBT, measured over the same test course and time-aligned.

It can be seen in these graphs that GB enables the DSA radio to transmit at a higher power level than LBT does, in particular when an NC is detected (and thus when LBT shuts the DSA radio off entirely on the channel in question, for re-rendezvous elsewhere), but usefully, elsewhere on the drive course, where LBT is restricted to 20 dBm.

During part of the drive course, the DSA radio transmits at over 40 dBm, more than a hundredfold power difference, under the guidance of GB. While at this higher power level, the DSA node does not interfere with the NC, never exceeding the allowed 6 dB INR. Through almost the entire period of transmission at higher power under GB, the INR at the NC remains below 0 dB.

One instance of interference to the NC can be seen. This occurs for GB around the time of the DSA radio's first detection of the NC, a brief excursion above 6 dB of INR.

VI. Conclusion

This paper describes the DSA radio system developed in DARPA XG Program during the period of 2006-2008. We made many improvements to the previous radio system developed under the DARPA XG Program.

The DSA Detector was redesigned to use the same receiver has the modem, hence, the expensive external spectrum sensor previously used was eliminated. Having the same receiver for both the DSA detector and for the modem also provided the benefit that same distortion, inter-modulation and other RF impairments existed for both the detector and the modem. Hence, DSA could be used to determine what operating frequencies had these problems so that other frequencies could be used as needed. With a separate, external spectrum sensor this was not possible.

The DSA Detector algorithms were implemented in a low cost, fixed point DSP. The DSA rendezvous, policy and other software were implemented in a low cost, general purpose processor. This proved that DSA can be implemented at a low incremental cost to existing communications devices.

The Group Behavior and Policy Control software was integrated with the other DSA software. Thus, the current DSA radio provides a complete, end-to-end DSA system that can support operation in a wide range of spectrum bands and regulatory environments.

During this period, we also completed additional testing of the Group Behavior software. These field tests show that the Group Behavior software enables a significantly higher DSA transmit power level than the conventional Listen-Before-Talk algorithm.

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