On Making the Current Military Radios Cognitive without Hardware or Firmware Modifications

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Abstract— Cognitive Radio (CR) using Dynamic Spectrum Access (DSA) provides the military radios, an ability to operate in un-predictable interference environments. CRs are capable of sensing their environment and autonomously changing the radio parameters such as frequency, bandwidth and power, to avoid interference. Large amount of resources have been invested by the Department of Defense (DoD) on building these radio systems which are currently not DSA enabled. This paper provides a way to make current military radios DSA capable without making any hardware or firmware modifications to them. Radios are made DSA capable by using an external sensor as compared to an embedded sensor containing advanced feature based sensing algorithms, application level messaging and a cognitive engine, which is written in a high level language that resides outside the radios. A real-time over-the-air demonstration for such a cognitive radio test-bed using a network of three Warfighter Information Network – Tactical (WIN-T) Local Area Waveform (LAW) nodes in friendly and un-friendly interference was carried out at the Ft. Dix facility of US Army CERDEC. This paper provides a brief overview of the system, operation of this test-bed and some field demonstration results.

Keywords - cognitive radio, dynamic sectrum access, WIN-T LAW, external sensing.

I. Introduction

Today’ s military wireless communications networks are vulnerable to unpredictable interference environments. Interference may come from adversaries or other friendly systems. Many such military wireless networks do not have the intelligence to autonomously move to other un-occupied frequency bands or alter their bandwidth. Cognitive Radio (CR) using Dynamic Spectrum Access (DSA) provides a solution where radios are capable of sensing their environment and autonomously changing the radio parameters such as frequency, bandwidth and power, to avoid interference ([1]-[4], [7]-[8]). Large amount of resources have been invested by the Department of Defense (DoD) on building these radio systems which are currently not DSA enabled. In order to make the current military radios *cognitive*, it will require more investment, unless some innovative and cost-effective solutions are found.

This paper provides a way to make current military radios DSA capable without making any hardware or firmware modifications. Under the auspecies of the US Army Communication-Electronics Research, Development and Engineering Center (CERDEC) sponsored Agile Spectrum Utilization for Robustness and Efficiency (ASURE) Program, we showed that it is possible to dynamically alter radio parameters such as the frequency of operation, Bandwidth (BW) and Power, while maintaining the network connectivity in a dynamic interference environment ([2]-[3]); thus demonstrating Gray space operation. Other Physical (PHY) and Medium Access Control (MAC) settings of the radios can also be modified provided they are configurable.

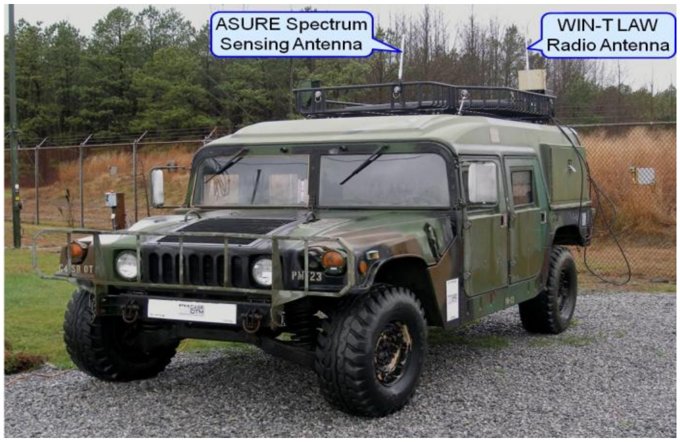

Figure 1. PM C4ISR-OTM vehicle containing an ASURE node consisting of a WIN-T LAW radio, external sensing and cognitive engine software

Radios are made DSA capable by using an external sensor as compared to an embedded sensor, to monitor the radio frequency spectrum for interference and find the backup channels for the radios to move to. Advanced feature based sensing algorithms are used to characterize the dynamic interference environment.

We show that it is possible to demonstrate cognitive networking capability without having a sensor at every node. Application level messaging enabled through Internet Protocol (IP) and Simple Network Management Protocol (SNMP) are used for spectrum monitoring, network management and radio control. The cognitive engine is written in a high level language such as JAVA^{TM} which makes it easily modifiable. The ASURE program demonstrated the performance of such a DSA-enabled Warfighter Information Network – Tactical (WIN-T) Local Area Waveform (LAW) radio network operating in the presence of friendly and un-friendly mobile interference. The ASURE architecture and algorithms have been designed such that they can operate with any radio system, as long as such a radio system provides the necessary interfaces (e. g. hardware interface in the form of serial or ethernet ports and Management Information Base - MIBs) for controling and monitoring the radios.

Figure 1. shows the PM C4ISR OTM vehicle containing an ASURE node consisting of a WIN-T LAW radio, external sensing and cognitive engine software. The ASURE demonstration was carried out at the Ft. Dix facility of the US Army CERDEC. The ASURE demonstration showed that it is possible to incorporate autonomous and advanced spectrum agility using non-DSA equipped military radios, while maintaining real-time system connectivity and link quality in the presence of dynamic interference environments.

This paper is organized as follows. Section II provides ASURE system description, Section III provides functional descriptions of ASURE modules, Section IV describes the Ft. Dix field demo, and finally Section VI concludes the paper.

II. ASURE System Description

A. *ASURE Logical Architecture*

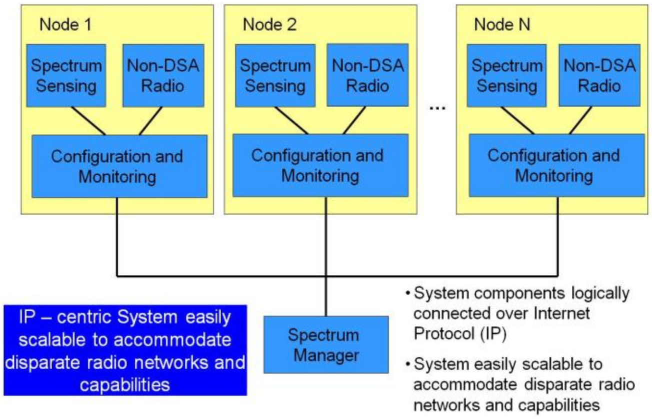
Node 1
Spectrum Sensing
Non-DSA Radio
Configuration and Monitoring
Node 2
Spectrum Sensing
Non-DSA Radio
Configuration and Monitoring
...
Node N
Spectrum Sensing
Non-DSA Radio
Configuration and Monitoring
IP – centric System easily scalable to accommodate disparate radio networks and capabilities
Spectrum Manager
• System components logically connected over Internet Protocol (IP)
• System easily scalable to accommodate disparate radio networks and capabilities

Figure 2. ASURE logical architecture

Figure 2. shows the ASURE test-bed logical architecture. It consists of one or more nodes, where each of the nodes contains a Spectrum Sensing Module (SSM), a non-DSA radio, and a Configuration and Monitoring (C&M) agent. C&M interfaces to the SSM and the radio. All the nodes are logically connected to an entity called the Spectrum Manager (SM) whom they report to. The SM acts as the cognitive engine of the system. It monitors the radio link statistics and the spectrum sensing information from each of the nodes to make a decision on whether change in frequency BW or power for the radio network are required. The SM may reside in any of the nodes, since it has a dedicated IP address associated with it, but in a Point to Multi-Point network (PMP) topology, the SM is likely to reside in the Control Node (CN).

All the modules within the node and within the ASURE system have a dedicated IP address associated with them which allows them to be accessed and configured using IP / SNMP application level messages. Making IP as a backbone allows the system to easily accommodate disparate radio networks and enables network scalability allowing seamless increase in the number of nodes within the network. Usage of IP and SNMP messaging at the application level to monitor and control the radios means that no changes are required to the hardware or firmware of the radios. In fact, there are no changes required to the software (e. g. MAC) messaging of the radios.

The system does require application level messaging for information exchange, system monitoring and control which results in some additional overheads due to IP encapsulation requirements. However, as we will show in this paper, these overheads are insignificant as compared to the actual information throughput of the system.

B. *ASURE Physical Architecture and Hardware Components*

Figure 3. shows the ASURE test-bed physical architecture. The ASURE test-bed *physical architecture* consists of one or more wireless communications nodes, where: Each node consists a software controllable non-DSA radio, which has the necessary interfaces that allows it to be configured, a Radio Frequency (RF) collector, a network layer switch, and a laptop. The laptop contains the spectrum sensing, C&M, and the SM cognitive engine algorithms. Figure 3. shows the test-bed with three nodes, in a PMP configuration. The network scalability and the network topology (e. g. PMP in this case) are decided by the capabilities of the radios, and are neither limited by the ASURE system architecture nor the cognitive radio algorithms that are utilized. The ASURE setup uses the radio links themselves for cognitive radio network monitoring and control. No separate backup link is required.

WIN-T LAW radios were used for the ASURE test-bed demonstration. However, any radio that provides software controllability may be used. For ASURE, the WIN-T LAW radios operated in the PMP mode. The WIN-T LAW radios are designed such that it is possible to control their parameters using network / application level SNMP messages that can read and write the radio MIB objects.

Agilent N6841A Commercial Off-the-Shelf (COTS) part, is used as an RF collector. The RF collector is essentially a tuner and a digitizer that is capable of providing real and imaginary

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(IQ) waveform samples collected in a particular band of interest to the spectrum sensing algorithms which then determine the nature of the signals present in these channels. The SSM consists of the RF collector hardware connected to the spectrum sensing algorithms running in a laptop.

The RF collector and the radio are connected via a network switch to a laptop, which runs various software programs related to C&M, SM and spectrum sensing. In the future, it is envisioned that all these software routines may run either on the radios or some other dedicated hardware.

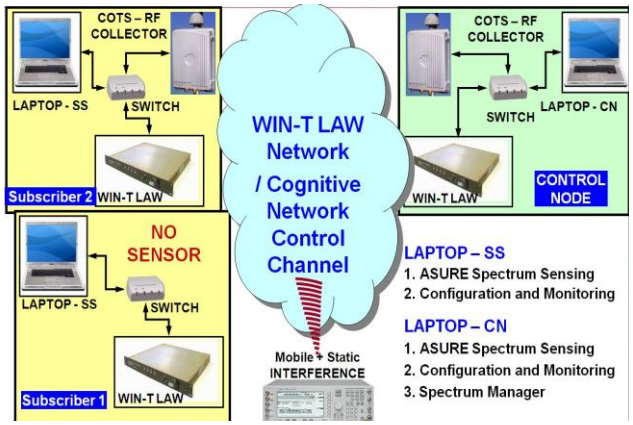


Figure 3. ASURE physical architecture

The dynamic interference environment was created by transmitting various types of waveforms using a signal generator, capable of operating in the frequency bands where the radios operate. Another WIN-T network was also used to create a network co-existence scenario.

III. Functional description of various modules

This section describes the operation of various hardware and software modules of the ASURE test-bed.

A. *Spectrum Sensing Module*

Figure 4. shows the ASURE SSM. The SSM consists of the N6841A COTS RF collector which is connected over an Ethernet cable to a computer running custom designed spectrum sensing algorithms. Together this forms the SSM. The N6841A part is a moderate cost wideband RF receiver with frequency coverage from 20 MHz to 5.9 GHz, digital Intermediate Frequency (IF) BW of 20 MHz, Transmission Control Protocol (TCP) network interface, capture memory buffer of 512 MB, optional integrated precision Global Positioning System (GPS) receiver with high precision clock synchronization via GPS or network interface (e. g. IEEE 1588). N6841A related Dynamic Link Libraries (DLLs) can be downloaded to control the hardware and extract real time information from it. It is environmentally rugged IP67-rated weatherproof sealed unit with no moving internal parts.

Use of a Low Noise pre-Amplifier (LNA) is highly recommended at the front end of the N6841A to reduce the effective Noise Figure (NF) (Note that the N6841A unit has a typical NF of 20 dB), and improve the sensitivity. Hence, a COTS Low Noise pre-Amplifier (LNA) from Mini-Circuits^{TM}, designed to operate in the stated frequencies was added in between the antenna and N6841A. This resulted in reasonable improvement in the sensitivity of the sensor.

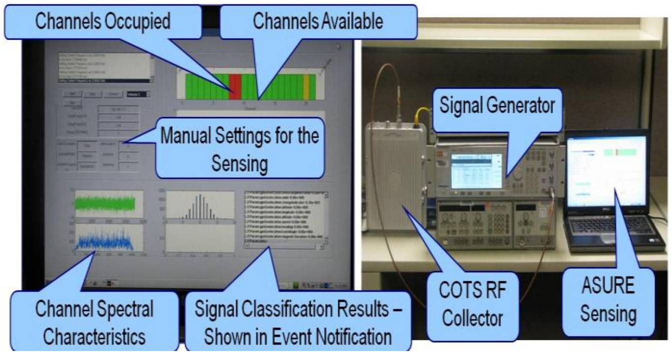

Channels Occupied
Channels Available
Manual Settings for the Sensing
Signal Generator
Channel Spectral Characteristics
Signal Classification Results – Shown in Event Notification
COTS RF Collector
ASURE Sensing

Figure 4. ASURE spectrum sensing displays and lab set-up.

Two modes are defined for the SSM operation. In autonomous mode, the SSM is given a frequency range to scan for, and it provides periodic reports to the SM on where signals have been detected and which frequencies are available. In this mode of operation, the SSM does not perform signal classification for the detected signals. Some of the measurements that are reported to the SM include, reports on the frequency channels that are available and their aggregate power spectral density. These measurements are then used to prioritize the backup channels, in case the radio needs to move from its current operating channel. The SSM can also be operated in a client / server configuration, where the SM can ask the SSM to scan a specific channel to confirm the presence of a detected signal and to classify it. This signal classification information is then used to either make a more informed decision at the SM or is passed on to the higher layers such as Network Operations (NetOps) where this information may be used for spectrum planning and policy.

The SSM uses custom designed feature based spectrum sensing algorithms based on Higher Order Statistics (HOS) and cyclostationary features ([2]-[5]). Energy based signal detection is also available however, unlike in [6], it is not used extensively due to the security concerns [4].

B. *Configuration and Monitoring*

Figure 5. shows the ASURE Configuration and Monitoring (C&M) state machine diagram. Each flow on the state machine diagram is represented by a tuple of (event / action) which specifies the action taken in response to a particular event that has occurred. The numbers on the events indicate the ASURE Message IDs.

The C&M module is written in JAVA^{TM} and it resides in each of the nodes, interfacing the SSM and the radio. The C&M acts as a link between each of the nodes and the SM. C&M contains the software for monitoring and controlling the radio and the SSM. The C&M also contains local intelligence and decision making capabilities.

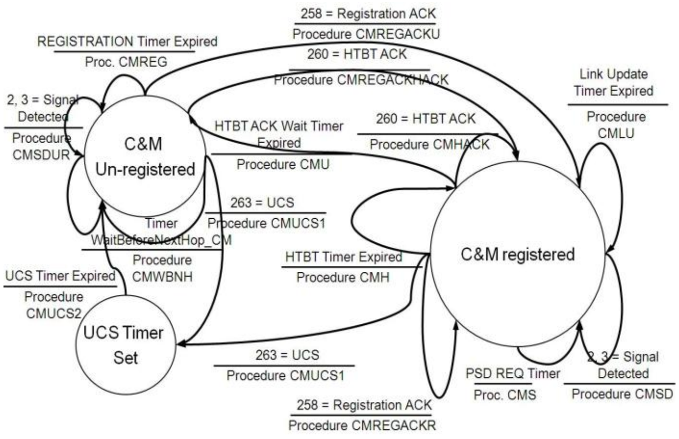


Figure 5. ASURE Configuration and Monitoring (C&M*)* Operation.

C&M periodically fetches spectrum sensing information from the SSM. In case of any changes to previously recorded information that resides in its local memory, it transmits this information to the SM. C&M also monitors the radio link parameters such as the Received Signal Strength Indicator (RSSI), the Carrier to Interference plus Noise Ratio (CINR), the modulation and coding format and the Packet Error Rate (PER) of the radios for every flow going in and out of the node. The C&M sends this information periodically to the SM. In case of sudden changes to any of these parameters, it is capable of sending urgent link update message to the SM, where the SM decides if change in frequency, BW or power are required.

C&M also absorbs the management and control commands from the SM and acts on them. These requests are of various types such as SSM configuration, radio re-configuration for channel move, specific sensing request etc. The radio re-configuration request from SM instructs the C&M to re-configure the radio parameters such as frequency of operation, bandwidth, power etc. which allows radios to circumvent the dynamic interference environment. The C&M is also responsible for executing a rendezvous, in case the link to the SM is lost.

C. ASURE Cognitive Engine - Spectrum Manager

Figure 6. shows the ASURE cognitive engine operation as a state machine diagram. The ASURE cognitive engine is also called as the Spectrum Manager (SM). Since the SM is addressed by its unique IP address, it is possible for the SM to reside in any part / module of the network.

The SM is responsible for absorbing the local sensing and link parameter information from each of the nodes and making a decision whether change in the radio network parameters such as frequency, BW or power are required. The ASURE capability of allowing the change in the radio operating frequency as well as BW allows Gray space utilization and provides greater agility to the network. Future versions of the SM are likely to be provided with an interface to the NetOps.

The SM keeps track of the sensing information from the various SSMs and uses this information to pre-compute the backup channel configuration. The backup channel configuration is computed as a tuple of (frequency, bandwidth, transmit power). The SM at any time pre-computes upto three backup channels and transmits this information to all the nodes periodically.

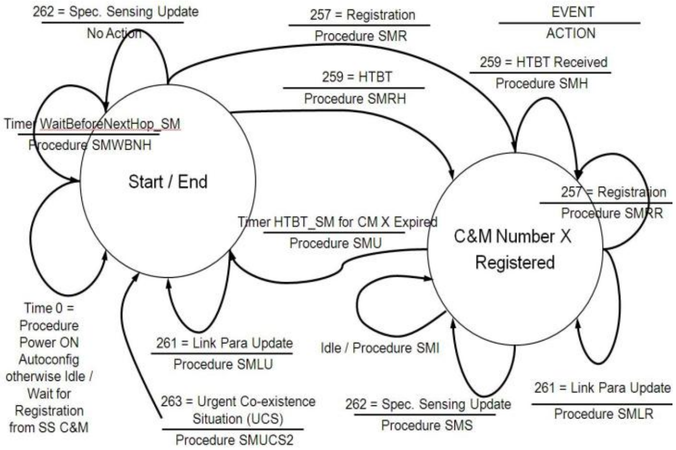
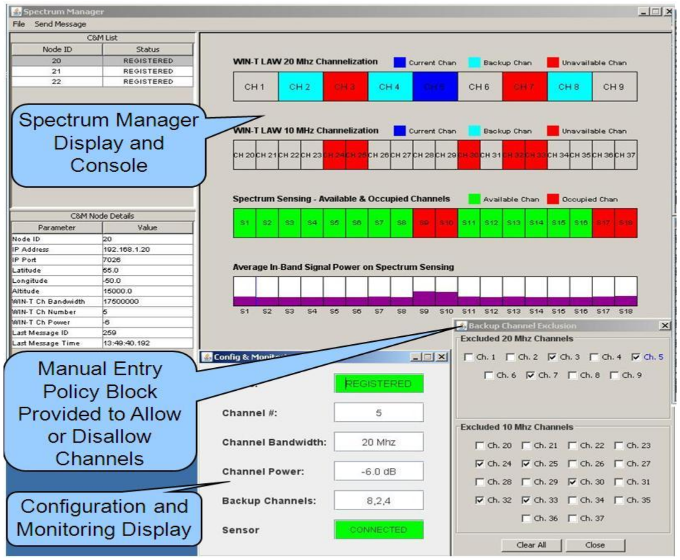


Figure 6. ASURE Cognitive Engine – Spectrum Manager Operation.



C&M List

Node ID	Status
20	REGISTERED
21	REGISTERED
22	REGISTERED

C&M Node Details

Parameter	Value
Node ID	20
IP Address	192.168.1.20
IP Port	7026
Latitude	55.0
Longitude	-50.0
Altitude	15000.0
WIN-T Ch Bandwidth	17500000
WIN-T Ch Number	5
WIN-T Ch Power	-6
Last Message ID	259
Last Message Time	13:49:40.192

WIN-T LAW 20 Mhz Channelization 🟦 Current Chan 🟦 Backup Chan 🟥 Unavailable Chan

CH 1	CH 2	CH 3	CH 4	CH 5	CH 6	CH 7	CH 8	CH 9

WIN-T LAW 10 MHz Channelization 🟦 Current Chan 🟦 Backup Chan 🟥 Unavailable Chan

CH 20	CH 21	CH 22	CH 23	CH 24	CH 25	CH 26	CH 27	CH 28	CH 29	CH 30	CH 31	CH 32	CH 33	CH 34	CH 35	CH 36	CH 37

Spectrum Sensing - Available & Occupied Channels 🟩 Available Chan 🟥 Occupied Chan

S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	S16	S17	S18

Average In-Band Signal Power on Spectrum Sensing

S1 S2 S3 S4 S5 S6 S7 S8 S9 S10 S11 S12 S13 S14 S15 S16 S17 S18

	REGISTERED
Channel #:	5
Channel Bandwidth:	20 Mhz
Channel Power:	-6.0 dB
Backup Channels:	8,2,4
Sensor	CONNECTED

Excluded 20 Mhz Channels

☐ Ch. 1 ☐ Ch. 2 ☑ Ch. 3 ☐ Ch. 4 ☑ Ch. 5
☐ Ch. 6 ☑ Ch. 7 ☐ Ch. 8 ☐ Ch. 9

Excluded 10 Mhz Channels

☐ Ch. 20 ☐ Ch. 21 ☐ Ch. 22 ☐ Ch. 23
☑ Ch. 24 ☑ Ch. 25 ☐ Ch. 26 ☐ Ch. 27
☐ Ch. 28 ☐ Ch. 29 ☑ Ch. 30 ☐ Ch. 31
☑ Ch. 32 ☑ Ch. 33 ☐ Ch. 34 ☐ Ch. 35
☐ Ch. 36 ☐ Ch. 37

Clear All Close

Figure 7. SM Display Console.

When a signal is detected on a particular channel, the SM has a capability to further investigate it by asking the sensing algorithms to classify the signal type and report back. Based on this information, the SM makes a decision on whether the detected signal is authentic and whether the channel is available for operation. The SM may also capable of transmitting this information to the NetOps in order to facilitate the spectrum planning decision. Such an interface has not been provided as yet.

SM at any given time keeps track of all the C&Ms that have registered with it. The SM has the intelligence to reason, if a connection was broken because of interference or if it was broken because of poor link margin. In cases when the link is about to go down due to interference, a command for network move is issued before the link is lost completely asking all the registered C&Ms to move to the first available backup channel. In cases when such a call does not go through, and the link to the SM is lost for more than a certain amount of time, the C&Ms have the local intelligence to move to the first backup channel. In situations where no backup channels are available, the C&M initiates a rendezvous algorithm to try and synchronize with the SM. The rendezvous algorithm becomes complicated when some of the nodes do not have a local sensor, as is the case for our system. This is because the computed backup channels may not be optimal for the nodes without a sensor (as no local sensing information is provided to the SM). This corner case was studied and a technique was proposed to mitigate this.

Figure 7. shows the SM display console demonstrating how the information fusion takes place from various nodes to the SM. The dark blue color represents the 'current operating channel,' the light blue color represents the 'backup channels'. The red color represents the 'disallowed' channels as specified by the policy. The policy block at this time is defined using manual entries by the users, but in future we envision that this information will be provided by the upper echelons as a part of the NetOps. The third row shows the fusion of the sensing information from various SSMs. Light green color represents channels where no signal has been detected and that are 'available' for radios to operate on. Red color represents channels where some signals (either a friendly network or some other interfering signals) were detected and hence they are 'disallowed' from use. The last row in violet represents the aggregate PSDs of the channels. Aggregate PSD is defined as

$$\mathrm{PSD}_{\mathrm{Aggregate}} = \frac{1}{N \cdot K} \sum_{n} \sum_{k} \left| X_{k,n} \right|^2 \quad k = 0, \ldots, K-1,$$

where X_k is the Fourier transform of the captured signals for a particular channel, k is the Fourier co-efficient and n represents the PSD information coming from a particular node. N and K represent the total number of nodes that have sensing capability and length of the Fourier transform respectively. The aggregate PSD is proportional to the sum of the powers of all the signals and the noise contained in that particular channel. It is to be noted that when no information bearing signal is detected for a particular channel, the aggregate PSD is a measure of total amount of interference plus the noise contained in it. Note that the Shannon capacity is defined by the following equation,

$$C = BW \cdot \log_2\left(1 + \frac{S}{I+N}\right) \approx BW \cdot \log_2\left(1 + \frac{S}{\mathrm{PSD}_{\mathrm{Aggregate}}}\right)$$

where C is the information rate, S is the signal power, BW is the Bandwidth, and $(I + N)$ is the total interference plus the noise power. For all the 'available' channels, where no signals are detected based on feature based sensing algorithms, the aggregate PSD is proportional to the interference plus the noise power. Hence the capacity, C, for a given fixed transmit power S is maximized by choosing a channel with lowest aggregate PSD. This logic is used to prioritize the backup channels.

D. ASURE Messaging

This section discusses the ASURE messaging. Since an extensive library of messages was defined for the ASURE system, it is not possible to discuss all the messaging in this paper. Figure 8. shows the messages that are exchanged between each of the C&Ms and the SM. The Registration message (MSG ID 257) is sent by the C&M to the SM, when it first tries to register with the SM. In response to the Registration, the SM sends Registration Acknowledgement message (Message ID 258) which also contains the configuration information for the C&M, the SSM and the radio.

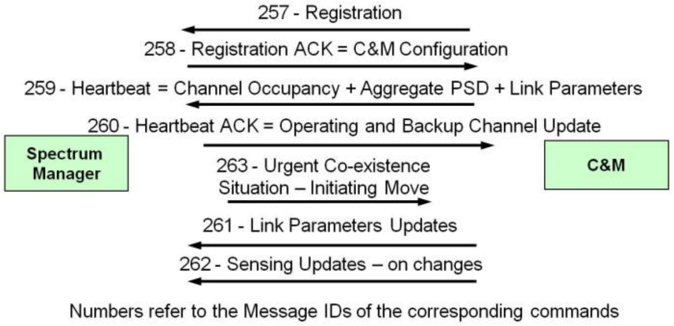

257 - Registration
258 - Registration ACK = C&M Configuration
259 - Heartbeat = Channel Occupancy + Aggregate PSD + Link Parameters
260 - Heartbeat ACK = Operating and Backup Channel Update
Spectrum Manager
263 - Urgent Co-existence Situation – Initiating Move
C&M
261 - Link Parameters Updates
262 - Sensing Updates – on changes
Numbers refer to the Message IDs of the corresponding commands

Figure 8. Messaging between the C&M and the SM

Once the registration is complete, the C&M sends Heartbeat message (Message ID 259) to the SM, periodically. The Heartbeat contains the channel occupancy, aggregate PSD and link parameters information for every flow through the node. In response to the Heartbeat message, the SM sends out the Heartbeat ACK message (Message ID 260) to the C&M, which contains the operating and backup channel information. Message ID 263 represents the Urgent Co-existence Situation message that commands all the C&Ms to move to the backup channel. Message IDs 261 and 262 contain urgent link update information and signal classification information respectively.

IV. ASURE FIELD TEST RESULTS

The ASURE field demonstration was carried out at the Ft. Dix facility of CERDEC. Ft. Dix has been uniquely laid out by PM C4ISR OTM to test and evaluate next generation on the move technologies. The ASURE demo consisted of three nodes operating in a PMP network topology. One of the nodes did not contain the SSM. Figure 9. shows the ASURE node with no SSM. This demonstrates that not all the nodes in a cognitive radio network require spectrum sensing capability.

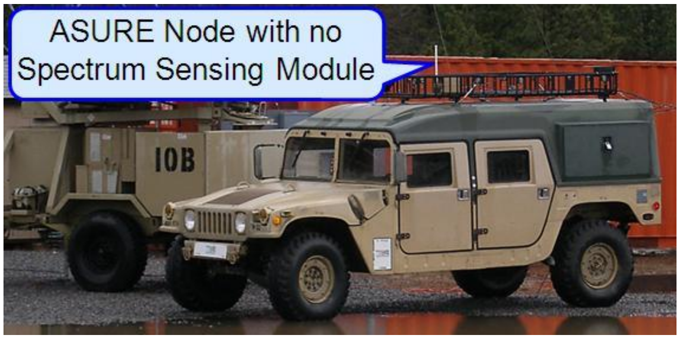
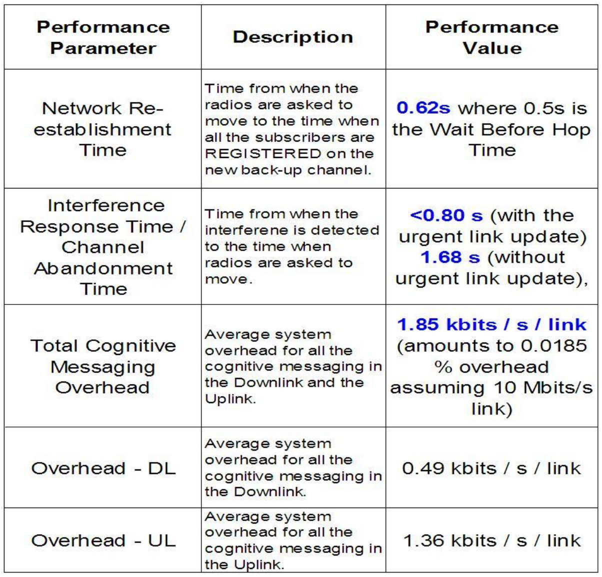


Figure 9. ASURE node with no Spectrum Sensing Module

Interference was created using a COTS Agilent signal generator emanating certain non-information bearing waveforms within the frequency range of operation of the radios. Another static WIN-T LAW radio network was also made to operate in the vicinity. A variety of tests were carried out to measure the ability of the ASURE network to operate in a dynamic interference environment. These tests consisted of testing the time to abandon the channel once the interference was detected, the time taken to re-establish the network on another channel, and system overhead due to all the cognitive messaging. These measured parameters have been listed in the following table.

TABLE I. ASURE System Performance



Performance Parameter	**Description**	**Performance Value**
Network Re-establishment Time	Time from when the radios are asked to move to the time when all the subscribers are REGISTERED on the new back-up channel.	**0.62s** where 0.5s is the Wait Before Hop Time
Interference Response Time / Channel Abandonment Time	Time from when the interferene is detected to the time when radios are asked to move.	**<0.80 s** (with the urgent link update) **1.68 s** (without urgent link update),
Total Cognitive Messaging Overhead	Average system overhead for all the cognitive messaging in the Downlink and the Uplink.	**1.85 kbits / s / link** (amounts to 0.0185 % overhead assuming 10 Mbits/s link)
Overhead - DL	Average system overhead for all the cognitive messaging in the Downlink.	0.49 kbits / s / link
Overhead - UL	Average system overhead for all the cognitive messaging in the Uplink.	1.36 kbits / s / link

The results in TABLE I. show that it is possible to make the current non-DSA military radios 'cognitive' without making any hardware or firmware modifications to them. The table also shows that the system works in spite of not having a sensor at every node. The network re-establishment and the channel abandonment times are quite small, in spite of the application level messaging, and can be improved in many ways. Finally, adding cognitive messaging at the application level does not add any significant penalty to the system throughput. The cognitive messaging overhead and timing are likely to increase linearly with the number of nodes in the system, however, some preliminary investigation has shown that the overhead per node can be substantially reduced by eliminating redundancy in the messaging that was incorporated to ensure robust operation in the dynamic interference environments.

Future expansion of the ASURE test-bed,is likely to include use of other disparate radios, optimizing the messaging, providing an interface to the NetOps for policy control, improving the signal classification algorithms, increasing the number of nodes to test the system scalability, modifying the ASURE system for mobile ad-hoc network (MANET) environments etc.

V. CONCLUSIONS

In this paper we showed that it is possible to incorporate autonomous and advanced spectrum agility in non-DSA equipped military radios without hardware or firmware modifications, while maintaining real-time system connectivity and link quality in the presence of dynamic interference environments. We also showed that not every node in the network requires spectrum sensing capability. We also showed that application level messaging can be used to monitor and control the radios. The cognitive messaging overhead was found to be miniscule as compared to the overall network throughput. The system operation was validated through real time field experiments at the Ft. Dix facility of the US Army CERDEC. Finally, this paper demonstrates that it is possible to make current military radios 'cognitive' in a cost-effective manner without making hardware or firmware modifications to them.

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