COGNITIVE RADIO TESTBED: REAL-WORLD ELECTROMAGNETIC SPECTRUM SURVEYS, MODELING, AND SIMULATION

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ABSTRACT

Electromagnetic environment conditions are crucial to operations of spectrum sensing Cognitive Radios (CR); also known as Dynamic Spectrum Access (DSA) radios. In order to validate the operation of CR/DSA radios, testbeds that can reliably model and reproduce the behavior of the real-world electromagnetic spectrum will be required. In this paper, we describe one aspect of such a testbed development; surveying, modeling and emulation of a real-world radio electromagnetic spectrum using two different approaches. In the first approach, spectrum survey measurements recorded via a spectrum analyzer were imported in Matlab, modeled, and manipulated to simulate a variety of "scenarios" that may be encountered in the real world. The resultant waveform was ported to a signal generator to simulate the real-world electromagnetic environment for the testbed. The second approach utilizes a real-time spectrum analyzer, an I&Q data management system, and a signal generator. The survey system recorded I&Q data components then played back the data to produce the electromagnetic spectrum background for the testbed. Overall, it has been shown that the two methods could be used to create realistic electromagnetic environments for testbed to support CR/DSA research and development. This is an important component of the testbed since it allows testing of CR/DSA radios/networks in a realistic electromagnetic environment.

***Keywords*—Cognitive Radios, CR, Dynamic Spectrum Access, DSA, Electromagnetic Environment, Spectrum, Primary User**

1. INTRODUCTION

Radio electromagnetic spectrum is a precious natural resource that is governed and licensed by governments for uses in radio communications. The spectrum is limited and currently statically allocated throughout the world, resulting in simply an insufficient amount of spectrum to meet the growing demands by both commercial and military users given the inefficient static allocations. Studies estimate a growth rate of 18% per year for spectrum demands in the future [1]; while the entire spectrum from 6 kHz to 300 GHz is allocated [2], at any given point in space and time, most spectrum is unused. In fact, a study determined that 94% of spectrum is unused worldwide [3]. Opportunistically reclaiming the unused allocated/licensed spectrum for other applications, without interference to the licensed user (Primary User (PU)), has great potential for resolving spectrum shortage. Mitola introduced the Cognitive Radio (CR) technology concept that could serve the purpose. The basic concept of Mitola's CR technology is that it allows an adaptive radio to adjust its operation based on information captured from the environment as well as measurements of its own performance [4].

Based on Mitola's CR concept the Defense Advanced Research Projects Agency (DARPA) develops NeXt Generation (XG) and Wireless Network after Next (WNaN) radios. XG and WNaN radios are DSA radios, which through adaptive mechanisms, opportunistically use licensed electromagnetic spectrum, without interference with the PU. DARPA's goals are to enable a factor of ten increase in spectrum usage [3]. Currently, military and commercial interests are high in CR/DSA technologies research and development to promote greater spectrum efficiency. Testbeds are needed to support CR/DSA technology research and development. This paper is the first in a series of papers to describe the development of such a testbed. Per reference [4], electromagnetic environment conditions are crucial to operation of CR/DSA radios, thus testbed simulation of an electromagnetic environment should be as realistic as possible. Two systems that could serve the purpose are presented. Methods of surveying, modeling, and simulation of the real-world electromagnetic spectrum are described.

2. MEASUREMENT SYSTEMS AND RESULTS

To survey the electromagnetic environment, two different systems, developed independently at NRL and USNA, were used to record spectrum measurements in the 700-800 MHz frequency range in and around the greater Washington DC metro area. The USNA system was a Swept Spectrum approach that utilized an omnidirectional antenna in conjunction with an Anritsu spectrum analyzer and Miteq low noise amplifier. The NRL system utilized an omniantenna, a real-time spectrum analyzer, a disk array, a data flow control unit, an I&Q playback generator, and anI&Q signal generator.

2.1 Swept Spectrum Measurement System

The Swept Spectrum Measurement System was built to survey electromagnetic spectrum in the frequency range of [700 MHz – 3000 MHz]. A basic block diagram of the spectrum occupancy measurement system is shown in Fig. 1. In order to accurately record extremely weak signals, the measurement system utilized an ultra-low noise Miteq AFS3 amplifier (LNA in the figure). At the input to the amplifier, a 700-3000 MHz bandpass filter, constructed from a 700 MHz high-pass filter and a 3000 MHz low-pass filter, was utilized to prevent strong out-of-band signals from creating spurious signals in the amplifier and distorting the results. Additionally, a PIN Diode limiter was connected to the amplifier to protect its input from strong signals. The amplifier output was connected to an Anritsu MS2724B spectrum analyzer, and a laptop computer was utilized to download and record data from the spectrum analyzer. A GPS disciplined oscillator provided a precise 10 MHz reference signal for the spectrum analyzer. Data postprocessing and analysis was performed off-line via Matlab.

At the highest resolution, the measured system noise floor was -133 dBm, allowing it to observe signals that were 10 to 30 dB weaker than those previously recorded in the literature. The low noise floor is important because a narrowband receiver, one with a bandwidth of less than 100 kHz and a typical noise figure of less than 5 dB, will have a noise floor in the -120 dBm to -130 dBm range and will be able to achieve good performance when the received signal power is in the -110 dBm to -120 dBm range [5].

To validate that <u>*all*</u> recorded signals were free of internally generated spurious signals, the measurement system was thoroughly characterized in an RF isolation chamber, and key system parameters are given in Table 1.

In addition to the system characterization, several tests were performed to evaluate the dynamic range of the measurement system and determine the maximum amplitude for internally generated spurious signals.

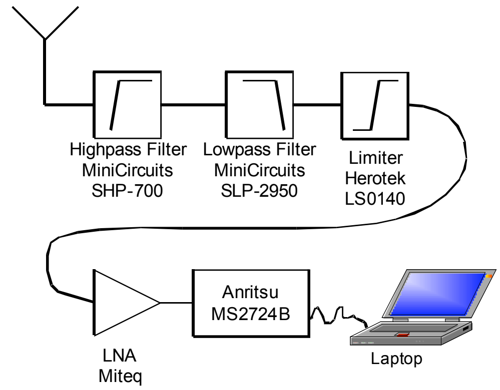

Fig. 1 - A block diagram of the USNA Swept Spectrum Measurement System

Table 1: Spectrum Occupancy Measurement System Parameters

Parameter	Value
Noise Figure	3.1 dB
1 dB Compression Point	5.0 dB
Output 3rd Order Intercept Point	+15.1 dBm
Output 2nd Order Intercept Point	+28.5 dBm
Strongest spurious signal	-110 dBm

Table 1 – Measurement system parameters

For the first test, a single tone signal was input to the system at a frequency of 1.0 GHz and amplitude of -50 dBm (approximately 3 dB stronger that the strongest signal observed in the environment). The resulting analysis determined that no spurious signals appeared above the -133 dBm noise floor.

For the second test, nine unmodulated tones, spaced 2.0 MHz apart and centered at 750 MHz, with an average amplitude of -50.0 dBm, were input to the measurement system. To determine whether the spurious signals were generated internally by the measurement system or produced by the signal generator, the output of the signal generator was connected directly to a Tektronix SA2600 real-time spectrum analyzer. Fig. 2 shows the comparison of the two recorded spectra (note that the noise floor of the SA2600 alone is significantly higher than that of the measurement system). From Fig. 2, we can observe that two large spurious signals at 710 and 790 MHz were produced directly by the signal generator and were not generated internally by the measurement system. We also observed that the maximum amplitude of any spurious signal (whether generated by the signal generator or measurement system) is -105 dBm, or 55 dB below the peak carrier amplitude. This spurious level (whether as an absolute or relative level) thus represents a lower limit for the usability of the measurement system, as recorded measurement data that falls below this level could be spurious signals rather than environmental signals.

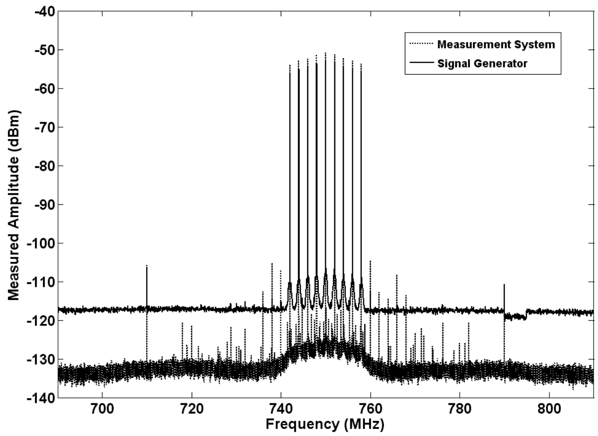

Fig. 2: Spurious signal evaluation of the spectrum occupancy measurement system with a multitone CW input signal. The black line is the spectrum produced by the signal generator, and the blue line is the spectrum recorded by the measurement system.

For the third test, three broadband digital signals, at a center frequency of 750 MHz, with bandwidth of 1.25 MHz, spaced 5 MHz apart, and an average amplitude of -65 dBm, were input to the measurement system.

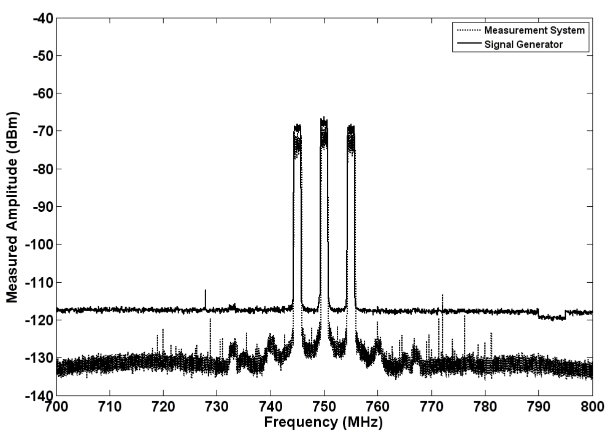

Fig. 3: Spurious signal evaluation of the spectrum occupancy measurement system with a multitone broadband input signal. The black line is the spectrum produced by the signal generator, and the blue line is the spectrum recorded by the measurement system.

Fig. 3 shows the resulting spectrum recorded by the measurement system, as well as the output of the signal generator as recorded by a Tektronix SA2600. For wideband inputs, we observe that the maximum amplitude of spurious signals is -115 dBm, or 50 dB below the average amplitude of the wideband input signal. By performing both a CW and wideband digital multitone test, we have confidence that the measurement system responds similarly to both types of signals.

2.2 Real Time I&Q Spectrum Measurement System

The NRL system employed a real-time spectrum analyzer as an RF front end receiver. “Real-time” is a relative term and in the context of this study it’s determined mostly by the sampling rate and processing speed of the spectrum analyzer. The system recorded the electromagnetic spectrum, decomposed it into I&Q components and stored the I&Q data for later use. In playback mode, I&Q components are fed into a signal generator, which regenerated the captured spectrum. Playback spectrum was captured with the same real-time spectrum analyzer for validation purpose.

This Real Time system consists of a vertical active OMNI antenna, a Tektronix 9 kHz – 14 GHz real-time spectrum analyzer, and an X-COM set which consists of a disk array, a data flow control unit, an I&Q playback generator, and an I&Q signal generator. A basic block diagram of The system is given in Fig. 4.

The active vertical OMNI antenna has antenna gain factor of [10 dB to 7 dB] in the frequency range of interest. The spectrum analyzer has a frequency range of 9 kHz – 14 GHz, acquisition bandwidth of 40 MHz, 14 bit 100 MS/s A/D, internal acquisition memory of 1 GB, and a DANL of -151 dBm/Hz at 2 GHz. The data flow control unit acted as a “data traffic cop” which controlled all of the data flows in the system. With a sampling rate of 2.5 times the acquisition bandwidth the maximum duration of the electromagnetic environment to be recorded with the spectrum analyzer’s internal memory is 6 seconds for a 20 MHz bandwidth and 3 seconds for a 40 MHz bandwidth.

To capture data for longer durations, the system utilized an external storage disk array. With the setup as shown in Fig. 4, the real-time spectrum analyzer captured and decomposed the electromagnetic spectrum into I&Q components. The I&Q components were continuously streaming to the external storage disk array, which had a capacity of 2 TB, 1 TB for Inphase and 1 TB for Quadrature components, resulting in a record time of up to 1.5 hours at 40 MHz real-time bandwidth and up to 3 hours at 20 MHz real-time bandwidth measurements. The disk array can be daisy chained for expansion of capacity, if necessary.

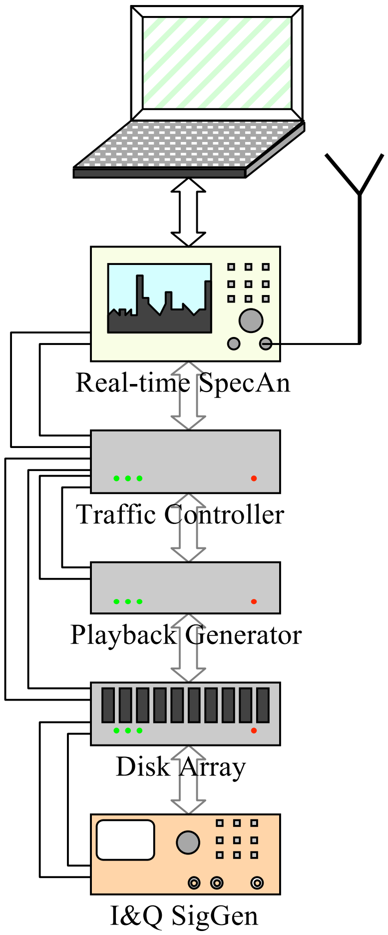

Fig 4 – Block diagram of the Real Time measurement system with data streaming

3. SPECTRUM MEASUREMENTS

To evaluate the measurement system, spectrum occupancy measurements were performed in suburban and urban areas in the vicinity of Washington DC between June and August of 2009.

3.1 Swept Spectrum Measurements

For the suburban area measurements, the measurement system was installed on a tower, at a height above ground of approximately 30 meters. A broadband discone antenna was utilized, which had a 270° field of view of the area. Data were recorded in 2.0 MHz segments across the 696–810 MHz frequency band. The spectrum analyzer was configured to utilize a 3 kHz resolution bandwidth and record 551 points in each 2 MHz segment, and required 12 minutes to complete each sweep. Measurements were repeated every 15 minutes from 2:30pm on June 12 (immediately before the US Analog TV broadcast shutdown), 2009 to Midnight June 13, 2009.

The urban area measurements were recorded on the top floor of a mall parking garage, a height of approximately 15 meters above the ground. Measurements were performed on the afternoon of June 12 and again on June 16. An active vertical dipole was installed such that it had a 360° view of the surrounding area. Data were recorded in 2.0 MHz segments across a 696–810 MHz block. As with the suburban area measurements, the spectrum analyzer was configured to utilize a 3 kHz resolution bandwidth and record 551 points in each 2 MHz segment. Measurements were repeated every 15 minutes for a period of 2 hours on each measurement day.

Fig. 5 shows the spectrogram recorded from the suburban area measurements; a similar spectral environment was observed at the urban area location. From the figure, we can observe a strong analog TV transmission at a carrier frequency of 718 MHz, as well as a few weak transient signals at a variety of other frequencies.

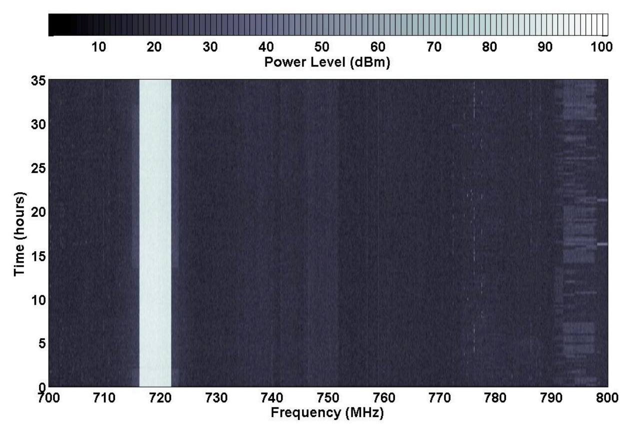

Fig. 5 - Spectrogram recorded by the measurement system in the suburban area location

3.1 Real Time Spectrum Measurements

Real Time spectrum measurements were performed in the vicinity of Washington DC in August of 2009. The system was placed on ground level with no obstruction within 25 m from the OMNI antenna and the sky was clear. Data was collected at center frequency of 780 MHz with real-time acquisition bandwidths of 40 MHz, 20 MHz, and 5 MHz, resolution bandwidth of 20 kHz, video bandwidth of 20 kHz, and 0 dB RF attenuation. Measurements were performed at different real-time acquisition bandwidths for analysis of the system consistency. Screen shots of real-time spectral displays were taken as shown in Figure 6.

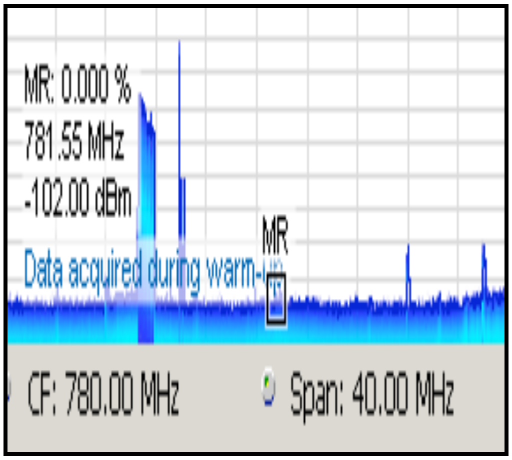

Fig. 6 – Screen shot of real-time spectrum at CF 780 MHz, BW 40 MHz, August 2009

4. SPECTRUM MODELING AND PLAYBACK

4.1 Matlab Modeling of Swept Spectrum Measurements

The task in this section was to take a set of eight frequency spectrum snapshots (illustrated in Figure 7) create a time domain signal for each snapshot, concatenate all of the time domain signals together, and replay them using an Arbitrary Waveform Generator (AWG) in order to emulate a changing frequency spectrum. The second stage of modeling, which is currently ongoing, will be to insert or remove prerecorded signals at various locations in the environment in order to evaluate the ability of a DSA radio to sense and adapt to its environment.

The first task of data manipulation was to pick a threshold below which the spectrum will be considered empty. This threshold was set to -110 dBm (based on the performance of the measurement system), and any signal below this value was set to an amplitude of zero.

The next task in signal recreation was to prepare the signal for inverse-Fourier transform which would return the signal to the time domain. This was accomplished by creating a reflected snapshot of the signal and combining it with the original. At this point, a computer-generated random phase was added to each data point on the spectrum and the inverse-Fourier transform took place. The process was then repeated for each of the eight spectral snapshots, the eight snapshots were then concatenated together into a single time-domain waveform. To prevent discontinuities at the boundaries from creating spurious signals, each time-domain signal was windowed using a Hamming window. The resulting signal was then downloaded into a GAGE GA11G Arbitrary Waveform Generator. Each segment of the eight pieces of the concatenated signal may be replayed by the AWG for any specific amount of time, which makes it possible to replicate the spectral sweeps which took place at the time that the data was originally recorded.

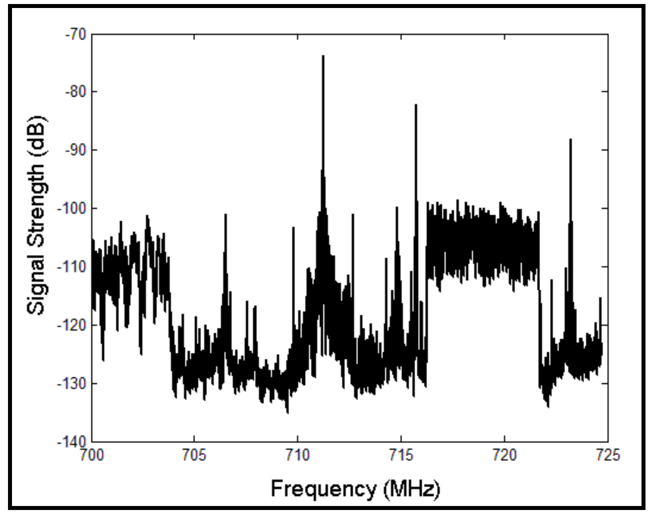

Fig. 7 – Example Swept Spectrum measurement used in Matlab modeling and signal recreation.

To evaluate the performance of the generated modeled signal, the AWG signal was input into the Anritsu spectrum analyzer, and the resulting signal is shown in Fig. 8. When compared to the original signal (Fig. 7), it is evident that there are spurious signals present within the modeled spectrum, specifically at 699 and 706 MHz, and that the waveform between 700 and 705 MHz is distorted. The spurs are a result of resampling the time-domain signal to match the fixed 1.0 GHz sampling frequency of the AWG. The spectrum distortion is a result of the relatively weak amplitude of the 700-705 MHz signal, much of which is well below the -110 dBm threshold.

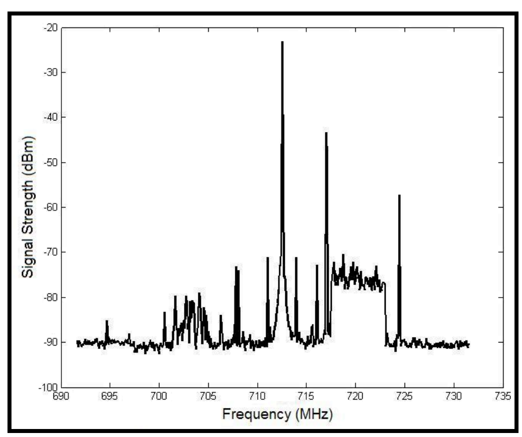

Fig. 8 – Example AWG output from the Swept Spectrum Matlab model.

4.2 Laboratory Playback of Real-Time Spectrum Measurements

The captured I&Q data from the Real Time measurement system were used for analysis and playback in the laboratory environment. During playback, I&Q data were streamed from the storage disk array to the I&Q playback generator which generated analog I&Q data to the I&Q signal generator. The I&Q signal generator re-generated the captured electromagnetic environment and the playback signal was received and captured with the same real-time spectrum analyzer and data record system for later analysis and verification. An example screen shot of the playback is given in Figure 9.

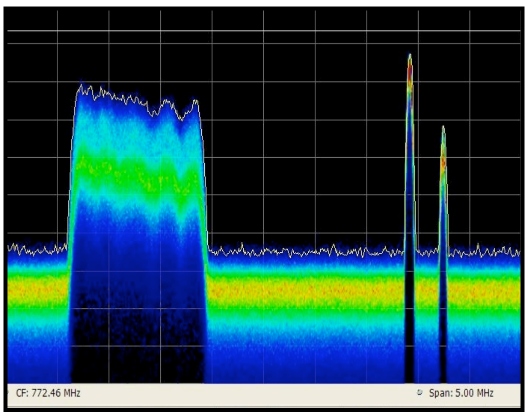

Fig. 9 – Screen shot of playback spectrum at CF 772 MHz , BW 5 MHz

Correlations between the captured real-time and playback data sets could be performed for quantification of the simulation error. Visually, the screen shots qualitatively show that the playbacks resembled the real-time electromagnetic environments. Also, the same level of resembling could be found from visual displays of spectra collected in swept spectrum measurement system as discussed earlier. This measurement/playback system thus should be sufficient in providing a real-world electromagnetic environment backdrop for the testbed. Waveforms signatures of legacy radios, emergency systems, radars, interference signals, and jamming signals could be added to create environments that may be encountered in the real world for the testbed.

5. CONCLUSIONS

Two methods to create realistic electromagnetic testbed environments to support research and development of CR/DSA radio technologies were presented. The first method was to survey and record the environment, model the environment with Matlab, and then port the modeling result to a signal generator for generation of the environment for the testbed. Playback spectrum from AWG resembled data plotted from Matlab modeling. The advantage of this method is that it provides flexibility in manipulating the waveform to a desired DSA scenario. The second method was to survey and record the environment in I&Q component format. The recorded I&Q data later was ported to a signal generator for generation of the testbed environment. This method requires less programming effort and it produced a playback electromagnetic environment which visually resembles the real-time environment. However, manipulation of the waveform to create a real-life DSA scenario seems to be more complex and require additional instruments.

Overall, it has been shown that the methods could be used to create realistic electromagnetic environments to support research and development of CR/DSA technologies. Future plans include modeling, simulation and, correlation analysis of real-time and playback data sets of the real-time spectrum system. A library of waveforms for legacy radios, emergency systems, radars, interference signals, jamming signals, etc., could be built to allow simulation of different scenarios for the testbed.

6. REFERENCES

[1] *Report of the Defense Science Board Task Force on Tactical Battlefield Communications, Office of the Under Secretary of Defense for Acquisition, Technology & Logistics*, February 2000

[2] Telecommunication, online, 2007; http://wwww.access.gpo.gov/cgi-bin/cfrassemble.cgi?title=200747

[3] *DARPA XG communications Program Overview*, Preston Marshall, Todd Martin, Feb., 2007

[4] J. Mitola III, *"Cognitive Radio",* Licentiate proposal, KTH, Stockholm, Sweden, Decm. 1998

[5] Christopher R. Anderson, Charles B. Cameron, United States Naval Academy, *How Empty is Empty? Weak-Signal Spectrum Survey Measurements and Analysis for Cognitive Radio*, SDR Forum Technical Conference, Washington DC, November 2009.