Agilent Cognitive Radio Algorithm Development and Testing

White Paper

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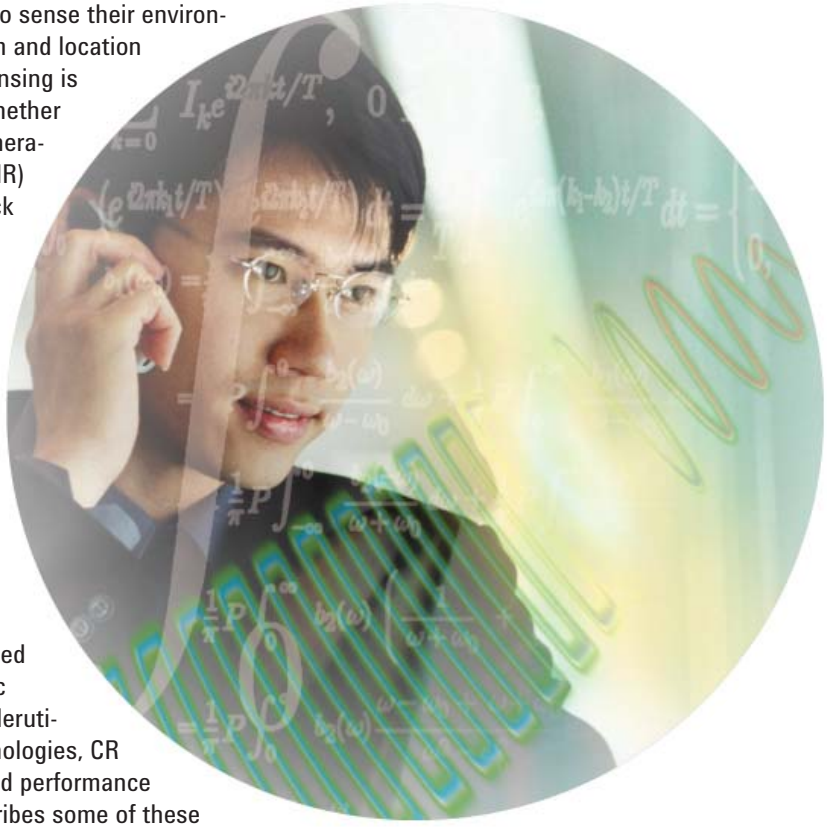
Introduction

The term "cognitive radio" (CR) means different things to different people. However, most seem to agree that cognitive radios have, as a fundamental building block, the requirement to sense their environment. Specifically, they require spectrum and location sensing. Fast and accurate spectrum sensing is critical to dynamic spectrum sharing, whether for television (TV) whitespace, next generation (XG) radio, or land mobile radio (LMR) applications. The spectrum sensing block is common to most, if not all, dynamic spectrum access technologies, where the goal is to find and occupy underutilized, or "whitespace" spectrum. This is distinctly different from multi-mode, multi-band cell phones which search for occupied spectrum in the form of base-station downlink signals and then take their instructions from the cellular system. Cellular systems are quite sophisticated and achieve high spectral efficiency using highly coordinated and controlled spectrum access. Cognitive radio systems achieve increased spectral utilization through opportunistic access to what the radio believes is underutilized spectrum. As with most new technologies, CR technology brings with it new design and performance verification challenges. This paper describes some of these challenges and introduces a new tool, the cognitive radio algorithm R&D testbed.



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For the purposes of this paper, we will take a somewhat inclusive approach to the definition of cognitive radio, including even the simplest of forms dynamic spectrum-sharing technologies, such as detect-and-avoid (DAA) and dynamic-frequency-selection (DFS). With this admittedly broad definition, a cognitive radio is defined as a radio that can sense its environment and then modify its behavior, based on a set of rules (policy), and without operator intervention. The term whitespace is used generically in this discussion so as to not limit its scope to TV whitespace.

The performance of a cognitive radio system depends on many factors. Some spectrum sensing algorithms are fast and low-complexity. Others provide high sensitivity and reliability, but use more computational resources and may require longer detection intervals. The cognition engine may be implemented with simple logic or it may incorporate neural networks. CR performance generally increases when the radio has access to more relevant information. For example, cognitive radios might share information to enable cooperative spectrum sensing. They might also access external information from sources such as protected transmitter databases. As we increase the sophistication of cognitive radios, we can perhaps evolve from simple DFS and DAA radio technology to truly-cognitive radios that fabricate signals which fully utilize non-contiguous segments of **underutilized** spectrum in a predictive manner.

It is worth noting that **underutilized** spectrum is not the same thing as **unused** spectrum. It is generally true though, that **unused** spectrum is **underutilized** – provided it is truly **unused**. In some cases, spectrum that appears to be **unused** may actually be used. For example, if it is monitored by receivers (e.g., radio astronomy) or if use of the spectrum would result in interference due to poor selectivity in a victim receiver tuned to an adjacent frequency. It is also generally true that occupied spectrum may be **underutilized** if additional RF energy can be injected without causing unwanted interference. A simple example would be the addition of a second spread-spectrum signal to spectrum already "occupied" by an existing spread-spectrum signal. Clearly, accurate and reliable spectrum sensing is not without its challenges.

The key functional blocks of a cognitive radio are shown in Figure 1. The radio policy can be described as a set of rules which provide operational boundaries and limitations. The actual operating characteristics of the radio/modem are determined by the behavior and control block using information from the other functional blocks. As an example, the behavior and control block could select a modulation and frequency – based on what's allowed by the policy – for the geographic area determined by the location sensing block, using spectrum resources deemed as available by both the spectrum sensing and database blocks.

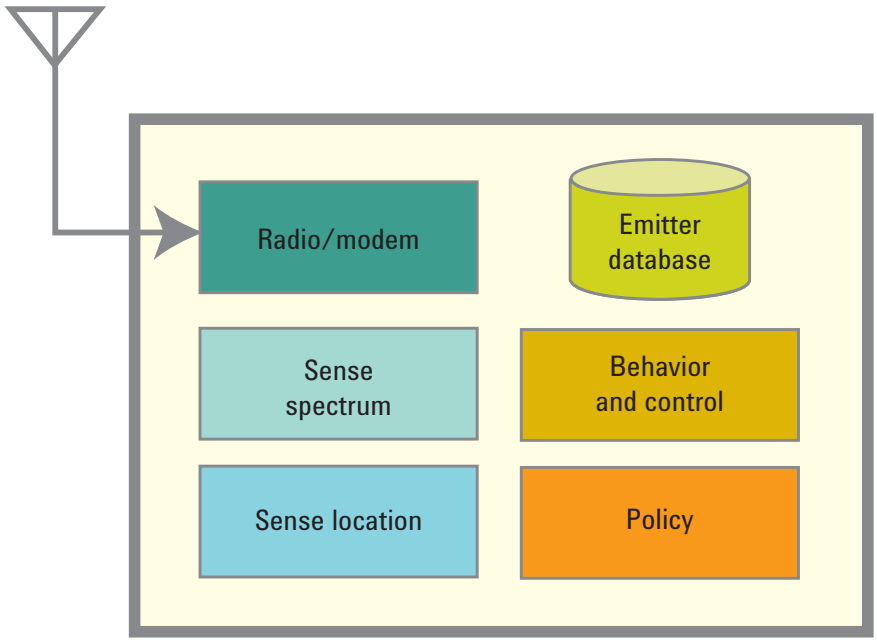

Figure 1. A basic cognitive radio

One motivation for cognitive radios is increased spectrum utilization in situations where it is not practical to have a centralized and all-knowing spectrum resource manager. In such situations, cognitive radios determine what spectrum resources are available and how best to use them. This process, sometimes referred to as "filling the whitespace," is depicted in Figure 2. Here, one of the whitespace radios appears to simply change frequencies. The other radio seems to anticipate the behavior of the protected signals and completely modify its signal's spectral shape to avoid interference, while filling the new spectrum holes.

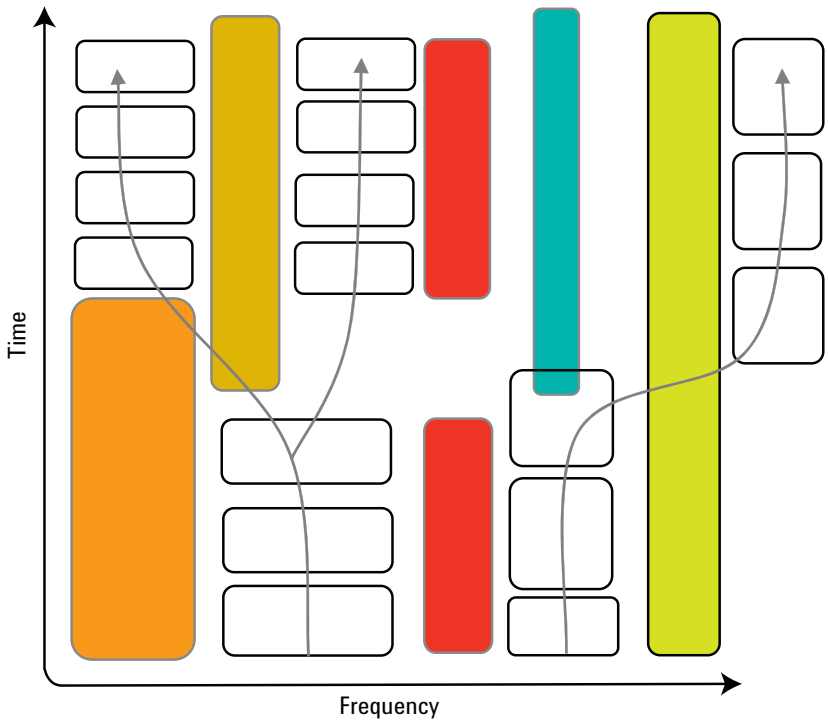

Figure 2. Filling the whitespace

Orthogonal frequency-division multiplexing (OFDM) technologies are particularly well suited to cognitive radio applications because of the ease with which signals can be adapted to channel conditions and capacity requirements. This is evident in radio standards such as Mobile WiMAX™, and Long Term Evolution (LTE), both of which utilize a form of OFDM called orthogonal frequency-division multiple access (OFDMA). Mobile WiMAX can support 5, 7, 8.75, and 10-MHz channel bandwidths with fast Fourier transform (FFT) sizes of 512 or 1024. Similarly, LTE supports 1.4, 3, 5, 10, 15, and 20-MHz bandwidths. OFDM signals also have the potential to be modified on a subcarrier-by-subcarrier basis. By selectively disabling subcarriers, wideband signals can avoid interfering with narrow-band signals, even if they are located in the same main channel. While not specifically designed for cognitive radio or whitespace applications, we will use these standard signals to demonstrate key concepts.

Challenges and Barriers to Cognitive Radio Development

Cognitive radio development requirements represent a new paradigm for R&D engineers by challenging established design and test methodologies. In particular, CR development poses significant challenges and barriers to developing and testing CR whitespace algorithms, including:

- Real-world spectral environments need to be used for algorithm development and testing. However, the use of live signals creates test conditions that cannot be replicated from one day to the next. Short field trials may not experience the full range of conditions, while long field trials are expensive and may be impractical.
- Laboratory and R&D environments provide the design tools and equipment needed to develop and test algorithms, but emulating real-world CR spectral environments to adequately design and test CR algorithms can be very difficult.
- Detect-and-avoid 'what-if' scenarios are difficult to evaluate in a lab environment, and are also difficult to test methodically in field environments.
- Metrology-grade test equipment is needed to test radio algorithms, but off-the-shelf test equipment typically does not support signal types that represent the realistic CR environments that the radio would be exposed to.
- Algorithms need to be tested with real-world impairments such as intermodulation distortion and spurious signals (both internally and externally generated).

These challenges and barriers highlight the need to innovate new algorithm development and test methodologies that combine real-world CR spectral environments with the controlled, repeatable and toolset-rich R&D/lab environment to accelerate algorithm development and testing before deploying the radio hardware to the field.

Cognitive radio requirements for maximum rerformance and minimum interference

1. Quickly and accurately detect a wide variety of protected signals under dynamic channel conditions. Signals can vary in a number of ways, including: bandwidth, duration, modulation, and cyclo-stationarity properties.
2. Identify underutilized spectrum in the presense of strong adjacent channel signals while avoiding false-positive detections with varying levels of noise.
3. Make timely and intelligent decisions within the constraints of the policy that maximize radio system performance, while minimizing interference and the use of radio and spectral resources.
4. Do all of the above within the practical constraints of hardware performance limitations such as RF performance (e.g., spurious and distortion), battery consumption and computational resources.

A Paradigm Shift in Algorithm Development and Testing

A new tool, the cognitive radio algorithm R&D testbed, combines remote field sensing with a toolset-rich controlled lab environment (Figure 3). Doing so allows CR algorithms to be developed and tested with real-world CR environment signals. Using this testbed, engineers can:

- Capture live signals at one or more locations for live testing, or record for later playback.
- Synthesize signals using simulated sources and channel models (to model transmitters and impairments).
- Combine captured and synthesized signals.
- Test spectrum-sensing algorithms (single or cooperative).
- Test cognition engine performance.
- Test radio link performance.

The remote field portion of the CR R&D testbed consists of one or more N6841A RF sensors that are installed at various geographic locations. The sensor locations are selected to gather data from different environments, or, to test cooperative sensing algorithms within an environment.

The N6841A RF sensors are effectively wideband RF receivers/digitizers that supply the spectrum-sensing algorithms with baseband I/Q time-series data. The data is accurately time-stamped with time-of-day information obtained either from the integrated GPS receiver, or the built-in IEEE 1588 network-based precision time protocol (PTP). The receiver's information bandwidth (and bandwidth-proportional sample rate) can be reduced from a maximum of 20 MHz, to something better suited to the needs of the cognitive radio and spectrum-sensing algorithms. The receiver's tuning range is 20 MHz to 6 GHz. The RF sensors are small and weatherproof, making them easy to install--an important consideration when the installation is temporary, or when greater flexibility in site selection is desired. More information on the N6841A sensor can be found at:
http://www.agilent.com/find/RFsensor

The lab environment portion of the CR R&D testbed utilizes Agilent's SystemVue software to capture the CR environment data from the remote N6841A sensors. SystemVue's math language and math language debugger are used to write and test CR whitespace algorithms with the remote field-captured signals (Figure 4). More information on SystemVue can be found at:
http://www.agilent.com/find/SystemVue

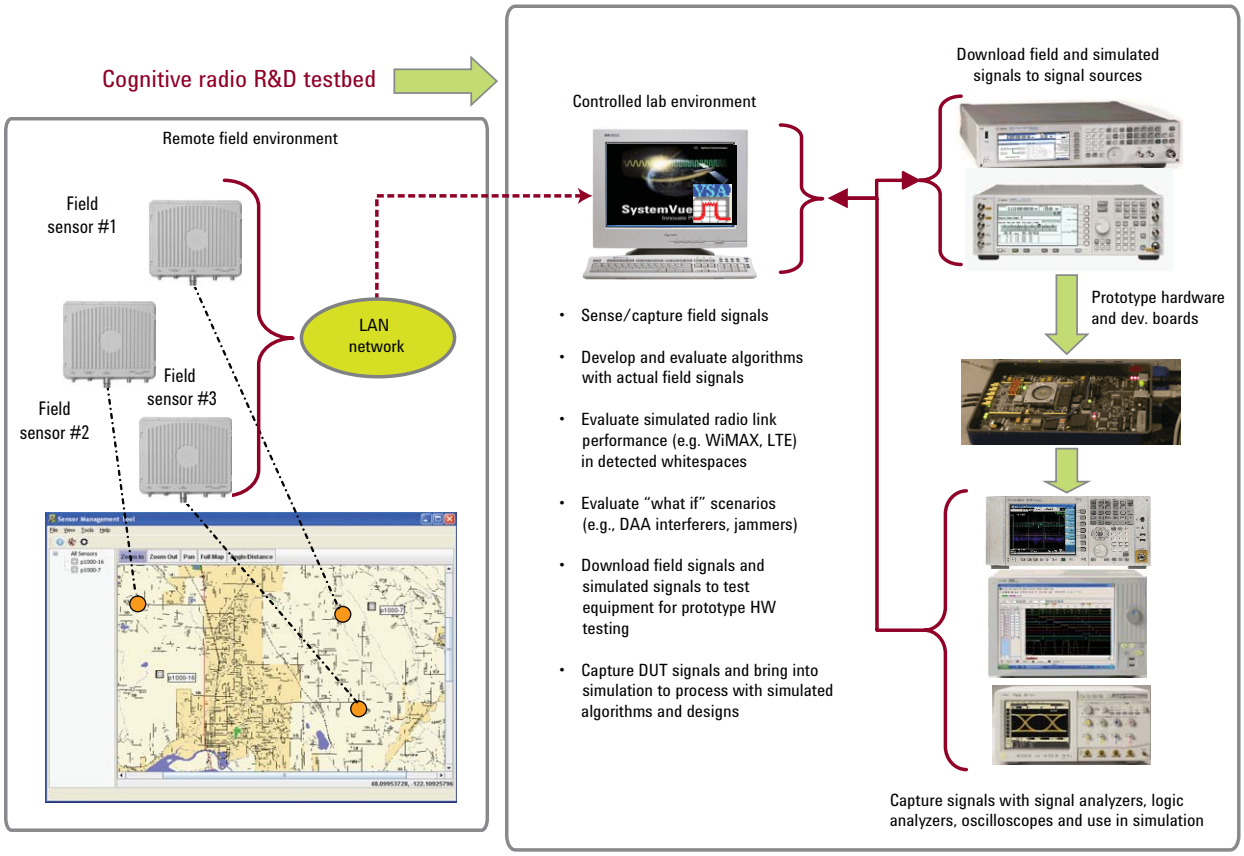

Figure 3. Cognitive radio R&D algorithm development testbed

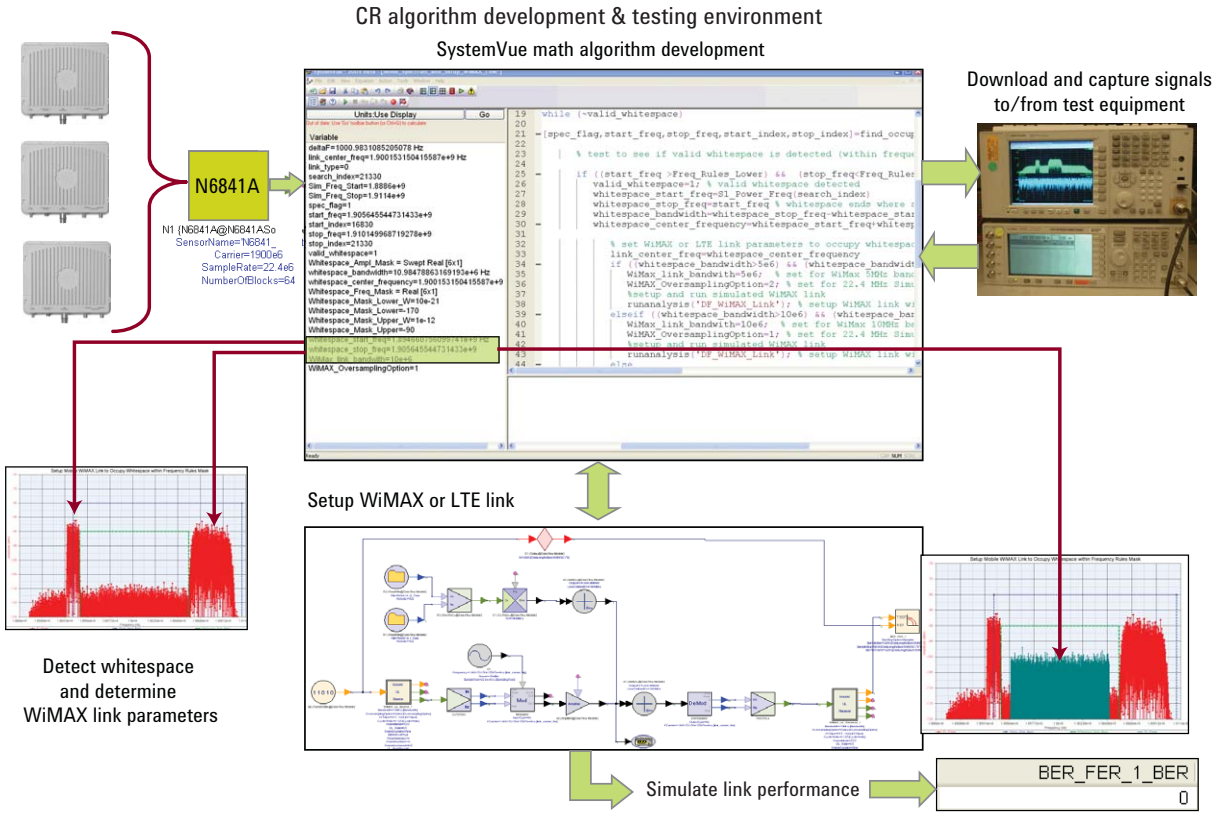

Figure 4. Using SystemVue's math algorithm environment to develop and test CR whitespace algorithms

The OFDMA simulation modeling capability in SystemVue can then be used to configure and evaluate OFDMA Mobile WiMAX and LTE link performance. SystemVue's math language scales the OFDMA bandwidths and establishes the transmission center frequencies within the detected CR whitespace to evaluate the coded, OFDMA bit-error-rate (BER) performance of the radio link. Simulation also provides the flexibility to evaluate "what-if" scenarios, a prime example of which is determining the impact of swept interferers on OFDMA link coded-BER/block-error-rate (BLER) performance for detect-and-avoid scenarios.

It can be useful to download and store remote field-sensor data to metrology-grade test equipment for hardware device-under-test (DUT) testing in the lab environment. Simulation provides the link between the remotely located field sensors and signal generators. It allows the captured field-sensor data to be downloaded to signal generator arbitrary waveform generators to re-create the field-captured signal in the lab environment. Once the waveform is downloaded to the signal generator arb, it can be stored in non-volatile memory. To facilitate DUT testing, DUT outputs can be captured and then read back into simulation to post-process signals. An example of this is testing the coded BER/BLER of a CR RF receiver. Here, simulation provides the baseband post-processing required to support the coded-BER/BLER measurement.

Case Study: A Mobile WiMAX CR Whitespace Algorithm

To better understand how the CR R&D algorithm testbed can be applied, consider the development and test of a Mobile WiMAX CR whitespace algorithm using the flow shown in Figure 5.

The flow involves capturing the CR spectral environment from the remote field location. The sensor is remotely located in western Washington State, while the simulation and test equipment setup is located in an office environment in eastern Washington State.

SystemVue's math algorithm processes the captured CR spectral environment to determine potential whitespace. The potential whitespace frequencies are evaluated against a policy to determine valid whitespace frequencies and available bandwidth to support an OFDMA Mobile WiMAX link. The math language algorithm then configures and scales the Mobile WiMAX center frequency and channel bandwidth to either 5 or 10 MHz, depending on the available whitespace it sensed and calculated. Next, the coded BER of the configured Mobile WiMAX radio link is evaluated to determine radio link performance.

The captured CR environment is also downloaded to a signal generator to re-create and analyze the CR environment. Lastly, the CR environment spectrum is de-modulated both in simulation and with test equipment using the Agilent 89601 vector signal analysis (VSA) software to identify the CR environment.

More details on these specific steps are as follows.

Step 1: Capture remote CR environment and read into SystemVue

The first step in this case study is to capture the CR environment using an N6841A sensor remotely located in western Washington State (Figure 6). This is accomplished from the convenience of an office environment in eastern Washington State using a custom N6841A link for SystemVue.

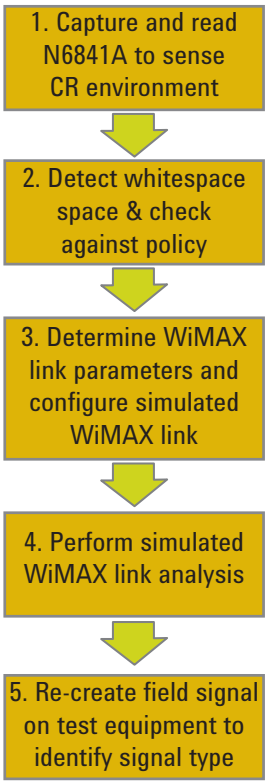

Figure 5. Cognitive radio whitespace algorithm case study flow

Instructions on installing and downloading the required dynamic link libraries (DLLs) for the custom N6841A link can be found at:

http://edocs.soco.agilent.com/display/eesofkc/SystemVue+N6841A

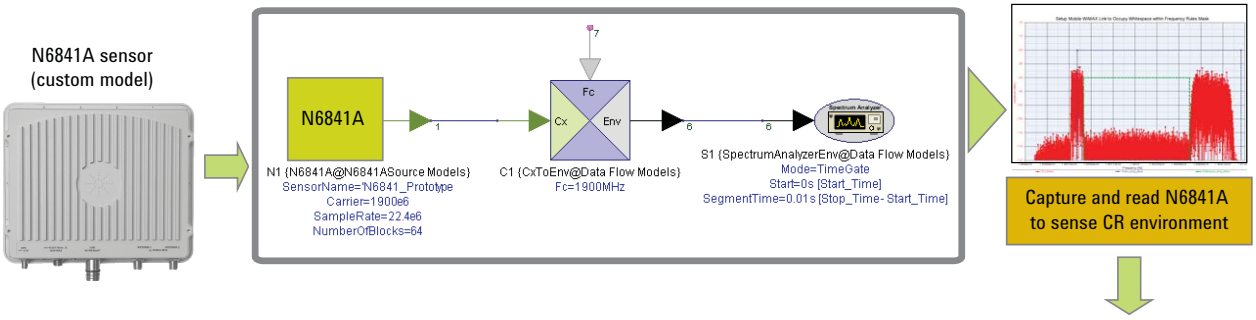

Figure 6. Capture remote CR environment from field and read into SystemVue

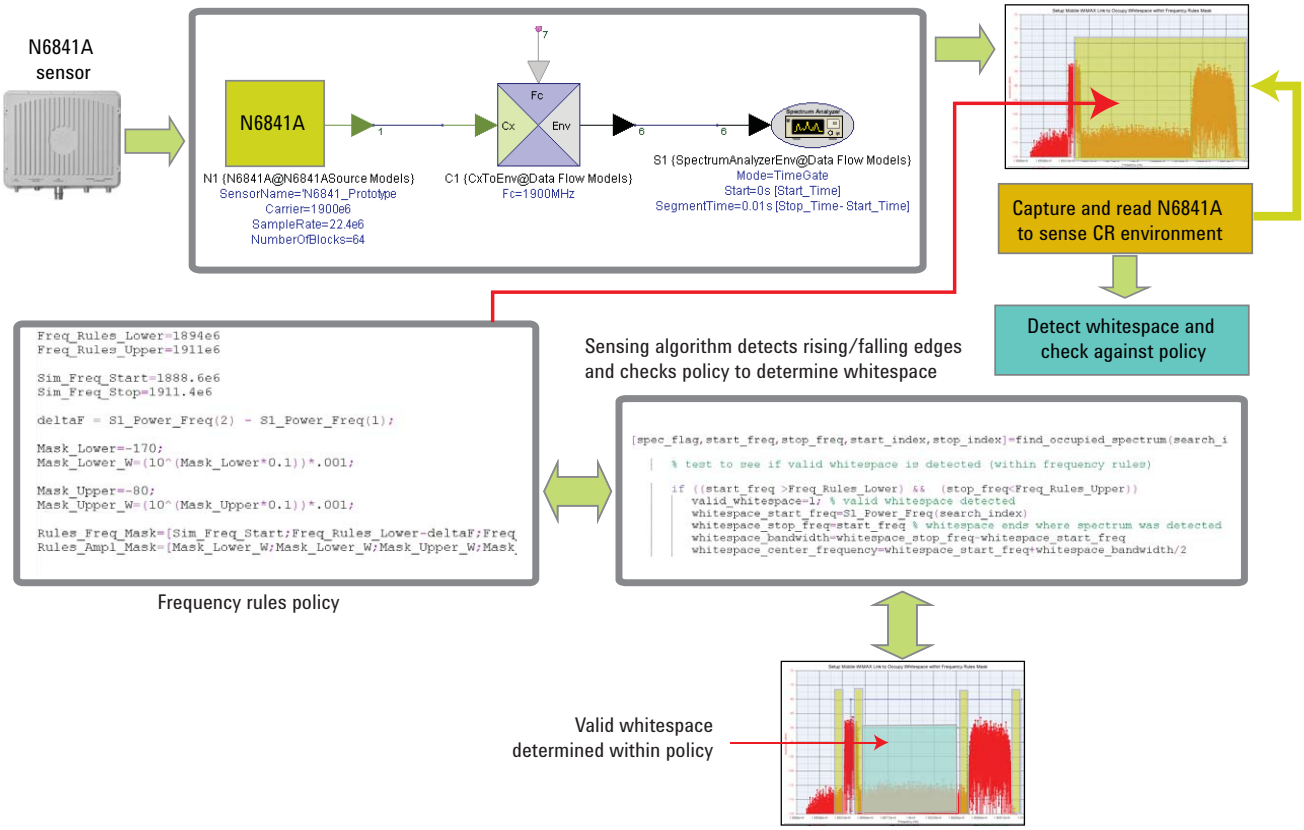

Figure 7. Sense whitespace, compare to policy and determine valid whitespace for OFDMA transmission

The custom N6841A link serves as a simulation signal source to read the captured signal into SystemVue where it is then stored using a spectrum analyzer sink. This enables the stored spectrum data to be post-processed and evaluated using the CR whitespace algorithm modeled in SystemVue as per Step 2.

Step 2: Whitespace algorithms sense the spectrum to determine valid whitespace

Once the CR environment has been captured and stored in the SystemVue dataset, several math algorithms are utilized to determine the available whitespace and determine if it is valid within the constraints imposed by the radio's policy (Figure 7).

The primary whitespace algorithm calls a secondary algorithm to detect rising and falling edges on the sensed, CR environment spectrum. This secondary algorithm effectively integrates the spectral power within a user-defined resolution bandwidth, sweeps the frequency span and compares the integrated power to user-defined power thresholds. The rising and falling edges, graphically illustrated in Figure 7 as the vertical bars on the lower spectrum, are compared against a frequency rules policy to determine the validity of detected whitespace. Valid transmission frequencies are displayed as the blue spectral mask on the upper spectrum in SystemVue. Once valid whitespace is determined, it is displayed as the green spectral mask on the lower spectrum.

Real-world whitespace algorithms can be quite involved and sophisticated, and thus challenging to develop and debug. The algorithms used in this case study are fundamental; however, they demonstrate how the CR R&D algorithm testbed can be used to develop and test more elaborate and robust whitespace algorithms. SystemVue's math language debugging capability was quite useful in debugging algorithm issues during the development of this whitespace algorithm code. The screen capture of the debugger in Figure 8 shows where a breakpoint is set in the algorithm code.

Once the breakpoint is set, the algorithm code can be single-stepped. Calculated values from the code are displayed on the left-side of the math language interface. Breakpoints can also be set in functions or other algorithms called from the main algorithm (e.g., the algorithm which detects rising and falling spectrum edges).

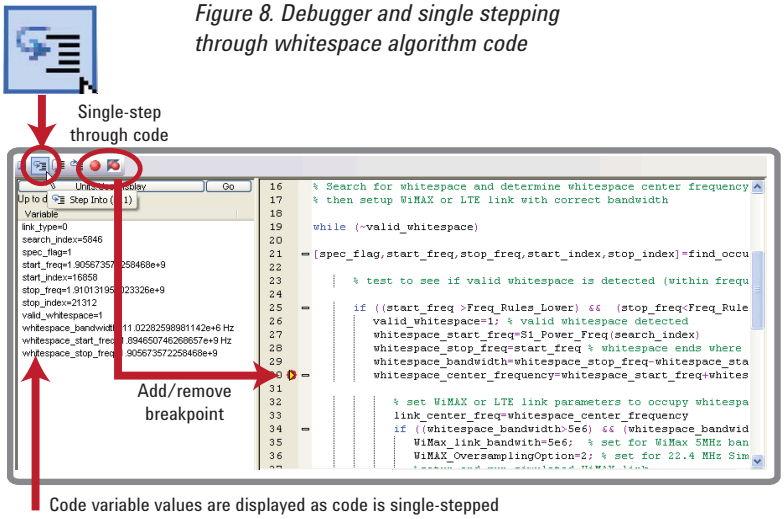

Figure 8. Debugger and single stepping through whitespace algorithm code

Steps 3 and 4: Whitespace algorithms sense the spectrum to determine valid whitespace

Next, the rising and falling edges of the sensed CR spectrum are compared to the frequency rules policy to determine the valid whitespace within the lower and upper frequencies defined in the policy. In Figure 9, the policy frequency limits are displayed by the blue rectangle in the spectrum, while the calculated valid whitepace is displayed as the green rectangle. The CR algorithm then determines if the whitespace is sufficient to support a 5- or 10-MHz OFDMA Mobile WiMAX or LTE link. It scales the OFDMA WiMAX or LTE channel bandwidth configuration accordingly, to fill the available whitespace and centers the OFDMA spectrum within the valid whitespace. A user-defined preference is set in the algorithm to specify whether a Mobile WiMAX link or LTE link will be used to occupy the spectrum.

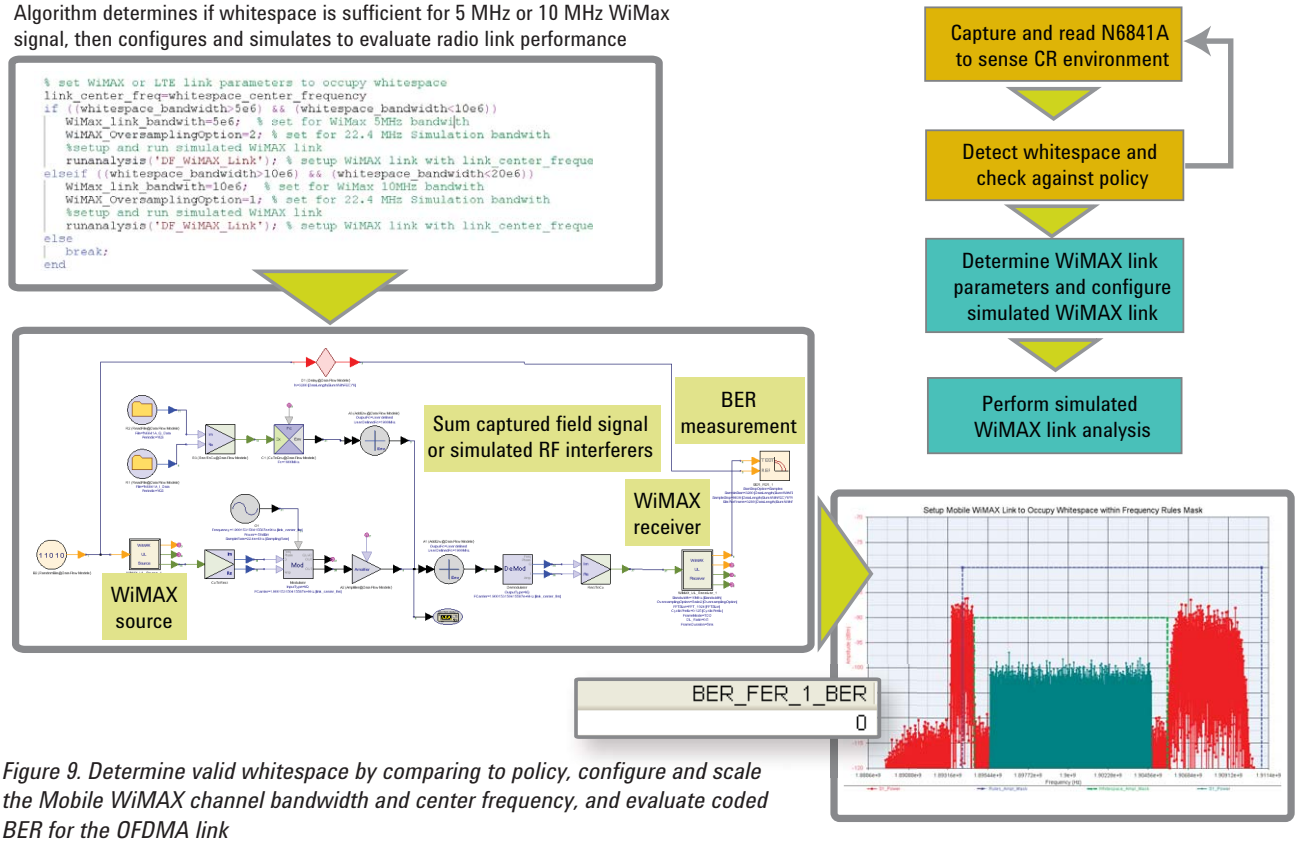

Figure 9. Determine valid whitespace by comparing to policy, configure and scale the Mobile WiMAX channel bandwidth and center frequency, and evaluate coded BER for the OFDMA link

The rectangular-shaped spectrum (middle spectrum) on the spectrum plot in Figure 9 is the Mobile WiMAX spectrum. It has been centered in the valid whitespace and scaled to occupy the available whitespace bandwidth. The two red spectrums on either side are the sensed CR environment that was detected with the N6841A sensor. The Mobile WiMAX schematic on the left is configured by the math algorithm and simulated to evaluate the coded BER performance of the Mobile WiMAX link.

To evaluate detect-and-avoid scenarios, simulated interferers can be introduced into simulation and swept to evaluate the impact of the interferer on OFDMA link performance. Figure 10 shows a differential quadrature phase-shift keying (DQPSK) narrowband interferer being swept across the CR frequency environment, along with its impact to the Mobile WiMAX OFDMA BER performance.

Step 5: Identify CR environment signals

When sensing spectrum in the real world, it is very likely that one will observe signals that raise questions about their origin and perhaps even their legitimacy. In TV whitespace applications, TV and wireless microphone signals must be protected, while most other signals--especially other whitespace signals--are not. For these reasons, there is often a need to identify over-the-air signals to verify correct behavior of the spectrum sensing and cognition algorithms.

One tool that has proven very useful for analyzing and identifying unknown signals is the 89601 VSA. It is unique in its ability to isolate and analyze signals in time, frequency and modulation domains. The tool can be used to observe the burst length of a signal, its power statistics and its spectral characteristics. Gate markers allow this analysis to be performed over adjustable time intervals, such as when analyzing a portion of a signal searching for training sequences. Auto-correlation functions can be used to search the signal for periodicity. Many demodulators both analog (AM/FM/PM/IQ) and digital (too numerous to list) are also available for more detailed analysis.

The 89601 VSA can be used with Agilent test equipment, as well as with Agilent's SystemVue software. When used with SystemVue, it processes simulated signals instead of DUT hardware signals with test equipment. Several possibilities exist for identifying remotely sensed signals: identifying the signal in simulation by analyzing SystemVue's N6841A sensor data with the 89601 VSA software or using SystemVue to download the N6841A sensor data to a signal generator and then using the 89601 VSA to analyze the signal. Both possibilities are examined below.

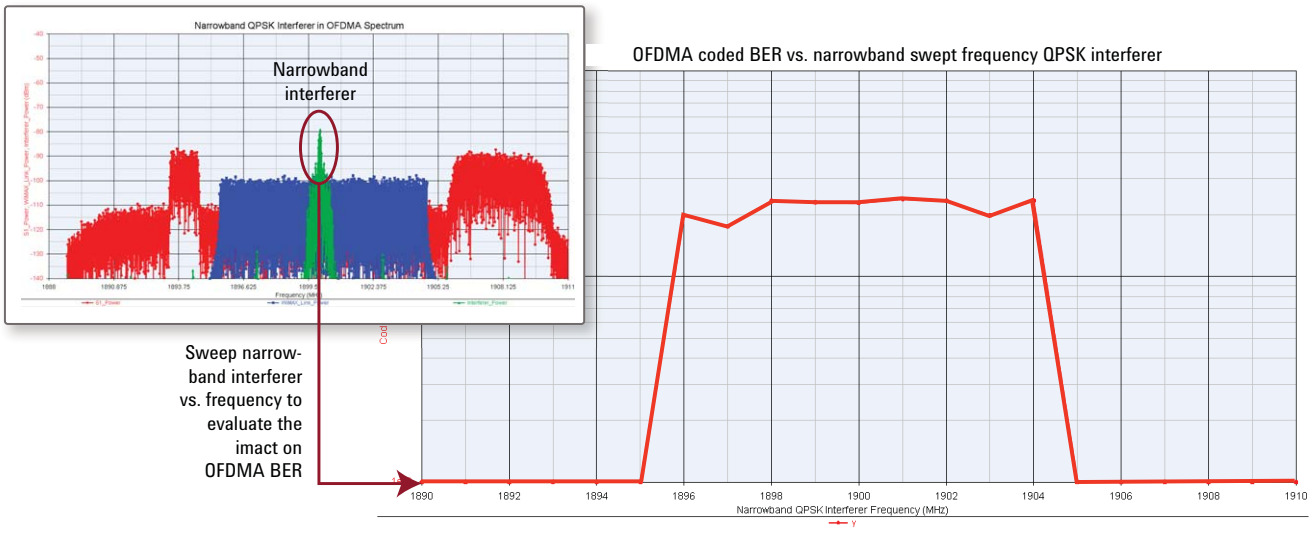

Figure 10. Impact of swept narrowband interferer on OFDMA BER

The first possibility is to identify the signal in simulation using the VSA simulation measurement capability as shown in the upper-left corner of Figure 11. The sensed spectrum from the remote N6841A sensor is read into SystemVue and then demodulated by the 89601 VSA software. While the 89601 VSA is measurement software which runs on Agilent test equipment (e.g., RF signal analyzers, logic analyzer and oscilloscopes), here it measures simulated signals from SystemVue, where the simulated signal is the captured sensed spectrum from the N6841A sensor. The sensed spectrum shows two spectral peaks--the blue spectrum traces on the lower left of the VSA display in Figure 11. By setting the VSA's center frequency to center on one of the spectrums, and trying different demodulation configurations pre-set on the VSA software, this signal type can be identified as a WCDMA downlink signal. The code domain is shown on the upper left, constellation on the upper right, and EVM on the lower right of the VSA display.

The second possibility is to download the N6841A captured signal to an Agilent ESG or MXG signal generator, as shown in the lower-right corner of Figure 11. This is accomplished using the sink on the lower-right of the SystemVue schematic. The sink downloads the simulated I and Q to the signal generator's arbitrary waveform generator, turning the simulated signal into a physical real-world test signal for DUT testing. In this example, the captured signal from the N6841A is downloaded to an ESG arbitrary waveform generator and the RF output of the ESG is connected to an MXA signal analyzer. The same 89601 VSA software used for the demodulation analysis in SystemVue is also used in the MXA to demodulate the ESG RF output. Once the CR environment signal has been downloaded to the ESG or MXG, it can be stored in non-volatile memory for further testing in the lab environment.

Summary

This white paper details a novel new R&D testbed for developing and testing cognitive radio whitespace algorithms. It combines simulation and test to enable sensor data to be captured at remote field locations and used in the convenience of an office or lab environment to develop and test cognitive radio algorithms. This offers the benefit of using real-world environment signals (captured remotely) to develop and test algorithms in an R&D environment, with a rich set of simulation tools and metrology-grade test equipment. Flexible simulation can be used to evaluate "what-if" interference scenarios for detect-and-avoid situations. Seamless integration between simulation and test equipment enables remotely detected signals to be identified in simulation, or on the testbench, by downloading and analyzing signals with test equipment.

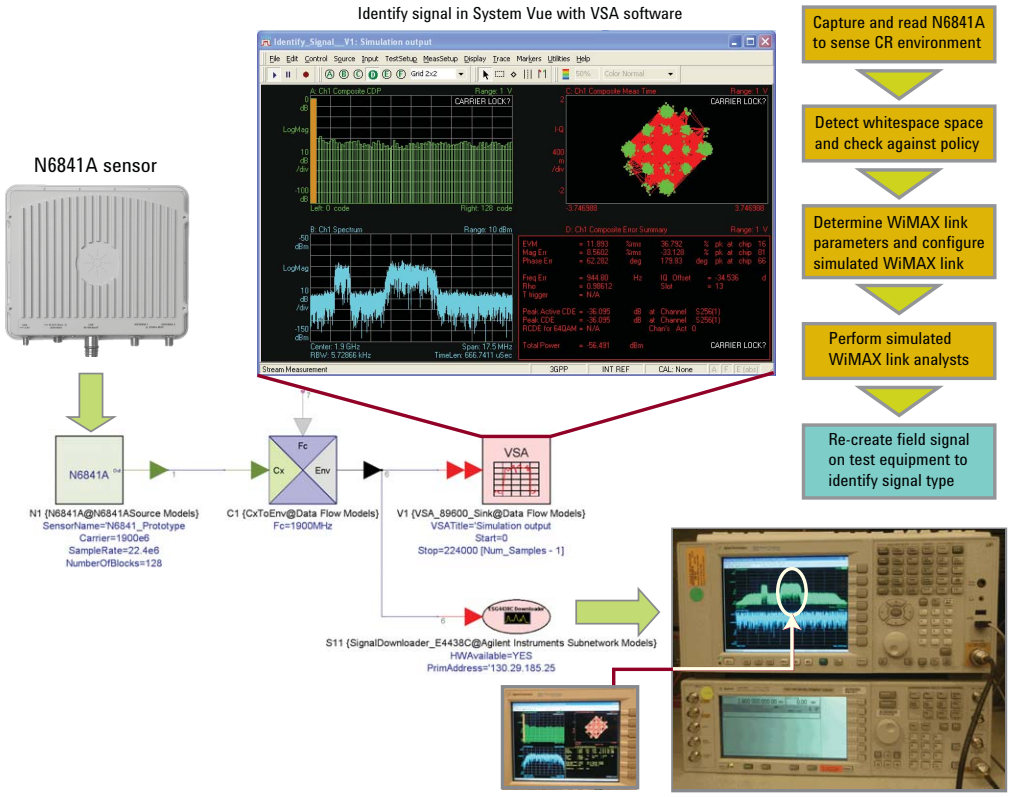

Figure 11. Identifying remotely-sensed signals using the CR R&D testbed

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