Modeling Cognitive Radio Performance in High Spectral Density Signal Environments

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ABSTRACT

This paper will show the methodology to model the throughput performance of a Cognitive Radio operating in a high density RF signals environment. Most modeling of SDRs and Cognitive Radios are typically done using a single, ideal waveform. At best, some noise and multipath might be added. In the real world, Cognitive Radios must be able to function successfully in areas that can contain many different radiation sources at various power levels and frequencies. This paper will model the combined effects of a desired RF signal combined with several different measured RF spectral environments, measured on a Vector Spectrum Analyzer, all being applied to the receiver input, processed through the receiver and through the DSP as it attempts to adapt to the applied RF spectral environment. Effects such as Desensitization, ADC aliasing and over-ranging and spurious products effects will be modeled using waveform throughput as the means of measuring radio performance. The waveform, which worked well in an "ideal environment," will be shown to fail to meet the required throughput requirement in a "real world" RF spectral environment. This methodology will show the Cognitive Radio Platform Architect or the Algorithm Developer how they can evaluate system performance in "real world" RF spectral environments throughout the development and implementation process, thus saving time, reducing cost and improving immunity to intentional and unintentional jamming.

• 1. INTRODUCTION [1]

A "Cognitive Radio" (CR) needs to sense its spectral environment and then quickly modify its behavior to find and occupy the available whitespace spectrum based upon a set of rules (policy). Ideally the CR needs to be very flexible in terms of its ability to find unutilized white space.

The ideal Cognitive Radio would be a digital radio with few unchangeable RF components, such as RF filters, where virtually all of the signal processing will be done in the digital domain. From a DSP engineer's viewpoint, they would like to have the Analog to Digital Converter (ADC) positioned directly at the antenna input (Fig. 1.). Obviously, this technique has some significant limitations to its successful implementation, at least with today's technology. Some of those limitations include detecting very small signals, on the order of -80 dBm or less, in the presence of many high level signals, thus requiring both a wide bandwidth and also frequency selectivity with a large dynamic range. The primary focus of this paper will be to recover the desired signal(s) while still taking into account the dense real-world spectral environment that these Cognitive Radios will need to be able to continuously adapt to, in order to successfully complete their mission.

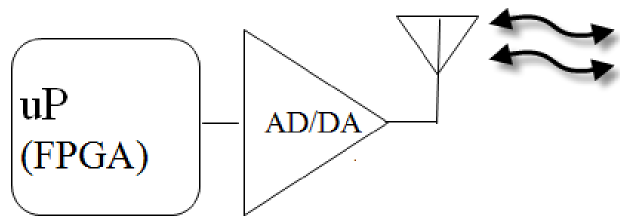

Figure 1 - The "Ideal" Digital Radio

2. UNDERSAMPLING [2]

With a conventional superheterodyne radio, the mixer and Local Oscillator (LO) would be used to down-convert the RF signal to a lower IF frequency, where an ADC could then process the data in its first Nyquist zone. This would require multiple RF and IF filters plus amplification, mixing and a local oscillator (LO). In a digital radio a technique called Undersampling can be used to accomplish this task. This simplifies the receiver RF/IF configuration significantly and thus reduces its size, cost and development time. By sampling at significantly less than the RF signal's carrier frequency the aliased image of that signal will appear in Nyquist Zone 1 at the ADC output. (Fig 2).

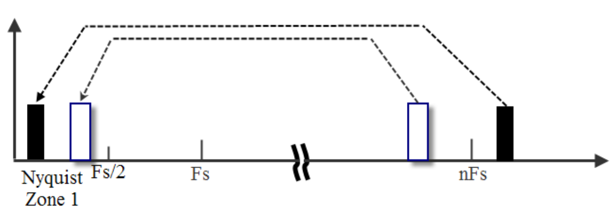

Figure 2 - ADC Undersampling Representation

A method of determining how an RF frequency will be mapped into Nyquist Zone 1 is to create a simple m-code

Table 1 - Nyquist Zone m-code Segment

```
% Nyquist Zone m-code segment
Fc = 834.78e6;                % Carrier Freq
Fs = 170e6;                   % Samp. Freq
Fs2 = Fs/2;                   % Nyquist Freq
NQzone = ceil(Fc/Fs2);        % Nyquist Zone
EO = rem(NQzone,2);           % 1=Even 0=Odd

if (EO)
        Fif = rem(Fc,Fs);     % if Odd Zone
else
        Fif = Fs-rem(Fc,Fs)   % if Even Zone
end
```

segment (Table 1). In this m-code, the rem(a,b) function determines the remainder of the value **a** divided by the value **b**. NQzone result determines which zone the original RF signal came from. The EO parameter determines if the original carrier frequency (Fc) was in an even or odd Nyquist zone. If EO is even, then the final Nyquist Zone 1 aliased frequency will have a spectral inversion. Having this knowledge is critical for the subsequent demodulation in the DSP or microprocessor. This spectral inversion is similar to what would occur when using a high-side LO in a conventional Superheterodyne receiver configuration. If EO is odd then no spectral inversion will occur.

As a practical application, a GSM signal is used with a center frequency (Fc) of 834.78 MHz and a sampling frequency (Fs) of 170 MHz. The ADC results would be as

Table 2 - GSM Signal Results

Fc = 834.78 MHz and Fs = 170 MHz	
NQzone = 10	Original Nyquist Zone
EO = 0	Even Nyquist Zone, Spectral Inversion
Fif = 15.22 MHz	Aliased Frequency at ADC output

shown in (Table 2). It would be mapped from the 10th Nyquist zone and thus have a spectral inversion. The ADC IF frequency would be 15.22 MHz. In another example, in this case a WCDMA signal at 1934 MHz, the results are

Table 3 WCDMA Signal Results

Fc = 1934 MHz and Fs = 170 MHz	
NQzone = 23	Original Nyquist Zone
EO = 1	Odd Nyquist Zone, No Spec. Inversion
Fif = 64 MHz	Aliased Frequency at ADC output

shown on (Table 3). In this case there is no spectral inversion.

3. DIGITAL RADIO SIMULATION [3]

While the m-code calculations are useful for theoretical modeling, they represent very simple models of signals that might be present in the Digital Radio's path and thus will get mapped into the ADC's output. To do a more complex model that can incorporate both simple and complex signals and noise a simulation tool called SpectraSys[2] will be utilized to perform a Spectral Domain analysis of the radio. (Fig 3)

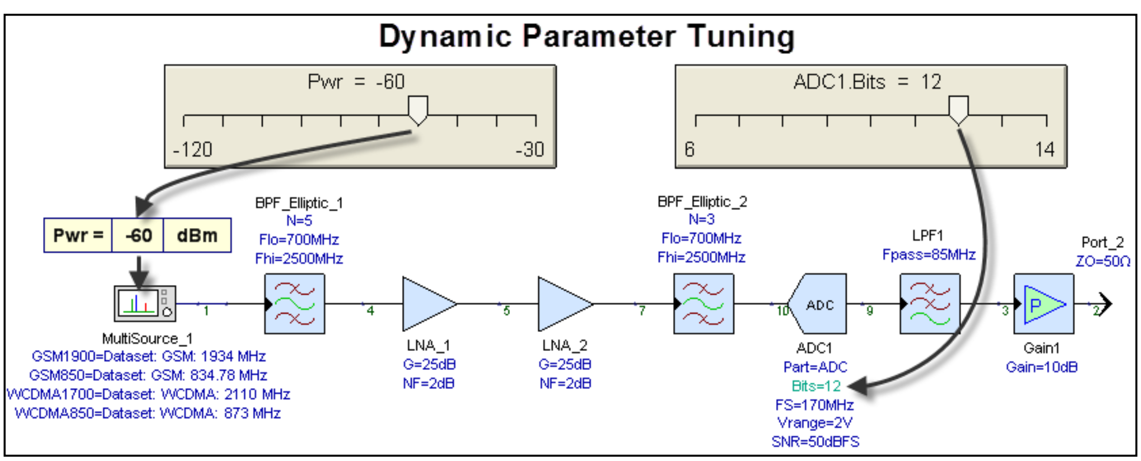

Figure 3 - Digital Radio - Spectral Domain Model with Applied Multiple Waveforms

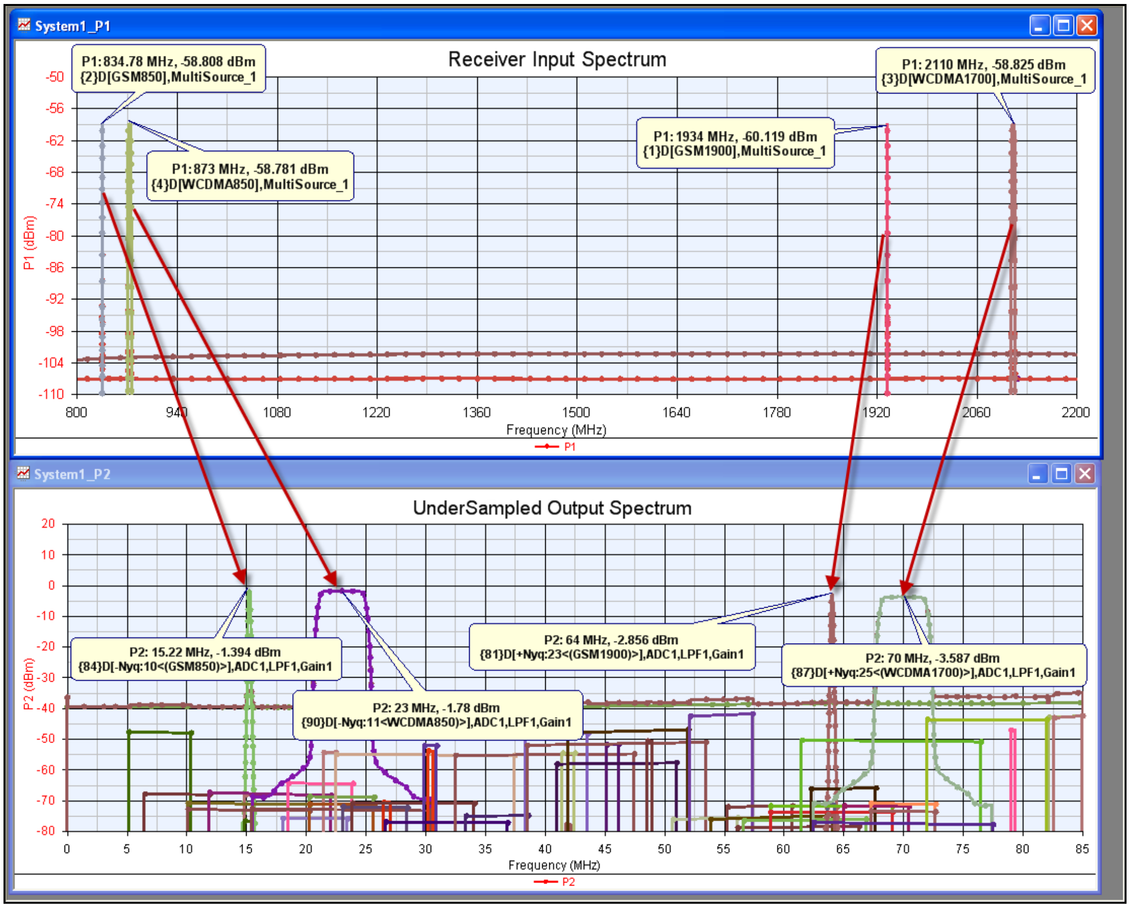

Figure 4 - Spectral Representation at Receiver Input and ADC Output

In this example four different signals are presented at the receiver input. The types and center frequencies are as indicated in Figure 3. There are two GSM signals and two WCDMA signals. Each of these is represented by its complete spectral description, including phase. These signals can be generated by measurements from test equipment or from imported data. Every spectral product is propagated through the receiver, along with any intermodulation or spurious products that are generated. The program also keeps track of reflections, and signals will not only propagate forward through the receiver, but in reverse also, due to the finite isolation of these components. As the receiver design is implemented with hardware the individual stages can be represented by circuit level models and by measurements such as S-parameters, and X-parameters.[4]

The tabular simulation results (Fig 5) represent the performance response for the receiver. It can be easily seen that the ADC is what's limiting the dynamic range of the system (11.4 dB).and the ADC Nyquist Zone frequency is centered at 15.22 MHz, and is also the biggest contributor to the System Noise Figure. The LNA and the input Bandpass Filter also contribute significantly the total system Noise Figure. An interesting evaluation is to tune the number of ADC bits to see where it begins to affect the Total System Noise. It turns out that 8 bits or less starts to significantly affect receiver performance. Stage dynamic range (Stage DR) indicates that the ADC will limit the input signal to about -49 dB before distortion will occur. This allows the System Architect to see what is happening within the system and where further improvements may be required.

Part Name	GSM850 (dBm)	Freq (MHz)	Stage DR (dB)	Tot Pwr (dBm)	Casc. NF (dB)	AN (dB)
MultiSource_1	-59.835	834.78	153.89	-53.89	0	0
BPF_Elliptic_1	-62.158	834.78	155.39	-55.39	2.323	2.323
LNA_1	-37.162	834.78	40.242	-30.242	4.367	2.044
LNA_2	-13.589	834.78	26.5	-8.5	4.373	5.171e-3
BPF_Elliptic_2	-17.941	834.78	113.129	-13.129	4.372	-232.2e-6
ADC1	-12.419	15.22	11.352	-7.373	10.068	5.696
LPF1	-12.419	15.22	107.375	-7.375	10.092	0.024
Gain1	-2.419	15.22	97.375	2.625	10.092	13.25e-6

Figure 5 - Receiver Cascaded Parameters

4. COGNITIVE RADIO SIMULATION

This is a Cognitive Radio whitespace algorithm example using a Data Flow simulator that demonstrates spectrum sensing and adaptive OFDMA spectrum usage with a 3GPP LTE (Long Term Evolution) commercial downlink waveform (Fig. 6). The LTE RF Waveform is summed together with measured interference signals. An m-code algorithm is then used to locate available 'white-space' based upon the policy and adapt the LTE waveform to optimally occupy that space (Figs. 7 & 8).

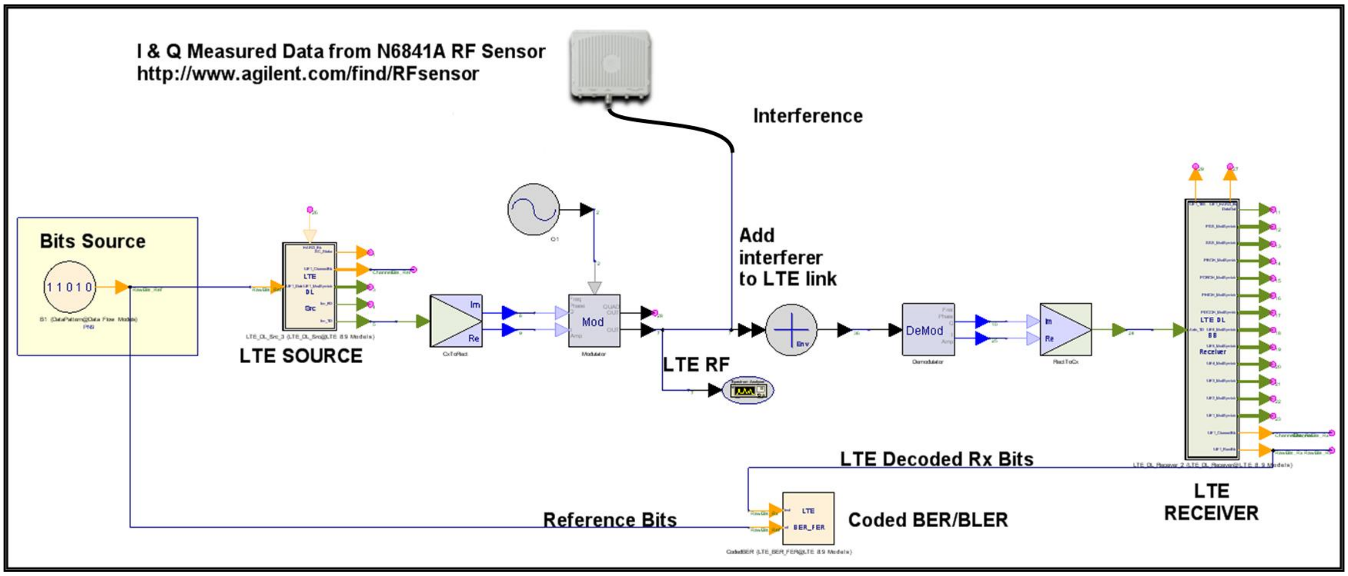

Figure 6 - Cognitive Radio Schematic

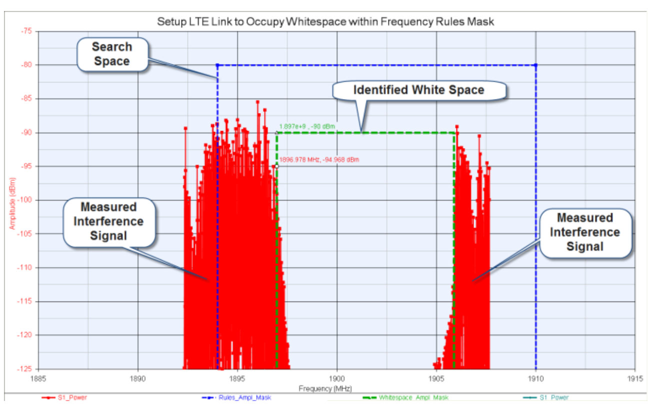

Figure 7 - White Space Identification

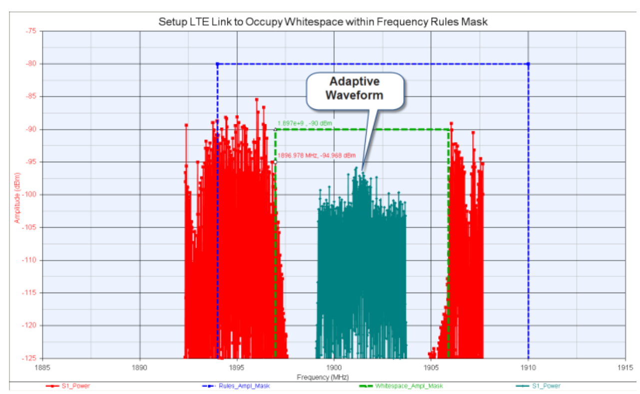

Figure 8 - Adaptive Waveform

Envelope simulation is used in this example. The I & Q envelope of the 1900 MHz carrier frequency is sampled at a rate of 22.8 MHz If baseband sampling was used it would require a sample rate of more than 3800 MHz. (2* 1900 MHz). This example will run some 170 times faster with no loss of accuracy. The BER simulation time was approximately 20 seconds of an HP 8530 laptop with 4 GB of RAM. To run the same simulation without envelope simulation would take about an hour to complete. This makes BER simulations like this practical.

Note that LTE is being used here as an example signal. A user could replace these with their own radio design. The cognition and sensing algorithms in this example are fundamental to demonstrate a concept. A user could replace these with their own algorithms, which are likely to be more sophisticated and robust. The user could also connect to physical hardware through test-equipment links for further verification.

5. CONCLUSIONS

This paper has shown a direct conversion Digital Radio can be efficiently modeled in the Spectral Domain for rapid development and evaluation with multiple applied waveforms. The aliased signals at the ADC output will properly represent the aliased signals that will be present. This was followed by demonstrating a Cognitive Radio which dynamically identifies unutilized space and adapts the LTE waveform to occupy that 'White-Space'.

6. REFERENCES

[1] G Jue, "Agilent Cognitive Radio Algorithm Development and Testing" Agilent Technologies White Paper, *Oct. 2009*

[2] Y Kunisawa, "Study on a Multiple Signal Receiver Using Undersampling Scheme," Proceeding of the *SDR 05 Technical Conference, Nov. 2005*

[3] For more information go to www.agilent.com/find/SystemVue

[4] For more information go to www.agilent.com/find/X-Parameters