Spectrum Sensing and Reconstruction for Cognitive Radio

Amanpreet S Saini, Zhen Hu, Robert Qiu
Department of Electrical and Computer Engineering, Center for Manufacturing Research
Tennessee Tech University, Cookeville TN, USA
Email: {assaini21, zhu21, rqiu}@tntech.edu

***Abstract*—The Federal Communications Commission (FCC) opened free 'white space' spectrum on November 4, 2008. In this way, Google and other technology companies that wanted access to more free spectrum have gotten their wish [1]. The prerequisite of the access to the free spectrum is to find this kind of spectrum. This paper deals with spectrum sensing and spectrum reconstruction under the umbrella of cognitive radio which is the smart radio to explore and exploit the free spectrum. Spectrum analyzer is used to emulate cognitive radio to do spectrum sensing. The advantage of equipment-based spectrum sensing is to perform quick and semi-continuous measurements and extract more information about the spectrum under investigation. Total variation (TV) reconstruction method is employed to rebuild the spectrum and find the boundary of the frequency band which is occupied.**

***Index Terms*—Spectrum sensing, spectrum reconstruction, cognitive radio, total variation.**

I. Introduction

Based on FCC's regulation for the radio spectrum, a certain frequency band can only be occupied by the specific licensed users, who have full privileges on the spectrum access to this frequency band. It is clearly mentioned in many reports that the spectrum under the present regulation is either under-utilized or un-utilized by its licensed users [2], [3]. Meanwhile, many other unlicensed users [4], [5]want to use this under/un-utilized spectrum but are not able to do so just because they have no privilege to use the spectrum. In response to this issue, FCC opened free 'white space' spectrum and introduced a new term in the wireless community called "Cognitive Radio". "Cognitive Radio" means an intelligent/agile radio which is not only capable to do spectrum sensing but also able to alter the transmitted power and transmission schemes so that the information can be transmitted through the un-utilized spectrum. The spectrum sensing is the main work of cognitive radio. Cognitive radio should sense the spectrum and make sure whether the spectrum is available or not. If the spectrum is used by the licensed users, cognitive radio should keep silent; otherwise, cognitive radio can access this spectrum.

In this paper, spectrum analyzer is used to emulate cognitive radio to do spectrum sensing. The main goal of this work is to get the data of spectrum for the future researches, such as the modeling of the spectrum, the study on the efficient algorithm of sensing spectrum and transmission schemes [6]. Previously, spectrum analyzer was controlled manually and the capability of spectrum sensing was limited. Now, Laboratory Virtual Instrumentation Engineering Workbench (LabVIEW) is used in our lab to remotely control spectrum analyzer. In this way, the semi-continuous measurements can be done and the data can be recorded automatically. The time needed for each measurement is around 80-110ms, which includes the sweep time and time to record/save data. In this way, more information about spectrum can be obtained and extracted.

The rest of the paper is organized as follows. Section II describes the whole procedure of spectrum sensing. Sensing setup, instrument control, sensing capability, sensing scenario and sensing result will be presented. Section III will discuss signal processing for the reconstruction of the spectrum in the noise. In section IV, numerical result will be provided and section V will make a conclusion for this paper.

II. Spectrum Sensing

A. Sensing Setup

Our sensing setup consists of a computer/laptop, spectrum analyzer and one omni directional antenna. National Instruments (NI) LabVIEW-8.5 is installed on the computer to control the spectrum analyzer and acquire the sensing data. The computer and spectrum analyzer are connected using GPIB-USB2 cable. A linearly polarized omni directional antenna with 50 ohm unbalanced feed impedance is used for all sensing scenarios. Figure 1 shows the setup diagram.

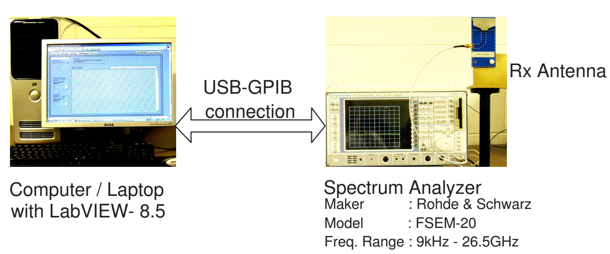

Fig. 1. Setup diagram

B. Instrument Control

LabVIEW is a platform that gives us a development environment for a visual programming language. This package is developed by NI and the graphical language is termed as 'G' language. This package is most commonly used for data acquisition, instrument control and for industrial automation.

Its user friendly nature enables it to run on a variety of operating systems including Microsoft Windows, UNIX, Linux and Mac OS. The LabVIEW program/subroutine is known as virtual instrument (VI) and each VI has three components [7]:

a. *Block Diagram:* It is the main part where all the graphical programming is done, a block diagram consists of VIs and even sub-VIs. Different VIs or sub-VIs are connected together by using respective wire connections on the block diagram. Each wire connector has different color, pertaining to the data type of the variable that is carried through the wire.

b. *Front Panel:* It is normally referred as the part where *controls* and *indicators* allow the operator to input data into or extract data from a running VI. The required output/acquired data in the form of graphs, data arrays etc. are available on the the front panel.

c. *Connector Pane:* The connector pane is used to represent a VI in the block diagram of other VIs.

Figure 2 shows the block diagram of developed VI to control spectrum analyzer. The LabVIEW based instrument driver library for spectrum analyzer was downloaded from the Rohde and Schwarz website. These drivers are used as sub VIs in the block diagram. All sub VIs are wired together in a order, to read sensing data of the sensed spectrum over a long time period. Meanwhile, the sensing time for each measurement is recorded in a different file.

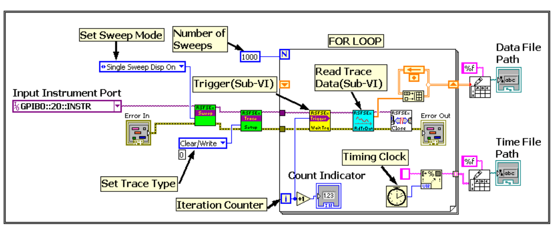

Fig. 2. LabVIEW block diagram

The procedure to sense the spectrum can be summarized in the following steps,

1. Connect the spectrum analyzer, computer/laptop and receiving antenna as shown in Figure 1.

2. Power on the spectrum analyzer and manually set parameters such as start/stop frequency, resolution bandwidth, video bandwidth, attenuation, sweep time etc.

3. Open the LabVIEW block diagram on the remote computer with NI's LabVIEW-8.5 installed on it.

4. Select the instrument GPIB port address from the menu list that appear on *'Input Instrument Port'* option box as seen in Figure 2.

5. Select the sweep mode as *Single Sweep Disp ON* in *'Set Sweep Mode'* option box shown in Figure 2. One sweep is characterized by three parameters ie. sweep time, resolution bandwidth and video bandwidth. Where, sweep time is the time taken by a spectral trace to complete its path from given start frequency to stop frequency during one trigger.

When an instrument is subjected to be controlled through a remote computer, then Choosing single sweep as an option has a potential reason than choosing continuous sweep. This is due to fact that when data acquisition is done from a remote computer and if the sweep mode is set as continuous sweep, then sensed data is not trustable. Whereas, if we use sweep type as single sweep, then it becomes easier to differentiate between each set of sensed data. But, in the later case, a quick trigger is required to re-initiate the sweeping process for continuous sensing and this is only possible if we use a automated process for instrument control.

6. Select the appropriate trace mode in *'Set Trace Type'* option box shown in Figure 2. A trace consists of 500 pixels on the horizontal frequency axis, that means the number of point for each measurement is 500. Selection of trace mode depends on our goal i.e. what type of data we need from the spectrum analyzer. Generally for a spectrum analyzer, commonly mentioned trace modes are:

a. *Clear/Write:* In this mode, the trace memory is overwritten by each sweep ie. if this mode is selected then the memory value of previous trace is cleared and we get anew data values during each sweep.

b. *Average:* With this mode, an average is taken from several foregoing measurements. When this mode is selected, then the first trace is recorded as discussed in *Clear/Write* mode and from the second measurement onwards an average is formed on each succeeding sweeps.

c. *Max Hold:* In this mode, the spectrum analyzer saves only the maximum values of previous and current traces. In this way, the maximum value attained by the signal can be determined over several sweeps.

d. *Min Hold:* Unlike *Max Hold*, *Min Hold* represents only the minimum values of the previous and current traces. In this way, the minimum values attained by the signal can be determined over several sweeps.

7. A *'FOR LOOP'* is introduced in the next step and the functionality attached with this *'FOR LOOP'* is described as follows.

a. As seen in Figure 2, inside the *'FOR LOOP'* is a sub VI to trigger spectrum analyzer and another sub-VI to read acquired trace data from the spectrum analyzer. These sub-VIs are wired one after another and during each iteration of loop, first a trigger is sent to the spectrum analyzer and then the sensing data is acquired pertaining to each iteration. Outside and at the top left corner of this loop is a option box *'Number of Sweeps'*, here user has to input a number, which signifies that loop executes repeatedly until the iteration counter *'i'*, shown inside at left bottom of loop, achieves a value equal to this typed number. For example as seen in Figure 2 this number is set to 1000, that means we get the sensed spectrum data for 1000 sweeps.

b. The second important functionality attached with this *'FOR LOOP'* is to acquire the time taken to complete each iteration. A *'Timing Clock'* is placed inside the loop, as seen in Figure 2. This clock automatically generates a millisecond timing value during each iteration.

c. Finally, the sensed data values and the generated timing values are virtually accumulated in the LabVIEW's memory and when the *'FOR LOOP'* execution is over, then two screens, one after the another, are popped up on the windows computer. These screens ask user to input the file name and allow user to save the acquired sensing data and timing files at a particular location on local computer/laptop.

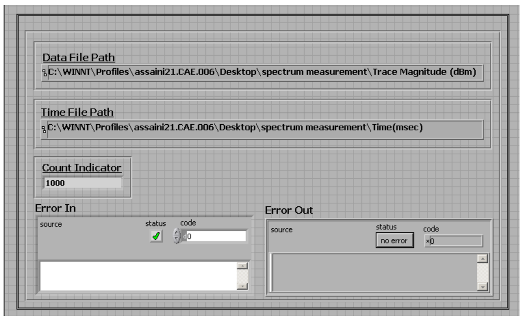

Fig. 3. LabVIEW front panel

Figure 3 shows the front panel of the developed VI. As seen in Figure 3, the output paths for the respective files and the loop iteration values are listed separately on three different indicators. These paths correspond to the location of the sensed data file and the acquired-time file on local computer. Acquired data can easily be loaded and processed using MATLAB.

C. Sensing Capability

The quick sensing is very important for cognitive radio to catch the real time and detailed usage of the spectrum. The main advantage of our equipment-based spectrum sensing is that semi-continuous measurements can be executed and the corresponding sensed data can be recorded automatically for the online or offline signal processing. The time delay between the continuous measurements is around 80-110ms, which includes the sweep time and time to record/save data.

D. Sensing Scenario

Four sensing scenarios are considered in this paper. The first three spectrum sensings for CDMA signal, GSM signal and Wi-Fi signal are executed in the indoor office environment and the fourth for digital TV (DTV) signal is performed in the outdoor environment. The location of the indoor office is at 'Wireless Networking Systems Lab' and the outdoor location is the roof-top of Prescott Hall, both of which are in Tennessee Technological University. Three dimensional (3-D) spectrums of Time (s) vs Frequency (MHz) vs Magnitude (dBm) are plotted using MATLAB for these four scenarios.

Following is the description of four scenarios as considered here:

1. When a call connection is made from CDMA based cell phone to Land-line based phone, the spectrum of CDMA signal is sensed. The sensed frequency band is from 800 MHz to 1100 MHz.

2. When a call connection is made from GSM based cell phone to Land-line based phone, the spectrum of GSM signal is sensed. The sensed frequency band is from 1700 MHz to 2000 MHz.

3. When a Wi-Fi connection is established on notebook computer, the spectrum of Wi-Fi signal is sensed. The sensed frequency band is from 2300 MHz to 2600 MHz.

4. A DTV signal is sensed from 697.5 MHz to 704.5 MHz.

E. Sensing Result

1000 thousand sweeps are done and 1000 thousand sensing data are recorded continuously in one spectrum sensing task. Following parameters are used in all sensing scenarios:

Resolution Bandwidth = 20 kHz
Video Bandwidth = 20 kHz
Sweep Time = 5 ms
RF Attenuation = 10 dB
Trace Type = Clear/Write
Sweep Mode = Single Sweep Display ON
Number of Points = 500 points per sweep.

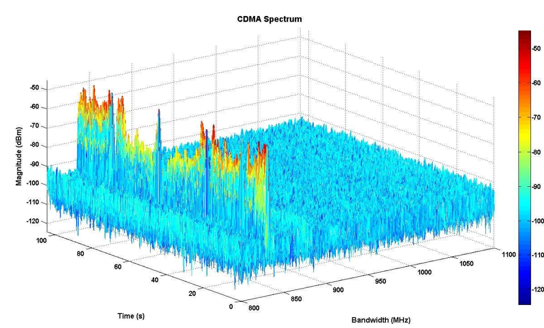

Fig. 4. CDMA Spectrum

Figure 4 shows 3-D spectrum of CDMA signal. In Figure 4, the strong peaks between 800 MHz and 900 MHz show the CDMA signal, when a call connection is established between a CDMA based cell phone and a Land-line based phone. Whereas, the blank spaces between these strong peaks correspond to the time when call connection is not established.

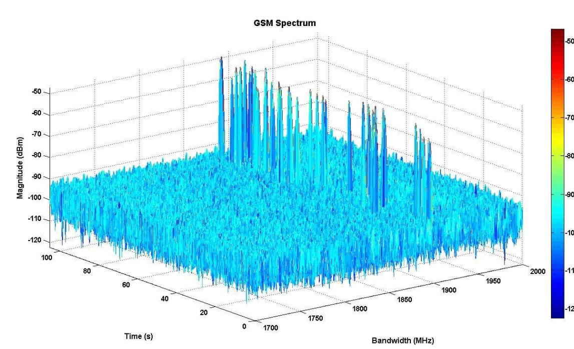

Fig. 5. GSM Spectrum

Figure 5 shows 3-D spectrum of GSM signal. In Figure 5, strong peaks between 1850 MHz and 1950 MHz show the

GSM signal, when a call connection is established between a GSM based cell phone and a Land-line based phone. Whereas, the blank spaces between these strong peaks correspond to the time when the call connection is not established.

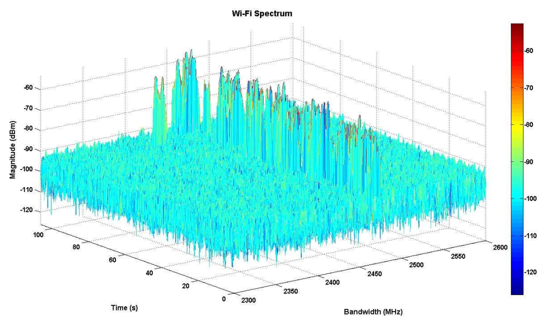

Fig. 6. Wi-Fi Spectrum

Figure 6 shows 3-D spectrum of Wi-Fi signal. In Figure 6, strong peaks between 2400 MHz and 2500 MHz show the Wi-Fi signal, when a Wi-Fi connection is established on a Wi-Fi enabled notebook computer. A Wi-Fi signal is emitted by Wi-Fi enabled router which is connected with the CAT-5 cable provided by the University for Internet connection. Whereas, the blank spaces between the strong peaks correspond to the time when the Wi-Fi connection is not established on the notebook computer.

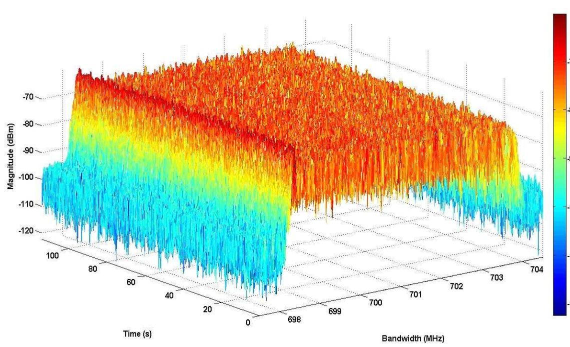

Fig. 7. DTV Spectrum

Figure 7 shows 3-D spectrum of DTV signal. In Figure 7, a strong peak around 698.4 MHz frequency corresponds to the pilot signal of the sensed DTV channel. The frequency span is 6 MHz and this signal is broadcasted by the local television station and the transmitter is in line of sight (LOS) from the sensing location with the aerial distance of around 8 miles.

III. Spectrum Reconstruction

In real cognitive radio, spectrum will be sensed with the influence of noise. Even if spectrum analyzer is used to do spectrum sensing, the sensed data will be corrupted by the additive noise. In order to get the relatively clear spectrum or get the boundary of the frequency band which is now occupied by the licensed users, spectrum should be reconstructed from the noisy sensed data.

Assume the noiseless spectrum can be presented by a vector $s \in \mathbf{R}^n$. The coefficient s_i corresponds to the value of spectrum at evenly sensed frequency without noise. The noisy sensed data can be expressed as,

$$s_{\text{noise}} = s + v \tag{1}$$

The preliminary goal is to form an estimate $\hat{s}$ of s given the noisy sensed data s_{noise} [8]. But in some application scenarios, we do not need to know the detail of the occupied frequency band and the detection of the boundary of the frequency band will be more important for cognitive radio. A wavelet approach is used to detect the edge of the spectrum [9]. Because on the boundary of the frequency band which is occupied, there will be a occasional rapid variation, i.e the irregularity of the spectrum, this kind of variation should be preserved and the additive noise should be suppressed, when spectrum reconstruction is performed. Based on this requirements, total variation (TV) reconstruction method can also be competent for this kind of job. TV is based on the smoothing function [8],

$$\phi_{\text{TV}}\left(\hat{s}\right) = \sum_{i=1}^{n-1} \left|\hat{s}_{i+1} - \hat{s}_i\right| \tag{2}$$

which is called the *total variation* of $s \in \mathbf{R}^n$.

IV. Numerical Results

Take one measurement of Wi-Fi signal shown in Figure 8 as an example to give the performance of TV reconstruction method. Because *Clear/Write* is chosen as the trace mode, the signal in Figure 8 can be considered as $\hat{s}$.

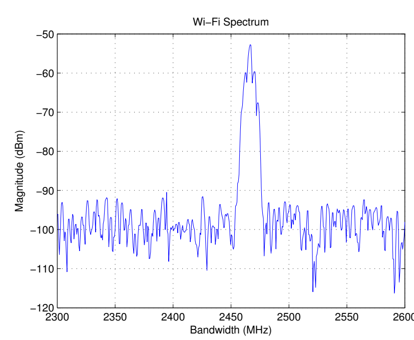

Fig. 8. Wi-Fi Spectrum under investigation

If $\phi_{\text{TV}}\left(\hat{s}\right)$ is set to $\text{TV}_{\text{Threshold}}$, then the corresponding $\hat{s}$ will be obtained by using CVX tool [10]. The distance between $\hat{s}$ and s_{noise} can be quantified by the following index,

$$\text{TV}_{\text{distance}} = \sqrt{\sum_{i=1}^{n} \left(\hat{s}_i - s_{\text{noise},i}\right)^2} \tag{3}$$

Figure 9 shows the relationship between $\text{TV}_{\text{Threshold}}$ and $\text{TV}_{\text{distance}}$, which can also be treated as the optimal trade-off curve between $\text{TV}_{\text{Threshold}}$ and $\text{TV}_{\text{distance}}$. If $\text{TV}_{\text{Threshold}}$ is set relatively small, the distance between $\hat{s}$ and s_{noise} will be larger, which means the reconstructed signal will be far away from the noisy signal. While, the larger $\mathrm{TV}_{\mathrm{Threshold}}$ will cause the higher similarity between $\hat{s}$ and s_{noise}.

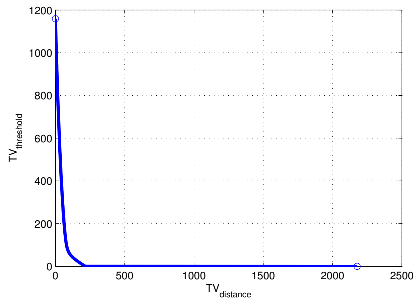

Fig. 9. Optimal trade-off curve between $\mathrm{TV}_{\mathrm{Threshold}}$ and $\mathrm{TV}_{\mathrm{distance}}$

Specifically, when $\mathrm{TV}_{\mathrm{Threshold}}$ is set to 30, $\hat{s}$ and s_{noise} are shown in Figure 10. When $\mathrm{TV}_{\mathrm{Threshold}}$ is set to 300, $\hat{s}$ and s_{noise} are shown in Figure 11. From Figure 10 and 11, it is easily to get the conclusion that TV reconstruction method can well preserve the occasional rapid variation and remove much of the noise in the noisy signal [8]. When $\mathrm{TV}_{\mathrm{Threshold}}$ is equal to 30, though the detail of the spectrum is smoothed, the boundary of the frequency band is well retained for the following detection and the small variations caused by noise are all canceled. If $\mathrm{TV}_{\mathrm{Threshold}}$ is equal to 300, $\hat{s}$ is more close to s_{noise} and some variations introduced by noise are kept which will cause the false alarm in the following detection. However, the boundary of the frequency band is still very clear.

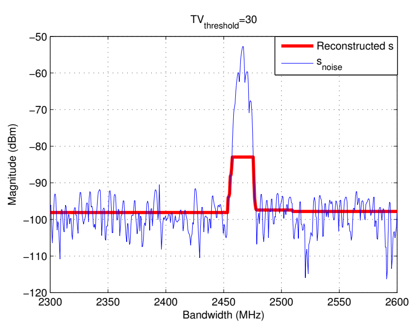

Fig. 10. $\hat{s}$ and s_{noise} When $\mathrm{TV}_{\mathrm{Threshold}}$ is equal to 30

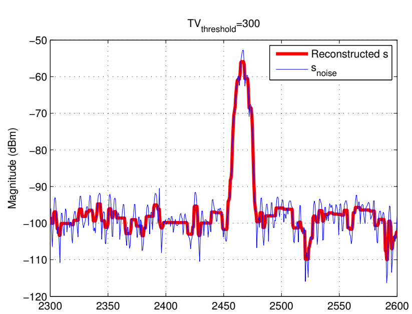

Fig. 11. $\hat{s}$ and s_{noise} When $\mathrm{TV}_{\mathrm{Threshold}}$ is equal to 300

Thus, if spectrum sensing is performed with high SNR, $\mathrm{TV}_{\mathrm{Threshold}}$ can be set higher to keep more information about the spectrum. While, for the spectrum sensing with low SNR, $\mathrm{TV}_{\mathrm{Threshold}}$ should be small to suppress the noise and preserve the boundary of the frequency band. Meanwhile, TV reconstruction method can also be extended to rebuild the spectrums for the semi-continuous measurements. For each measurement, TV reconstruction method with the same $\mathrm{TV}_{\mathrm{Threshold}}$ is executed. Then, along the time axis, the change of the boundary of the frequency band will be observed and detected, which will indirectly infer the availability of the frequency band of interest.

V. Conclusion

This paper deals with spectrum sensing and spectrum reconstruction for cognitive radio. Spectrum analyzer is used to emulate cognitive radio to do spectrum sensing. The whole procedure of spectrum sensing including sensing setup, instrument control, sensing capability, sensing scenario and sensing result is presented in detail. The main advantage of equipment-based spectrum sensing is to perform quick and semi-continuous measurements. The time needed for each measurement is around 80-110ms. 3-D spectrums of CDMA signal, GSM signal, Wi-Fi signal and DTV signal are shown in this paper. Meanwhile, TV reconstruction method is employed here to rebuild the spectrum and find the boundary of the frequency band which is occupied.

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