TV White-Space Device Prototype Using Covariance-Based Signal Detection

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Abstract— **Measurements performed at several locations clearly show that frequency spectrum is under-utilized. Cognitive radio is a strong candidate to ensure better spectrum utilization by providing access in an opportunistic manner. Recently the Federal Communications Commission (FCC) in the USA and the Office of Communications (Ofcom) in UK are considering of allowing opportunistic secondary usage of wireless device in part of the TV bands. Before such services can be materialized, the concept of cognitive radio, especially spectrum sensing, needs to be proven. Although, theoretically or through simulations, various spectrum sensing algorithms showed promising results, the actual performance under realistic conditions has not been fully tested. Therefore, there is a need to build such systems and test them under real-world environment. In this demonstration, we are going to show the white-space device prototype based on the covariance-based signal detection method. This method is signal independent and may be applied on any signal waveform or system. The spectrum sensing algorithm is implemented on a platform comprising primarily FPGA and DSP. The processing of the algorithm is done at real time. To test the performance of the prototype, a signal generator is used to generate the signal source and the probability of detection is calculated in a PC attached to the prototype. The purpose of the setup is to measure the sensitivity of the spectrum sensing device. Key performance measurement metrics used are the probability of detection and false alarm rate. The significance of such demonstration is that once spectrum sensing is proven to function well in practical environment, application of cognitive radio in real systems will likely happen in the near future.**

Keywords—White-space device, spectrum sensing, cognitive radio, TV Bands

I. INTRODUCTION

The ongoing migration of analog television (TV) to digital will open up a huge opportunity for new wireless services to utilize the vacated TV bands. These are generally recognized to be among the best possible spectrum that could be made available for future wireless services. Many companies have developed algorithms and systems for making use of TV bands as secondary access. Two notably groups pushing for such accesses are the White Spaces Coalition and Wireless Innovation Alliance (WIA). A device that is capable of detecting the vacant channel and utilizes it is termed a white-space device (WSD).

IEEE 802.22 Wireless Regional Area Networks (WRAN) is one of the first systems to include concept of cognitive radio [1]. It is actively looking at systems that could utilize the vacant spectrums in an opportunistic manner while still maintaining normal operations of primary users. The key difference between WRAN and other non-cognitive radio wireless systems lies in the use of spectrum sensing techniques in the former case.

In order to protect the licensed primary users, the requirement for spectrum sensing is set at very stringent levels. IEEE 802.22 defined sensitivities up to -116 dBm, which is at least 30 dB below the normal sensitivity level of primary user receivers to cater for the possibility of secondary user nodes hidden from primary users of the spectrum. This high sensitivity requirement coupled with other impairments such as noise uncertainty and fading impose major challenges for spectrum sensing designs.

Spectrum sensing can be generally classified into three major categories, i.e., energy detection [2], [3], [4], matched filtering [2], [5], [6] and cyclostationary detection [7], [8], [9]. Matched filtering requires the knowledge of the waveforms while cyclostationary detection needs to know the cyclic frequencies of the primary users. Although energy detection does not require these knowledge, it is susceptible to noise uncertainty [2]. In addition, energy detection is optimal for detecting independent and identically distributed (i.i.d.) signal but not correlated signals typically found in practical systems [10].

To overcome the shortcomings of energy detection, we proposed covariance-based signal detection [11] and maximum-minimum Eigenvalue signal detection [12] schemes. These schemes were shown to provide better resilience towards noise uncertainty and various estimation errors such as timing, frequency, etc. To find out the effects of real-world signals on the performance of the spectrum sensing, and to have realistic evaluation of the spectrum sensing schemes, we implemented the covariance-based spectrum sensing algorithms on real-time platform and perform real-world measurements.

The rest of the paper is organized as follows. Section II provides a review of the spectrum sensing algorithm. Section III describes the architecture and implementation of the WSD prototype. Section IV outlines the test methodology and test setup. Finally, some concluding remarks are given in Section V.

II. SPECTRUM SENSING ALGORITHM

This section gives a review of the covariance-based signal detection scheme.

Let $y(t)$ be the continuous time received signal. We sample the received signal $y(t)$ at a sampling rate f_s. Let $T_s = 1/f_s$ be the sampling period. The received discrete signal is then $x(n) = y(nT_s)$. There are two hypotheses:

$$H_0 : x(n) = \eta(n) \qquad (1).$$

$$H_1 : x(n) = s(n) + \eta(n), \qquad (2).$$

where *H₀* is the case when signal is absence while *H₁* denotes the case when signal is present, $s(n)$ is the transmitted signal passed through a wireless channel (including multipath fading effects and can be superposition of multiple signals), and $\eta(n)$ is the noise sample. The received signal is passed through a filter. Let $f(k),\ k = 0,1,...,K$ be the filter, where K is the order of the filter. After filtering, the received signal is

$$\tilde{x}(n) = \sum_{k=0}^{K} f(k)x(n-k). \qquad (3).$$

Let

$$\tilde{s}(n) = \sum_{k=0}^{K} f(k)s(n-k), \text{ and} \qquad (4).$$

$$\tilde{\eta}(n) = \sum_{k=0}^{K} f(k)\eta(n-k), \qquad (5).$$

the hypotheses after filtering become

$$H_0 : \tilde{x}(n) = \tilde{\eta}(n) \qquad (6).$$

$$H_1 : \tilde{x}(n) = \tilde{s}(n) + \tilde{\eta}(n). \qquad (7).$$

If the sampling rate f_s is larger than the channel bandwidth, W, we can down-sample the received signal. Let $M \geq 1$ be the down-sampling factor. For notation simplicity, we re-use $\tilde{x}(n)$ to denote the received signal samples after down-sampling, i.e., $\tilde{x}(n) = \tilde{x}(Mn)$.

Choose a smoothing factor L and define

$$\mathbf{x}(n) = [\tilde{x}(n) \quad \tilde{x}(n-1) \quad ... \quad \tilde{x}(n-L+1)]^T, \qquad (8).$$
$$n = 0,1,...,N_s - 1$$

where N_s is the number of samples collected. The value of L can be chosen as any positive integer number larger than one. A typical value is around 10. Define a $L \times (K+1+(L-1)M)$ matrix as

$$\mathbf{H} = \begin{bmatrix} f(0) & ... & ... & f(K) & 0 & ... & 0 \\ 0 & ... & f(0) & ... & f(K) & ... & 0 \\ & & ... & & ... & & \\ 0 & ... & ... & ... & f(0) & ... & f(K) \end{bmatrix} \qquad (9).$$

and let $\mathbf{G} = \mathbf{H}\mathbf{H}^H$. Decompose the matrix into $\mathbf{G} = \mathbf{Q}^2$, where $\mathbf{Q}$ is a $L \times L$ Hermitian matrix. The matrix $\mathbf{G}$ is not related to signal and noise, and can be computed offline. If analog filter or both analog filter and digital filter are used, the matrix $\mathbf{G}$ should be revised to include the effects of all the filters. In general, $\mathbf{G}$ can be obtained as the covariance matrix of the received signal when the input signal is white noise only (this can be done in laboratory offline). The matrices **G** and **Q** are computed only once and only **Q** is used in detection.

Denote the statistical covariance matrix of the received signal as

$$\mathbf{R}_x = \mathrm{E}(\mathbf{x}(n)\mathbf{x}(n)^H), \qquad (10).$$

we obtain

$$\mathbf{R}_x = \mathbf{R}_s + \sigma_\eta^2 \mathbf{G} \qquad (11).$$

where $\mathbf{R}_s$ is the statistical covariance matrix of the signal (including fading, multipath and filtering) and σ_η^2 is the noise variance.

Define

$$\tilde{\mathbf{R}}_x = \mathbf{Q}^{-1}\mathbf{R}_x\mathbf{Q}^{-1} \qquad (12).$$

and

$$\tilde{\mathbf{R}}_s = \mathbf{Q}^{-1}\mathbf{R}_s\mathbf{Q}^{-1}, \qquad (13).$$

we obtain

$$\tilde{\mathbf{R}}_x = \tilde{\mathbf{R}}_s + \sigma_\eta{}^2\mathbf{I}. \qquad (14).$$

If there is no signal, $\tilde{\mathbf{R}}_s = 0$. Hence the off-diagonal elements of $\tilde{\mathbf{R}}_x$ are all zeros. If signal presents, $\tilde{\mathbf{R}}_s$ is almost surely not a diagonal matrix. Hence, some of the off-diagonal elements of $\tilde{\mathbf{R}}_x$ should not be zeros.

Denote the elements of the matrix by r_{nm} and let

$$\mathrm{T}_1 = \frac{1}{L}\sum_{n=1}^{L}\sum_{m=1}^{L} |r_{nm}|;\ \mathrm{T}_2 = \frac{1}{L}\sum_{n=1}^{L}|r_{nn}|. \qquad (15).$$

We obtain $\mathrm{T}_1 = \mathrm{T}_2$ if there is no signal; otherwise $\mathrm{T}_1 > \mathrm{T}_2$.

The following outlines the step-by-step procedure for performing signal detection.

Step 1. Sample and filter the received signal as described above.

Step 2. Compute the auto-correlations of the received signal

$$\lambda(l) = \frac{1}{N_s}\sum_{m=0}^{N_s-1}\tilde{x}(m)\tilde{x}^*(m-l),\ l = 0,1,\ldots,L-1, \qquad (16).$$

and form the sample covariance matrix as

$$\mathbf{R}(N_s) = \begin{bmatrix} \lambda(0) & \lambda(1) & \ldots & \lambda(L-1) \\ \lambda(1)^* & \lambda(0) & \ldots & \lambda(L-2) \\ \vdots & \vdots & \vdots & \vdots \\ \lambda(L-1)^* & \lambda(L-2)^* & \ldots & \lambda(0) \end{bmatrix} \qquad (17).$$

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Note that the sample covariance matrix is Hermitian and Toeplitz.

Step 3. Transform the sample covariance matrix to obtain

$$\tilde{\mathbf{R}}(N_s) = \mathbf{Q}^{-1}\mathbf{R}(N_s)\mathbf{Q}^{-1}. \qquad (18).$$

Step 4. Compute

$$\mathrm{T}_1(N_s) = \frac{1}{L}\sum_{n=1}^{L}\sum_{m=1}^{L} |r_{nm}(N_s)| \qquad (19).$$

$$\mathrm{T}_2(N_s) = \frac{1}{L}\sum_{n=1}^{L}|r_{nn}(N_s)| \qquad (20).$$

where $r_{nm}(N_s)$ are the elements of the sample covariance matrix.

Step 5. Determine the presence of the signal based on $\mathrm{T}_1(N_s)/\mathrm{T}_2(N_s)$ ratio, i.e., if $\mathrm{T}_1(N_s)/\mathrm{T}_2(N_s) > \gamma$ (threshold), signal exists; otherwise, signal not exists.

The threshold γ is determined offline by the ratio $\mathrm{T}_1(N_s)/\mathrm{T}_2(N_s)$ and the required probability of false alarm (P_{fa}). When there is no signal, the ratio is not related to noise power at all. Hence, it does not have the noise power uncertainty problem. The method does not require noise power estimation.

III. ARCHITECTURE AND IMPLEMENTATION

The covariance-based spectrum sensing algorithm elaborated in Section II is implemented on stand-alone hardware prototype. The WSD prototype is implemented to determine the occupation of a TV channel by either DTV, wireless microphone or other primary transmissions. The top-level architecture of the implementation is shown in Fig. 1. The main system parameters of the sensing prototype are listed in Table 1.

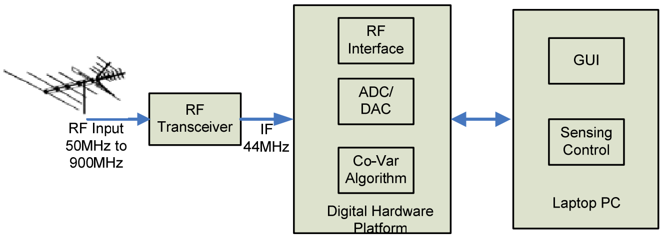

Fig. 1: Spectrum Sensing Architecture

An industry standard commercial off-the-shelf (COTS) RF transceiver down-converts the TV Band channel in the frequency range from 50MHz – 1000MHz to a 44MHz analog IF (intermediate frequency). The bandwidth of the channelization filter dictates the spectrum sensing bandwidth. The current prototype is catered for sensing the TV channels of 6MHz bandwidth (BW). This could be easily modified to sensing TV channels of 7MHz and 8MHz BW by varying the channelization filter. The analog IF signal is digitized and further down-converted to a digital IF in the digital hardware platform. The sensing algorithm and its control modules are implemented on the COTS digital hardware platform. The platform consists of ADC, Xilinx FPGA and TI C6416 DSP.

Table 1: System Parameters

No.	Description	Value
1.	Tunable Frequency Range	470MHz – 860MHz (with antenna) 48MHz – 1000MHz

		(conducted test)
2.	Channel Bandwidth	6MHz
3.	Tuning Step Size	250KHz
4.	Antenna	Omni-directional, -1 dB to -2 dB gain
5.	Waveform Type	Not specific to any waveform

The digital hardware platform is controlled through the JTAG port on the platform. A laptop PC's USB port along with a JTAG emulator is used for the purpose. The control to the WSD prototype is presented through a Graphical User Interface (GUI). The GUI is implemented using LabView as shown in Fig. 2. The GUI provides various controls such as provision to enter the channel frequency to be scanned and the number of scans. The probability of detection is also calculated real-time by the same GUI. All the scanned output data is logged onto a file for easy post processing using spread sheet applications.

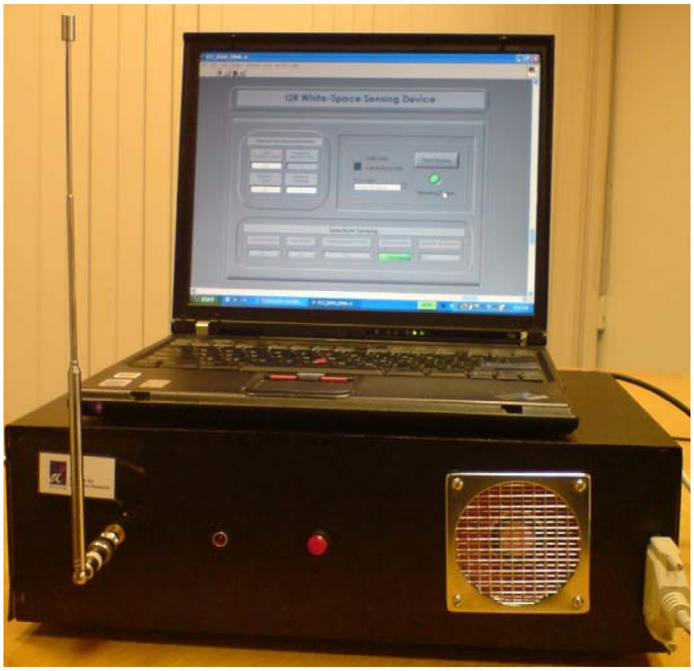

Fig. 2: WSD prototype

IV. Demonstration Setup

To demonstrate the capability of the WSD prototype to reliably detect whether a television channel is occupied or not; and to determine the minimum signal level present in the channel that can be successfully detected as a valid signal, some setups are required. Until now there is no standardized procedure for evaluating the performance of the WSD. The FCC recently performed such tests using various self-defined test scenarios [13]. In this demo, we would like to repeat some of the test scenarios using the WSD prototype that we developed.

A. System calibration

Prior to testing, the WSD prototype needs to be calibrated in order to obtain the **Q** matrix (from **G** and **H** matrices as outlined in (9)). This may be performed preferably in a clean environment such as an anechoic chamber or Faraday cage. The WSD device may be terminated or connected to a signal generator with no transmission. The covariance matrix with circuit noise and filter imperfection is obtained from this setup. The **Q** matrix corresponding to no signal condition can then be computed and used in the subsequent tests. With this **Q** matrix, the threshold, γ, corresponding to $P_{fa} = 0.1$ is obtained.

B. Setup for conducted test demonstrations

The test setup consists of an ATSC signal generator, a calibrated attenuator, spectrum analyzer and the WSD prototype as shown in Fig. 3.

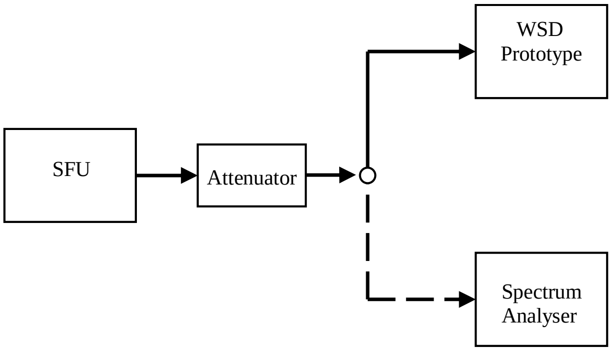

Fig. 3: Measurement setup for DTV signal.

Broadcast Test System from Rhode & Schwarz (SFU) is used to generate the ATSC signal. The frequency of SFU is set to the TV channel frequency of interest. The signal power is measured using the spectrum analyzer. This signal is fed to the antenna input of WSD prototype through a co-axial cable. P_d and P_{fa} are calculated for this signal level and displayed on the screen. Test is repeated after lowering the signal power in 5dB steps until -100dBm and in 1dB steps below -100dBm. Tests are then repeated for different TV channels.

Test setup for measuring the performance of the WSD prototype in the presence of wireless microphone signal is similar to the one used for the ATSC signal. Since it is not straightforward to perform conducted test with actual wireless microphone, a single tone FM modulated signal is used to represent a wireless microphone signal. The test signal is modulated using 1 KHz signal with a deviation of 24 KHz. Measurement setup is shown in Fig. 4.

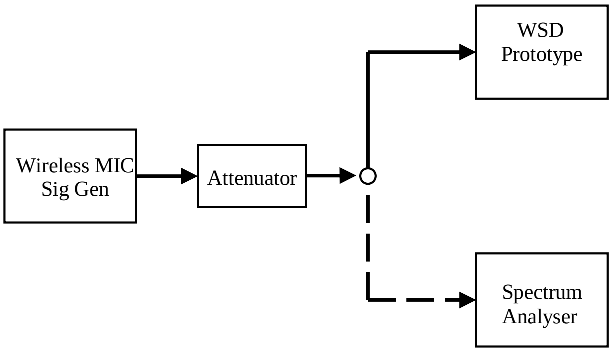

Fig. 4: Measurement setup for wireless microphone signal.

The measurement procedure is the same as in the case of the ATSC signal measurement. Multiple readings are taken for each signal power and channel frequencies.

C. *Setup for over-the-air test demonstrations*

We are going to perform over-the-air demonstration in the exhibition venue. As the information for digital ATSC TV transmission could be obtained to certain level of accuracy from the internet [14], [15], we will use this information as a guideline for checking against the ATSC detection of our device.

V. CONCLUSION

In this paper, we presented a white-space device prototype which will be used for Dyspan 2008 demonstration. The algorithm was reviewed in the paper followed by the implementation details. Various test setups for the demonstration were also explained. With successful demonstration of good detection sensitivities in practical environment, the general public will have better confidence towards the use of spectrum sensing for detection of under-utilized spectrum. If the use of spectrum can be determined dynamically through real-time spectrum sensing, the scarce spectrum can be better utilized to fulfill the future demands of higher data rate communications. This could potentially increase the broadband adoption rates and thus gross domestic production of the countries/world. It could also reduce the problem of digital divide by penetrating into areas/regions not currently covered by broadband communications.

REFERENCES

[1] IEEE 802.22 Wireless Regional Area Networks, http://www.ieee802.org/22/.

[2] A. Sahai and D. Cabric, “Spectrum sensing: fundamental limits and practical challenges,” in *Proc. IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN)*, Baltimore, MD, Nov. 2005.

[3] A. Sonnenschein and P. M. Fishman, “Radiometric detection of spread-spectrum signals in noise of uncertainty power,” *IEEE Trans. on Aerospace and Electronic Systems*, vol. 28, no. 3, pp. 654–660, 1992.

[4] R. Tandra and A. Sahai, “Fundamental limits on detection in low SNR under noise uncertainty,” in *Proc. WirelessCom 2005*, Maui, HI, June 2005.

[5] D. Cabric, A. Tkachenko, and R. W. Brodersen, “Spectrum sensing measurements of pilot, energy, and collaborative detection,” in *Proc. Military Comm. Conf. (MILCOM)*, pp. 1–7, Oct. 2006.

[6] H.-S. Chen, W. Gao, and D. G. Daut, “Signature based spectrum sensing algorithms for IEEE 802.22 WRAN,” in *IEEE Intern. Conf. Comm. (ICC)*, June 2007.

[7] W. A. Gardner, “Exploitation of spectral redundancy in cyclostationary signals,” *IEEE Signal Processing Magazine*, vol. 8, pp. 14–36, 1991.

[8] W. A. Gardner, W. A. Brown, III, and C.-K. Chen, “Spectral correlation of modulated signals: part ii-digital modulation,” *IEEE Trans. Communications*, vol. 35, no. 6, pp. 595–601, 1987.

[9] N. Han, S. H. Shon, J. O. Joo, and J. M. Kim, “Spectral correlation based signal detection method for spectrum sensing in IEEE 802.22 WRAN systems,” in *Intern. Conf. Advanced Communication Technology*, Korea, Feb. 2006.

[10] S. M. Kay, *Fundamentals of Statistical Signal Processing: Detection Theory*, vol. 2, Prentice Hall, 1998.

[11] Y. H. Zeng and Y-C. Liang, “Covariance based signal detection for cognitive radio”, In *Proc. IEEE DySpan*, 2007.

[12] Y. H. Zeng and Y-C. Liang, “Maximum-minimum eigenvalue detection for cognitive radio”, in *Proc. IEEE PIMRC*, 2007.

[13] S. K. Jones and T. W. Phillips, “Initial evaluation of the performance of prototype TV-band white space devices”, *OET Report FCC/OET 07-TR-1006*, Federal Communications Commission, 2007.

[14] http://tvfool.com/

[15] http://www.fcc.gov/fcc-bin/audio/tvq.html