A Cognitive Radio (CR) Testbed System Employing A Wideband Multi-Resolution Spectrum Sensing (MRSS) Technique

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Abstract—**A Cognitive Radio (CR) access technique is a promising solution for the dynamic spectrum resource usage. This paper presented a CR testbed system employing a wideband Multi-Resolution Spectrum Sensing (MRSS) technique. Analog implementation of the MRSS block offers wideband, low-power, and real-time operation. The MRSS experiments were performed using the developed CR testbed system. The experiment results showed that the MRSS technique detected wideband 100-MHz spectrum in a sparse or a precise manner without any increase of hardware burden. Moreover, this MRSS technique detected a variety of sophisticated signal formats adopted in the current and emerging wireless standards – IS-95, WCDMA, GSM, EDGE, Wi-Fi (IEEE802.11a/b/g), ATSC, DVB, etc.**

Index Terms— **Cognitive Radio (CR), testbed, spectrum sensing, analog wideband spectrum sensing, wavelet transform, Multi-Resolution Spectrum Sensing (MRSS)**

I. INTRODUCTION

With the ever-increasing demand for bandwidth due to the current and the emerging wireless services, spectrum scarcity problem has been more serious [1-4]. Meanwhile, licensed spectrum is relatively unused across time and frequency. Recently, a Cognitive Radio (CR) technology has been proposed to improve the efficiency of spectrum usage [3, 4]. Finally, the FCC has commenced to develop an unlicensed recycling- technique for the licensed TV bands – VHF/UHF [1].

On the CR regulation, a CR access system should provide invisible spectrum access to the licensees over a wide frequency range covering multiple communication standards [1-5]. The realization of CR requires the following features: (i) wideband spectrum sensing, and (ii) real-time spectrum allocation, and (iii) adaptive frequency-agile link operation.

To achieve this invisible spectrum access, a spectrum sensing needs to be performed over the fairly wide bandwidth [2-6]. Pre-occupied spectrum segments, where the energy level is over the certain threshold level, and candidate spectrum segments for CR users are identified. These sensing results are reported to the Medium Access Control (MAC) unit, which reports this spectrum usage status to a base-station. This base-station allocates specific spectrum segment to each CR user-terminal.

As the CR concept is newly suggested concept, its system requirements are being defined and developed [3-5]. In order to provide a versatile environment for developing various CR technologies, a reconfigurable testbed system is needed to verify the developed signal processing techniques and the implemented hardware. Moreover, CR system detects the interference signals having heterogeneous signal formats or network protocols [1, 4-6]. Thus, various types of signal formats adopted by wireless applications should be generated and tested very easily.

This paper introduces a CR testbed system platform showing the reconfigurable features for radio front-end as well as the scalable features for a spectrum sensing technique. Section II presents a CR testbed system configuration and its operations. Section III introduces the theoretical background of a Multi-Resolution Spectrum Sensing (MRSS) technique. Its experiment results are presented and discussed in section IV.

II. A COGNITIVE RADIO (CR) TESTBED SYSTEM

This paper suggested a CR tested system to provide flexible, versatile, and easy-to-use test environment. A vector signal generator (VSG) and a vector signal analyzer (VSA) were employed to provide a variety of built-in-standard wireless signals (i.e. IEEE802.16, IEEE802.11a/b/g, 3G-wireless, cellular, American Television Standard Committee (ATSC), Digital Video Broadcasting (DVB), etc.). The hardware control programs for these instruments were developed on the Matlab™ environment. Moreover, the multi-standard or multi-band signals can be accommodated with dual-channel signal generator and high speed data acquisition capabilities.

Fig. 1 and 2 show the system configuration and actual setup of a CR testbed system, respectively. This testbed system consists of a personal computer (PC), a VSG, a VSA, a spectrum analyzer, a power amplifier, a low-noise amplifier, a VHF/UHF tuner board, MRSS H/W and antennas. Signal processing program was also developed with Matlab™ environment. Instruments are controlled with IEEE488.2

interface. Meanwhile, data acquisition (DAQ) cards with PCI interface are installed in the PC. The specification of each building block is shown in Table I.

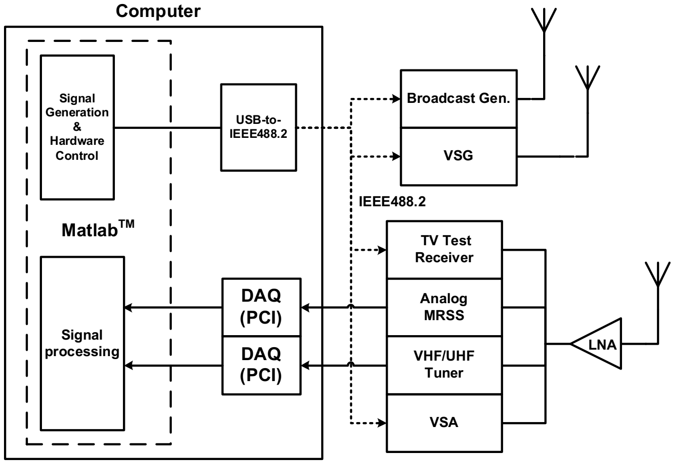


Figure 1. Configuration of the developed CR testbed system.

TABLE I
SYSTEM SPECIFICATIONS OF CR TESBED BUILDING BLOCKS

Instrument	Specification
VSG	Dual RF-path vector signal generator I/Q modulation bandwidth : 56 MHz RF Frequency - Path A :100 KHz ~ 6 GHz, Path B :100 KHz to 3 GHz
Broadcast Test System	Output Frequency : 100 KHz ~ 3 GHz I/Q modulation bandwidth : 180 MHz Format– NTSC, PAL, ATSC/8-VSB, DVB-T/H/C/S
VHF/UHF Tuner	Input RF Frequency : 50 ~ 878 MHz Gain : 53 dB, Noise Figure : 8 dB
DAQ Card	PCI-interface Dual channel/12-bit resolution Max. 400 MSample/sec Input Dynamic Range : 100 mV ~ 5 V
VSA	Input RF frequency : up to 8 GHz I/Q demodulation bandwidth : 28 MHz Signal analysis for – 3GPP FDD/HSDPA/cdma2000/cdma2000 1xEV-DV, 1xEV-DO – GSM/EDGE/Bluetooth® – WLAN : IEEE802.11a/b/g – Wi-Max : IEEE802.16
TV Test Receiver	Input frequency : 5MHz ~ 1 GHz ATSC/8-VSB Demodulation
H/W Interface	USB-to-IEEE488.2 Interface Converter

Built-in digital TV standard signals (ATSC, DVB) and wireless communication standard signals are generated from the Broadcasting Signal Generator (BSG) and VSG, respectively. This VSG generates analog I/Q baseband signals and performs I/Q modulation with given sampling clock and carrier frequency values, respectively. Dual RF signals are available from VSG to emulate the desired CR access signal and the interfering signal. These wireless signals are radiated with each antenna. A variety of antennas with different beam patterns and polarizations are employed.

Transmitted signals and interference signals are received with an antenna and amplified with an LNA. This received signal is investigated with the MRSS H/W to identify its spectral usage status. This spectrum sensing is performed in analog domain and the resulting sensing results are digitized by a DAQ card. MRSS experiment results are analyzed with a spectrum-sensing performance-analysis software. Once a vacant spectrum is allocated for CR link, reconfiguration control signal changes configuration of the TV tuner board. Thus, CR link performance is analyzed with a PHY signal processing software. Meanwhile, this received signal is analyzed with a spectrum analyzer and VSA, continuously.

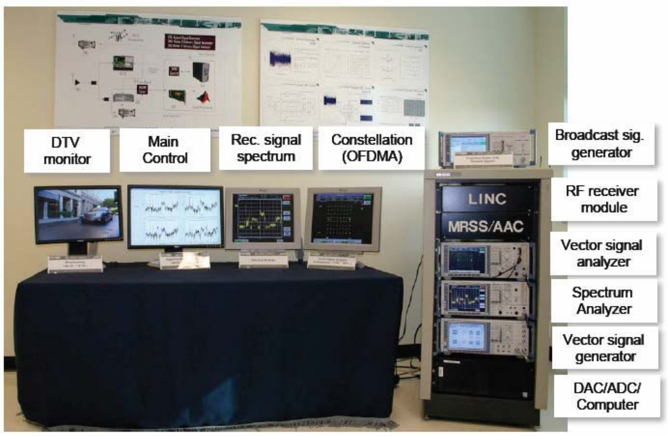


Figure 2. Picture of the developed CR testbed system.

III. A WIDEBAND MRSS TECHNIQUE

In order to provide multi-resolution spectrum sensing feature, wavelet transform was employed to the suggested MRSS technique [6]. By adjusting this wavelet's pulse width and its carrier frequency, spectral contents can be represented with scalable resolution or multi-resolution [6]. Moreover, analog implementation of MRSS is introduced to realize real-time and low power operation.

Fig. 3 shows the functional block diagram of the suggested analog MRSS technique. Building blocks consist of a wavelet waveform generator, multipliers and integrators for computing correlation values, and low speed ADCs to digitize the calculated analog correlation values. Since the MRSS processing is performed in the analog domain, low-power and real-time operations are realizable. Moreover, a wavelet pulse provides a band-pass filtering effect for noisy RF input signals.

Waveforms $w_{I,k}(t)$ and $w_{Q,k}(t)$ are generated by modulating a window pulse $w(t)$ with the sinusoidal signals $cos(2\pi f_k t)$ and

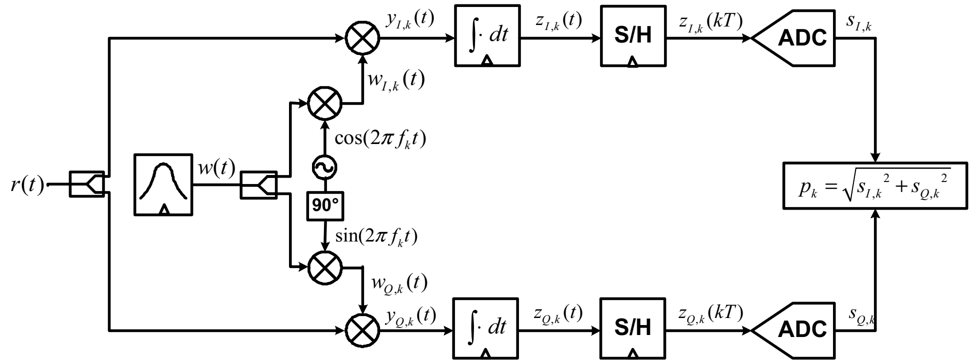


Figure 3. Functional block diagram of the suggested MRSS technique.

$\sin(2\pi f_k t)$, respectively, as shown in eq. (1-2).

$$w_{I,k}(t) = w(t)\cdot\cos(2\pi f_k t) \quad \text{for } k=0,\ldots, KK \tag{1}$$

$$w_{Q,k}(t) = w(t)\cdot\sin(2\pi f_k t) \quad \text{for } k=0,\ldots, KK \tag{2}$$

, where $KK = Round[(f_{stop} - f_{start})/f_{sweep}]$, and $f_k = (f_{start} + k\cdot f_{sweep})$.

The frequency span (f_{stop} - f_{start}) is investigated by sweeping f_k with the increment of f_{sweep}. By virtue of scalable window bandwidth B_w (i.e. B_w is reciprocal of the window pulse width T_w.), spectrum-sensing resolution-bandwidth is variable. Meanwhile, the total time-duration T_{total} spent for spectrum sensing within (f_{stop} - f_{start}) is inversely proportional to the B_w and f_{sweep}, as shown in eq. (3).

$$T_{total} = T_w \cdot KK \propto \frac{1}{B_w}\cdot\frac{1}{f_{sweep}} \tag{3}$$

Correlations of the input signal $r(t)$ with $w_{I,k}(t)$ and $w_{Q,k}(t)$ are calculated, respectively. These correlation values $z_{I,k}(t)$ and $z_{Q,k}(t)$ represent the spectral contents of the input signal $r(t)$ for each frequency f_k, as shown in eq. (4-5).

$$z_{I,k}(t) = \left(\frac{1}{T_w}\right)\cdot\left(\int_{k\cdot T_w}^{(k+1)\cdot T_w} y_{I,k}(t)\cdot dt\right) \tag{4}$$

$$z_{Q,k}(t) = \left(\frac{1}{T_w}\right)\cdot\left(\int_{k\cdot T_w}^{(k+1)\cdot T_w} y_{Q,k}(t)\cdot dt\right) \tag{5}$$

$s_{I,k}$ and $s_{Q,k}$ are the discrete values of $z_{I,k}(t)$ and $z_{Q,k}(t)$ sampled at every T_w, as shown in eq. (6-7).

$$s_{I,k} = z_{I,k}(kT_w) \tag{6}$$

$$s_{Q,k} = z_{Q,k}(kT_w) \tag{7}$$

Finally, as shown in eq. (8), the magnitude p_k is described by the square-root of $s_{I,k}$ and $s_{Q,k}$, representing the spectral density at the frequency f_k.

$$p_k = \sqrt{s_{I,k}^{\;2} + s_{Q,k}^{\;2}} \tag{8}$$

To improve the reliability performance of the MRSS technique, p_k is calculated repeatedly for the N_{Avg} consecutive iterations and the corresponding results are averaged, as shown in eq. (9).

$$P_{k,Avg.} = \left(1/N_{Avg.}\right)\cdot\sum_{n=1}^{N_{Avg.}} p_{k,n} \tag{9}$$

, where $p_{k,n}$ is the n-th MRSS result calculated at f_k.

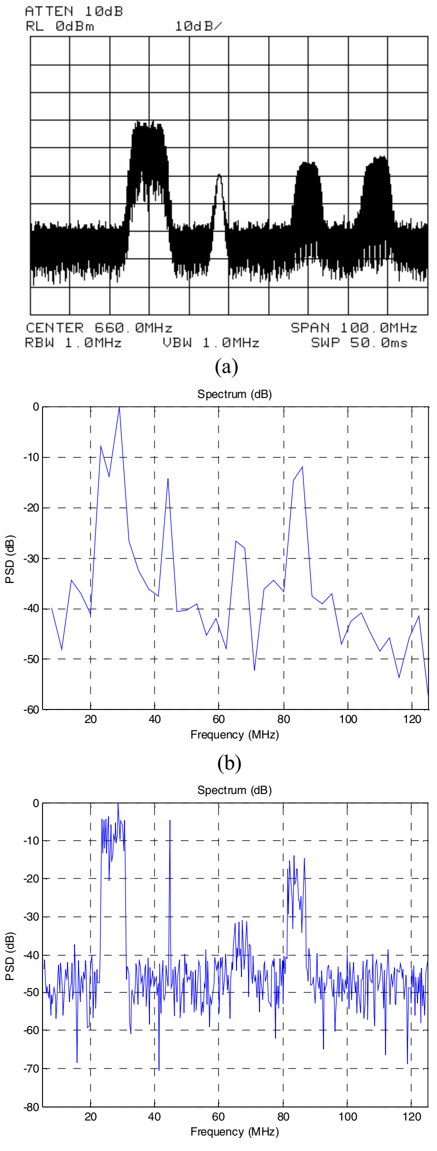
IV. MRSS EXPERIMENT RESULTS

For the verification of the MRSS concept, the developed testbed system was used. Experiments were performed for wireless microphone, US and European digital television standard signals, (i.e. ATSC and DVB, respectively), as shown in Fig. 4 – 5. The experiment conditions for each signal are summarized in Table II.

Fig. 4(a) shows the power spectrum of the input RF signal $r(t)$ from the LNA output. Fig. 4(b) and 4(c) show the MRSS spectra detected in a sparse (i.e. 1-MHz B_w, 3-MHz f_{sweep}) and a precise (i.e. 100-KHz B_w, 300-KHz f_{sweep}) manners, respectively. In Fig. 4(b), the sparse-MRSS result shows a wideband spectrum shape with blunt peaks for four input signals. Meanwhile, Fig. 4(c) shows four sharp peaks for each signal, indicating a better detection performance in terms of sensing-resolution bandwidth. Meanwhile, this sparse MRSS takes just 10 % of the sensing-time spent for the precise MRSS, according to eq. (3). Therefore, the suggested MRSS technique is able to examine a wideband spectrum in a fast/sparse manner or, if needed, in a precise manner without any increase of hardware burden.

TABLE II
PARAMETERS FOR THE MRSS EXPERIMENTS

Item	Bandwidth	Carrier Frequency	Power (dBm)	Remark
Wireless Microphone	68 KHz	658 MHz	- 50, -80	FM
ATSC	6 MHz	680 MHz	- 45, -75	8-VSB
DVB-T	7 MHz	640 MHz 695 MHz	- 30 - 45, -60	OFDM
MRSS parameter	Sweep Span	100 MHz		
	Sweep Increment	Sparse : 1 MHz Precise : 100 KHz		
	Resolution bandwidth	Sparse : 3 MHz Precise : 300 KHz		
	Averaging	1		No averaging



(a)

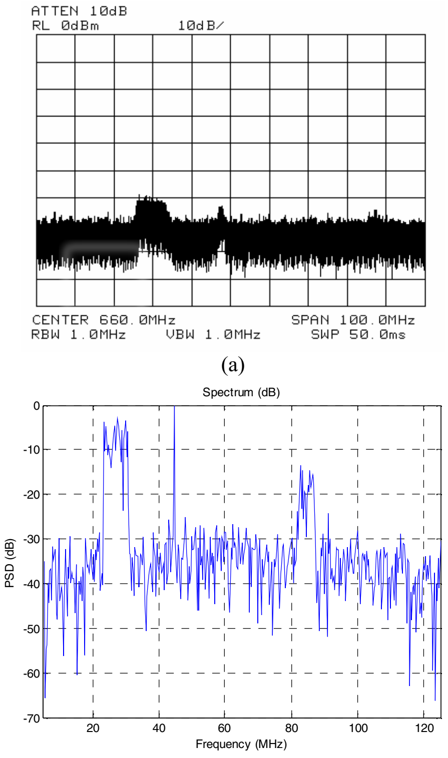
(b)

(c)

Figure 4. MRSS spectrum sensing results for DVB-T, wireless microphone, ATSC signals. (a) Input RF signal spectrum, (b) spectrum detected in a sparse manner (i.e. 1-MHz B_w, 3-MHz f_{sweep}), and (c) spectrum detected in a precise manner (i.e. 100-KHz B_w, 300-KHz f_{sweep}).

Fig. 5(a) shows the spectra of DVB-T, wireless microphone, ATSC signals with signal power of -60, -80, and -75 dBm, respectively. Fig. 5(b) indicates that MRSS is able to achieve a detection margin of 27, 30, and 15 dB for DVB-T, wireless microphone, ATSC signals, respectively, with a detection threshold level of -30 dB.

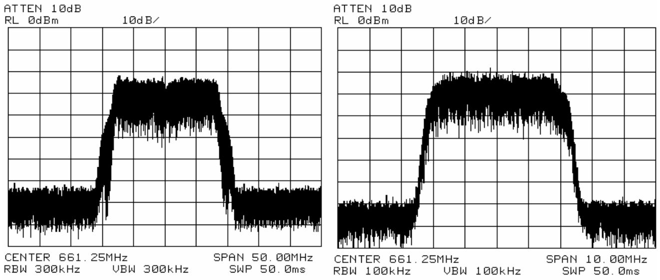
Moreover, this MRSS technique provides the universal spectrum-sensing performance for a variety of sophisticated signal formats adopted in the current and emerging wireless standards – IS-95, WCDMA, GSM, EDGE, Wi-Fi (IEEE 802.11a/b/g), ATSC, DVB, etc. To show this universal sensing performance of the MRSS, experiments were performed to the signals compatible to the wireless standards such as GSM, EDGE, IS-95, WCDMA, IEEE802.11a, as shown in Fig. 6-9.



(a)

(b)

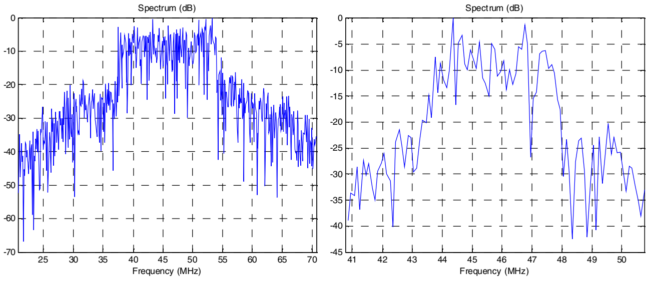
Figure 5. Sensitivity performance of MRSS. (a) Spectrum and (b) the corres -ponding MRSS simulation results of DVB-T, wireless microphone and ATSC signals having -60, -80 and -75 dBm.



(a)

(b)

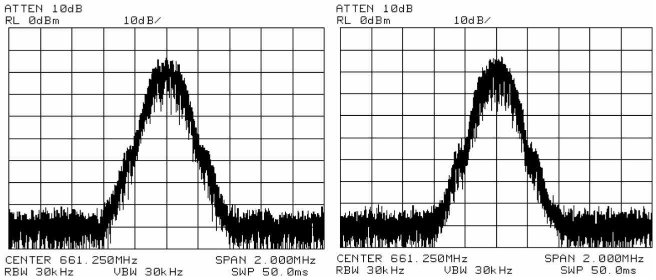
Figure 6. Actual spectrum of (a) IEEE802.11a and (b) WCDMA signal.



(a)

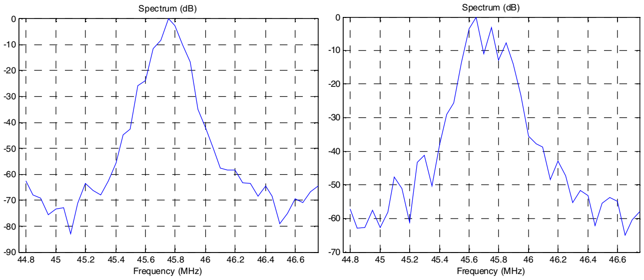
(b)

Figure 7. MRSS experiment results of (a) IEEE802.11a and (b) WCDMA signal.



(a) (b)

Figure 8. Actual spectrum of (a) GSM and (b) EDGE signal.



(a) (b)

Figure 9. MRSS experiment results of (a) GSM and (b) EDGE signal.

V. CONCLUSION

This paper presented a CR testbed system platform with a wideband MRSS technique. This tesbed system was designed to provide the flexible and versatile environment for developing CR access techniques. Moreover, theoretical background of the suggested MRSS technique was presented. Its analog-fashioned implementation may offer wideband, low-power, and real-time spectrum-sensing operation.

The MRSS experiments were performed for a variety of signal formats employing the developed CR testbed system. The experiment results showed the MRSS technique is able to examine a wideband spectrum in a fast sparse manner or, if needed, in a precise manner without any increase of hardware burden. Moreover, this MRSS technique is able to detect a variety of sophisticated signal formats adopted in the current and emerging wireless standards – IS-95, WCDMA, GSM, EDGE, Wi-Fi (IEEE802.11a/b/g), ATSC, DVB, etc.

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