

A Wideband Analog Multi-Resolution Spectrum Sensing (MRSS) Technique for Cognitive Radio (CR) Systems

Invited Paper

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Abstract—Spectrum sensing technology is most vital to the implementation of a CR system using dynamic spectrum resource management. This paper suggested a CR system architecture with a wideband dual-stage spectrum sensing technique - a coarse and a fine spectrum sensing. Specifically, the coarse spectrum sensing technique adopted wavelet transforms in this architecture to provide a Multi-Resolution Spectrum Sensing (MRSS) feature. Analog implementation of the MRSS block offers wideband, low-power, and real-time operation. From the system simulation results, MRSS achieved 15-, 20-, and 30-dB detection margin for FM, VSB, and OFDM signals, having the corresponding signal power of -110, -120, and -120 dBm, respectively.

I. INTRODUCTION

With the tremendous growth of wireless applications, many spectrum segments have been allocated to the licensed spectrum users. These licensees have the privileged rights to use this authorized spectrum for commercial or public use. However, these licensed spectrum resources have not been fully exploited depending on the locations and time [1, 2]. Thus, advances in wireless technology have been urged to create a new wireless communication system to use spectrum more efficiently than in the past.

Recently, a Cognitive Radio (CR) access technology has been proposed as a promising solution for improving the efficiency of spectrum usage by adopting dynamic spectrum resource management concept [3, 4]. 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 role of spectrum sensing in the CR system is to locate unoccupied spectrum segments as quickly and accurately as possible. Inaccurate or delayed sensing results deter communication of the primary user occupying the spectrum. Thus, spectrum sensing speed and accuracy are extremely important. From a CR system commercialization standpoint, minimizing hardware complexity as well as power consumption is also critical.

There have been proposed various methods for spectrum sensing such as energy detection methods [6] and feature detection methods [7, 8]. Non-coherent energy detectors [6] are primarily suggested for detection of narrow band analog modulated signals. This method is simple and is able to locate spectrum-occupancy information quickly. However,

its sensing capability is vulnerable to noise. Furthermore, it is difficult to detect a frequency-hopping signal and wide-bandwidth digital modulation signals such as spread-spectrum and multi-carrier modulation.

Meanwhile, feature detection methods [7, 8] locate the repetitive signature of a modulated signal by time- or frequency-domain signal processing. Its spectrum-sensing performance is robust to noise-like signals. However, this method demands excessive Analog-Digital Converter (ADC) requirement and signal processing capabilities, thus, accompanying a large amount of power consumption.

In this paper, a CR system with a dual spectrum sensing mechanism is proposed. A stage-by-stage combination of a coarse and a fine sensing is implemented to meet the sensing speed and accuracy requirements of the CR system. Specifically, a wavelet transform-based Multi-Resolution Spectrum Sensing (MRSS) technique is presented as a coarse sensing method. Moreover, the analog implementation of MRSS is introduced to realize real-time and low power operation.

II. A COGNITIVE RADIO SYSTEM ARCHITECTURE

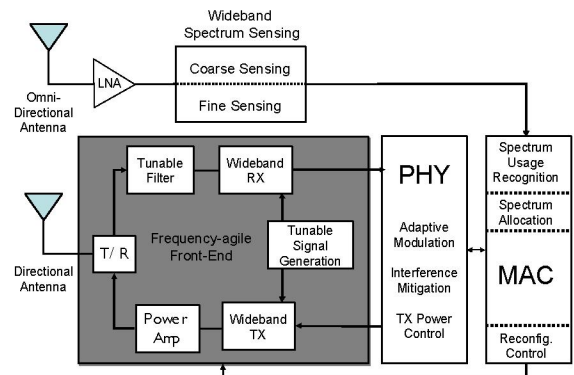


Figure 1. Functional block diagram of the proposed CR access system architecture.

In order to ensure a friendly coexistence with the authorized spectrum users, a CR access system should include the following operations; (i) the detection and recognition of the spectrum usage pattern or status, (ii) the identification of the available spectrum resource for a safe CR link, (iii) the establishment of an air interface at the allo-

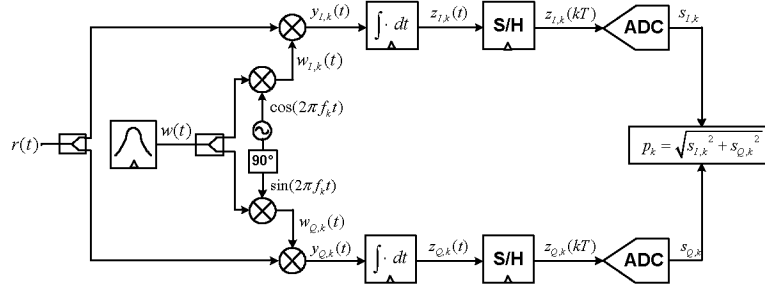


Figure 2. Functional block diagram of the suggested MRSS technique.

cated frequency, and (iv) the optimization of the link performance – link throughput and link quality.

Fig. 1 shows the functional block diagram of the suggested CR access system architecture. It is comprised of (a) wideband antennas: omni-directional for the spectrum sensing and directive for the CR link, (b) a frequency-agile RF front-end (RFE) block with wideband and reconfigurable features, (c) a dual-stage wideband spectrum sensing block, (d) a PHYsical (PHY) layer block, and (e) a Medium Access Control (MAC) block.

In the beginning of the spectrum-sensing process, a coarse sensing is performed over the entire frequency range with a fairly wide resolution-bandwidth. Through this step, pre-occupied spectrum segments, where the energy level is over the threshold level, and candidate spectrum segments for CR users are identified. This coarse sensing result is reported to the MAC. Then, for these candidate spectrum segments, the fine sensing detects unique features of the modulated signals. If the spectrum segment is confirmed to be unoccupied through the rigorous fine sensing, the MAC assigns this spectrum segment for CR links. Otherwise, the MAC specifies another channel and repeats the fine sensing process.

III. A WIDEBAND MRSS TECHNIQUE

A. Theoretical Background

Wavelet transforms may have various choices of basis functions. Certain types of those may have a resolution bandwidth as an additional freedom-of-design [9]. A wavelet transform coefficient is obtained from the correlation between a given signal and a specific wavelet basis-waveform. Therefore, by adjusting this wavelet's pulse width and its carrier frequency, spectral contents can be represented with scalable resolution or multi-resolution [9].

Fig. 2 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. Thus, image- and noise-rejection filters are not needed. 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 $\sin(2\pi f_k t)$, respectively, as shown in eq. (1-2).

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

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

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

The frequency span $(f_{\text{stop}} - f_{\text{start}})$ can be investigated by sweeping f_k with the increment of f_{sweep} . By virtue of scalable window bandwidth B_w (i.e. B_w is the 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 $(f_{\text{stop}} - f_{\text{start}})$ is inversely proportional to the B_w and f_{sweep} , as shown in eq. (3).

$$T_{\text{total}} = T_w \cdot KK \propto \frac{1}{B_w} \cdot \frac{1}{f_{\text{sweep}}} \quad (3)$$

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)

$$z_{I,k}(t) = \left(\frac{1}{T_w} \right) \cdot \left(\int_{k \cdot T_w}^{(k+1) \cdot T_w} [r(t) \cdot w_{I,k}(t)] \cdot dt \right) \quad (4)$$

$$z_{Q,k}(t) = \left(\frac{1}{T_w} \right) \cdot \left(\int_{k \cdot T_w}^{(k+1) \cdot T_w} [r(t) \cdot w_{Q,k}(t)] \cdot dt \right) \quad (5)$$

$s_{I,k}$ 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).

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

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

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 .

$$p_k = \sqrt{s_{I,k}^2 + s_{Q,k}^2} \quad (8)$$

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

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

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

B. MRSS System Simulation Results

For the verification of the MRSS spectrum sensing concept, a system simulation was performed for Frequency Modulation (FM), Vestigial-Side Band (VSB), and Orthogonal Frequency Division Multiplexing (OFDM) signals, as shown in Fig. 3. The simulation conditions for each signal are summarized in Table I.

TABLE I. SIMULATION PARAMETERS FOR THE MRSS SIMULATION

Modulation	Bandwidth	Carrier Frequency	Power	Remark
FM	200 KHz	597 MHz	- 40 dBm	Wireless Microphone
VSB	6 MHz	615 MHz	- 50 dBm	ATSC
OFDM	7 MHz	633 MHz	- 50 dBm	DVB
LNA	Gain	60 dB		
	Noise figure	10 dB		
Sweep	Span	200 MHz		# of sweep Sparse : 40 Precise : 100
	Increment (f_{sweep})	Sparse : 5 MHz Precise : 2 MHz		
Wavelet	Resolution bandwidth (B_w)	Sparse : 10 MHz Precise : 1 MHz		
Averaging	$N_{Avg.}$	1		

In this system simulation, LNA's gain and noise figure were assumed to be 60 dB and 10 dB, respectively. Fig. 3(a) shows the power spectrum of the input RF signal $r(t)$ from the LNA output. Fig. 3(b) and 3(c) show the MRSS spectra detected in sparse (i.e. 10-MHz B_w , 5-MHz f_{sweep}) and precise (i.e. 1-MHz B_w , 2-MHz f_{sweep}) manners, respectively. In Fig. 3(b), the MRSS simulation result shows a wideband spectrum shape with blunt peaks for three input signals. Meanwhile, Fig. 3(c) shows three sharp peaks for each signal, indicating a better detection performance in terms of sensing resolution. However, this sparse MRSS takes 25-times shorter sensing-time compared to the case of 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.

In order to show the effect of averaging on MRSS performance, a system simulation was performed for the

identical signal spectrum, shown in Fig. 3(a), with different numbers of averaging (i.e. $N_{Avg.}$).

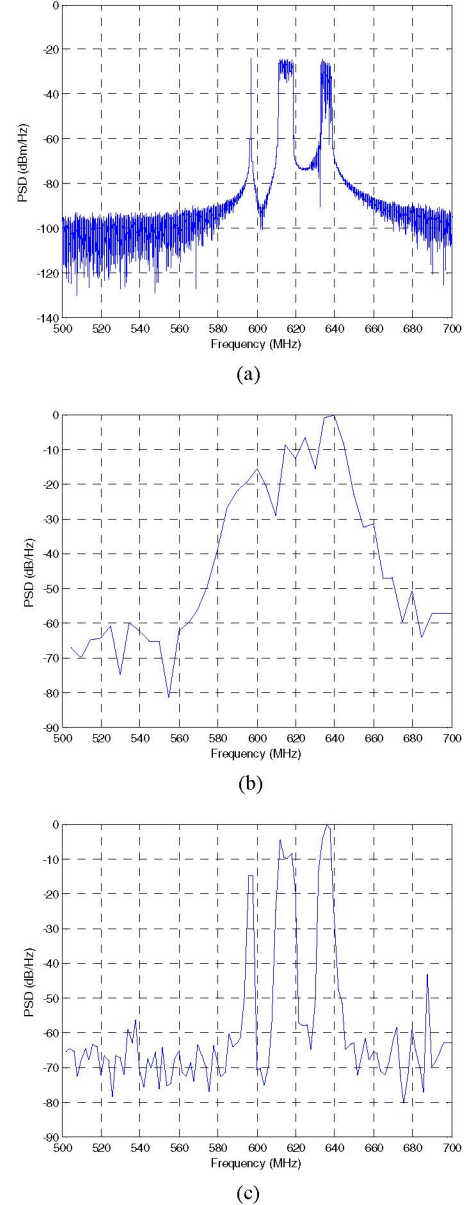


Figure 3. MRSS spectrum sensing results for FM, VSB and OFDM signals. (a) Input RF signal spectrum, (b) spectrum detected in a sparse manner (i.e. 10-MHz B_w , 5-MHz f_{sweep}), and (c) spectrum detected in a precise manner (i.e. 1-MHz B_w , 2-MHz f_{sweep}).

Fig. 4(a) and 4(b) show the corresponding MRSS results for $N_{Avg.} = 1$ and 15, respectively. For a fair comparison, the same resolution bandwidth and sweep increment (i.e. 1-MHz B_w , 1-MHz f_{sweep}) were applied for both of the cases. The averaging of signal spectra obtained with $N_{Avg.} = 15$ reduced the noise floor level by 7 dB and made signals' spectra more discernable. Fig. 5(a) shows the spectra of FM, VSB and OFDM signals with signal power of -110, -120, and -120 dBm at the LNA input, respectively. Fig. 5(b) indicates that

MRSS is able to achieve a detection margin of 15, 20, and 30 dB for FM, VSB and OFDM signals, respectively, with a detection threshold level of -30 dB.

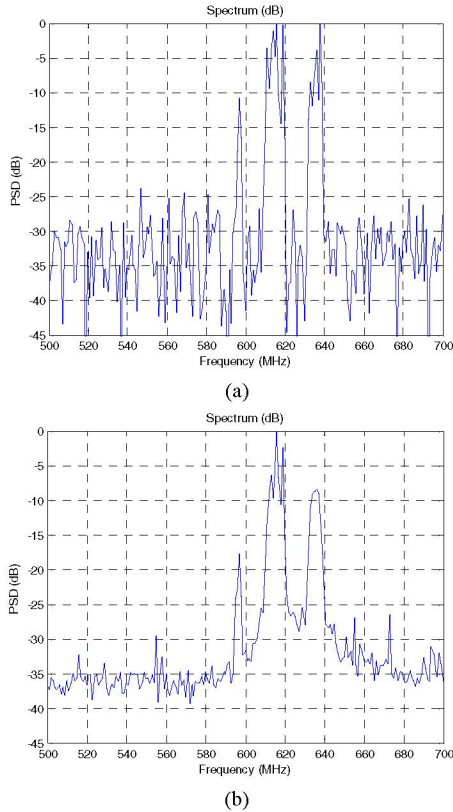


Figure 4. MRSS simulation results to show the effect of averaging on sensing performance with different numbers of averaging (a) $N_{Avg} = 1$ and (b) $N_{Avg} = 15$.

IV. CONCLUSION

This paper suggested a CR system architecture with a wideband spectrum sensing feature operating in dual stages – coarse and fine sensing. These two sensing stages collaborate with each other to enhance the accuracy of spectrum sensing performance.

The coarse spectrum sensing technique adopted a wavelet transform to provide the multi-resolution sensing feature over a wide frequency range. This MRSS feature with the flexible detecting resolution can be implemented in analog fashion to realize low-power and real-time operation.

The system simulation results showed that the suggested MRSS technique can examine a wideband spectrum in a fast sparse manner or, if needed, in a precise manner without any increase of hardware burden. Moreover, its reliability performance can be improved by 7 dB with 15-times of averaging.

In terms of spectrum-sensing sensitivity-performance, the MRSS achieved a detection margin of 15, 20, and 30 dB for FM, VSB and OFDM signals, with the corresponding signal powers of -110, -120, and -120 dBm, respectively.

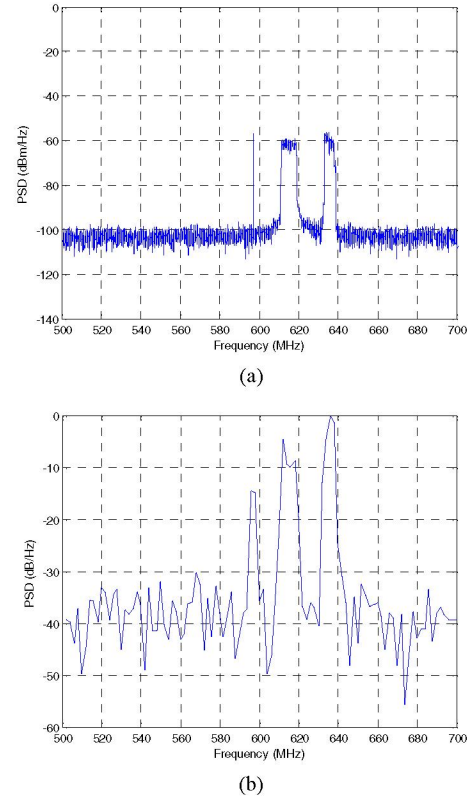


Figure 5. Sensitivity performance of MRSS. (a) Spectrum and (b) the corresponding MRSS simulation results of FM, VSB and OFDM signals having -110, -120 and -120 dBm.

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