Listen-while-Talking: A Technique for Primary User Protection

Nilesh Khambekar
Department of Computer
Science and Engineering
University at Buffalo, SUNY
Buffalo, New York 14260-2000

Chad Spooner
NorthWest Research Associates
cmspooner@nwra.com

Vipin Chaudhary
Department of Computer
Science and Engineering
University at Buffalo, SUNY
Buffalo, New York 14260-2000

***Abstract*—Cognitive radios opportunistically share the spectrum with the primary users. In this paper, we address the problem of detecting the presence of a primary user while a secondary user is transmitting data, in order to avoid harmful interference to the primary user. We have proposed an inband spectrum sensing technique utilizing the OFDM guard interval for scanning the spectrum. The spectrum sensing data from the discontiguous OFDM guard intervals is combined to obtain a long coherent data segment. We have shown that cyclostationarity can be exploited for the user detection even when the sensing data is discontiguous. The 'Listen-while-Talking' technique reliably detects the ATSC DTV signal in 8.5 ms when SNR is -21 dB. The inband spectrum sensing technique provides protection to primary users and saves the system capacity compared to the conventional system which uses idle period.**

I. INTRODUCTION

Opportunistic spectrum access [1] allows temporary usage of unused channels without causing unacceptable interference to primary users. It is crucially important for secondary users to detect the unused channels before starting the transmission. This is achieved by sensing the channel before transmission to check if a primary user has occupied the channel. This approach is commonly called 'Listen-before-Talk'. To guarantee the protection of primary users, it is also important to ensure that a primary user has not started using the channel while a secondary user is transmitting data on the channel. Thus, inband spectrum sensing is an important function for opportunistic spectrum access.

To be able to vacate the spectrum as soon as a primary user starts transmitting, frequent spectrum sensing would be necessary during secondary transmission which results in the loss of secondary user throughput. Alternately, a dedicated receiver could be used at the cost of hardware efficiency. We address the problem of inband spectrum sensing for secondary users without compromising system capacity and hardware efficiency.

We have developed an inband spectrum sensing technique called 'Listen-while-Talking' that utilizes guard interval from multiple OFDM symbols. The cyclic prefix of the symbol is not inserted into the guard interval at the transmitter, instead, the idle guard interval is used for scanning the channel. Spectrum sensing data acquired in a single OFDM guard interval of 5μs is not sufficient for reliable primary user detection. We have presented a method of combining discontiguous sensing-data segments for application to a cyclostationary feature detection technique. ATSC DTV signal is reliably detected using standard cyclostationary feature detector with conjugate spectral coherence as the detection statistic.

The salient contributions of the paper are as follows.

1) The proposed 'Listen-while-Talking' inband sensing technique, the secondary user can immediately vacate the spectrum and not cause interference to a primary user.
2) The proposed technique does not require the MAC layer to schedule idle period for the detection of a primary user and thus significantly saves the secondary system capacity.
3) We have shown that the cyclic features in the signal can be preserved from discontiguous sensing data segments.

This work is based on the earlier work [2] wherein we proposed method for securing the circular convolution at the receiver side and thus does not affect the receiver performance under various channel conditions. The earlier work together with the proposed method of combining discontiguous sensing data segments enables embedding the spectrum sensing functionality in the physical layer.

This paper is organized as follows. A brief review of spectrum sensing related literature is presented in Section II. System model and the scheme for achieving idle interval in the OFDM symbol for spectrum sensing is described in Section III. Section IV introduces the method for combining spectrum sensing data from discontiguous OFDM guard intervals to exploit cyclostationarity. Section V presents the cyclostationary feature detector structure and rationale. Section VI reviews the cyclostationary nature of the primary signal of interest (ATSC DTV). Sections VII and VIII provide evaluation of the proposed 'Listen-while-Talking' sensing technique to protect the primary user's spectrum rights. Finally, conclusions are given in Section IX.

II. RELATED WORK

Spectrum sensing is a vital functionality for dynamic spectrum access. It is achieved by matched filtering, energy detection, eigenvalue sensing, signature based detection and cyclostationary feature detection [3], [4]. Cabric *et al.* [3] have discussed the implementation issues in the spectrum sensing using cognitive radios. Tandra *et al.* have outlined the fundamental limits and practical challenges in spectrum sensing [5]. Cardoero *et al.* [6] outlined the challenges in the design of PHY and MAC layer for IEEE 802.22 air interface. Kim *et al.* proposed signal detection and pattern matching based signal classification algorithm exploiting cyclostationarity [7]. Chen *et.al* [8] provided statistical analysis of the spectral correlation density (SCD) of the stationary white Gaussian process and applied the cyclic spectral analysis for detection of ATSC DTV signal under low SNR conditions.

Opportunistic spectrum sharing under severe fading or shadowing demands very high sensitivity which is difficult to meet. Collaborative spectrum sensing [9–11] amongst cognitive radios can increase the accuracy and relax the required sensitivity of individual sensing units. The collaborative spectrum sensing also helps in overcoming the channel randomness and the device uncertainties.

Inband sensing is accomplished by monitoring the primary channel periodically. Inband sensing relies on the detection of the primary transmitter and needs to use the detection range to protect the primary receivers. Alternatively, a beacon is transmitted by the active primary receivers through an out-of-band control channel [12]. The proposed 'Listen-while-Talking' technique complements the existing primary user protection approaches while saving the secondary system capacity.

III. IDLE OFDM GUARD INTERVAL FOR INBAND SPECTRUM SENSING

The proposed 'Listen-while-Talking' technique is based on the OFDM modulation scheme. This section describes how the channel is sensed by the secondary transmitter employing OFDM scheme.

In OFDM systems, a block of data is transmitted as an OFDM symbol. A guard interval is introduced between two successive symbols to avoid inter-symbol interference and it is generally longer than the anticipated channel delay spread. A cyclic prefix which is the tail portion of the symbol is inserted at the head of the symbol, or guard interval, which provides resistance against intercarrier interference (ICI).

In order to achieve an idle guard interval suitable for spectrum sensing, we do not insert the cyclic prefix in the guard interval. This choice implies that the received symbol represents a linear convolution and ICI is seen after the receiver's FFT operation.

We use the scheme shown in Fig. 1. to preserve circular convolution and avoid ICI at the OFDM receiver. A detailed evaluation of this scheme is provided in [2]. The OFDM guard interval at the transmitter is free for use for inband spectrum sensing.

IV. EXPLOITING CYCLOSTATIONARITY IN THE DISCONTIGUOUS DATA

This section describes the gating scheme for combining discontiguous sensing data for applying the cyclic spectral analysis techniques.

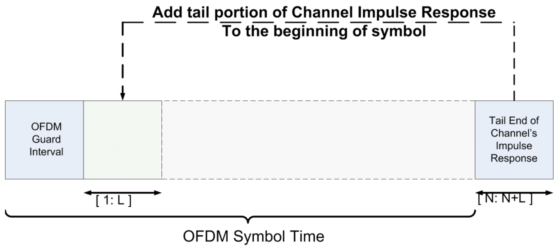

Fig. 1. Scheme for preserving circular convolution at the receiver

The sampling of the data is not contiguous since the data is only sampled during the idle portion of the OFDM symbol, i.e., the guard interval. We insert zeroes in the sampled data during the active portion of the OFDM symbol. Thus, the received signal that is available for sensing is equivalent to a gated version of the actual signal as shown in Fig 2.

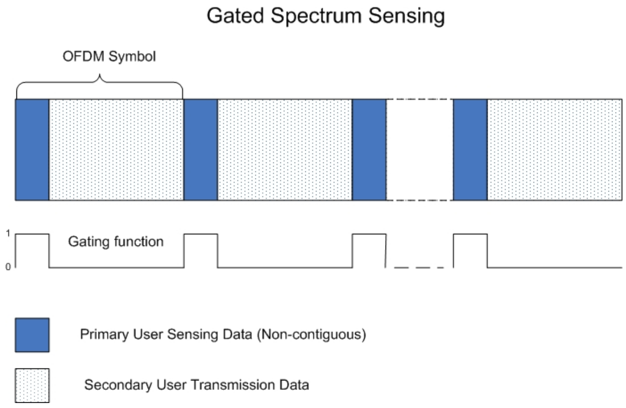

Fig. 2. Gated Spectrum Sensing

Let $d(t)$ be the signal to be detected and $x(t)$ be the observed signal. Then we have

$$x(t) = g(t)(d(t) + w(t)) \tag{1}$$

where g(t) is a periodic binary-valued ($\{0,1\}$) rectangular-pulse gating function with duty cycle $\frac{T_g}{T_s}$ where T_g is the length of guard interval and T_s is the symbol length. Let the nth-order cumulant function [13] for the random signal $a(t)$ be denoted by $C_a(t,\tau;n,m)$, where m is the number of optional conjugations used and τ is an n-dimensional vector of delays τ_j. Also denote the nth-order moment function by $R_a(t,\tau;n,m)$. It can be shown [13] that the cumulant for $g(t)d(t)$ is given by the cumulant for $d(t)$ multiplied by the nth-order moment for the function $g(t)$. Moreover, since $g(t)$, $d(t)$, and $w(t)$ are statistically independent, the cumulant for $x(t)$ is the sum of the cumulants for $g(t)d(t)$ and $g(t)w(t)$. Therefore, the cumulant for $x(t)$ can be expressed as

$$\begin{aligned} C_x(t,\tau;n,m) &= R_g(t,\tau;n,m)\left(C_d(t,\tau;n,m)\right. \\ &\quad \left. + C_w(t,\tau;n,m)\right). \end{aligned}$$

Each cumulant function can be expressed as a Fourier series,

$$C_a(t,\tau;n,m) = \sum_{\beta_a} C_a^{\beta_a}(\tau;n,m)e^{i2\pi\beta_a t},$$

where the Fourier coefficient $C_a^{\beta_a}$ is called the cyclic cumulant and the Fourier frequency β_a is called a cycle frequency. Note that the moment function for the non-random periodic gating function is also expressible as a Fourier series, and since the product of the gating function with multiple versions of itself must have a non-zero average value, the Fourier coefficient for the zero-valued cycle frequency $\beta_g = 0$ is non-zero.

The cyclic cumulants for stationary noise are zero for $n > 2$ and for $n = 2$ are zero unless $\beta_w = 0$ and $m = 1$ [13]. Therefore, the cycle frequencies for $x(t)$ are equal to

$$\beta_x = \beta_g + (\beta_d + \beta_w),$$

which requires that the cyclic cumulant $C_g^{\beta_g}$ be nonzero and at least one of $C_d^{\beta_d}$ and $C_w^{\beta_w}$ be non-zero. Due to the aforementioned properties of $g(t)$ and $w(t)$, this means that every cycle frequency β_d is also a cycle frequency of $x(t)$. There are additional cycle frequencies for $x(t)$ as well, due to the potentially large number of cycle frequencies in the moment $R_g(t,\tau;n,m)$.

In what follows, we restrict our attention to second-order analysis ($n = 2$), for which the cyclic cumulant is equal to a delay-shifted version of the conventional cyclic autocorrelation function. Typically, the Fourier transform of the cyclic autocorrelation is the preferred analysis tool, and it is called the spectral correlation function or cyclic spectrum. Second-order cycle frequencies are conventionally denoted by α, higher-order by β.

A cyclostationary feature detector can now be used for the primary user detection from the gated data acquired during the transmission of the secondary signal. Cyclostationary feature detection provides multiple advantages as compared to matched filtering or energy detection. The cyclostationary feature detection provides noncoherent primary user detection (the symbol clock and carrier phases of the signal are not needed) by exploiting cyclostationarity. Additionally, cyclic spectrum analysis preserves phase and frequency information in the modulated signal which is not possible in the power spectrum analysis. Finally, this signal detection technique is not as sensitive as energy detection to uncertainties in or time-varying behavior of stationary noise and interference.

V. CYCLOSTATIONARY FEATURE DETECTOR

In this section, we present a signal detector to determine the presence or absence of a cyclostationary signal having spectral coherence at a spectral frequency f and cycle frequency α.

The discrete Fourier transform of x(t) is defined by

$$X(f) = \sum_{t=0}^{N-1} x(t)e^{-i2\pi ft} \tag{2}$$

where f = $\frac{n}{N}$ for $n = 0, 1, \dots, N-1$ and N is the total samples acquired during k OFDM symbols. The periodogram is given by

$$I(f) = \frac{1}{N}|X(f)|^2 \tag{3}$$

The power spectrum estimate is obtained by smoothing the periodogram.

$$\hat{S}(f) = w(f) \otimes I(f) \tag{4}$$

$$\hat{S}(f) = \frac{1}{N}\sum_{t=0}^{N-1} w(f - n/N)|X(n/N)|^2 \tag{5}$$

For spectral correlation function, the conjugate cyclic periodogram [14] is calculated as follows

$$I_*^{\alpha}(f) = \frac{1}{N}X(f + \alpha/2)X(\alpha/2 - f) \tag{6}$$

where α is the cycle frequency of interest.

The conjugate spectral correlation function is estimated by smoothing the conjugate cyclic periodogram.

$$\hat{S}_*^{\alpha}(f) = \frac{1}{N}\sum_{t=0}^{N-1} w(f - n/N)X(n/N + \alpha/2)X(\alpha/2 - n/N) \tag{7}$$

The correlation coefficient is obtained by normalizing the spectral correlation function.

$$C_*(f) = \frac{S_*^{\alpha}(f)}{[S(f + \alpha/2)S(\alpha/2 - f)]^{1/2}} \tag{8}$$

The $C_*(0)$ is used as detection statistic to determine the presence or absence of the primary user.

VI. CYCLIC FEATURES OF ATSC DTV

This section describes the the cyclostationary nature of the primary user's signal.

The primary signal modulation type is ATSC DTV, which is a broadcast digital TV signal employing vestigial 8PAM with a low-level pilot tone and a 832-symbol pseudonoise synchronization sequence that appears every 24 ms. The 8-level vestigial sideband (8VSB) signal sends symbols at a rate of 10.762 MHz and is heavily filtered to fit into the 6 MHz wide broadcast TV channels. However, due to the nature of the baseband 8PAM modulation type, the signal exhibits two second-order conjugate ($n = 2, m = 0$) cycle frequencies at $\alpha = 2f_{pilot}$ and $\alpha = 2f_{pilot} + f_{symbol}$. It is these two cycle frequencies that we aim to exploit with cyclostationary feature detector applied to the gated signal. Measured PSD and spectral correlation functions for a simulated ATSC DTV signal are shown in Figure 3.

VII. EVALUATION OF LISTEN-WHILE-TALKING

To evaluate the DTV detection performance of the 'Listen-while-Talking' approach, ATSC DTV signal was simulated as per specifications described in section VI. The bandpass purely stationary noise is added to meet the target SNR. The secondary user employs OFDM for transmission and simultaneously senses the channel using the proposed gating technique. The gating signal is a binary valued periodic signal with frequency 40 kHz. The pulse width is set to 5 μs. This

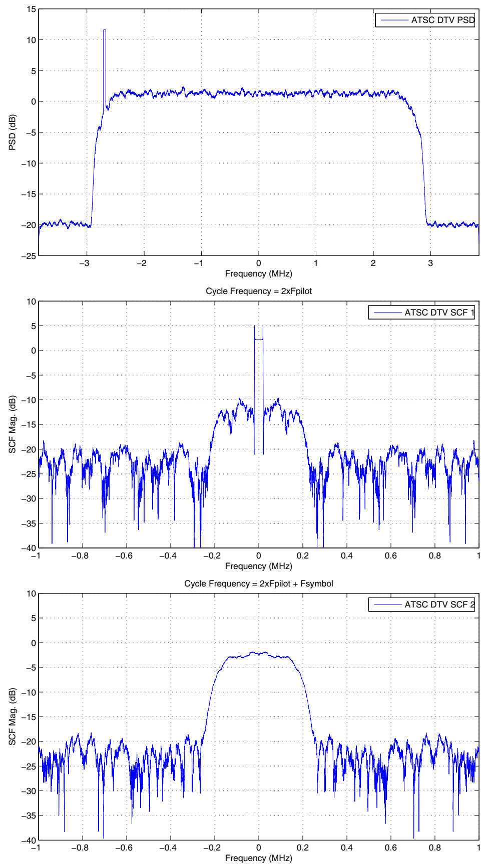

Fig. 3. ATSC DTV signal shows two second-order conjugate cycle fequencies

means that a secondary user would be acquiring sensing data for 5 μs every 25 μs. The spectrum data is acquired at the sampling rate of 7.69 MHz. The sensing data is filtered by a bandpass filter and scaled to achieve desired signal power as mentioned in [15]. The pilot tone is filtered out and the resulting notched data is passed to the cyclostationary feature detector[1]. The overall procedure of detection is shown in Figure 4.

The cyclostationary feature detector described in Section V was used to detect the presence of the cyclic features. The detector used frequency smoothing window of approximatly 550 kHz width. We performed Monte Carlo trials with gated sensing data and non-gated sensing data and plotted ROC for the detectors. From the ROC plots in Figure 5, we observe that the gated-version of the signal preserved the cyclic features present in the primary signal with SNR -21 dB.

Figure 6 shows performance of the detector with gated data for various SNR values. The sensing time is 8.5ms

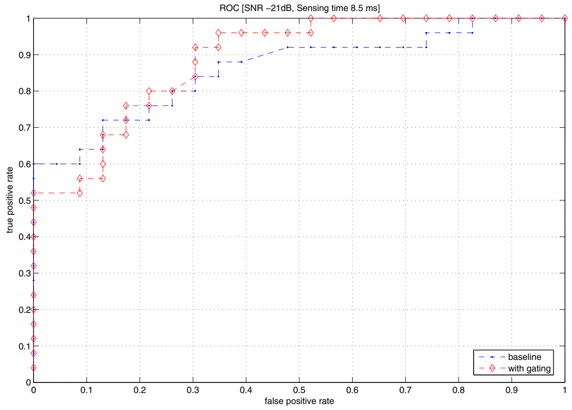

Fig. 5. ROC plots for cyclostationary feature detector using contiguous and discontiguous sensing data. Sensing time 8.5 ms

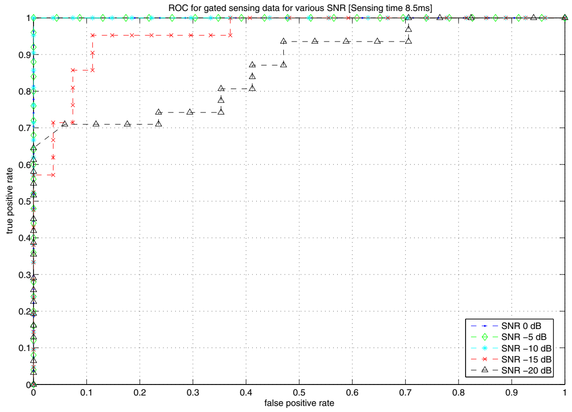

Fig. 6. ROC plots for the cyclostationary feature detector using gated sensing data for various SNR values

VIII. ENHANCEMENT TO THE ATSC DTV DETECTOR FOR LOW SNR

In this section, we introduce an enhancement to the cyclostationary feature detector for ATSC DTV signal for improving low SNR performance The ATSC DTV signal shows two cyclic features. Exploiting the joint detection of cyclic features, the detection statistic is modified as follows

$$detection - statistic = \hat{S}_*^{\alpha 1}(0) + \hat{S}_*^{\alpha 2}(0) \tag{9}$$

where $\alpha 1$ and $\alpha 2$ are the two cycle frequencies for ATSC DTV signal. The detection statistic represnts the summation of the normalized spectral correlation functions for the two cycle frequencies.

The ROC plots for the ATSC DTV detector based on the new detection statistic are shown in Figure 7. Comparing the plots with Figure 5, we see the detection performance is significantly improved for -21 dB SNR.

When the SNR is not quite as low, the primary user detection can be achieved more quickly. Figure 8 shows the

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[1] There exist a few methods based on pilot tone energy and location detection; the cyclostationary feature detector does not rely on the energy of the ATSC DTV pilot tone and thus provides better performance in case of spectral nulls at the pilot tone

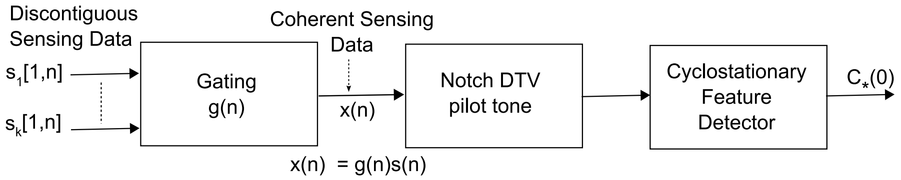

Fig. 4. System implementation of the cyclostationary feature detector

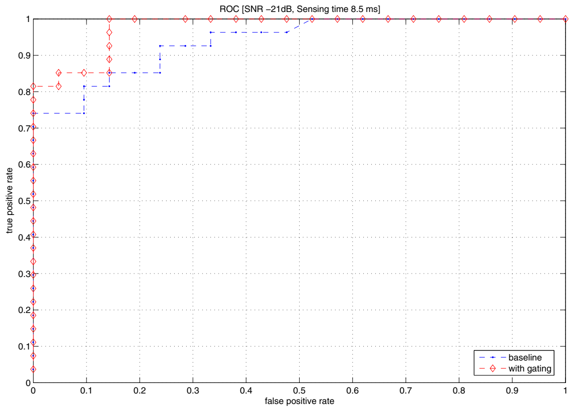

Fig. 7. ROC plots for the joint cyclic feature detector using contiguous and discontiguous sensing data. (Sensing time 8.5 ms)

performance of the enhanced ATSC DTV detector using the gated data for various SNR values.

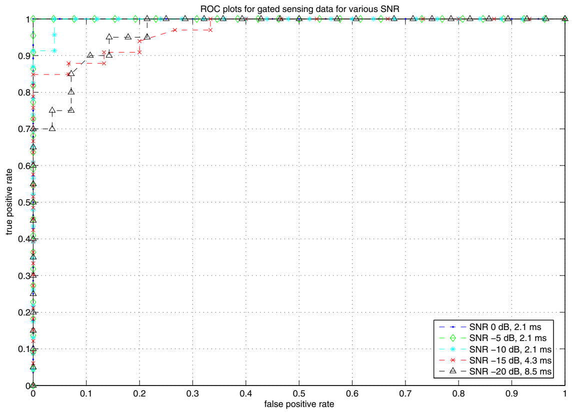

Fig. 8. ROC plots for the joint cyclic feature detector using gated sensing data for various SNR values

IX. CONCLUSIONS

We have presented an inband sensing technique, 'Listen-while-Talking', for the detection of primary users when a secondary user is transmitting data. The technique combines the discontiguous short (5 μs) sensing intervals to form coherent sensing data. We have analytically shown that the technique preserves the cyclic features in the primary signal. The simulation results show that the conventional cyclostationary feature detector using dis-continous sensing data is able to detect the cyclic features in the primary user signals. Using the proposed 'Listen-while-Talking' inband sensing technique, the secondary user can immediately vacate the spectrum and not cause interference to a primary user. We exploited the joint detection of the ATSC DTV cyclic features to reliably detect the signal in 8.5 ms when SNR is -21 dB. Finaly, the 'Listen-while-Talking' technique does not require the MAC layer to schedule idle period for the detection of a primary user and thus significantly saves the secondary system capacity.

REFERENCES

[1] Qing Zhao; Swami, A, "A Survey of Dynamic Spectrum Access: Signal Processing and Networking Perspectives," *Acoustics, Speech and Signal Processing*, April 2007.

[2] Nilesh Khambekar, Liang Dong and Vipin Chaudhary, "Utilizing OFDM Guard Interval for Spectrum Sensing," *Wireless Communications and Networking*, March 2007.

[3] D. Cabric, S. M. Mishra, and R. W. Brodersen, "Implementation Issues in Spectrum Sensing for Cognitive Radios," *38th Annual Asilomar Conference on Signals, Systems and Computers*, November 2004.

[4] S. Shellhammer, "Spectrum Sensing in IEEE 802.22," *First Workshop on Cognitive Info. Process. (CIP 2008)*, Jun 2008.

[5] R. Tandra, A. Sahai, "Fundamental Limits on Detection in Low SNR under Noise Uncertainty," *WirelessCom Symposium on Signal Processing*, June 2005.

[6] C. Cardoero, K. Challapalli, D. Birru, and Sai Shankar, "IEEE 802.22: the first worldwide wireless standard based on cognitive radios," *New Frontiers in Dynamic Spectrum Access Networks, DySpAN'05*, November 2005.

[7] K. Kim, I.A.Akbar, K.K. Bae, J. Urn, C.M. Spooner, J.H. Reed, "Cyclostationary Approaches to Signal Detection and Classification in Cognitive Radio," *New Frontiers in Dynamic Spectrum Access Networks, DySPAN*, April 2007.

[8] H. Chen W. Gao, and D.G. Daut, "Spectrum Sensing Using Cyclostationary Properties and Application to IEEE 802.22 WRAN," *Global Telecommunications Conference, GLOBECOM 07*, Nov 2007.

[9] E. Visostky, S. Kuffner and R. Peterson, "On Collaborative Detection of TV Transmissions in Support of Dynamic Spectrum Sharing," *New Frontiers in Dynamic Spectrum Access Networks*, Nov 2005.

[10] A. Gashemi and E. Sousa, "Collaborative Spectrum Sensing for Opportunistic Access in Fading Environments," *New Frontiers in Dynamic Spectrum Access Networks*, Nov 2005.

[11] H. Liu, B. Krishnamachari, and Q. Zhao, "Cooperation and Learning in Multiuser Opportunistic Spectrum Access," *IEEE Workshop on Towards Cognition in Wireless Networks (CogNet)*, May 2008.

[12] A.P. Hulbert, "Spectrum Sharing Through Beacons," *Personal, Indoor and Mobile Radio Communications*, Sept 2005.

[13] C. M. Spooner and W. A. Gardner, "The Cumulant Theory of Cyclostationary Time-Series, Part I: Foundation and Part II: Development and Applications," *EEE Trans Sig Proc Vol. 42, pp. 3387–3429*, Dec 1994.

[14] W. Gardner, "Statistical Spectrum Analysis: A Nonprobabilistic Theory," *Englewood Cliffs, NJ: Prentice Hall*, 1987.

[15] S. Mathur, R. Tandra, S. Shellhammer, and M. Ghosh, "Initial Signal Processing of Captured DTV Signals for Evaluation of Detection Algorithms," *IEEE 802.22-06/0158r4*, Sept 2006.