SPECTRUM SENSING IN IEEE 802.22

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ABSTRACT

The IEEE is developing a standard for cognitive wireless regional area networks operating in unused television channels. One of the cognitive features of this standard is spectrum sensing, which is used to identify unused television channels. This paper describes the requirements for spectrum sensing and the spectrum sensing framework. A description is given of the method used for evaluating specific spectrum sensing techniques. Finally, the paper provides a survey of the spectrum sensing techniques that are included in the draft standard.

Index Terms— Cognitive Radio, Spectrum Sensing, IEEE 802.22

1. INTRODUCTION

The IEEE 802.22 working group is developing a standard for a Cognitive Wireless Regional Area Network (WRAN), that will operate in unused television channels and provide fixed wireless access services. The final standard will support 6, 7 and 8 MHz channels for worldwide operation. The WRAN is based on an orthogonal frequency division multiple access (OFDMA) PHY layer. The standard is under development and is currently in draft form [1].

Spectrum sensing involves making observations of the radio frequency (RF) spectrum and reporting on the availability of unused spectrum for use by the WRAN. This paper reviews spectrum sensing within IEEE 802.22. Section 2 describes the IEEE 802.22 spectrum sensing requirements. Section 3 describes the spectrum sensing framework, including a summary of the standardized reporting of spectrum sensing results. As part of the process of developing IEEE 802.22 the working group evaluated a variety of spectrum sensing techniques. Section 4 describes the evaluation methodology that was used to evaluate spectrum sensing techniques. Finally, a survey of the various spectrum sensing techniques is provided. These sensing techniques are included in an Informative Annex within the IEEE 802.22 draft standard. Section 5 summarizes the *blind sensing techniques* that do not rely on specific features of the signal being sensed. Section 6 describes *signal specific sensing techniques* that rely on specific features of the signal.

2. SPECTRUM SENSING REQUIREMENTS

Each station in an 802.22 network is required to perform spectrum sensing. The 802.22 network consists of a base station and a number of client stations, referred to as customer premise equipment (CPE). The base station controls when sensing is performed and the results of all spectrum sensing are reported to the base station. The final decision as to the availability of a television channel is made by the base station. The base station can rely on spectrum sensing results, geolocation information and auxiliary information provided by the network manager, to make its final decision about channel availability. Since all sensing results are reported to the base station one can think of spectrum sensing as a signal processing and reporting function. The draft standard does not mandate use of a specific signal processing technique, instead it mandates specific sensing performance and a standardized reporting structure. The required sensing performance is summarized in this section. The information to be included in the standardized reporting structure is described in the next section.

The sensing requirements, along with all the other requirements, are found in the IEEE 802.22 functional requirements document [2], which can be found on the IEEE 802.22 working group web site [3]. Sensing is required for analog television, digital television and wireless microphones. The broadcast industry uses wireless microphones in vacant television channels. The format of the analog and digital television broadcasts depend on the region of operation. In North America, for example, analog television is based on NTSC and digital television is based on ATSC. The format of the wireless microphone signals are not standardized. They tend to be analog frequency modulation (FM) transmitters. The bandwidth is typically limited to 200 kHz, based on regional regulations.

The required detection time for all three signal types (ana-

	Analog TV	Digital TV	Wireless Mics
Sensitivity	-94 dBm	-116 dBm	-107 dBm
SNR	1 dB	-21 dB	-12 dB

Table 1. Sensing Receiver Sensitivity Requirements

log TV, digital TV and wireless microphones) is 2 seconds. The required sensing sensitivity is the power level at which the probability of detection is 0.9, while the probability of false alarm is 0.1. Table 1 summarizes the required sensing receiver sensitivity for the three licensed signals types. If we assume a conservative sensing receiver noise figure of 11 dB, as is done in the 802.22 working group [4], then the required sensing receiver SNR detection level in dB is also summarized in Table 1. In this case the noise is measured over a 6 MHz television channel.

We see from these sensing requirements that some of the licensed signals (e.g digital TV) must be sensed at a very low SNR. This represents the primary challenge in spectrum sensing. The rational for these requirements is to ensure protection of licensed transmissions.

3. SPECTRUM SENSING FRAMEWORK

IEEE 802.22 does not mandate the use of a specific sensing technique in either the base station or CPE. However, it is required that the spectrum sensing conform to the Spectrum Sensing Framework which specifies the inputs and outputs of the spectrum sensor, and also its behavior. The spectrum sensing framework is illustrated in Figure 1. This section gives a brief overview of the inputs and outputs of the spectrum sensing. This framework is supported by specific medium access control (MAC) messages for controlling the spectrum sensing in the CPE from the base station and for reporting the sensing results to the base station. The details of the MAC signaling is outside the scope of this paper.

The first two inputs, *Channel Number* and *Channel Bandwidth*, specify which channel to sense and the channel bandwidth. The bandwidth is necessary since this to be an international standard and hence multiple channel bandwidths are supported. The type of signal to sense for is specified by the *Signal Type* input. Signal types include the various analog TV signals (e.g. NTSC), digital TV signals (e.g ATSC), wireless microphone signals, etc. It is possible to sense for multiple signal types simultaneously, however, to simplify the description we will focus on sensing for a single signal type at a time. The *Sensing Mode* input signal specifies which of the sensing modes to use. There are three sensing modes specified in the draft. In the first sensing mode the *Signal Present Decision* is active. This output, as well as the other outputs, will be described shortly. In the second (optional) sensing mode both the *Signal Present Decision* and the *Confidence Metric* are active. Finally, in the third (optional) sensing mode the *Field Strength Estimate* and the *Field Strength (FS) Estimate Accuracy* are both active. Finally, the *Max* P_{FA} specifies the maximum allowed probability of false alarm when only noise is present in the channel.

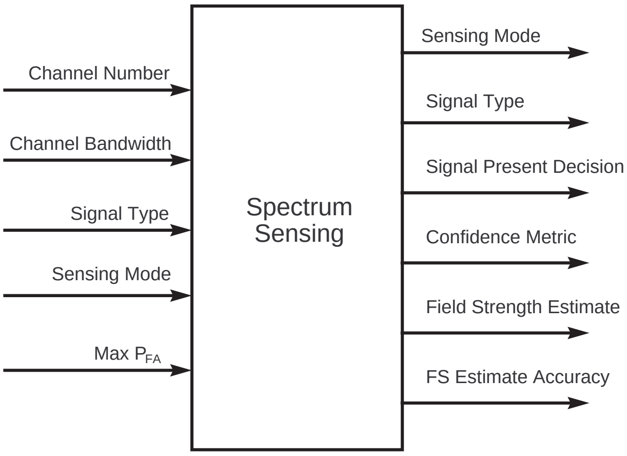

Fig. 1. Spectrum Sensing Framework

The *Sensing Mode* and *Signal Type* outputs are just passed through from the input since they are used in interpreting the other outputs. The *Signal Present Decision* output is a binary value that specifies whether the signal type that was specified is present in the channel. This output is the result of a binary hypothesis test that tests whether the channel contains noise only or signal plus noise. The *Confidence Metric* output is a measure of the confidence that the spectrum sensor has in the *Signal Present Decision* output. For example, if the test statistic far exceeds the threshold used in the binary hypothesis test, then the confidence metric would be high. If however, the test statistic barely exceeded the threshold then the confidence metric would be low. This confidence metric is additional information that the base station can use when combining spectrum sensing results from multiple WRAN stations. The final two outputs provide even more information to the base station in making its final decision about the availability of the specified channel. The *Field Strength Estimate* output is an estimate of the electromagnetic field strength of the specified signal. This estimate of the field strength is particularly useful in determining if the station making the estimate is near the television protected contour which specifies the televisions that must be protected from interference. Finally, the *FS Estimate Accuracy* is a measure of the accuracy of the field strength estimate.

4. EVALUATION METHODOLOGY

Though a specific sensing technique is not mandated in the 802.22 draft, the working group did evaluate a number of

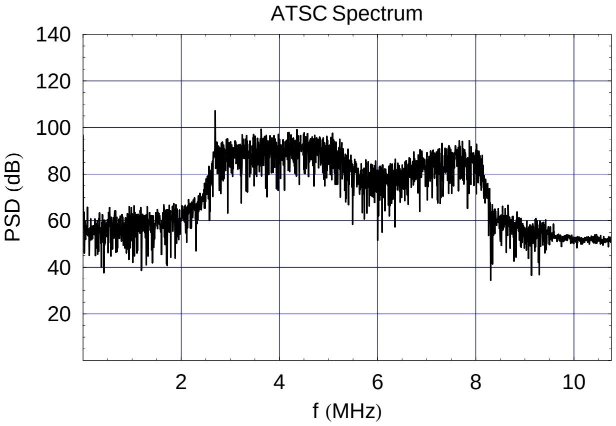

Fig. 2. Spectrum of Captured ATSC Signal

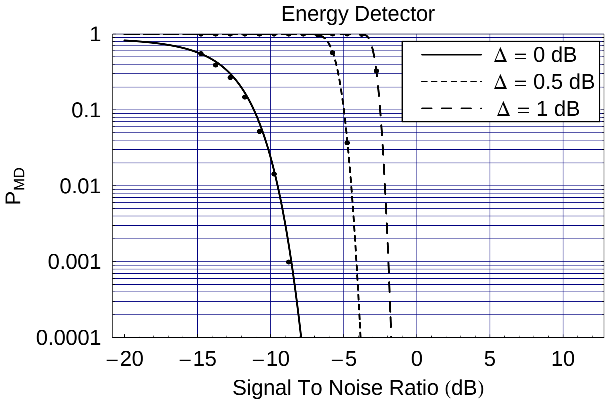

Fig. 3. Energy Detector with Noise Uncertainty

sensing techniques. This section briefly summarizes that evaluation methodology and subsequent sections summarize the spectrum sensing techniques that were evaluated and included in the draft.

The simulations required for evaluation are described in [4]. One of the unique features of this evaluation methodology is the use of actual captured signals for the specific case of ATSC. The working group used fifty signals that were collected by the ATSC committee in New York City and Washington DC. The advantage of using these signals is that real-world multipath is represented in these captured signals. These signals are collected at an intermediate frequency (IF) of 5.38 MHz and are sampled at a rate of 21.5 MHz. The spectrum of a representative signal is shown in Figure 2 where we see the effects of multipath fading. In this example the ATSC pilot signal can be seen, however, there are signals in which there is significant fading at the pilot frequency.

Simulations were only performed for the mandatory sensing mode, where the output is a single binary decision. The threshold in the sensing technique is set to give a false alarm rate of 0.1. Probability of detection curves were run for all the captured signals (in the case of ATSC). Noise was added to the signals to simulated very low SNR signals. The probability of detection was averaged over all the captured signals. In some cases the individual results for specific signals were also provided. Typically, the probability of misdetection (one minus the probability of detection) was plotted versus SNR. Results for some of the sensing techniques are shown in subsequent sections.

5. BLIND SENSING TECHNIQUES

Blind sensing techniques, that do not rely on any special signal features, are described in this section. IEEE 802.22 presentations and documents on both the blind and signal specific sensing techniques are available on the IEEE 802.22 working group web site [3].

5.1. Energy Detector

The energy (power) detector estimates the signal power in the channel and compares that estimate to a threshold [5]. The energy detector begins with the complex baseband signal typically sampled at the Nyquist rate of 6 MHz. The baseband signal is a complex signal with a spectrum that spans from -3 MHz to 3 MHz. The baseband signal is $y(n) = x(n) + w(n)$ where $x(n)$ is the signal component and $w(n)$ is additive white Gaussian noise. The signal power is P_S and the noise power is P_N. The test statistic is,

$$T = \frac{1}{M} \sum_{m=1}^{M} y(m) y^*(m) \tag{1}$$

For large M we can apply the Central Limit Theorem and then this test statistic is a Normal random variable with the following distribution,

$$T \sim N\left(P_S + P_N, \frac{(P_S + P_N)^2}{M}\right) \tag{2}$$

The energy detector compares this test statistic T to a threshold γ. The value of the threshold is selected to meet the false alarm rate target. For large M the performance of this sensing technique can be shown to work well even at very low SNR. However, this sensing technique relies on *a priori* knowledge of the noise power. Let us assume that our estimate of the noise power is accurate to within a tolerance of $\pm\Delta$ dB. In other words our *a priori* estimate of the noise power is given by $\hat{P}_N = P_N + P_E$, where the error in the estimate is bounded such that $-\Delta \leq P_E \leq \Delta$. We call this *a priori* error, *noise uncertainty* [6].

Figure 3 shows the performance of the energy detector with several values of noise uncertainty, for case when $M = 1200$. The figure shows both theoretical curves and isolated points for simulation results. We see that with no noise uncertainty ($\Delta = 0$) that the energy detector can perform well at negative SNR values. For longer sensing times (e.g. larger M)

the performance continues to improve. However, when there is uncertainty in the noise power the performance is limited to an SNR a little less than zero dB. So the energy detector is not a robust detector at negative SNR due to the requirement to have very precise knowledge of the noise power. More example of the energy detector with noise uncertainty can be found in [7].

5.2. Eigenvalue-based Sensing

Another blind sensing technique uses eigenvalues of the correlation matrix. The sensor calculates estimates of the autocorrelation function of the received signal, which we denote as $R_{yy}(m)$. The correlation matrix is given by,

$$R = \begin{pmatrix} R_{yy}(0) & \dots & R_{yy}(L-1) \\ R_{yy}(1) & \dots & R_{yy}(L-2) \\ \vdots & & \vdots \\ R_{yy}(L-1) & & R_{yy}(0) \end{pmatrix} \qquad (3)$$

The correlation matrix is then transformed by a whitening matrix Q which corrects for the frequency response of the receive filter. The whitened correlation matrix is given by $\tilde{R} = Q^{-1} R Q^{-H}$. Let λ_i be the eigenvalues of the matrix $\tilde{R}$.

There are several test statistics that can be used. The first one is the ratio of the largest eigenvalue and the smallest eigenvalue, $T = \lambda_{max}/\lambda_{min}$.

In another test statistic we first estimate the average signal power (ρ) and then let the test statistic be the ratio of the signal power estimate and the smallest eigenvalue, $T = \rho/\lambda_{min}$. Both of these test statistics are measures of the non-whiteness of the spectrum.

5.3. Multi-resolution Sensing

The final blind sensing technique produces a multi-resolution power spectral density (PSD) estimate using a tunable wavelet filter that can change its center frequency and it bandwidth. The filter is swept over a range of frequencies and the power at each frequency is recorded. The power spectral density estimate can be used to test the non-whiteness of the spectrum, as in the previous sensing technique.

6. SIGNAL SPECIFIC SENSING TECHNIQUES

Signal specific sensing techniques, that utilize specific signal features, are described in this section.

6.1. ATSC Signature Sensing

The ATSC Data Field consists of a sequence of segments [8]. Every 313 of these segments is the Data Field Sync. This field contains a 511-bit PN sequence (PN511) and three 63-bit PN sequences (PN63). One of the 63-bit PN sequences alternates its polarity every data field. These know PN sequences can be used as a signature when sensing for the ATSC signal.

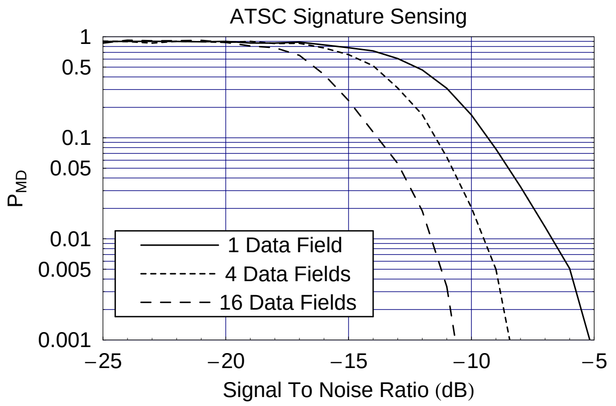

Fig. 4. ATSC Signature Sensing

This ATSC signature sensing technique contains a correlator that correlates the received baseband signal with a prestored sequence based on a combination of the PN511 and two of the PN63 sequences. The PN63 sequence that alternates in polarity is not used. Detection of a single ATSC Data Field Sync can be accomplished by making the test statistic the maximum of the absolute value of the correlator output. The correlator is run over 24.2 ms, which is the duration of an ATSC Data Field. This sensing time corresponds to over 10^5 samples, at 6 MHz sampling.

If additional sensing time is available one can develop a more sensitive sensing technique. Combining results from multiple Data Field Sync signals is a challenge since over a period of 24.2 ms the multipath channel can change, even in a fixed wireless system. As a result the polarity of the output of the correlator due to the Data Field Sync can change. Also, the exact timing of when the peak output of the correlator occurs can also change up to several samples. To combine the peaks from the correlator from multiple Data Field Sync signals one must select the largest N peaks from each Data Field period and then combine the peaks from multiple Data Fields if they occur within a time window of W samples. By combining peaks from multiple Data Fields it is possible to produce a more sensitive sensing technique. Results for this sensing technique are given if Figure 4 for one, four and sixteen ATSC Data Fields. For a sensing time of 16 Data Fields the sensitivity is approximately -14 dB SNR, when averaged over a set of actual ATSC signal collected in real multipath channels.

6.2. FFT-based ATSC Pilot Sensing

The ATSC signal includes a sinusoidal pilot signal that is used in demodulation. There are several possible pilot frequencies that can be used. After the digital transition is complete there will be only two possible pilot frequencies: 309440.6 and

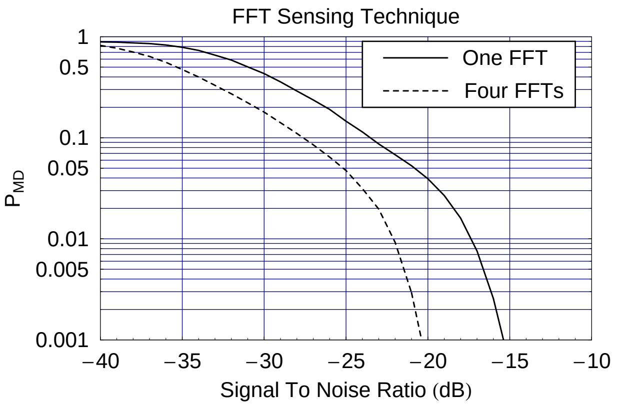

Fig. 5. ATSC Pilot FFT Sensing Technique

328843.6 Hz. The pilot frequency is measured from the lower edge of the TV channel and is accurate to within ±10Hz. The difference between these two pilot frequencies is approximately 19.4 kHz.

This sensing technique involves estimating the power spectral density in the neighborhood of the pilot frequency. The midpoint between these two pilot frequencies is down converted to DC and the signal is filtered with a narrow-band low-pass filter. The filter double-sided bandwidth needs to be more that 19.4 kHz to ensure that the pilot signal is within the bandwidth of the filter. In addition, there is an error in the receiver local oscillator (LO) frequency that is controlled by the LO frequency accuracy. In this simulation the filter bandwidth of 25 kHz was used.

There are several possible test statistics that can be used. We will give results for the first test statistic, and just provide a description of the second test statistic.

The power spectral density is estimated using a periodogram [9] which is based on the discrete Fourier transform (DFT),

$$P(\omega) = \frac{1}{M} \left| \sum_{m=0}^{M-1} y(m) e^{-j\omega m} \right|^2 \qquad (4)$$

which can be implemented efficiently using the fast Fourier transform (FFT).

The signal-to-noise ratio of the estimate can be improved by averaging a sequence of periodograms.

The first test statistic is the maximum of all the values in the power spectral density estimate. However, since the pilot is a narrow-band signal it is susceptible to Rayleigh fading. So the results of this sensing technique are much worse in a fading channel than in an AWGN channel. None the less, the results are quite good. Figure 5 give the results when a 2048-point FFT is used with either a single FFT or when averaging over four FFTs. The 802.22 OFDMA PHY uses a 2048-point FFT, which can be reused in this sensing technique. The results are averaged over 50 real-world multipath channels. We see that the sensitivity of below -25 dB SNR can be attained, with a false alarm rate of 0.1.

The second FFT-based sensing technique is similar to the first. This technique computes two power spectral density estimates and then finds the frequency of the maximum of the PSD for each of the PSD estimates. This should be the ATSC pilot in both cases. The test statistic is the frequency difference between these two frequencies. The sensitivity of this approach are also quite good.

6.3. Higher Order Statistics Sensing

This sensing technique is based on the noise statistics being Gaussian. These higher order statistics (HOS) can be used to test how well the distribution of the test statistic meets a Gaussian distribution [10]. The receive signal is converted to baseband and filtered. Then the nominal ATSC pilot frequency is converted to DC and the signal is filtered again with a narrowband filter. The resultant signal is converted to the frequency domain using an FFT. A 2048-point FFT is recommended, since it is also used in the OFDM modulator/demodulator. Then the higher order moments and cumulants (higher than second order) of the real and the imaginary parts of the frequency domain signal are calculated. If only noise is present then the real and imaginary part of the frequency domain signal are both Gaussian, so these higher order cumulants are zero. In this sensing technique a Gaussianity test is performed based on the value of the higher-order cumulants. If the signal fails the Gaussianity test then the sensing technique decides the ATSC pilot signal is present.

6.4. PLL-based ATSC Pilot Sensing

The next sensing technique consists of two frequency tracking blocks each attempting to track the ATSC pilot frequency. There are multiple methods of implementing the frequency tracking block. The draft suggest using a digital phase lock loop (PLL) using a version of the Costas loop. Each of the frequency trackers are initialized with a tracking frequency close to the expected pilot frequency. One frequency tracker is initialized with 30 kHz above the nominal pilot frequency and the other is initialized 30 kHz below the nominal pilot frequency. The test statistic is the absolute value of the difference between the final frequency estimates of each of the frequency trackers. If this difference in the two final frequency estimates is above a threshold then the sensing technique decides that an ATSC pilot signal is present. This sensing technique typically requires approximately 50 to 75 ms. The results depend strongly on the fading characteristics near the pilot frequency, but when averaged over a number of multipath channels, the sensitivity of this technique is approximately -12 to -14 dB.

6.5. Wireless Microphone Covariance Sensing

Similarly to the eigenvalue sensing technique described earlier, this technique calculates the sample covariance matrix. In the noise-only case this covariance matrix should approach a diagonal matrix since the noise is white. There are several test statistics that are recommended. The first test statistic is $T = T_1/T_2$, where T_1 is the sum of the magnitude of all the elements in the covariance matrix and T_2 is the sum of the magnitude of the diagonal elements of the covariance matrix. When the signal is white T_1 and T_2 should be approximately equal, since the off-diagonal terms should be approximately zero. However, when the wireless microphone signal is present the signal is no longer white and the test statistic is no longer close to one.

The second test statistic is very similar to the first. The only difference is that T_1 and T_2 are replaced with T_3 and T_4. These new functions are the sum of the magnitude squared of all the elements in the matrix and the diagonal elements, respectively.

For sensing times of around 10 ms the sensitivity of this technique is approximately -23 dB SNR.

6.6. Spectral Correlation Sensing

This sensing technique estimates the power spectral density of the received signal. This PSD estimate can be performed using an FFT. This PSD estimate is then correlated with a pre-stored PSD for the signal of interest. For ATSC or NTSC one may choose to take PSD estimates on non-uniform sampling in the frequency domain so as to emphasize specific spectral features. The test statistic is the correlation of the estimated PSD and the pre-stored PSD for the signal of interest. The signal is declared to be present if this test statistic exceeds a preset threshold.

6.7. ATSC Cyclostationary Sensing

The final sensing technique involves cyclostationary signal analysis. A cyclostationary signal is a signal that is not stationary, but whose autocorrelation function is periodic. A typical example of a cyclostationary process is a digital communication signal with a fixed symbol period. In this sensing technique the cyclostationary signal analysis focuses on the ATSC pilot signal instead of the periodic 8-VSB modulation. The process of converting the IF signal to baseband with the nominal pilot frequency converted to DC. This signal is then filtered with a narrow-band filter. Then the cyclic spectral density function is estimated from the sampled signal. The cyclic spectral density, $S_y^{\alpha}(k)$, is a function is a function of two parameters: the digital frequency k and the cyclic frequency α. For AWGN the cyclic spectral density is zero for $\alpha \neq 0$, so in the estimate of the cyclic spectral density then terms with non-zero α, should be small. However, if the ATSC pilot signal is present those terms in the cyclic spectral density can become quite large.

The test statistic is the maximum of the magnitude of the cyclic spectral density over all values of $\alpha \neq 0$.

7. CONCLUSIONS

An overview of spectrum sensing in the IEEE 802.22 draft standard is provided. The sensing requirements and framework are described. Then method used within the IEEE 802.22 working group for evaluating different spectrum sensing techniques was explained. Finally, a brief overview is provided of each of the sensing techniques included in the draft standard, with simulation results for a few of the sensing techniques.

8. REFERENCES

[1] IEEE P802.22/D0.5, *Draft Standard for Wireless Regional Area Networks Part 22: Cognitive Wireless RAN Medium Access Control (MAC) and Physical Layer (PHY) specifications: Policies and procedures for operation in the TV Bands*, Mar. 2008.

[2] Carl R. Stevenson, Carlos Cordeiro, Eli Sofer, and Gerald Chouinard, *Functional Requirements for the 802.22 WRAN Standard*, IEEE 802.22-05/0007r46, Sept. 2005.

[3] IEEE 802.22 Working Group, "`http://grouper.ieee.org/groups/802/22/`,".

[4] Steve Shellhammer, Victor Tawil, Gerald Chouinard, Max Muterspaugh, and Monisha Ghosh, *Spectrum Sensing Simulation Model*, IEEE 802.22-06/0028r10, Sept. 2006.

[5] H. Urkowitz, "Energy detection of unknown deterministic signals," *Proc. of IEEE*, pp. 523–531, Apr. 1967.

[6] Rahul Tandra, *Fundamental Limits of Detection in Low SNR*, Masters Thesis, University of California Berkeley, Spring 2005.

[7] Steve Shellhammer, Sai Nandagopalan, Rahul Tandra, and James Tomcik, "Performance of power detector sensors of DTV signals in IEEE 802.22 WRANs," *TAPAS Workshop*, Aug. 2006.

[8] Advanced Television Systems Committee, *ATSC Digital Television Standard (A/53) Revision E, with Amendments No. 1 and 2*, Sept. 2006.

[9] S. Kay and Jr S. L. Marple, "Spectral analysis: A modern perspective," *Proc. of IEEE*, pp. 1380–1419, Nov. 1981.

[10] J. M. Mendel, "Tutorial on higher order statistics (spectra) in signal processing and systems theory: Theoretical results and some applications," *Proc. of IEEE*, pp. 278–305, Mar. 1991.