SEQUENTIAL PILOT SENSING OF ATSC SIGNALS IN IEEE 802.22 COGNITIVE RADIO NETWORKS

Nikhil Kundargi, *Student Member, IEEE* Ahmed Tewfik, *Fellow, IEEE*

Department of Electrical Engineering
University of Minnesota, Twin Cities

ABSTRACT

The IEEE 802.22 Standard promises to be the first practical implementation of the cognitive radio technology. It is based on dynamic spectrum sensing and opportunistic access of the bands that are not currently in use by TV transmitters. FFT based pilot sensing of the TV signal is recommended in the standard. The sensing is carried out by averaging over a fixed number of multiple dwells (6-10). We propose a sequential version of the scheme where the number of dwells required is dynamically varying according to the fidelity of the received signal. We show via simulation that the proposed sequential sensing strategy yields a throughput gain and reduces system overhead.

Index Terms— Communication standards, Radio spectrum management, Digital TV, Signal detection

1. INTRODUCTION

Cognitive radios (CR) are based on a novel paradigm of opportunistic spectrum access [1], [2]. The FCC had constituted the Spectrum Policy Task Force (SPTF) to study spectrum utilization and its report concludes that an abundance of white space exists in currently licensed spectrum [3]. Users will be allowed to dynamically access these white spaces without interfering with the incumbent licensees. The IEEE 802.22 working group on Wireless Regional Area Networks (WRAN) has been formed with the mandate to create a standard for cognitive radio technology in the existing TV bands [4].

The rest of the paper is organized as follows. Section 2 gives the requirements of the CR based IEEE 802.22 standard pertaining to spectrum sensing. Section 3 reviews the theory behind pilot sensing method. Section 4 formulates the sequential pilot detection test. Section 5 lays out the simulation methodology and Section 6 gives the experimental performance of the test and quantifies the throughput gains. Finally Section 7 concludes the paper.

2. SPECTRUM SENSING IN IEEE 802.22

The spectrum sensing function is a critical part of the IEEE 802.22 standard [5]. It has the job of detecting the presence or absence of the licensed primary user (PU) and taking the appropriate action of either vacating the spectrum band in use or to continue using the band. The draft standard specifies the spectrum sensing requirements given in Table 1 [6]. The consumer premise equipment (CPE) is required to vacate a band within 2 seconds of the start of PU transmission.

The spectrum sensing methods are classified into two categories: blind methods which work irrespective of the nature and type of PU transmission and non-blind methods which exploit knowledge of the nature of PU transmission. The energy detector is a blind method. It makes a decision based on the estimate of the energy in the received signal. Non-blind techniques are based on feature detection. Typical features used are pilot energy and position, spectral correlation, cyclostationarity etc. The pilot detection method proposed in [7], [8] has a very good performance and has been studied in depth. We shall review the method in the next section.

Table 1. Spectrum Sensing Requirements

Parameter	Digital TV Detection Value
Channel Detection Time	≤ 2 sec
Channel Move Time (In-service monitoring)	2 sec
Channel Closing Transmission Time (Aggregate transmission time)	100 msec
Interference Detection Threshold	-116dBm

3. FFT BASED PILOT DETECTION

The FFT based pilot sensing method is a non-blind technique which meets the sensing requirements of the 802.22 draft standard. It uses the pilot present in Advanced Television Systems Committee (ATSC) DTV signals. The ATSC signal has an 8-VSB (Vestigial Side Band) modulation with signal levels of (-7,-5,-3,-1, 1, 3, 5, 7). For efficient carrier recovery at the receiving end, a pilot is added to the signal through a DC offset of 1.25. In this paper, we will focus only on ATSC signals.

The capture and preprocessing of the ATSC signals is described in section 5. We take the FFT of the captured signal over a period of 1 ms or 5 ms, called a dwell. A longer sensing duration gives a finer frequency resolution and better detector performance. The power in the signal at a particular frequency (say, the pilot frequency) is estimated as the square of the corresponding frequency bin in its FFT.

1-4244-1484-9/08/$25.00 ©2008 IEEE

Zoom FFT at the nominal pilot frequency or FFT of the down sampled signal can be used to reduce the processing complexity.

3.1. Distribution of Pilot Power

Consider a sequence x(n) of Additive White Gaussian Noise (AWGN). The FFT of x(n) has a real part p(k) and imaginary part q(k) as in (1-3). As p(k) and q(k) are linear combinations of independent identically distributed Gaussian variables, they follow a Normal distribution. The magnitude squared of X(k) follows a Chi Square distribution with 2 degrees of freedom as in (4).

$$x(n) \sim N(0,\sigma^2) \quad (1)$$

$$X(k) = FFT(x(n)) \quad (2)$$

$$p(k) = \mathrm{Re}\{X(k)\} = \sum_{n=0}^{N-1} x(n)\cos\left(\frac{2\pi\, kn}{N}\right) \quad (3a)$$

$$q(k) = \mathrm{Im}\{X(k)\} = -\sum_{n=0}^{N-1} x(n)\sin\left(\frac{2\pi\, kn}{N}\right) \quad (3b)$$

$$(X(k))^2 = (p(k))^2 + (q(k))^2 \sim \chi_2^2(0) \quad (4)$$

The hypothesis testing problem can be stated as in (5). We have to decide between a central Chi Square and a non-central Chi square distribution with a non centrality parameter equal to the SNR at the pilot frequency.

$$\begin{array}{ll} \text{H1: Pilot + Noise} & \text{H0: Noise} \\ \text{H1: } \chi^2(\lambda_{PILOT}) & \text{H0: } \chi^2(0) \end{array} \quad (5)$$

3.2. Likelihood Ratio Test

$$\Lambda(\lambda) = [\{\chi^2(\lambda_{PILOT})\}(\lambda)] / [\{\chi^2(0)\}(\lambda)] \quad (6)$$

$\Lambda(\lambda)$ is the Likelihood ratio. The test reduces to comparing the power in the bin corresponding to the pilot frequency to a threshold. The threshold is calculated using the Neyman-Pearson theorem to meet the required values for the probability of missed detection (PMD) and probability of false alarm (PFA). Calculation of the threshold requires the knowledge/estimation of the SNR at the pilot frequency, as do all energy detectors. We assume that a perfect estimate of the SNR is available for deriving the tests. The effect of uncertainty in knowledge of the SNR is neglected. If the signal is in a deep fade or is very weak, a single dwell may give erroneous results. Multiple dwells have to be used in practical implementations to improve the detection performance [8].

4. SEQUENTIAL PILOT SENSING

In the multiple-dwell implementation of pilot sensing, the number of dwells is fixed a priori, usually between 6 -10. We will now formulate a sequential implementation of the pilot sensing scheme, where depending upon the uncertainty of the decision, a variable number of dwells will be required. In our previous work, we have analyzed the energy detector in a sequential setting in the time domain [9], [10]. Here we will develop the sequential pilot sensing method and extend the framework of sequential detection to a non-blind feature based method .

The sequential probability ratio test (SPRT) allows us to arbitrarily specify the PMD and PFA we would like the system to operate at, by the virtue of the variable run length of the test. We keep accepting new samples till we can make a decision with a satisfactory certainty. The performance of a SPRT is measured in terms of the average sample number (the average number of dwells) required.

4.1. Sequential Test Formulation

At each iteration of the sequential test, we update the likelihood ratio, which is a function of all the samples received within that time (7). The updated likelihood ratio is compared with upper and lower thresholds. If either threshold is exceeded, we stop the test and reach a decision. Otherwise we accept more samples till we are in a position to decide. The formulation of the SPRT is as in (10). The Wald's approximations give us the thresholds in (11) [11].

$$\Lambda_n(y_1,..,y_n) = P_1(y_1,..,y_n) / P_0(y_1,..,y_n) \quad (7)$$

$$\begin{array}{l} P(y_1,...,y_n) = P(y_1)P(y_2)P(y_3)...P(y_n) \\ where\ P(y_n) = P(\chi^2(y_n)) \end{array} \quad (8)$$

$$\Lambda_n(y_1,..,y_n) = \{P_1(y_n)/P_0(y_n)\}\Lambda_{n-1}(y_1,..,y_{n-1}) \quad (9)$$

$$\begin{array}{l} \Lambda_n(y_1,...,y_n) > B \ \text{: Decide H1} \\ \Lambda_n(y_1,...,y_n) < A \ \text{: Decide H0} \\ A < \Lambda_n(y_1,...,y_n) < B \text{ : Wait for next sample} \end{array} \quad (10)$$

$$A = (1-P_D)/(1-P_F) \qquad B = P_D/P_F \quad (11)$$

The Wald-Wolfowitz theorem ensures that the average sample number (ASN) of the SPRT is no larger than the sample size of a fixed sample size test with the same performance [11]. This guarantees the optimality if the successive samples are independent. Thus, the SPRT allows us to arbitrarily choose a higher PD at the expense of a larger ASN. For a practical implementation, we use a Truncated SPRT [11] where, if at the end of a maximum allowed sample size, the decision hasn't been reached, we force the test to a decision by using a criteria (12). The standard specifies a maximum duration for performing the sensing task and this necessitates a decision at the end of the allotted time.

$$\begin{array}{l} \text{If } \log[\Lambda_n(y_1,...,y_n)/A] - \log[\mathrm{B}/\Lambda_n(y_1,...,y_n)] \geq 0 \\ \text{Then H1, else H0.} \end{array} \quad (12)$$

5. UNIFIED SENSING WITHOUT QUIET PERIODS

The IEEE 802.22 draft specifies quiet periods when the CR network stops transmitting and listens to detect the presence of a primary user, if any. All spectrum sensing schemes work only during these quiet periods. We propose a unified scheme where sensing is going on all the time in the background in addition to the existing quiet periods. We demodulate the 802.22 network signal which consists of OFDM symbols, and then use successive interference cancellation to recover an estimate of the spectrum of the residual signal and noise. Then, the energy detector or the pilot sensing schemes are run on this recovered residual signal. A recovered spectrum is shown in figure 1. This approach allows detection of reasonably strong ATSC signals, while the weaker signals will be detected in the next scheduled quiet period.

6. INITIAL PROCESSING OF ATSC CAPTURES

The draft of the standard lays down a uniform methodology for preprocessing the captured signal with the intention of being able to compare proposed sensing methods against common benchmarks. The ATSC signal has a bandwidth of 6 MHz and the pilot is at the lower edge of the band. The standard prescribes a database of 12 ATSC signal captures under varying real-world multi-path fading, frequency offsets and other distortions. The captures incorporate the changing wireless channel which we assume to be invariant over the duration of a sensing cycle. We will add a white noise component to them [12]. The signal is sampled at 21.52 Msamples/sec and down converted to a low central IF of 5.38 MHz (one fourth the sampling rate). An 8 MHz bandwidth IF filter was used when capturing the signals.

The 802.22 standard recommends the following steps (1-4) [12]. 1.) Filter the signal using a passband filter with a 6 MHz bandwidth with a center frequency of f_{IF} = 5.38MHz. The filter shall be a "brick wall" filter. 2.) Add the filtered noise and the scaled and filtered signal. 3.) Estimate pilot frequency as the peak in the FFT nearest to the nominal pilot frequency of 2.69MHz. 4) We need prior knowledge of the pilot power, the noise power at the pilot frequency and the pilot SNR to run the test. We will estimate them by averaging over a large number of realizations of the signal.

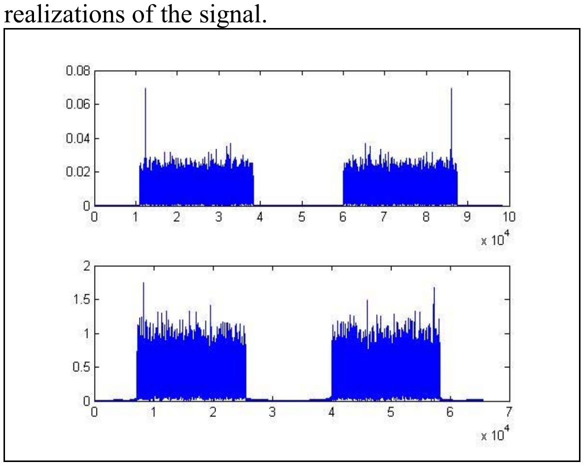

Fig. 1. (Top) FFT of residual signal of noise + DTV. (Bottom) FFT of recovered residual signal.

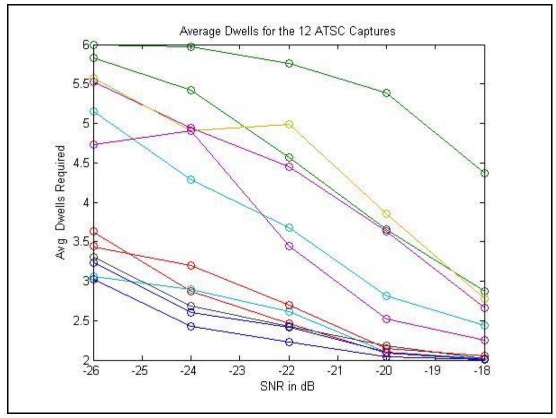

Fig. 2. Average Dwells vs SNR for 12 ATSC captures

7. SIMULATION RESULTS

The sequential pilot sensing test has been set up according to equations (9-11). We design for a nominal PD of 0.99 (PMD = 0.01) and a PFA of 0.01 where PMD is defined as 1-PD. These have been chosen to equal the best performance of the multiple-dwell test [8]. In practice, the actual PMD and PFA obtained are different from the values used for test setup. This is due to the use of a truncated sequential test for which the Wald-Wolfowitz theorem doesn't hold. Also, the independence of the AWGN samples maybe destroyed by noise shaping at the receiving filter. Inspite of these variations, the average performance of the test remains at least as good as that of the non sequential test as we show below.

Each simulation scenario is averaged over 1000 runs. Figures 3 and 4 plot the simulated performance of the test. Note that the number of dwells required is not constant but varies dynamically. Note also that the proposed sequential test outperforms the fixed test and yields a lower probability of missed detection. We have set up the test to run for a minimum of two dwells. The average number of dwells increases as the SNR is decreased from -18 dB to -26 dB as seen in Figure 2. Also, the spread of the dwells for a SNR of -26 dB is plotted in the histogram in figure 5. The SNR at the pilot frequency bin is significantly more than the signal SNR as in Table 2. This higher SNR is responsible for the excellent performance of the pilot sensing method.

Table 3 gives the throughput increase achieved by the sequential pilot detector over the multiple-dwell pilot detector. The throughput increase is defined as ratio of sensing time of the multiple dwell test to the average sensing time of the sequential test. The sequential test

Table 2. Signal SNR and Pilot SNR

Signal SNR	Pilot SNR
-15 dB	19.2 dB
-20 dB	14.20 dB
-25 dB	9.26 dB

Table 3. Average dwells required across all 12 ATSC Captures and Average Throughput Increase

SNR	Average Dwells(max of 6)	Throughput Increase
-18	2.456	2.44
-20	2.876	2.08
-22	3.478	1.72
-24	3.924	1.52
-26	4.376	1.37

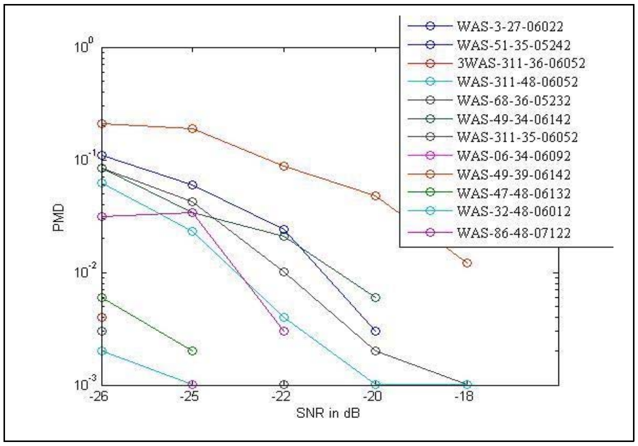

Fig. 3. PMD vs SNR for 12 ATSC Captures. (PFA=0.03)

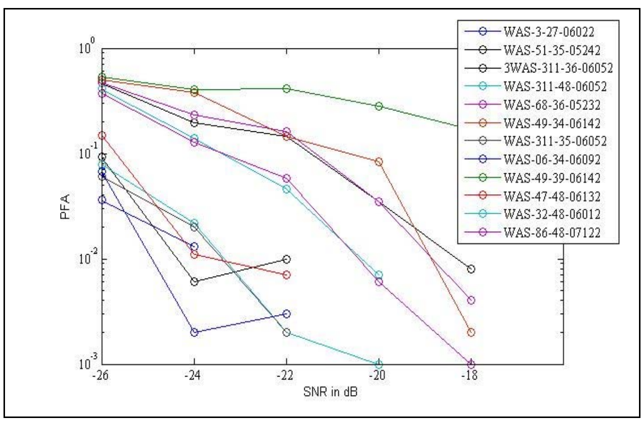

Fig 4. PFA vs SNR for 12 ATSC Captures. (PMD=0.01)

delivers a throughput gain in the range of 1.37 times to 2.44 times over the range of SNRs used in the simulations.

8. CONCLUSION

We have presented a sequential pilot sensing method to reliably detect a TV signal at very low SNRs which delivers enhanced throughput gain of upto 2.44 times over the multiple-dwell pilot sensing method. The performance was verified by extensive simulations on the standard database

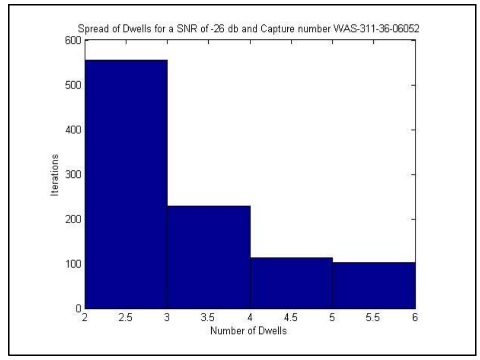

Fig 5. Histogram of dwells required at SNR -26dB

of ATSC captures as recommended in the IEEE 802.22 draft. Further work remains to be done on accurate estimation of the pilot SNR, the effects of noise uncertainty on the test performance and the performance improvements in the MAC layer due to the dynamic sensing time [13]. Also, the unified sensing scheme suggested in section 6 has the potential to significantly reduce the sensing overhead and is presently being analyzed.

9. REFERENCES

[1] S. Haykin, "Cognitive radio: brain-empowered wireless communications," IEEE Journal on Selected Areas in Communications, vol. 23, pp. 201-220, Feb. 2005.

[2] J. Mitola, et al., "Cognitive radio: Making software radios more personal," IEEE Pers. Commun., vol. 6, no. 4, pp. 13-18, Aug. 1999.

[3] Federal Communications Commission, "Spectrum policy task force report," 2002.

[4] IEEE 802.22, Working Group on Wireless Regional Area Networks (WRAN), http://grouper.ieee.org/groups/802/22/.

[5] S. Shellhammer, The Spectrum Sensing Function, IEEE 802.22/07-0074r3, April 2007.

[6] IEEE 802.22 draft standard, "IEEE P802.22TM/D0.3 Draft Standard for Wireless Regional Area Networks," doc. no. 22-07-0086-01-0000, May 2007.

[7] M. Ghosh, "Text on FFT-based pilot sensing," IEEE 802.22, doc. no. 22-07-0298-01-0000, July 2007.

[8] C. Cordeiro et al., "Spectrum Sensing for Dynamic Spectrum Access of TV Bands," IEEE CrownCom, Aug. 2007

[9] N. Kundargi and A. Tewfik, "Hierarchical Sequential Detection In The Context Of Dynamic Spectrum Access For Cognitive Radios," IEEE ICECS 2007

[10] N. Kundargi and A. Tewfik, "Hierarchical Sequential Detection for Dynamic Spectrum Sensing," IEEE 802.22, doc. no. 22-07-0360-00-0000, July 2007.

[11] H. V. Poor, An Introduction to Signal Detection and Estimation, 2nd ed. New York: Springer-Verlag, 1994.

[12] S. Mathur et al., "Initial signal processing of captured DTV signals," IEEE 802.22, doc. no. 22-06-0158-02-0000, Aug. 2006.

[13] C. Cordeiro, K. Challapali, and M. Ghosh, "Cognitive PHY and MAC Layer for Dynamic Spectrum Access and Sharing of TV Bands," in IEEE TAPAS, August 2006.