Performance Comparison of Eigenvalue based Blind Spectrum Sensing Algorithms

Dhana Lakshmi Potteti, Venkateswara Rao N

Abstract : In the past few years opportunistic spectral access schemes has been proved as a prominent solution for the prevailing problem of spectrum scarcity. These schemes employ spectral sensing approaches to detect the presence or absence of a primary user and to subsequently allow the secondary user to transmit the data. With the evolution of Multi I/p Multi O/p (MIMO) and massive MIMO systems that picked up momentum from 3G and 4G respectively, sensing with multiple antenna systems has been popularized. In this paper, blind spectrum sensing for multiple antenna systems using eigenvalue based approaches has been compared for Rayleigh and Nakagami fading channel environments. Particularly, Covariance Absolute VAule (CAV), Akaike Information Criterion (AIC) and Minimum Description Length (MDL), Weighted Covariance Detection (WCD) and Energy Detection (ED) based sensing schemes have been compared for their detection performance as a function of Signal to Noise Ratio (SNR). The simulation results showed that AIC and MDL based sensing approaches outperform the others compared in both Rayleigh and Nakagami fading channels.

Keywords: spectrum sensing, detection probability, opportunistic spectrum access, secondary user, multiple antenna sensing

I. INTRODUCTION

Opportunistic spectrum access allows limited spectral resources to be used by both licensed PU's and unlicensed SU's. However the priority is given to primary users and only when the primary users do not transmit, the secondary transmissions are allowed. Such systems termed as cognitive radio are a programmable radio that can be dynamically configured to be able to use the best available wireless channel in the spectrum, by adapting to the environment. Various spectral resources have been made available to diversified communication systems who form the licensed spectral radio. A survey on the spectral utilization of the available radio spectrum show that full spectral is not used at all the times [1]. Few bands are underutilized, some are over utilized and few more are unutilized. Hence instead of devising newer communication systems in newer frequency bands, cognitive radio speaks of utilizing the unused bands for newer communication systems, by not disturbing the licensed user communication. Hence, the interesting feature of the CR's are its ability to measure, sense,acquire, learn and be aware of the radio's operating environment in order to recognize spectrum space opportunities and efficiently use them for adaptive transmission. Hence the heart of a cognitive radio is spectrum sensing. In a typical spectral sensing process, secondary user continuously senses the available radio spectrum for the availability of a free band which implies the primary user's absence. Such sensing procedures can be blind or non-blind. Non-blind techniques require prior knowledge of the modulations and transmit signal waveforms used by the primary user [2, 3]. The blind techniques do not necessitate the prior knowledge of primary signal. The simplest among such techniques is the ED method [4]. However when noise uncertainties prevail, the ED performance reduces. In the presence of noise uncertainties, spectrum sensing based on eigenvalue based methods can render better performance than the ED method. In this paper, we consider a few eigenvalue based sensing approaches namely CAV detection [5], AIC and MDL based detection [6] and finally the WCD [7]. For the limited P_{FA} value, a CAV detector can be used with out any existed knowledge of the primary s/l or the noise power [5]. Informative theory criteria like AIC or MDL can compute and used for primary signal detection, without any fixed probability of false alarm value [6]. A weighted covariance detection (WCD) can also be used for a fixed value of the false alarm probability [7]. Into practice, by choosing the fixed sensal approach is a tradeoff b/w P_{DA} and calculational complexity. However it should be noted that depending on the channel power profile, the detection probability changes. Hence in this paper two different channel environments namely the Rayleigh and Nakagami fading environments are being considered. Most of the practical channel environments are in accordance with these distributions and these channels also have sparsity. Further the cognitive radio can have more than one sensing antenna. Hence, in this paper for a multiple antenna sensing system, a framework based on hypothesis testing problem (HTP) is discussed, simulations are performed by using digital quadrature phase shift keying (QPSK) transmissions and the performance of CAV, AIC and MDL, WCD and ED have been extracted and compared for both Rayleigh and Nakagami fading environments. The observations obtained have been discussed in both the channel environments.

The rest of the paper is organized as follows. Section 2 illustrates the adopted multiple antenna sensing system model and the corresponding detection framework. Further the eigenvalue based approaches have been discussed. Section 3 presents the details of simulation set up and the results of the detection performances from various eigenvalue based sensing approaches. The paper is concludes in section 4.

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II. BASIC SYSTEM MODEL SPECTRAL SENSING

Let us consider a multi antenna sensor system, where the receiving data from every N_r sensible antenna is to collect over one observated time window of length M.

Let the observation instants be $0 \le n \le M$. At the cognitive radio, the received vector at each instant n, is to be represented as

$$X(n) = [x_1(n) \quad x_2(n) \quad \cdots \quad x_{N_r}(n)]^T \tag{1}$$

The distinct base band equialent of the received signal at m^{th} sensing antenna can be modeled as

$$x_m(n) = s(n) \otimes h_m(n) + w_m(n), \quad 1 \le m \le N_r \tag{2}$$

Combining (1) and (2), the received vector $X(n)$ can be rewritten as

$$X(n) = HS(n) + W(n) \tag{3}$$

where, $W(n) = [w_1(n) \quad w_2(n) \quad \cdots \quad w_{N_r}(n)]^T$, $S(n) = [s(n) \quad s(n-1) \quad \cdots \quad s(n-L+1)]^T$ are the noise vector and the primary signal vector respectively. H is the channel matrix which can be deduced as

$$H = \begin{bmatrix} h_1(0) & h_1(1) & \cdots & h_1(L-1) \\ h_2(0) & h_2(1) & \cdots & h_2(L-1) \\ \vdots & & \vdots & \vdots \\ h_{N_r}(0) & h_{N_r}(1) & \cdots & h_{N_r}(L-1) \end{bmatrix} \tag{4}$$

Gathering M received vectors of the type given in (1), the HTP for multiple antenna sensing can be formulated as

$$H_0 : \mathbf{X} = \mathbf{W}$$
$$H_1 : \mathbf{X} = \mathbf{HS} + \mathbf{W} \tag{5}$$

where $\mathbf{X} = [X(M)^T \quad X(M-1)^T \quad \cdots \quad X(1)^T]^T$ is the received vector whose dimension is $MN_r \times 1$, $\mathbf{S} = [s(M) \quad s(M-1) \quad \cdots \quad s(-L+2)]^T$ is the primary user data vector of dimension $(M+L-1)\times 1$, $\mathbf{W} = [W(M)^T \quad W(M-1)^T \quad \cdots \quad W(1)^T]^T$ is the noise vector and channel matrix $\mathbf{H}$ can be deduced from (3), (4) and (5) as

$$\mathbf{H} = \begin{bmatrix} h_1(L-1) & h_1(L-2) & \cdots & h_1(0) & & & \\ \vdots & & \vdots & & & & \\ h_{N_r}(L-1) & h_{N_r}(L-2) & \cdots & h_{N_r}(0) & & & \\ & h_1(L-1) & h_1(L-2) & \cdots & h_1(0) & & \\ & \vdots & \vdots & \vdots & & & \\ & h_{N_r}(L-1) & h_{N_r}(L-2) & \cdots & h_{N_r}(0) & & \\ & & \ddots & & \ddots & & \end{bmatrix} \tag{6}$$

Note that M is the time window used for data aggregation. In accordance with the detection problem of (5), to sense the presence or absence of the signal, a test criterion or decision metric can be obtained, whose structure in general is

$$T \underset{H_0}{\overset{H_1}{\gtrless}} \Upsilon \tag{7}$$

In (7), T is the teststatistic and Υ represents threshold value for the test. According to (7), if $T > \Upsilon$ for any received data vector $\mathbf{X}$ it implies that hypothesis H_1 is true and thereby the band is being used by the primary user. Hence the seconday user cannot transmit data. Similarly if $T < \Upsilon$ then hypothesis $H_0$is true, which implies the slot is deprived of primary transmissions and hence the secondary user can transmit the data. Based on the sensing technique that we employ, the decision metric (7) can have various forms. IN blind spectrum sensing approaches, such test criterion are devised based on the covariance matrix and eigenvalue computations, discussed as follows.

A. *CAV based detection***:** Using the received data vector $\mathbf{X}$ we form the vector $\mathbf{X}_p$ of dimension G and compute the $G \times G$ statistical covariance matrix as $\mathbf{R}_x = \mathbf{E}\{\mathbf{X}_p \mathbf{X}_p^H\}$, where the averaging is done over N_{sam} different vectors of type $\mathbf{X}_p$. Note that $\mathrm{N}_{sam} = \frac{MN_r}{G}$ and $(.)^H$ is Hermitian transpose. If $(m,n)^{th}$ entry of $\mathbf{R}_x$ is r_{mn}, the test criterion (7) for CAV based approach can be derived as

$$\frac{T_1(\mathrm{N}_{sam})}{T_2(\mathrm{N}_{sam})} > \Upsilon_1 \tag{8}$$

where $T_1(\mathrm{N}_{sam}) = \frac{1}{G}\sum_{m=1}^{G}\sum_{n=1}^{G}|r_{mn}|$,

$T_2(\mathrm{N}_{sam}) = \frac{1}{G}\sum_{n=1}^{G}|r_{nn}|$, and threshold Υ_1 can be derived as

$$\Upsilon_1 = \frac{1+(G-1)\sqrt{\frac{2}{\pi N_{sam}}}}{1-Q^{-1}(P_{fa})\sqrt{\frac{2}{\pi N_{sam}}}} \tag{9}$$

In (9) $Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^\infty e^{\frac{-u^2}{2}} du$ denotes the usual Q function and P_{fa} represents the $\mathrm{P_{FA}}$ Note that the derivation of the threshold necessitates known value of P_{fa}, which implies that by controlling P_{fa} the detection performance changes.

B.*ITC based detection***:** The benefit of this approach lies in the fact that it doesn't require P_{fa} value to be set a priori. Original ITC sensing algorithm for multiple sensing antenna scenario considers the calculation of either AIC or MDL as a function of number of the eigenvalue. Then the minimum AIC/MDL decides the signal's presence or absence. Note that this method has more computational complexity because it deals with not only eigenvalue calculation (similar to CAV method) but also the calculation of AIC and MDL as a funtion of the eigenvalue number. Hence, a simplified ITC detection is considered [], which employs the following test criterion

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$$T_{ITC-AIC} = AIC(0) \underset{H_0}{\overset{H_1}{\gtrless}} AIC(1) \qquad (10)$$

Note that in (10), AIC should be replaced with MDL to obtain $T_{ITC-MDL}$ decision criterion. Unlike the test statistic and threshold relation of (7), this approach requires only two calculations $AIC(0)$ and $AIC(1)$ for signal detection. The functions $AIC(k)$ and $MDL(k)$ are defined as

$$AIC(k) = 2k(2G-k) + 2 - 2\log\left(\frac{\prod_{i=k+1}^{G} l_i^{1/(G-k)}}{\frac{1}{G-k}\sum_{i=k+1}^{G} l_i}\right)^{N_{sam}(G-k)} \qquad (11)$$

$$MDL(k) = \left(\frac{1}{2}k(2G-k) + \frac{1}{2}\right)\log N_{sam} - \log\left(\frac{\prod_{i=k+1}^{G} l_i^{1/(G-k)}}{\frac{1}{G-k}\sum_{i=k+1}^{G} l_i}\right)^{N_{sam}(G-k)} \qquad (12)$$

where $l_i, 0 \le i \le G$ are the MN_r different eigenvalues of auto covariance matrix $\mathbf{R}_x$ matrix.

C.*WCD based detection*:This approach requires P_{fa} value to be set, on similar lines to the CAV approach. correspondingly, first received data vector $\mathbf{X}$ and $\mathbf{X}_p$ are formulated, then $\mathbf{R}_x$ is calculated. Using its entries r_{mn}, the test statistic becomes

$$T_{WCD} = \sum_{i=1}^{G-1}\left(w_i \sum_{|m-n|=i} |r'_{mn}|\right) \qquad (13)$$

where $r'_{mn} = \frac{r_{mn}}{\hat{\sigma}^2}$, $\hat{\sigma}^2 = \frac{1}{G}\sum_{m=n} r_{mn}$ Note that the weights are:

$$w_i = \sum_{|m-n|=i} r'_{mn} \qquad (14)$$

The test criterion for WCD is

$$T_{WCD} \underset{H_0}{\overset{H_1}{\gtrless}} \Upsilon \qquad (15)$$

where $\Upsilon = \sigma Q^{-1}(P_{fa})$ with σ as the standard deviation of the T_{WCD} under hypothesis H_0. Though it is computationally complex compared to the CAV method, its performance can be better due to the weighted covariance nature. This fact is further strengthened by the simulation results.

III. SIMULATION RESULTS AND DISCUSSION

To compare the performances of the ED, CAV, AIC, MDL and the WCD approaches, the simulation set up considers the following parameters for simulation. The primary user is assumed to transmit QPSK data length 400 symbols. As the sensing system has mutiple antennas, each link is considered as an i.i.d link that has a power delay profile of the Brazil A type. Accordingly, the receiver data is aggregated from each of the 400 symbol transmissions to form the receiver data vector in (5). For obtaining detection performance of CAV, AIC, MDL and WCD based approaches, we choose $N_r = 4$, $M = 400$. Further to extract the eigenvalues of the covariance matrix, we choose $G = 20$ which implies 20 eigenvalues are extracted.

Consider the case of $N_r = 4$, where 4 different i.i.d. Rayleigh fading channel with Brazil A type PDP are simulated. It is assumed that each channel has same type of sparsity, which implies a common sparsity for all the channel. Accordingly the probability detection as a func of SNR are given in Figure 1. The performance curves obtained for Nakagami channels with Brazil-A PDP are given in Figure 2. The results in Figures 1 and 2 show that the detection performance of AIC and MDL is better than that of ED and CAV based detections, but WCD based detection performs significantly better than the AIC and MDL. However it is worth mentioning that the complexity of WCD is much more that the CAV and AIC/MDL based detection. So as complexity increased, the algorithm quality becomes better.

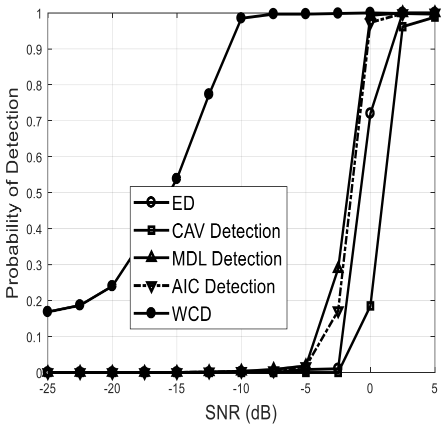

Figure 1: P_{DA} vs SNR (Rayleigh fading, exact sparse common support)

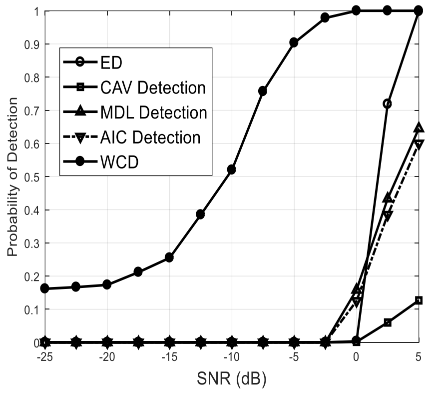

Figure 2: P_{DA} vs SNR (Nakagami fading, exact common support)

With the same system setup but assuming approxiate common sparsity, the received vectors have been obtained from simulations. Corresponding performances of detection probability as a function of SNR are given in Figure 3 for Rayleigh fading and Figure 4 for Nakagami fading. These plots confirm that WCD provides the best performance out of all the others considered here.

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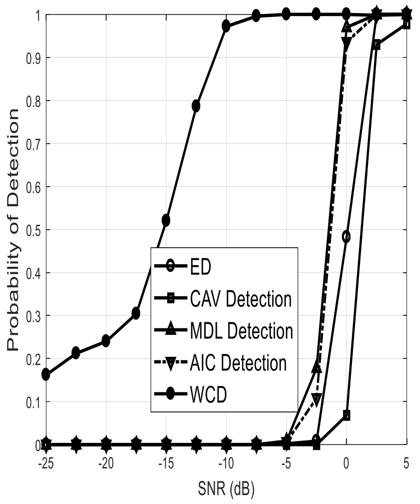

Figure 3: P$_{DA}$vs SNR (Rayleigh fading, approximate common support)

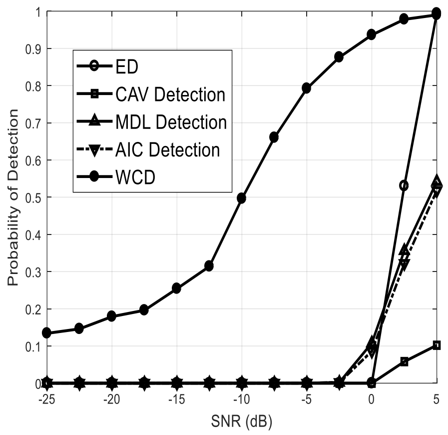

Figure 4: P$_{DA}$ vs SNR (Nakagami fading, approximated common support)

The comparison of the detection performance of WCD approach for the case of 4 and 8 receive antennas is shown in Figure 5. It can be observed that as the no. of antennas increase, the detection performance of the cognitive radio improves. These simulations have been obtained with QPSK transmissions and Rayleigh fading conditions.

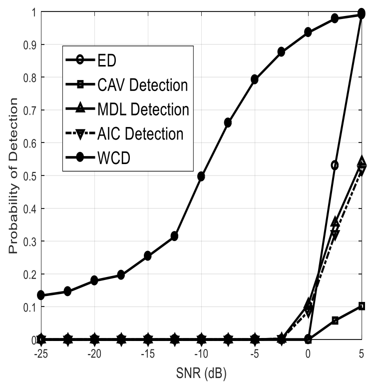

Figure 5: PD versus SNR for WCD approach

IV. CONCLUSION

In this research paper, opportunisticly spectral accessability has been presented using blind and particularly eigenvalue based spectrum sensing approaches. Three different detection approached names CAV based detection, AIC/MDL based detection and WCD based detection have been considered for multiantenna sense systems. These approaches are compared for their performance in both Rayleigh and Nakagami fading environment with exact and approximately common sparsity among the multiple channel links. It has been observed that WCD sensing approache has better performance compared to AIC/MDL and also the CAV approaches in both Rayleigh and Nakagami channel environments.

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