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TESTBED IMPLEMENTATION OF MULTI DIMENSIONAL SPECTRUM SENSING SCHEMES FOR COGNITIVE RADIO

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Abstract

Cognitive Radio (CR) is a promising technology to exploit the underutilized spectrum. Spectrum sensing is one of the most important components for the establishment of cognitive radio system. Spectrum sensing allows the secondary users (SUs) to detect the presence of the primary users (PUs). The aim of this work is to create a CR environment to study the spectrum sensing methods using Universal software radio Peripheral (USRP) boards. In this paper a novel method of estimation of spectrum opportunities in multiple dimensions especially the space and the angle dimensions are carried out on USRP boards. This paper typically provides the experimental results carried out in an indoor wireless environment. To enhance the sensing performance the space dimension is firstly studied using spatial diversity of the cooperative SUs. Secondly the receiver diversity is analyzed using multiple antennas to enhance the error performance of the wireless system. The spectrum usage is also determined in the angle dimension by investigating the direction of the dominant signals using MUSIC algorithm.

Keywords:

Cognitive Radio, Multi-Dimensional Sensing, Diversity, USRP, MUSIC Algorithm.

1. INTRODUCTION

The current spectrum allocation strategy for wireless communication is fixed which results in inefficient utilization of its frequency bands. To effectively use the underutilized bands cognitive radio arises as a promising solution that provides new ways of exploiting the available spectral resource. The cognitive radio system allows unlicensed users to communicate using the licensed spectrum allocated to the primary users when not fully utilized by it. The cognitive user continuously senses the presence of the primary user and exploits the spectrum such a way that they do not cause interference to the licensed users.

Several spectrum sensing schemes have been proposed to detect the presence of the primary user including energy detection, matched filter detection and cyclostationary feature detection. Energy detection is the most common method of sensing as it requires no information of the primary user signal.

The critical challenge is the detection when the SU is shadowed or in severe multipath fading environment and is commonly addressed as the hidden terminal problem. To increase the probability of detection in the faded scenarios, recent studies have proposed cooperative spectrum sensing which significantly reduces the hidden node problem [1] [2].

The use of multiple antennas for wireless communication systems has gained a lot of interest during the last decade. Multiple antennas are utilized to enhance the error performance in the wireless system [3] [4] [5]. The angle of arrival of the dominant signal is studied in [6] using MUSIC algorithm and the simulations were carried out in software.

In this paper a novel method of estimation of spectrum opportunities in multiple dimensions especially the space and the angle dimensions are carried out on USRP boards. Most of the studies in spectrum sensing are confined to MATLAB simulations but this paper typically provides the experimental results carried out in an indoor wireless environment.The idea of spatial diversity is firstly exploited by using cooperation among SUs to enhance the sensing performance. The sensing information is shared among the cooperating users for making a combined decision more precise than the individual decisions of the secondary users.

Secondly the receiver diversity is studied using multiple antennas to enhance the error performance of the wireless communication system. The spectrum usage is also determined in the angle dimension by investigating the direction of the dominant signals using MUSIC algorithm. The evaluation is carried out in an indoor wireless environment using National Instruments USRP (NI-USRP 2922) radios at 2.4GHz.

This paper is organized as follows: Section 2 gives the overview of energy detection based sensing, Section 3 and section 4 discusses the sensing in space and angle dimension. Section 5 and section 6 provide the measurement setup and results respectively, section 7 concludes the paper.

2. ENERGY DETECTION

Energy detector (ED) is used in this paper because of its low computational and implementation complexities. The received primary user signal is passed through a noise pre filter which serves to limit the noise bandwidth. The energy detector comprises of the square law device followed by an integrator. The existence of the primary user is determined by comparing the output from the integrator block to a known threshold λ which is derived from the statistics of the noise [7].

Analytically, signal detection can be reduced to a simple identification problem, formalized as a hypothesis test,

$$x(k) = H_0 : n(k)$$
$$x(k) = H_1 : s(k) + n(k) \quad (1)$$

where, $x(k)$ is the signal received by the SU, $s(k)$ is the signal transmitted by PU, $n(k)$ is the additive noise at the SU.

The probability of detecting a signal present on a particular frequency as formulated in [8] is given as,

$$P_D = P_r\left(M > \lambda \mid H_1\right) = Q_{\tau\omega}\left(\sqrt{2\gamma}, \sqrt{\lambda}\right) \quad (2)$$

$$P_m = 1 - P_D \tag{3}$$

The probability that the detector incorrectly decides that a particular frequency is occupied when it actually is not is given as,

$$P_F = P_r\left(M > \lambda \mid H_0\right) = \frac{\Gamma\left(\tau\omega, \frac{\lambda}{2}\right)}{\Gamma(\tau\omega)} \tag{4}$$

For a given false alarm rate the threshold is calculated using blind Neyman - Pearson criteria,

$$\lambda = Q^{-1}(P_{fa}) \tag{5}$$

where, τ is the time taken for detection by the secondary users the detection bandwidth is ω, γ is the Signal to Noise ratio, λ is the energy threshold, $Q_{\tau\omega}$ is generalized Marcum Q Function, $\Gamma(\cdot)$ is gamma function and $\Gamma(\cdot,\cdot)$ is Incomplete gamma function.

3. SPATIAL DOMAIN

3.1 COOPERATIVE DIVERSITY

In cooperative sensing the spatially located SUs share the sensing information for making a combined decision. This method of cooperative diversity enhances the sensing performance when the signal received by SU is deeply faded by using the individual CR sensing results to make a combined decision.

A hard fusion scheme is investigated where the SUs make a local decision and transmit the one bit decision to the fusion center.

3.1.1 Logical-AND rule

In this rule, the local decisions made by each SU are sent to the fusion centre. The fusion centre then makes the final decision. If all the SUs report a presence of the PU i.e. logical one, then only the final decision is that the PU is present and band is not vacant. This is the Logical-AND rule. Cooperative detection performance with this fusion rule as formulated in [8] is given as,

$$P_{d,AND} = P_{d,i}^{M} \tag{6}$$

3.1.2 Logical-OR rule

In this rule, even if any one of the SUs sends a logical one, the final decision made by the fusion centre is one i.e. the PU is present and band is not vacant. Cooperative detection performance with this fusion rule can be evaluated using Eq.(7).

$$P_{d,OR} = 1 - \left(1 - P_{d,i}\right)^{M} \tag{7}$$

3.2 RECEIVER DIVERSITY

To improve the Quality of Service (QoS) of wireless transmission multiple antennas are installed at the transmitter or/at the receiver side to reduce the error rate as well as enhance the quality and capacity of the communication system.

The benefits of using multiple antennas system are:

i) Increased data rates by means of spatial multiplexing techniques

ii) Decreased error rates by means of spatial diversity techniques.

iii) Improved signal-to-noise ratio (SNR) by means of beam forming techniques.

Spatial diversity at the receiver side employs multiple antennas spaced in such a way that the mutual correlation between antennas is reduced and thereby increasing the diversity gain. The receiver diversity gain is achieved by combining the signals from different antennas using the basic combining methods such selection combining (SC), equal gain combining (EGC) and maximum ratio combining (MRC).

In this paper, we consider the scenario of Single input multiple output (SIMO) system where multiple receiver antennas are used, and there is only one transmit antenna.

The maximum ratio combining (MRC) technique is used in this study where the channel amplitude and phase are compensated and branch signals are combined linearly. The output SNR (γ_{MRC}) of the MRC receiver is formulated in [9] as a sum of individual branch SNR values where L is the number of diversity branches.

$$\gamma_{MRC} = \sum_{i=1}^{L} \gamma_i \tag{8}$$

4. ANGLE DIMENSION

The Direction-of-Arrival (DOA) estimation of the primary user signal using smart antenna systems has gained a lot of significance. In specific by determining the PU's direction of transmission the SU can transmit in the other direction without causing interference to the primary user. The most commonly used DOA estimation methods include MUSIC, ESPRIT, capon Min-norm and Bartlett methods. MUSIC and ESPRIT algorithms offer high resolution and accuracy and hence are extensively used in the design of smart antennas [10].

MUSIC stands for Multiple Signal Classification and is based on exploiting the eigen structure of input covariance matrix. Unbiased estimates of the number of signals, the angles of arrival and the strengths of the signals are achieved by this DOA estimation algorithm [11].

Let D be the number of signals impinging on N element uniform linear array, the number of signal eigen values is D and the number of noise eigen values is N-D. The array correlation matrix with uncorrelated noise and equal variances formulated in [10] is given by,

$$R_{xx} = A \cdot R_{ss} \cdot A^H + \sigma^2 \cdot I \tag{9}$$

where,

$A = [a(\theta_1), a(\theta_2), \ldots, a(\theta_D)]$ is $M \times N$ array steering matrix and H is the transpose of the conjugate.

$R_{ss} = [s_1(k), s_2(k), \ldots, s_D(k)]^T$ is $D \times D$ source correlation matrix. σ_n^2 is the noise variance and I is the Identity Matrix.

R_{xx} has D eigen vectors associated with signals and $N - D$ eigen vectors associated with noise.

We can construct the $N \times (N\text{-}D)$ subspace spanned by the noise eigen vectors such that,

$$E_N = [E_1, E_2, \ldots, E_{N-D}] \tag{10}$$

The noise subspace eigen vectors are orthogonal to array steering vectors at the angles of arrivals θ_1, θ_2 ,…, θ_D and the Music Pseudo spectrum is given as,

$$P_{MU}(\theta)=\frac{1}{abs\left(a^H(\theta)E_N E_N^H a(\theta)\right)} \tag{11}$$

5. MEASUREMENT SETUP AND IMPLEMENTATION

The experiment is conducted in an indoor wireless environment. The experimental setup consists of National Instruments USRP (NI-USRP 2922) devices and Lab VIEW 2012 on the host machines. USRPs operate at 2.4GHz ISM band with 400KHz bandwidth. The project setup was created by using Lab VIEW Software and USRP Hardware. USRP device is used to physically receive the signal from real time environment. It is connected to the Ethernet port of host PC.

(a) Distance between transmitter and receiver (1m)

(b) Distance between transmitter and receiver is 0.3 m

Fig.1. Experimental setup using NI-USRP 2922 devices

The Fig.1(a) and Fig.1(b) show the experimental setup when the distance between the transmitter and receiver is taken as 1m and 0.3m respectively. Multi-antenna configuration is performed by connecting two USRPs using MIMO cable which enables in creating a SU equipped with two antennas in the spatial domain. The diversity combiner used is EGC for its simplicity and moderate gain. Cooperative sensing has been implemented using three USRPs which function as PU, SU1 and SU2 & fusion center respectively.

5.1 STEPS INVOLVED IN THE TESTBED IMPLEMENTATION

5.1.1 Single input Single output (SISO- One transmitter and one receiver)

1) The USRP transmitter (TX1) transmits packet at 2.4GHz
2) The receiver (RX1) is set to receive the signal from the transmitter at frequency of 2.4GHZ using antenna port1 of the receiver.
3) The signal and the noise power are calculated for 1000 samples of the received signal.
4) The channel is declared vacant if the signal to noise ratio is less than the set threshold.

5.1.2 Single input Multiple Output (SIMO-One transmitter and two receivers)

1) The USRP receivers (RX1 and RX2) are connected via the MIMO cable.
2) The receivers are set to receive the signal from the transmitter at frequency of 2.4GHz using antenna port1 and port2 of the receivers.
3) The signal and the noise power are calculated for 1000 samples of the received signal at RX1 and RX2.
4) Using Antenna diversity combiners-Selection combining the value of the highest SNR is selected
5) The channel is declared vacant if the signal to noise ratio is less than the set threshold.
6) Repeat step 4 and 5 by using Equal gain combining as the diversity combining technique. SNRs from RX1 and RX2 are summed to decide the channel occupancy.

6. RESULTS

Firstly the receiver diversity scheme is studied by calculating the probability of detection for different SNR values by fixing the probability of false alarm.

In Fig.2 the probability of true detection vs SNR is analyzed in real time for a SISO system. The probability of detection Vs SNR for the false alarm probability of 0.1 is given and it is observed that as the SNR increases the detection probability increases.

From Fig.3 and Fig.4 it is observed that as the number of samples increases from 1000 to 100000 for a SNR of approximately 7dB it is possible to achieve 10% higher detection probability for false alarm as low as 0.1. Hence the probability of misdetection reduces as the number of samples used in the sensing process increases.

It is observed from Fig.4 and Fig.5 that the performance of energy detector is very poor in the low SNR regions. Whereas in the high SNR regimes the performance increases and better ROC curves are obtained.

For SIMO system, the probability of true detection vs SNR is analyzed in an indoor wireless environment using EGC scheme. At an SNR value of 7dB, the Fig.6 shows 0.1% higher detection probability with increase in false alarm when the CR is equipped with two antennas compared to single antenna system shown in Fig.4 when 10000 samples are used for detection.

In low SNR region multiple antennas gives better ROC when lesser number of samples are used in the detection process. In high SNR regions performance level of multi antenna and single antenna is almost the same.

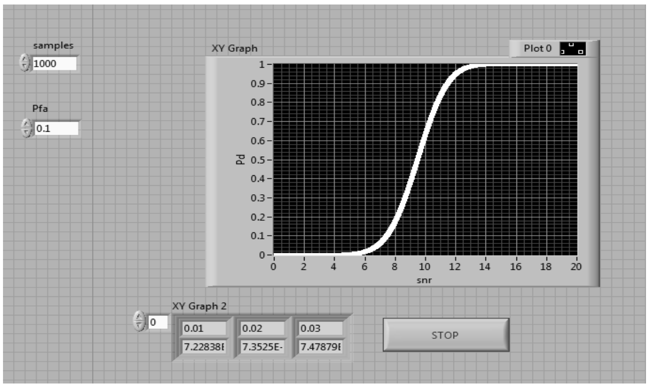

Fig.2. P_d vs. SNR for P_{fa} = 0.1

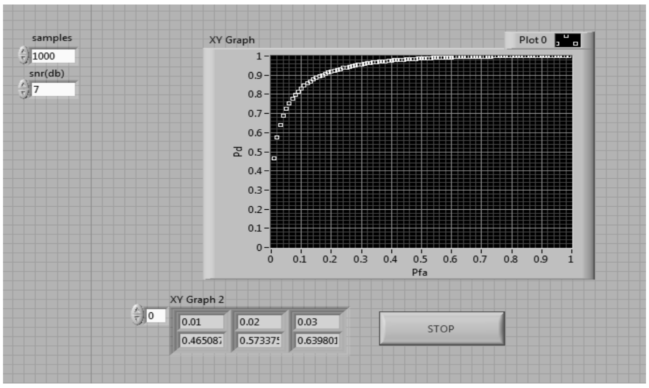

Fig.3. P_d vs. P_{fa} for SNR = 7dB and N = 1000

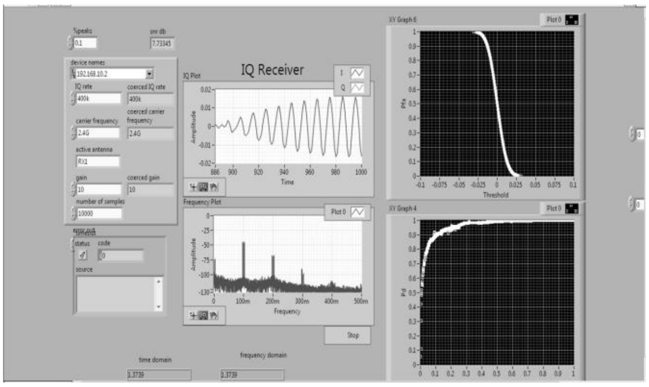

Fig.4. P_d vs. P_{fa} for SNR = 7dB and N = 10000

The probability of detection for single and multiple antenna system is 0.08 and 0.45 respectively with 1m distance and 0.6 and 0.99 respectively with 0.3m distance. It is observed that as the spacing between the transmitter and receiver decreases the detection increases. Also using multiple antenna system provides reduced misdetection probability compared to that of single antenna system.

Cooperative diversity was implemented using single PU and two SUs. The results of both SUs were combined at a fusion center using AND and OR combination rule. It was observed that OR rule enhances P_d whereas AND rule suppresses it.

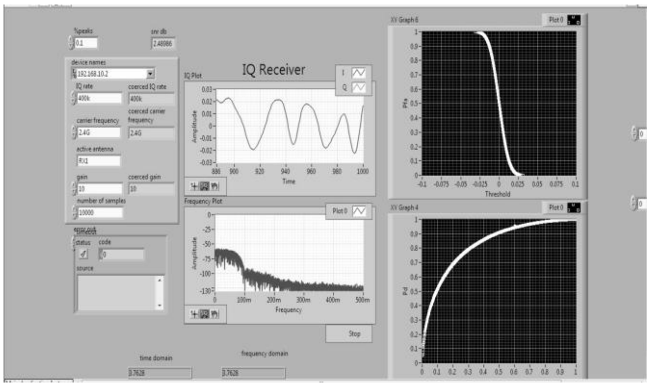

Fig.5. P_d vs. P_{fa} for SNR = 2.4dB and N = 10000

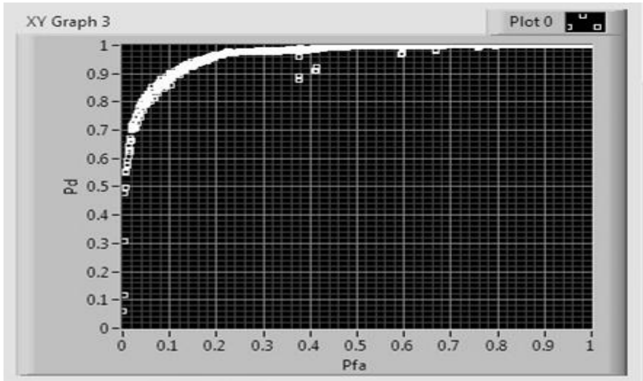

Fig.6. P_d vs. P_{fa} for SNR = 7dB and N = 10000 and L = 2

The Table.1 summarizes the detection performance for the OR and the AND fusion rules for different false alarm rates in cooperative diversity scheme. It is observed that the OR rule outperforms AND rule by providing higher PU detection rate.

Table1. Probability of Detection for the AND & OR fusion rules

Probability of false Alarm (P_{fa})	**Probability of detection (P_d)**	
	AND	**OR**
0.1	0.6372	0.9593
0.2	0.7906	0.9877
0.3	0.8796	0.9961
0.4	0.9588	0.9995
0.5	0.9787	0.9999
0.6	0.9962	0.9999
0.7	0.9999	0.9999
0.8	0.9999	0.9999
0.9	0.9999	0.9999

The ROC using the theoretical expressions given in section 2 and 3 are implemented in MATLAB and the plot of ROC when the CR is equipped with 1 and 2 antennas are given in Fig.7.

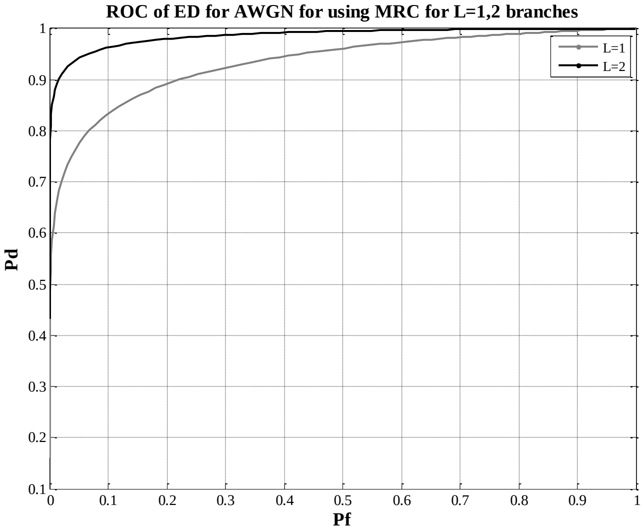

Fig.7. ROC of Energy detector using Maximum ratio combining for L = 1, 2 branches.

It is observed that the detection probability achieved in the experimentation given in Fig.3 using USRP is lesser compared to the theoretical results.

The Fig.8 gives the theoretical results of using cooperative diversity. It is observed that by increasing the number of cooperating CRs at the sensing process the probability of detection increases at very low SNR regimes (i.e. negative values of SNR).

Thus a comparative analysis from Fig.4 and Fig.6 shows higher detection probability with increase in false alarm when the CR is equipped with two antennas compared to single antenna system. The Fig.8 shows increase in detection probability when number of CRs in sensing process increases. Thus by using receiver and cooperative diversity the detection probability can be improved in low SNR regions and hence enhance the sensing accuracy.

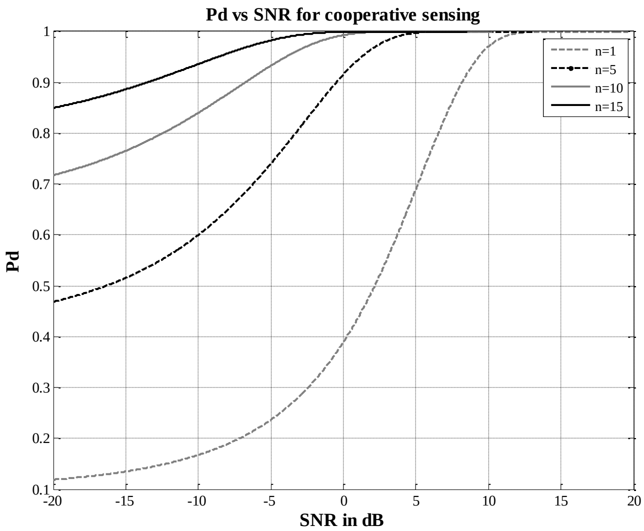

Fig.8. P_d vs. SNR for cooperative sensing with P_{fa} = 0.1 and N=1000 using OR fusion rule

The angle dimension is exploited by determining the strength of the transmitted signal and the angle of arrival using MUSIC algorithm. Further for getting more accurate detection we also examine the direction of arrival of the desired signal. The Fig.9 shows the direction of arrival estimation using MUSIC algorithm.

The primary signal angles provided are 20 and 60 degrees and the results of MUSIC algorithm shows the highest peak at the 60 degrees which indicates that the direction of the desired signal and a null can be steered towards the unwanted signal.

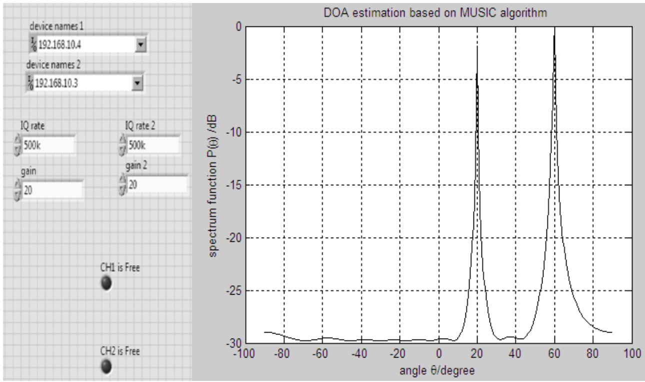

Fig.9. DOA Estimation Based on MUSIC Algorithm

7. CONCLUSION

The idea of multi dimensional spectrum sensing is explored for identifying spectrum holes. The space and the angle dimension are studied in an indoor wireless environment. Using the NI USRP boards to mimic the CR environment a statistical and comparative analysis of the spectrum sensing algorithms were carried out. Using spatial diversity the sensing performance enhancement can be achieved by using multi-antenna at the sensing node or by cooperation between sensing nodes. Also it was found that multi-antenna enhances the probability of detection in low SNR region. Cooperative sensing decreases probability of mis detection and probability of false alarm considerably. The angle dimension is exploited to determine if a primary user is transmitting in a specific direction so that the CR can transmit in the other direction without causing interference to the primary user. The effect on detection probability and SNR were studied for different diversity techniques in the experimental study using NI-USRP 2922 devices.

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