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Performance Evaluation of MIMO Based Spectrum Sensing in Cognitive Radio

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Abstract: *In this paper, one of the most important aspect of the Cognitive Radio i.e. Spectrum Sensing is considered. A new technique based on Multiple Input Multiple Output (MIMO) antennas is proposed for Spectrum Sensing in Cognitive Radio. This paper shows the results which prove that the use of MIMO antennas increases the "Probability of Detection" and decreases the "Probability of Missed Detection" of the target. Thus, this technique increases the chance to exploit spectrum resources more efficiently, so that spectrum scarcity problem is alleviated.*

Keywords: *Cognitive Radio (CR), Probability of Detection (P_d), Probability of Missed Detection (P_m), Primary User (PU), Secondary User (SU).*

I. Introduction

Spectrum Scarcity is one of the major hurdles faced by telecom operators, resulting in poor system performance [1]. To overcome this looming spectrum scarcity, a team of 3GPP is examining the incorporation of Cognitive Radio (CR) in wireless network systems. Other than this initiative, currently extensive studies and tremendous researches on Cognitive Radio are being carried out in different parts of the world [2]. Basically, Cognitive Radio is a smarter concept of using the unused spectrum bands. In CR, primary user (PU) is assigned a license to explore some resources of the spectrum, while as secondary user exploits the resources dynamically only in absence of PU [3] [4]. The basic idea of a Cognitive Radio is "reusing" the spectrum bands which are not properly exploited by the PUs. In order to accomplish this goal, secondary users are required to frequently perform spectrum sensing [5]. Whenever the primary users become active, the secondary users have to detect the presence of PUs with a high probability and vacate to other unused channel to avoid interference [5] [6]. Spectrum sensing, being highly crucial process of CR, has attracted a worldwide attention from the researchers [7]. Spectrum Sensing has multitude of implementation issues [8]. Several spectrum sensing methods like Matched filter Detection, Energy Detection, Feature Detection etc, have been proposed till date but all of them are having some limitation. Matched filter detector proves optimal when a prior knowledge of the PU signal is available. But its use is severely limited because of the fact that the information of the PU signal is hardly available at the SUs [7]. Energy detection, a naive signal detection approach does not require a prior knowledge of the PU signal. But it shows poor performance under low SNR conditions, and is unable to differentiate the interference from other SUs sharing the same channel and the PU [8]. To overcome this limitation, Feature detection exploits built-in periodicity of received signal to differentiate PU signal from interference and noise. In [9], performance of energy detector was analyzed when the primary user (PU) randomly arrives or departs during the sensing period. The four scenarios of PU activity are considered: fully present, completely absent, initially absent then arrive during sensing and initially present then depart during sensing. The average detection performance is calculated based on conditional detection performance when PU arrives or departs at a specific location. Simulation results show that higher PU traffic with more frequent state transitions result in worse performance degradation due to shorter PU signal observed. This study gives us little information how the threshold is calculated. In [10], for a given pair of arrival and departure time instants, an exact expression is derived for conditional detection probability which is further used to formulate exact mean detection probability. This provided an exact performance analysis for energy detector under both arrival and departure of the primary user's signal. Prior this, various works used approximation techniques to characterize the detection performance. In [11], a sensing scheme based on the cyclostationarity approach for randomly arriving or departing signals is proposed where a test statistic for spectrum sensing is derived using spectral autocoherence function (SAF) of the PU signal leading to better results. In [12], an improved energy detector (ED) with weights is proposed to improve detection performance in the environment of non-stationary PUs. Simulations showed better detection performances with a reduced probability of false alarm compared to conventional ED. All these methods have various advantages, but they suffer from some limitations too. In order, to address the problems related to spectrum sensing in CR, a new concept of MIMO technology is introduced in Cognitive Radio. This technique increases the spectral efficiency leading to improvement in the system performance. Here, multiple antennas are placed both on primary user as well as secondary user to increase the probability of sensing a target. Incorporation of MIMO antennas helps in spatial multiplexing as well as reliable communication between PU and SU [14]. In this paper, a basic Cognitive Radio algorithm is implemented to sense the spectrum for different combinations of the users. Here, five different combinations of users are considered and power spectral density (PSD) is plotted for each combination. To evaluate the performance of the whole system, a threshold is calculated using energy detection method and different combination of MIMO antennas are incorporated both on PU as well as SU. The probability of detection of target and probability of missed detection is calculated for each configuration and compared with threshold. Simulations show significant increment in Probability of Detection and decrement in Probability of Missed Detection with the increase in diversity order.

II. Classical Hypothetical Analysis of Spectrum Sensing

Spectrum sensing is the most important key element in Cognitive Radio. It enables the CR to adapt to its environment by detecting spectrum holes. In CR, the PU has higher priority or legacy rights on the usage of the spectrum. Fig.1 shows the principle of spectrum sensing [8].

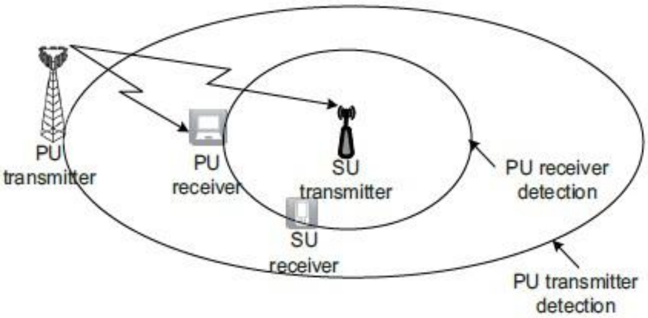

Fig.1. Basic concept of Spectrum Sensing

In the Fig. 1, the PU transmitter is transmitting data to the PU receiver in a licensed spectrum band, while a pair of SUs tries to access the spectrum. To protect the PU transmission, the SU transmitter needs to perform spectrum sensing to detect whether there is a PU receiver in the coverage of the SU transmitter [8]. The spectrum sensing scheme basically employs transmitter detection, in which we determine the frequency at which the transmitter is operating. A hypothesis model for transmitter detection is described ahead. In general, it is difficult for the SUs to differentiate the PU signals from other pre-existing SU transmitter signals. Therefore, all are treated as one received signal, $s(t)$. The received signal at the SU, $x(t)$, can be expressed as

$$x(t) = \begin{cases} n(t) & H_0 \\ s(t) + n(t) & H_1 \end{cases}$$

where $n(t)$ represents AWGN. H_0 and H_1 represent the hypothesis of the absence and presence of PU signals respectively. The performance of detection algorithm depends on some important parameters: the probability of detection (P_d), the probability of false alarm (P_f), and the probability of missed detection (P_m). **T**he total error rate is the sum of the probability of false alarm P_f and the probability of missed detection P_m or $(1 - P_d)$ [9]. Thus, the total error rate is given by:

$$P_e = P_f + P_m = P_f + (1 - P_d),$$

where $(1 - P_d)$ shows the probability of missed detection (P_m). The sensitivity of system depends on the probability of detection (P_d) and specificity of the system depends on probability of false alarm (P_f) and probability of missed detection (P_m). P_d is the probability of correctly detecting the PU signal present in the considered frequency band. In terms of hypothesis, it is given as:

$$P_d = P_r \text{ (signal is detected} \mid H_1)$$

P_f is the probability that the detection algorithm falsely decides that PU is present in the scanned frequency band when it actually is absent, and it is written as

$$P_f = P_r \text{ (signal is detected} \mid H_0)$$

The goal is to maximize P_d and minimize P_f to increase system performance. Probability of missed detection P_m is the complement of P_d. P_m which indicates the likelihood of not detecting the primary transmission when PU is active in the band of interest and can be formulated as:

$$P_m = 1 - P_d = P_r \text{ (signal is not detected} \mid H_1)$$

Total probability of making a wrong decision on spectrum occupancy is given by the weighted sum of P_f and P_m. Hence, the key challenge in transmitter detection approach is to keep both P_f and P_m under control because high P_f corresponds to poor spectrum utilization by CR and high P_m may result in increased interference at primary user. There are two basic hypothesis testing criteria in spectrum sensing: the Neyman-Pearson (NP) and Baye's tests [13]. The NP test aims at maximizing P_d (or minimizing P_m) under the constraint of $P_f \leq \alpha$, where α is the maximum false alarm probability. While, the Baye's test minimizes the average cost given by:

$$R = \sum_{i=0}^{1} \sum_{j=0}^{1} C_{ij} P_r \left(H_i / H_j\right) P_r\left(H_j\right)$$

where C_{ij} are the cost of declaring H_i when H_j is true, $P_r(H_i)$ is the prior probability of hypothesis H_i and $P_r\left(H_i/H_j\right)$ is the probability of declaring H_i when H_j is true. Both of the tests are equivalent to the likelihood ratio test (LRT) given by:

$$\Lambda(x) = \frac{P(x/H_1)}{P(x/H_0)}$$

where $P(x(1), x(2), \ldots, x(M) \mid H_i)$ is the distribution of observations $x = [x(1), x(2), \ldots, x(M)]^T$ under hypothesis H_i , i belongs to {0, 1}, $\Lambda(x)$ is the likelihood ratio. In both tests, the distributions of $P(\mathbf{x} \mid H_i)$ are known. When there are unknown parameters in the probability density functions (PDFs), the test is called composite hypothesis testing. Generalized likelihood ratio test (GLRT) is one kind of the composite hypothesis test. In the GLRT, the unknown parameters are determined by the maximum likelihood estimates (MLE) [13].The decision between the two hypotheses is made by comparing a test statistic T with a threshold γ. The probability of false alarm and detection are given by the equations

$$P_f = P(T > \gamma \mid H_0) \qquad \& \qquad P_d = P(T > \gamma \mid H_1)$$

According to Neyman-Pearson's theorem, for a fixed probability of false alarm, the test statistic that maximizes the probability of detection is the likelihood ratio test (LRT). In order to use the LRT, perfect knowledge of the $P(y/H_j)$ parameters is usually required. However, in cognitive radio scenarios, this information is sometimes unavailable. In such cases, other approaches like the Bayesian method and the Generalized Likelihood Ratio test (GLRT) are more adequate [13]. In the Bayesian method, the likelihood functions are estimated by marginalization, that is,

$$P(y/H_j) = \int P(y \mid H_j, \Theta_j) \, P\left(\Theta_j \mid H_j\right) d\Theta_j$$

where Θ_j defines the possible values for the unknown parameters under H_j. The Θ_j are treated as random variables with a priori known distribution $P\left(\Theta_j \mid H_j\right)$. The drawbacks of this method are the fact that the marginalization operand in above equation is not easily computed and the distribution assigned to the unknown parameters affects dramatically the performance results. In the GLRT method, the maximum likelihood estimation (ML) is used to estimate the value of the unknown parameters which are, in turn, used in a normal LRT test.

III. Incorporation of MIMO in Cognitive Radio

Wireless transmissions via MIMO transmissions have received considerable attention during the past decade. MIMO technology is serving as a building block of next-generation wireless communication systems supporting much higher data rates than UMTS and HSDPA based 3G networks [15]. MIMO is actually a signal processing technique used to increase the performance of wireless communication systems using multiple antennas at the transmitter and receiver [16]. A general MIMO system model is shown in Fig. 2. We present a communication system with N_T transmit antennas and N_R receive antennas. Antennas T_{x_1} ……..,$T_{x_{N_T}}$ respectively send signals $x_1, \ldots, x_{N_T}$ to receive antennas $R_{x_1}, \ldots, R_{x_{N_R}}$. Each receiver antenna combines the incoming signals which coherently add up. The received signals at antennas $R_{x_1}, \ldots, R_{x_{N_R}}$ are respectively denoted by $y_1 \ldots, y_{N_R}$. We express the received signal at antenna T_{x_q} ; $q = 1, \ldots, N_R$ as:

$$y_q = \sum_{p=1}^{N_T} h_{qp} \cdot x_p + b_q \qquad \text{where } q=1,\ldots\ldots\ldots N_R$$

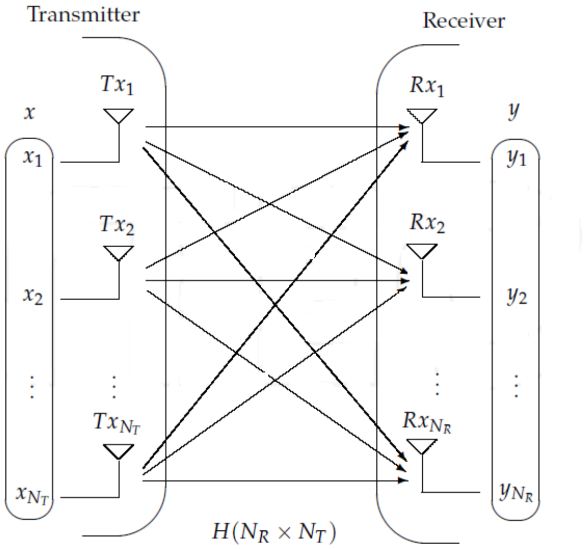

Fig 2. General MIMO system model

The flat fading MIMO channel model is described by the input-output relationship as:

$$y = H \cdot x + b$$

where H is the ($N_R \times N_T$) complex channel matrix given by:

$$H = \begin{pmatrix} h_{11} & h_{12} & \cdots & h_{1N_T} \\ \vdots & \vdots & \ddots & \vdots \\ h_{N_R 1} & h_{N_R 2} & \cdots & h_{N_R N_T} \end{pmatrix}$$

h_{qp} is the complex channel gain which links transmit antenna Tx_p to receive antenna Rx_q.

Here $x = [x_1, \ldots\ldots\ldots, x_{N_T}]^T$ is the ($N_T \times 1$) complex transmitted signal vector.

$y = [y_1, \ldots\ldots.. y_{N_R}]^T$ is the ($N_R \times 1$) complex received signal vector.

$b = [b_1, \ldots\ldots.. b_{N_R}]^T$ is the ($N_R \times 1$) complex additive noise signal vector.

The continuous time delay MIMO channel model of the ($N_R \times N_T$) MIMO channel H associated with time delay τ and noise signal b(t) is expressed as:

$$y(t) = \int H(t,\tau)\, x(t-x)d\tau + b(t)$$

where y(t) is the spatio-temporal output signal , x(t) is the spatio-temporal input signal , b(t) is the spatio-temporal noise signal.

MIMO technology helps in achieving many desirable functions for wireless transmissions, such as folded capacity increase without bandwidth expansion, dramatic enhancement of transmission reliability via space-time coding and effective co-channel interference suppression for multiuser transmissions [16]. Because of such advantages, MIMO has been adopted in next-generation WiFi, WiMax, and cellular network standards. MIMO technology also proves useful in spectrum sensing in Cognitive Radio. Most prior research on radio resource allocation for CR networks assumed single antenna at both primary and secondary transceiver. But here, multi-antennas are placed both on the PU and on SU .e.g. Two antenna system as shown in Fig.3. These multiple antennas can be used to allocate transmit dimensions in space and hence provide the secondary user more degrees of freedom in space, in addition to time and frequency, so as to balance between maximizing its own transmit rate and minimizing the interference powers at the primary users. Transmission of signal through different paths, exploiting receiver and transmitter diversity, maintains reliable communication between PU and SU. Thus, there is an increase in both capacity and spectral efficiency. MIMO technique helps in combating multipath scattering between PU and SU by providing spatial diversity leading to reliable sensing. Further, this technique exploits multipath scattering by providing spatial multiplexing leading to higher throughput.

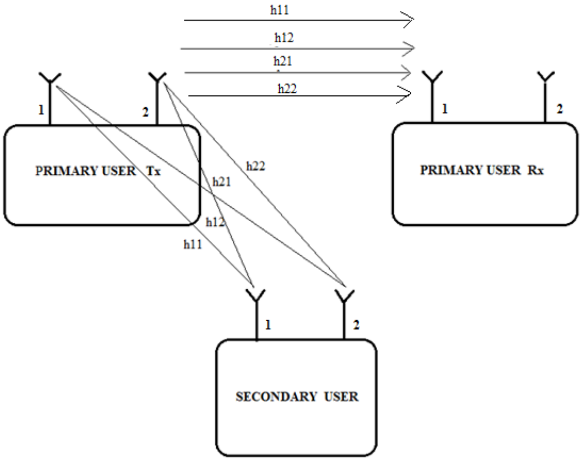

Fig 3. Basic Two –antenna MIMO System incorporated in CR.

Here in this paper, results have been shown in the form of graphs which prove that incorporating MIMO antennas of different configurations in Cognitive Radio systems enhance the accuracy in spectrum sensing.

IV. Results and Discussions

A. Spectrum Sensing in Cognitive Radio for different combinations of users

Here we use a basic idea of spectrum sensing using MATLAB program. We consider five different PUs with transmission signal frequency equal to 1 kHz, 2 kHz, 3 kHz, 4 kHz and 5 kHz respectively. Different cases have been considered describing different combinations of primary users. We calculate the sum of all the PU in each case and we use a basic method to calculate the Power spectral Density of the resultant signal. Further, we consider the entry of SU who is supposed to occupy the empty slot (i.e. where PU is absent).After, the entry of SU, we calculate the sum of the PU signals and SU signal and plot the PSD. Here, sampling frequency is equal to 12kHz.We choose SNR=15dB and attenuation percentage=5 in each case.

CASE I) PUs U1,U2,U3,U4,U5 are Present

In this case, all the five PUs are present.

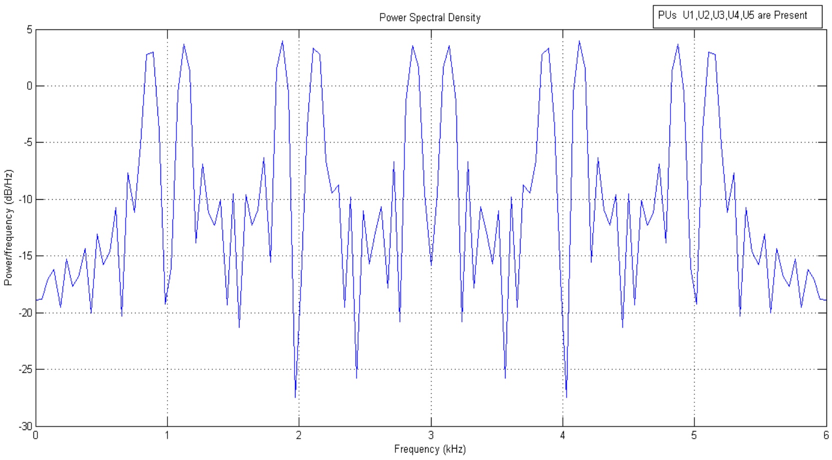

Fig 4. Power Spectral Density when all PUs are present

Since there is no free slot, hence the SU is asked to try again later. A slot for SU can also be freed. Further, noise has been added to the signals. Here SNR=15 is taken. Also the signals are attenuated taking 5% as attenuation percentage. The PSD of the summation of resultant noisy attenuated signals is given in Fig.4.

CASE II) PUs U1,U2,U3,U4 are Present while U5 is Absent

Here only four PUs are present. The PSD of the resultant summation signal of these four PUs is calculated. Fig.5 shows PSD of the four present PUs. SU senses the spectrum and finds one empty slot. So, this empty slot is given to the secondary user. We calculate the PSD of the attenuated PU signals and SU signals and plot the PSD as shown in Fig.6

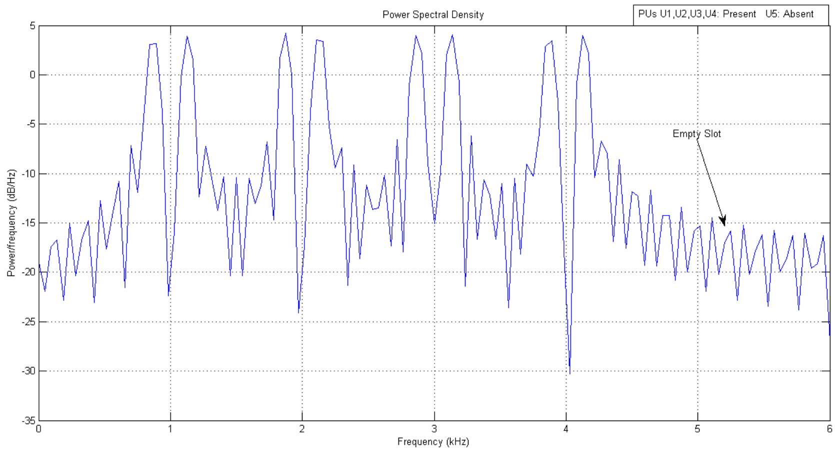

Fig 5. Power Spectral Density of the four present PUs

From the Fig 5, we can see that only four PUs are present and there is also one empty slot which can provide a place for the entry of SU.

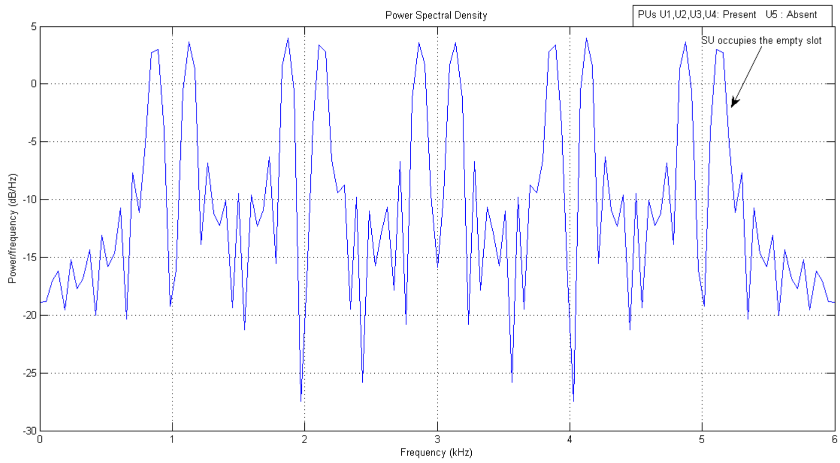

Fig 6. PSD of four present PUs and one SU

From the Fig 6, we can see that the SU occupies the empty slot and starts its transmission.

CASE III) PUs U1,U2,U3 are Present while U4,U5 are Absent

Here only three PUs are present. We calculate the PSD of the resultant summation signal of these three PUs and plot PSD of these three present PUs in Fig 7. It is clear from Fig.7 that three PUs are present and two slots are empty providing a scope for the entry of SU. SU senses the spectrum and finds two empty slots. So, SU chooses one of the empty slots and begins its transmission. We calculate the PSD of the attenuated PU signals and SU signals and plot it as shown in Fig.8.

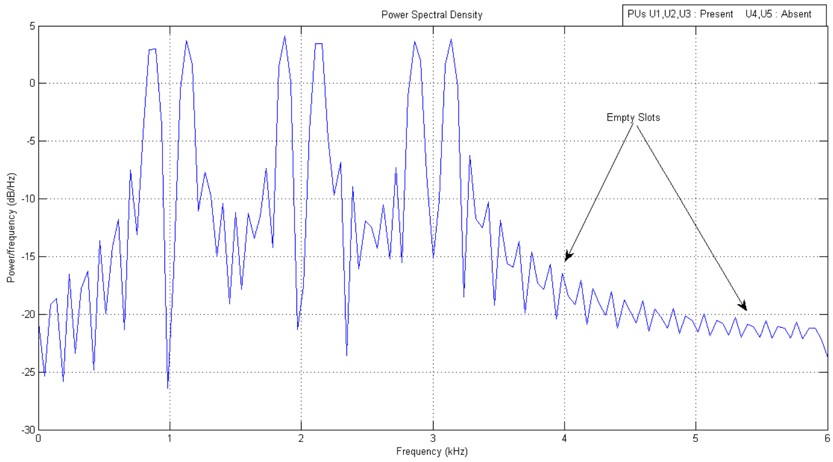

Fig 7. PSD of the three present PUs

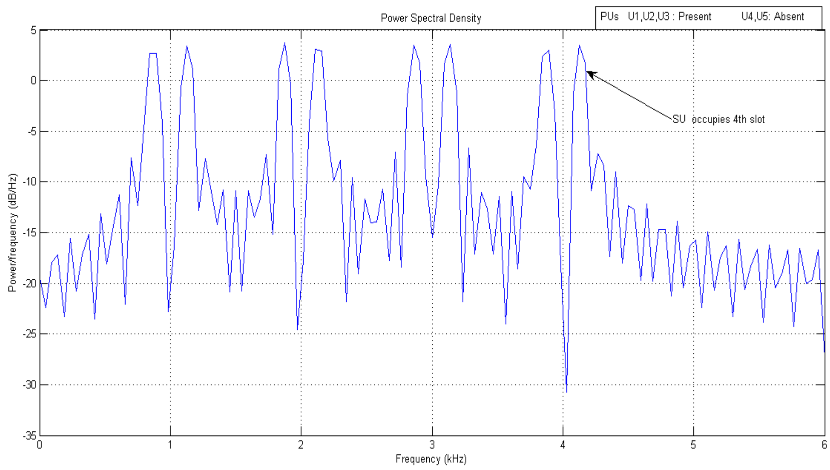

Fig 8. PSD of three present PU signals and one SU

CASE IV) PUs U1,U2 are Present while U3,U4,U5 are Absent

Here only two PUs are present leading to formation of three empty slots.

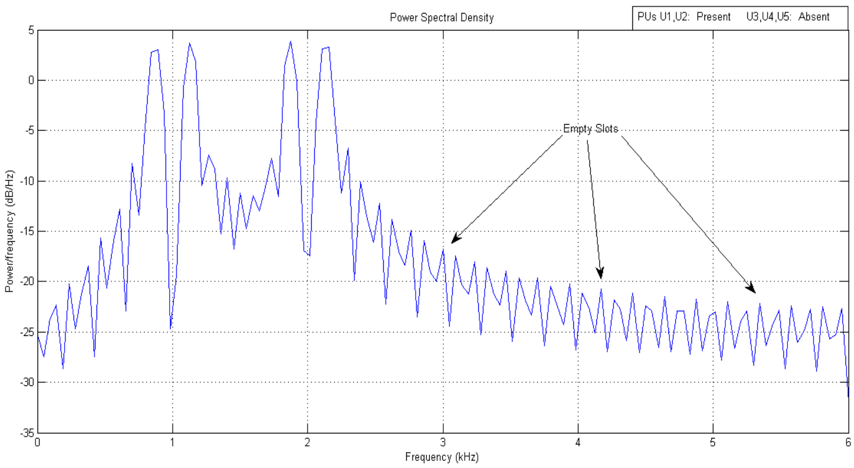

Fig.9. PSD of the two present PUs

We calculate the PSD of the resultant summation signal of these two PUs and plot the PSD as shown in Fig.9. SU senses the spectrum and finds three empty slots. SU chooses one of the empty slots and begins its transmission. The PSD of the attenuated PU signals and SU signals is calculated and plotted in Fig.10.

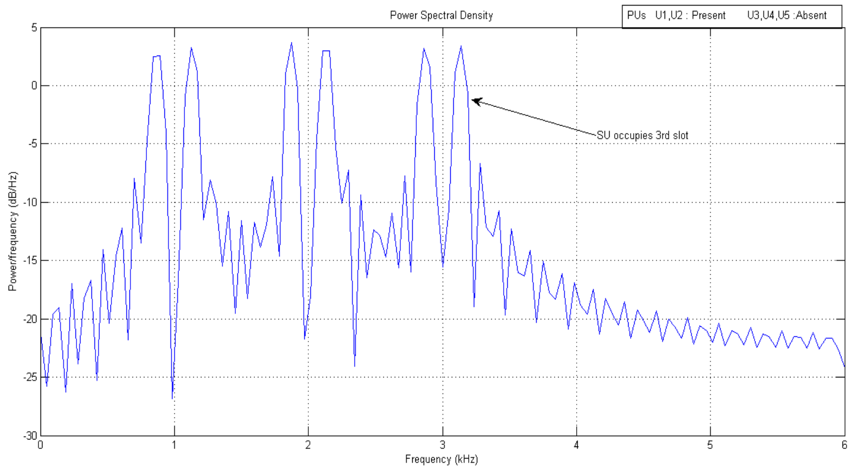

Fig 10. PSD of two present PU signals and one SU

CASE V) PU U1 is Present and PUs U2,U3,U4,U5 are Absent

Here only one PU is present and four empty slots are present. The PSD of PU signal is calculated and the plot showing PSD of the PU is given in Fig.11.

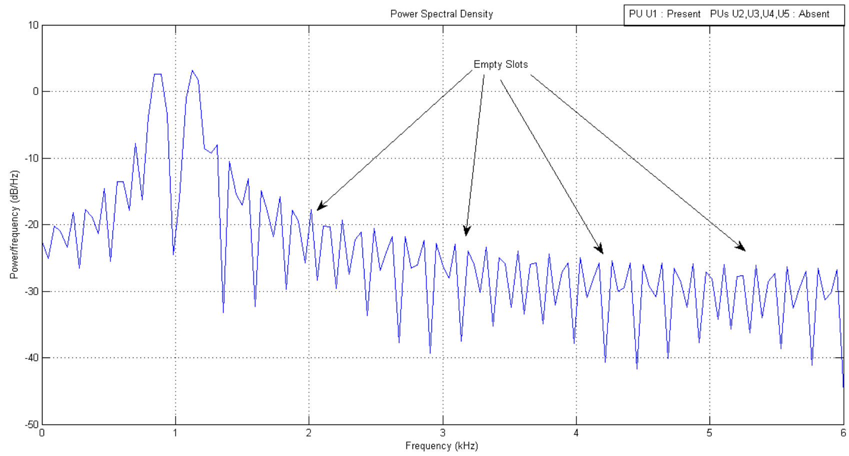

Fig.11. PSD of the present PU

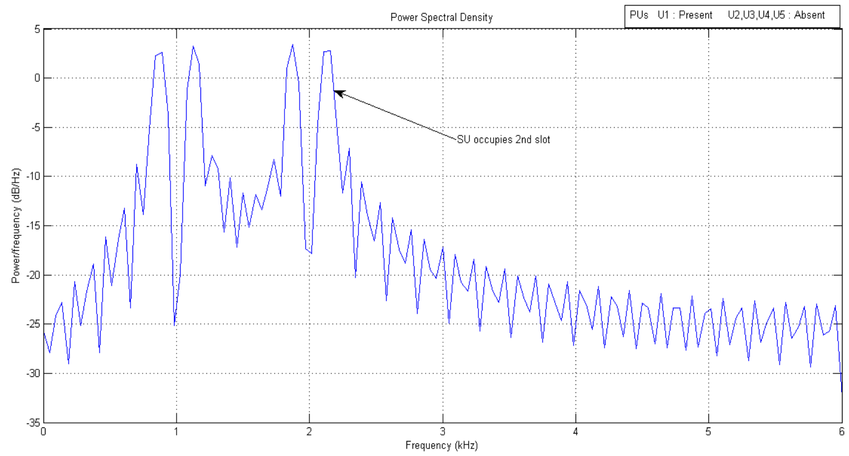

Fig.12. PSD of the present PU signal and one SU

SU senses the spectrum and finds four empty slots .So, SU chooses one of the empty slots and begins its transmission. The PSD of the attenuated PU signal and SU signals has been calculated and plot is shown in Fig. 12.

B. Performance Evaluation using Multi-input Multi-output antennas

Here we consider a basic energy detector method to show the effect of using different configurations of MIMO antennas on the Probability of detection and Probability of False alarm. Here the energy of the received signal is calculated and compared to a threshold (γ) to take the local decision that the PU signal is present or absent. The threshold value is set to meet the target probability of missed detection according to the noise power. We choose SNR equal to -14dB. We generate AWGN noise and real valued Gaussian PU signal. SU receives the noisy PU signal. We calculate the energy of received signal and compare it with threshold. Further, we calculate the probability of detection and probability of missed detection for different configurations of MIMO antennas.

Fig.13 shows the effect on probability of detection by incorporating MIMO antennas for spectrum sensing in CRs. On applying different MIMO configurations, there is an increase in P_d of the target. Since use of MIMO antennas lead to higher gain, their use in spectrum sensing lead to an increase in probability of detection. It can be seen from the Fig.13 that P_d increases with the increase in diversity order of MIMO with 4*4 MIMO showing highest Probability of Detection

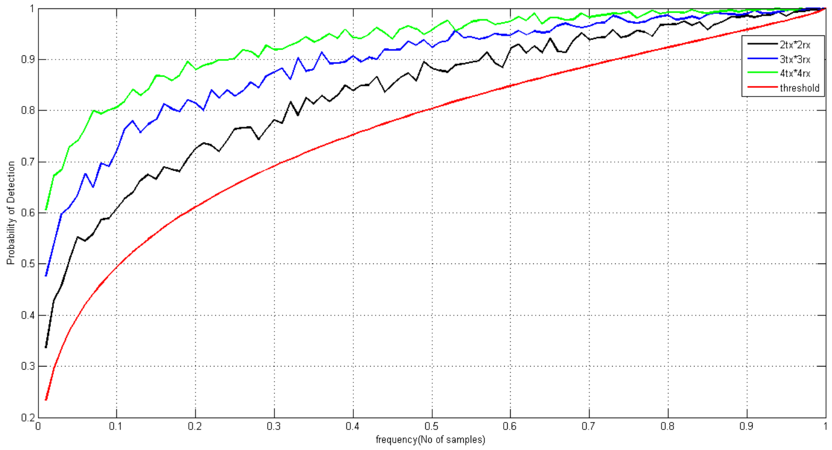

Fig13. Probability of Detection for different MIMO antenna configurations

Fig 14. shows the effect on probability of missed detection by using MIMO antennas for spectrum sensing . Increase in diversity order of different MIMO antenna configurations leads to a decrease in P_m of the target. Since use of MIMO antennas leads to high throughput leading to a decrease in probability of missed detection.

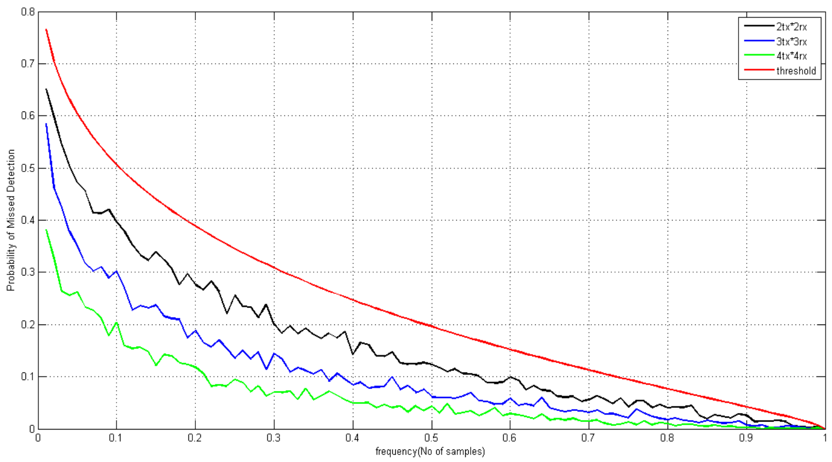

Fig 14. Probability of Missed Detection for different MIMO antenna configurations

Lower value of probability of missed detection refers to the probability that the SU rarely misses the PU signal when the PU is transmitting. Thus, lower probability of missed detection means accurate spectrum sensing. Fig. 14 shows that P_m decreases with the increase in diversity order of MIMO with 4*4 MIMO antenna configuration showing lowest Probability of Missed Detection.

V. Conclusion

Cognitive radio marks a big turning point in the field of wireless communication. It can fill up the gap between spectrum scarcity and increasing spectrum demands. One of the prime requirements of CR is to have a reliable spectrum sensing. MIMO technology is an efficient way to achieve the goal of reliable and accurate spectrum sensing. With the incorporation of multiple antennas at both PU and SU, the spatial dimensions are exploited to have better spectrum sensing. In this paper, it has been shown that on applying higher diversity order MIMO antennas at both PU and SU, there is an increase in the Probability of Detection of PU signal leading to lesser chances of interference. Further, higher the diversity order of MIMO antenna, lower will be the Probability of Missed Detection leading to better system performance. In the future, we can incorporate the relaying technology in Cognitive radios for the capacity enhancement and interference mitigation. With these improvements, our network coverage will get enhanced especially at cell borders where users experience low connectivity and SINR. Moreover, we can also implement different error detection and correction codes like convolutional codes to detect and correct the errors leading to the decrement in BER and consequently enhances our system performance.

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