Cooperative Spectrum Sensing with Square Law Combining Diversity Reception

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***Abstract*— Cognitive radio (CR) technique is useful for to know the uses of radio spectrum. CR is used to sense the spectrum periodically to know the primary user activity in fading environment. Cooperation among multiple CRs helps to enhance the reliability of detection of the primary user (PU), to overcome the unreliable decision by a single CR due to channel uncertainties. Along with the Co-operation of multiple users, diversity techniques are often used to reduce the fading the effect as well as to increase the detection probability. In this paper, we have consider first with no diversity case, and extended to the square-law combining (SLC) diversity technique when wireless users experience different fading channels like (Rayleigh, Rician, Nakagami, Hoyt and Weibull) in the communication channel. The method used in this is, Cooperative spectrum sensing (CSS) with Energy detection over various fading channels using SLC diversity scheme. Finally, performance evaluation is exhibited using receiver operating characteristics (ROC) curves which are drawn between P_f vs P_d for different numbers of diversity branches, various values of average SNRs, time band width product and different values of fading parameter. It is observed from the simulation is that the Weibull fading performance is better than other fading channels while SLC diversity is used.**

Key words*— Cognitive Radio, Cooperative Spectrum Sensing, fading channels, Square Law Combining.

I. INTRODUCTION

Now a days utility of radio spectrum became high because of increasing in the wireless applications. The available spectrum is limited and it will not meet the increasing demand. According to the survey reports most of the available frequencies in the spectrum are perfectly not utilized [1]. By allowing the secondary users called cognitive radio users (CR) to access the spectrum when the licensed users called primary users (PU) are inactive, to improve the spectrum utilization effectively. To overcome the problem of interference between CR users and PU users, CR users always sense the radio spectrum whether the primary user is present or not in the available spectrum. When the primary user is absent CRs allowed to use the spectrum holes without interfering with the PU. Most frequently used detection scheme to detect the spectrum holes is Energy detection (ED) [2], because it can be implemented easily, less hardware complexity, non coherent detector and does not require channel state information (CSI) [10]. To mitigate the effect of fading, multiple CRs are often designed to collaborate in spectrum sensing which can be called Cooperative spectrum sensing (CSS) [7]. Sensing performance is low in single CR based ED as compared to multiple CR based ED. By considering multiple CRs, sensing cooperation [9] among them is created and it leads to improve the detection performance. More important thing in CSS process [6] is, the fusion center (FC) collects the information from the individual CRs and then it uses different diversity schemes on the available data to detect the activity of primary user. FC consist the information of , how secondary users access the PU in opportunistic manner without interfering the operation of PU and how multiple users are collaborated to improve the detection performance in various fading channels using Hard decision rules[5]. Now at the FC, on the received local sensing information soft data fusion like square law combining technique (SLC) scheme is applied to decide about the activity of PU. From fig. 2, it may be noted that the channel between the PU and CRs are called sensing channels (S-channels) and the channel between the CRs and the FC are called reporting channels (R-channels). In this paper, we have consider R-channel is free from fading effect and S-channel is effected by different fading channels like Rayleigh, Rician, Nakagami, Weibull and Hoyt fading channels. In [6], only noise is considered in S-channel. In practical case this may not be true always because of fading and shadowing effects in the S-channel will lead noisy in the R-channel. In this paper, we have considered the performance of energy detection (ED) [2] to detect the PU in the different fading environments.

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By using the diversity techniques along with the cooperation of multiple CR users fading effect can be decreases which results improvement in detection performance. Finally, found that: (i) the performance of energy detection does not degrade significantly at low and moderate shadowing conditions, (ii)diversity detection highly mitigates the effect of fading on detection performance. In this paper, we derive expressions for the average probabilities of detection, using energy detection with SLC diversity reception scheme over independent and identically distributed (i.i.d.) Rayleigh, Rician, Hoyt, Nakagami & Weibull [11] fading channels. The main scope of the paper is, evaluated the detection probability of all fading channel, which are stated above and comparison between them using Square law combing technique with receiver operating characteristics (ROC) curves and also we state that in case of Weibull fading channel detection performance is better than the remaining fading channels. The rest of the paper is organized as follows. Section II, describe the system model. In Section III, we have derived the expressions for the average detection probability for different fading channels using SLC. Simulation results are presented in Section IV, with conclusions given in Section V.

II. System Model

We have developed a simulation model using MATLAB for energy detection based spectrum sensing. The results are obtained from simulation method are perfectly matched with the theoretical results under various fading environments, with different cases like SNR values, fading parameters, number of diversity branches and that can shown in section-IV. The analytical expressions for the probability of detection in various fading channels (Rayleigh, Rician, Nakagami, Hoyt & Weibull) was given in [3]-[4] & [14].

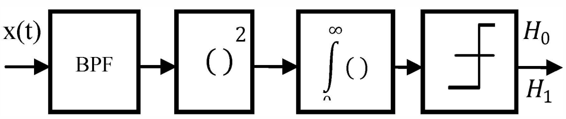

Fig.1. Block diagram of Energy Detection

Whenever the signal from the primary transmitter is unknown to us, energy detector is used to detect that signal and it is a non-coherent detector. Fig.1 represents the block diagram of ED[2]. It can be described as, the received signal is passed through the band pass filter and this filter selects the required frequency as f_c . Output of band pass filter is passed through the non-linear device called squaring device, it will measure the energy associated with the signal. Non linear device output is passed through an integrator, it will measure energy over the fixed duration of time window. After this block the energy y(t) of the signal, is compared with the threshold value (λ) to decide whether the primary signal is present or not. The sensing performance is degraded when the CR user effected by shadowing and fading even though it uses energy detector.

The received signal in narrowband energy detection follows a two hypothesis can be shown as below [5],[14]

$$r(t) = \begin{cases} n(t) & H_0 \\ h * s(t) + n(t) & H_1 \end{cases} \quad (1)$$

where *r(t)* is the signal received by secondary user and *s(t)* is primary user's transmitted signal, *n(t)* is the Additive White Gaussian Noise (AWGN), and h is the amplitude gain of the channel. The samples of *n(t)* are assumed to be zero-mean Gaussian random variables with variance N_0W where W and N_0 denoting the single-sided signal bandwidth and a single-sided noise power spectral density [5]. The received signal is first pre-filtered by an ideal band pass filter with transfer function [14].

$$H(f) = \begin{cases} \frac{2}{\sqrt{N_{01}}} & |f - f_c| \leq W \\ 0 & |f - f_c| > W \end{cases} \quad (2)$$

The test statistics H_0/H_1 determines whether the noise or signal is present. These H_0/H_1 are the outputs of ED [14].

$$Y \sim \begin{cases} {\chi^2}_{2u}, & H_0 \\ {\chi^2}_{2u}(2y), & H_1 \end{cases} \quad (3)$$

y is SNR, χ^2_{2u} central chi-square distributions with degree of freedom (DoF), $2u$ ($u = T\,W$), $\chi^2_{2u}(2y)$ denote the non-central chi-square distributions, with degree of freedom is $2u$, and it has a non-central parameter $2y$. For an AWGN channel, the probabilities of false alarm and detection of the energy detector are given by [3],[5][14]

$$P_d = P(Y > \lambda | H_1) = Q_m\left(\sqrt{2\gamma}, \lambda\right) \quad (4)$$

$$P_f = P(Y > \lambda | H_0) = \frac{\Gamma(m, \lambda/2)}{\Gamma(m)} \quad (5)$$

where $\Gamma(a, b)$ is the incomplete gamma function [12] and $Q_m(a, b)$ is the generalized Marcum Q-function [13].

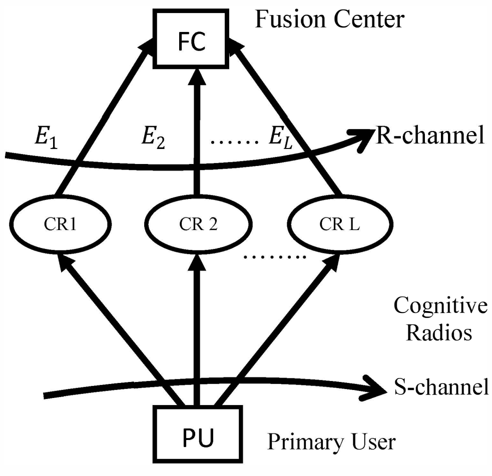

Fig.2. Cooperative spectrum sensing network

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Probability of false alarm, P_f , is remains same in different fading channels because it does not depend upon average S-channel SNR, P_f, will remain the same as in P_f (5) [3]. In contrast, when the channel gain ($h(t)$) varies, the average probability of detection (P_d) can be calculated by averaging P_d in (4) over all possible SNR values as [3]

$$\overline{P_d} = \int_0^{\infty} P_d(y, \lambda) f(y) dy \qquad (6)$$

where $f(y)$ denotes the probability density function (PDF) of the SNR in a fading channel.

III. SQUARE LAW COMBINING OVER FADING CHANNELS

This section describes about Square Law Combining (SLC) diversity reception technique and it's effect on different fading channel. We also provide the probability of detection equations for each fading channel when SLC combining technique is used. We are assuming that CRs are identically independent distributed (i.i.ds) over the fading channels.

A . Square Law Combining (SLC)

At the fusion center (FC) the received information from each and every CR is summed up and SLC diversity technique is used to know the activity of PU. Each is get the information about the PU by using energy detector, in which, the squared and integrated energy vectors, Y_1 , Y_2 · · · Y_L , , are obtained. This information is passed to the FC through the R-channel. At the FC after applying SLC technique the new test statistics, $Y_{SLC} = \sum_{i=1}^{L} Y_i$, is formed [9]. We have already assumed that all CRs i.i.ds, hence new test statistics Y_{SLC} , follows a central chi-square distribution with a *2Lu* DoF. Under H_1 hypothesis, it follows a non-central chi-square distribution with a *2Lu* DoF and non-central parameter of $2Y_{slc}$ as below [6],[10]

$$Y \sim \begin{cases} \chi^2{}_{2u}, & H_0 \\ \chi^2{}_{2u}(2y_{slc}), & H_1 \end{cases} \qquad (7)$$

Where $y_{Slc} = \sum_{i=1}^{L} Y_i$ for i.i.d. fading channels.

In the case of non-fading AWGN channels, using (4), (6) and (7), the probabilities of false alarm and detection under SLC diversity scheme can be given as

$$P_{fa}^{slc} = \frac{\Gamma(Lu, \lambda/2)}{\Gamma(Lu)} \qquad (8)$$

$$P_d^{slc} = Q_{Lu}(\sqrt{2y_{slc}}, \sqrt{\lambda}) \qquad (9)$$

As we discussed earlier when the S-channel experience a fading effect the average probability of false alarm will remains same, and the fading effect on detection probability can be evaluated by averaging P_d^{slc} in (9) over the combined SNR distribution as [3].

The PDF of the output SNR, y_{slc} for L i.i.d

$$\overline{P_d^{slc}} = \int_0^{\infty} P_d^{slc}(y_{slc}, \lambda) f(y_{slc}) dy_{slc}, \quad y_{slc} > 0 \qquad (10)$$

B. Rayleigh fading channel

In this case, we assume that the S-channel between PU and CR is Rayleigh faded(h_k). Rayleigh distribution is a reasonable model when there are many objects in the environment that scatter the radio signal before it arrives at the receiver. It is more severe than Rician fading. Rayleigh fading coefficient can be generated using two Gaussian random variables $a \sim (0, \sigma^2)$ and $b \sim (0, \sigma^2)$ with same mean and same variances. Envelope of h_k follows a Rayleigh distribution i.e $h_k = \sqrt{a^2 + b^2}$ [11],[9],[5].

$$f_{Ray}(L, y_{slc}) = \frac{1}{\Gamma(L)} \left(\frac{L}{\bar{\gamma}}\right)^N \gamma_{slc}^{N-1} \exp\left(\frac{-L * \gamma_{slc}}{\bar{\gamma}}\right) \quad \gamma_{slc} \geq 0 \qquad (11)$$

Thus, the average detection probability can be expressed as

$$\overline{P_{d,slc}^{Ray}(\lambda, L, \gamma_{slc})} = \int_0^{\infty} Q_{Lm}(\sqrt{2\gamma_{slc}}, \sqrt{\lambda}) f_{Ray}(L, y_{slc}) d\gamma_{slc} \qquad (12)$$

By solving above equation, closed form formula for detection probability can be obtained by replacing *m* by L, each $\bar{\gamma}$ by $\overline{\gamma_{slc}}$ and each N by LN in [3, eq.(20)]

B. Rician fading channel

Consider, S-channel between PU and CR is Rician faded (h_k). If h_k is considered as Rician fading coefficient [11], it is generated using two Gaussian random variables $h_k = \sqrt{A^2 + B^2}$, where $A = N\sim(s, \sigma^2)$ and $B = N\sim(0, \sigma^2)$, and where $s = \sqrt{K/1 + K}$ and $\sigma = 1/\sqrt{2(1 + K)}$; The Rician fading factor, *K* (also called shape parameter and it is defined as the ratio of signal power in dominant component over the scattered power), indicates the severity of fading and the quality of the channel. The severity of fading reduces when the fading factor, *K*, increases [14]. The PDF equation for Rician fading channel when SLC diversity scheme is used

$$f_y(x) = \frac{k+1}{\bar{\gamma}} \exp\left(-K \frac{(1+k)L\gamma}{\bar{\gamma}}\right) * I_0 2\left(\sqrt{\frac{k(k+1)}{\bar{\gamma}}}\right) \quad (13)$$

Thus, the average detection probability $\overline{P_{d,slc}^{Rician}(\lambda, L, \gamma_{slc})}$ can be derived by averaging (13) over (9).

C. Nakagami fading channel

In this section, we will discuss the effect of Nakagami channel and the SLC diversity technique is

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used at the fusion center. In Nakagami channels, γ^k, represent the S-channel SNR of each branch where k = 1,2,....L, distribution can be written as [10] the PDF equation is given by

$$f_{Nak}(y_{slc}) = \frac{1}{\Gamma(mL)}\left(\frac{mL}{\bar{\gamma}}\right)^{L}(\gamma_{slc})^{mL-1}\exp\left(\frac{-m\gamma_{slc}}{\bar{\gamma}}\right) \quad \gamma_{slc} \geq 0 \qquad (14)$$

by observing from eq. (11) and eq.(14), we can state that

$$f_{Nak}(y_{slc}) = f_{Ray}(mL, y_{slc}) \qquad (15)$$

Equation (15) shows the relationship between Rayleigh and Nakagami fading channels. It is also shows that the PDF of the random variable y_{slc} with L branches in a Nakagami channel equals that in a Rayleigh channel with mL branches. Here m is acting as Nakagami fading parameter and also as a diversity order. Therefore, the average detection probability over Nakagami channels can be expresses as

$$\overline{P_{d,slc}^{Nak}}(\lambda, L, \gamma_{slc}) = \int_0^{\infty} Q_{Lm}(\sqrt{2\gamma_{slc}}, \sqrt{\lambda})\, f_{Nak}(L, y_{slc})\, d\gamma_{slc}$$

$$= \overline{P_{d,slc}^{Nak}}(\lambda, mL, \gamma_{slc}) \qquad (16)$$

referring to (15), $\overline{P_{d,Nak}^{slc}}$ is equivalent to P_d^{Nak} in [3, eq.(20)].

After replacing by replacing m by L, each $\bar{\gamma}$ by $\overline{\gamma_{slc}}$ and each N by LN, and can be expressed as

$$\overline{P_{d,Nak}^{slc}} = A_1 + \beta^{mL}\, e^{-\frac{\lambda}{2}} \sum_{n=1}^{m-1} \frac{\left(\frac{\lambda}{2}\right)^n}{n!}\, {}_1F_1\left(mL; n+1; {}^{\lambda(1-\beta)}/_{2}\right)] \qquad (17)$$

where β and A_1 are respectively given by

$$\beta = {}^{mL}/_{(mL + \overline{\gamma_{slc}})} \qquad \text{and}$$

$$A_1 = e^{-\frac{\lambda\beta}{2}}\left[\beta^{mL-1} L_{mL-1}\left(-\frac{\lambda(1-\beta)}{2}\right) + (1-\beta)\sum_{k=0}^{mL-2}\beta^k L_k\left(-\frac{\lambda(1-\beta)}{2}\right)\right] \qquad (18)$$

D. *Hoyt (Nakagami-q) fading channel*

Let's consider that the sensing channel between PU and CR user is Hoyt faded. Hoyt or Nakagami-q distribution is generally used to characterize the fading environments that are more severe than Rayleigh fading. The PDF of γ^k, where k =1,2,....L, distribution can be written as [12]

$$f_{hoyt}(y_{slc}) = \frac{1}{\sqrt{P\bar{\gamma}}}\exp\left(-\frac{\gamma_{slc}}{P\bar{\gamma}}\right) I_0\left(\frac{\gamma_{slc}\sqrt{1-P}}{P\bar{\gamma}}\right) \quad \gamma \geq 0 \qquad (19)$$

Where $\quad P = \frac{4q^2}{(1+q^2)^2}$; $0 \leq P \leq 1 \qquad (20)$

Detection probability equation can be calculated by substituting (18) in (10), gives $\overline{P_{d,hoyt}^{slc}}$.

E. *Weibull fading channel*

In order to show the small-scale variations of a signal in non-line-of-sight (NLOS) communication in multipath environments effectively, Weibull fading model has been introduced. The corresponding PDF of the instantaneous SNR per symbol γ is given by [8],

$$f_\gamma(\gamma) = \frac{V}{2}\left(\frac{\Gamma\left(1+\frac{2}{V}\right)}{\gamma}\right)^{\frac{V}{2}}(\gamma_{slc})^{\frac{a}{2}-1}\, e^{\left[\frac{(\gamma_{slc})}{\bar{\gamma}}\Gamma\left(1+\frac{2}{a}\right)\right]^{\frac{a}{2}}} \qquad (21)$$

where $\bar{\gamma}$ represent the average SNR per symbol .

The average detection probability expression P_d in case of a Weibull channel, can be obtained by averaging (19) over (10)

$$P_d = \sum_{l=0}^{u-1}\frac{\lambda^l e^{-\frac{\lambda}{2}}}{l!2^l} + \sum_{l=0}^{\infty}\frac{(-1)^l A^l \lambda^u}{l!u!2^u(\gamma_{slc})^{-\frac{la}{2}} e^{\frac{\lambda}{2}}}\,\Gamma\left(\frac{la}{2}+1\right)\, {}_1F_1\left(\frac{la}{2}+1, u+1, \frac{\lambda}{2}\right) \qquad (22)$$

Where, $\quad {}_1F_1(a,b,x) \triangleq \sum_{l=0}^{\infty}\frac{(a)_l x^l}{(b)_l l!} \qquad (23)$

is the Kummer's confluent hypergeometric function.

IV. RESULTS AND DISCUSSIONS

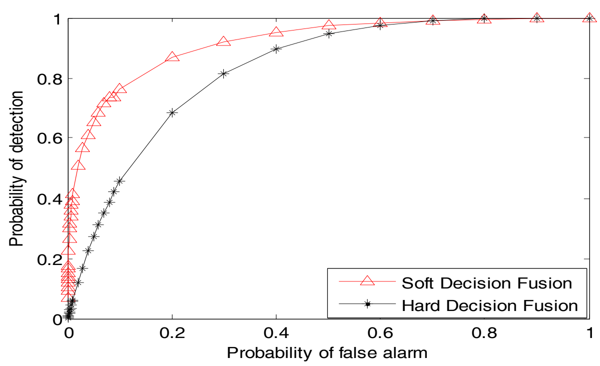

Fig.3. Comparison between Soft decision technique and Hard decision technique.

In simulation, Receiver operating characteristic (ROC), curves drawn between P_f Vs P_d are used to quantify the detection performance of energy detection under cooperative spectrum sensing. From fig.3, we can state that SLC diversity reception (soft decision fusion) scheme is compared with the majority logic (hard decision fusion) with N=3,u=5 and average SNR=5db. The CSS based on soft data fusion outperforms hard decision fusion at the cost of increased bandwidth.

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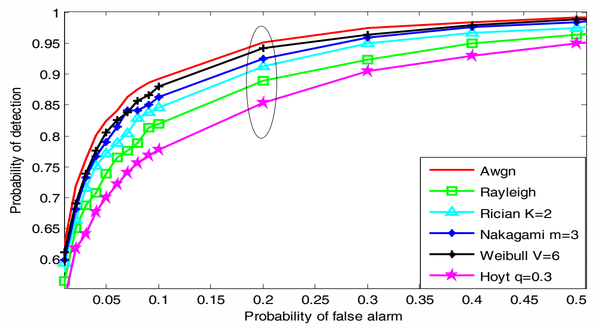

Fig.4. SLC diversity technique over different fading channel with various fading parameters.

In Fig.4, we have compared the probability detection performance of energy detection using SLC over all fading channels like AWGN, Rayleigh, Rician, Nakagami, Weibull & Hoyt fading channels with their respective fading parameters (K=2,m=3,V=6,q=0.3) are compared. It is illustrates that, when the communication channel effects with Weibull fading, the detection probability of primary user is more accurate than other fading channels. It is also observed that there will be less detection probability of primary user when communication channel consist of Hoyt fading channel. Hoyt fading channel exhibit severe fading than Rayleigh fading channel. SLC diversity reception performance is poor in Hoyt fading environment and it has better performance in Weibull fading environment, and it can also conclude that SLC performance is moderate in Nakagami- *m* fading channel environment is considered.

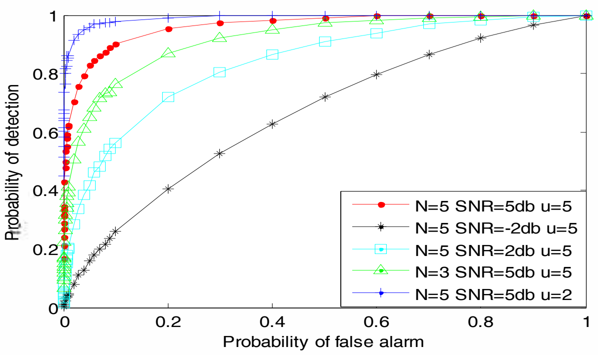

Fig.5. SLC diversity technique over AWGN channel with different cases.

From fig.5 and fig.6, we can depicts that the number of diversity branches are increased from N=3 to N=5 with fixed average SNR=5db and time band width product u=5, the detection probability increases because the cooperation among the secondary users increases as N increases. Keeping N=5 as constant, average SNR increases from -2db to 5 db, in this case also detection performance is increases because as the SNR increases signal value increase and noise performance is decreases. The time bandwidth product (*u*) also plays an important role to detect the PU. This can be observed from Fig.5, as *u* increases in from 2 to 5 the probability of detection decreases this can justified from the test statistics and is directly related to the degrees of freedom (DoF) of the test statistic as shown in (3).

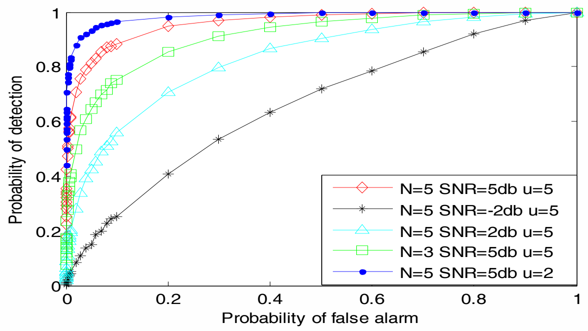

Fig.6. SLC diversity technique over Rayleigh channel with different cases.

For example, in the fig.5, if we choose a fixed probability of false alarm $P_f = 0.2$, when we increases u=2 to u=5 the probability of detection decrease when u value is increases.

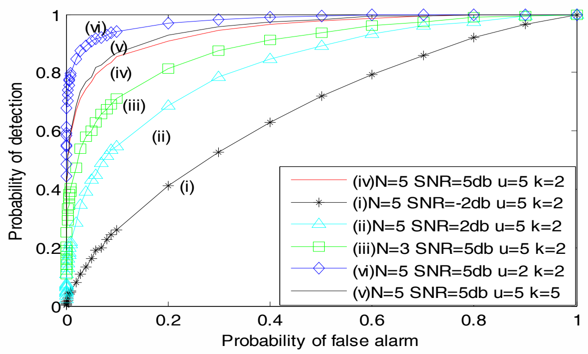

Fig.7. SLC diversity technique over Rician channel with different cases.

In fig.7, from curve (iv) & (v) are state that, the fading parameter is increased from K=2 to K=5, hence the detection probability is also increases because in Rician fading as the fading parameter increases LOS propagation increases. Fig.8, the Nakagami-*m* fading factor, *m* (also called shape factor), indicates the severity of fading and the quality of the channel.

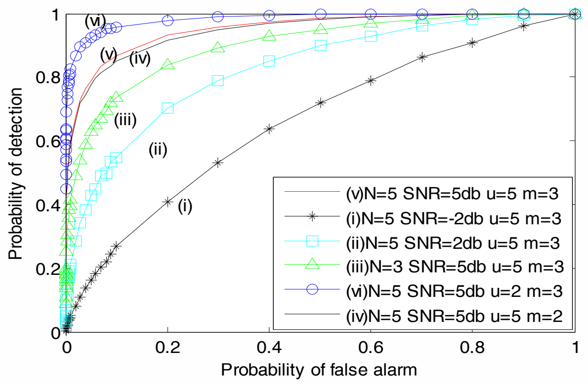

Fig.8. SLC diversity technique over Nakagami channel with different cases.

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As the fading parameter (m) increases, the severity of fading reduces which leads to increases the detection probability. As the fading parameter increases, the fading present in the S-channel is reduces hence misdetection probability of PU decreases. When Nakagami parameter (m) value set as 1, it results into Rayleigh fading channel and this can be observed in (15) and in the limit as $m \rightarrow \infty$, it converges to a non-fading channel called AWGN channel. In Fig. 8, it is shown that the performance of diversity reception over Nakagami-m fading channels with $m = 3$ is much better than $m = 2$, because the severity of fading for the former case is less than that of the latter case. Fig. 9, justifies that it is drawn between probability of detection Vs probability false alarm as a function of SNR, time band width product (u), number of users (N) and Weibull fading parameter (V) for Weibull fading channel. As we have discussed in above graphs probability of detection increases as number of users increases from N=3 to N=5, SNR=-2db to SNR=5db and V=3 to V=6 all these changes can be observable from fig.9.

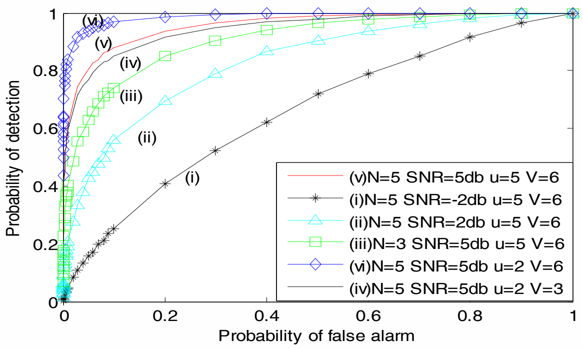

Fig.9. SLC diversity technique over Weibull channel with different cases.

In the same manner way we have justified in the fig.10 for SLC diversity technique over Hoyt fading channels with their respective fading parameter (q), SNR and (N).

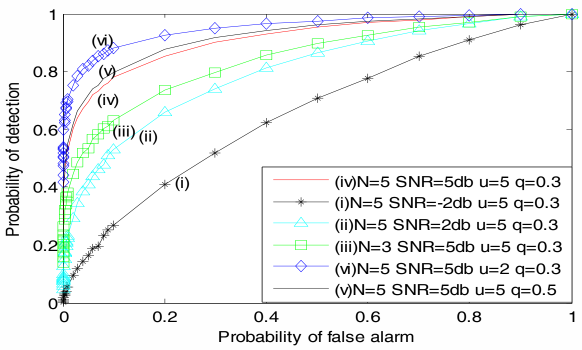

Fig.10. SLC diversity technique over Hoyt channel with different cases.

V. Conclusion

In this paper, we carry out the performance evaluation of soft data fusion scheme called Square Law Combining (SLC) in several fading channels such as AWGN, Rayleigh, Rician, Nakagami, Weibull & Hoyt channels. More precisely, we evaluate the comprehensive performance of cooperative spectrum sensing (CSS) through receiver operating curves (ROC) under soft data fusion SLC over various fading channels. A simulation study is carried out to evaluate the effects of fading on the performance of CSS under soft data fusions. The results based on our simulation method match exactly with the results obtained via analytical expressions. The performance comparison of soft data scheme SLC is evaluated for various network parameters such as number of CRs (N) in the network, time-bandwidth product (u), average S-channel SNR. Further, the performance of soft data fusion is compared with that of hard decision based fusion. The CSS based on soft data fusion outperforms hard decision fusion at the cost of increased bandwidth. Performance of a CR based spectrum sensing improves with increase in fading parameters of fading channels with reduction in severity of fading. This work can be extended to other combining techniques like SC, SSC, SLS, and MRC& EGC. We will compare all the results of different diversity technique and decide which combining technique performs better under various fading channels.

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