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Performance Analysis of Maximal Ratio Combining (MRC) and Square Law Combining (SLC), in Energy Detector for Cognitive Radio Networks Over Nakagami Fading Channels

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Abstract: In this paper, we compare two cooperative reception diversity schemes in energy detector for cognitive radio networks. Energy detector is equipped with the Maximal Ratio Combining (MRC) and Square Law Combining (SLC), where spectrum sensing performance is evaluated. Both the schemes are compared in single and multiple cognitive relay scenarios. The cognitive relays use amplify-and-forward relaying scheme for forwarding the received information towards the cognitive receiver. The assumed communication links are Nakagami-m fading where all the links are independent and identically distributed. The Nakagami shape parameter m is varied from 1 to 3. The receiver performance parameters, the probability of detection and false alarm are compared for MRC and SLC. The obtained simulated results help in the understanding and measuring of the improvement achieved through these diversity techniques in the energy detector.

Keywords: Cognitive Radio Network, MRC, SLC, Amplify-and-Forward, Relays, Nakagami Fading Channels.

1. INTRODUCTION

The radio spectrum, being one of the precious commodities, is at scarce as the last few decades show tremendous growth in the wireless access technologies. Bandwidth hungry applications which require high data rates and efficient spectrum utilization are on rise. However, the survey conducted by the Federal Communication Commission (FCC) shows that major portion of the spectrum is underutilized in the vast temporal and geographic zones of the world (FCC ET, 2002). To increase the spectral usage efficiency, cognitive radio networks evolved as a revolutionary technology. The cognitive radio network is an intelligent wireless network, where the Secondary Users (SUs) (unlicensed users) detect the idle spectrum bands via spectrum sensing. However, another promising feature of the cognitive radio network is interference avoidance to the Primary Users (PUs). This feature is achieved by changing transmission parameters of the SU (Hykin, 2005). For spectrum sensing, energy detector is the best and simplest sensing technique, employed at the receiver. Energy detector doesn't require any prior information about the transmitted signal (Visser *et al*., 2008). However, the hostile radio environment may cause the energy detector to give false results about the absence or presence of PUs activity. The energy detector detects no PU's activity when the radio link is affected by severe fading and shadowing.

To combat the uncertainty created by shadowing and fading effects of the radio environment, the concept of cooperation is introduced in the cognitive radio networks (Uchiyama *et al*., 2008) (Ghasemi *et al.*, 2007) (Mishra *et al*., 2006). Relay based cooperative spectrum sensing is described in detail by (Attapatu *et al*., 2009). Here, the radio links are assumed as Rayleigh fading and identically distributed. The signal fades as it propagates from transmitter towards receiver.

Nakagami fading channels is considered as the most popular fading channel in the wireless systems (Aalo, 1995). In (Zarin *et al.*, 2012), the authors have presented the receiver performance parameters in relay based spectrum sensing by considering the cooperative cognitive radio networks over Nakagami-m fading channel. Probability of detection (P_d) has been analyzed over Nakagami, Rician and Nakagami fading channels in (Ahmadian *et al*., 2010), where the authors have established that among cooperative spectrum sensing techniques, the energy detector gives better results. The realization of diversity techniques at receiver greatly increases the performance of the energy detector (Herath *et al*., 2011). The formulas for receiver parameters are derived by (Digham *et al.*, 2003) using diversity techniques of Square Law Combining (SLC) and Selection Combining (SC) over AWGN and Rayleigh fading communication paths (Fadel *et al*., 2007). Diversity techniques such as SC and Equal Gain Combining (ECG) are analyzed over Nakagami-m fading channel in (Herath *et al*., 2009), (Herath *et al*., 2008). In (Moe *et al*., 2000), the analysis of Maximal Ratio Combining (MRC) over Nakagami-m i.i.d fading channels is performed.

In our proposed research work, we use energy detector for spectrum sensing. The performance parameters of the energy detector are analyzed and

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compared using diversity techniques of SLC and MRC. All the cognitive relay stations act as passive radiators as they only take signal from PU and deliver it to the cognitive receiver without taking any hard decision about PUs presence or absence. The cognitive receive takes final decision about the presence or absence of PU by comparing the final output with some predefined decision threshold. The communication paths from PU to and from the cognitive relay stations are Nakagami-m fading links. All the links are assumed to be independent and identically distributed.

The paper organization is presented as follow. System description is explained in the Section 2 of the paper followed by the energy detector using SLC and MRC diversity techniques. Simulation results are presented in the Section 3 while the final concluding part is presented in the Section 4.

2. MATERIALS AND METHODS

System Description

A. Channel Model

The fading envelope of the transmitted signal at receiver is analyzed using Nakagami-m fading channel. The probability distribution of the Nakagami-m fading channel is related to the gamma distribution. Nakagami distribution is given by the Equation (1) as follows:

$$f|h_{xy}| = \left(\frac{m}{\Omega_{xy}}\right)^m \frac{2|h_{xy}|^{2m-1}}{\Gamma(m)} \times \exp\left(\frac{-m|h_{xy}|^2}{\Omega_{xy}}\right), |h_{xy}| \geq 0 \quad (1)$$

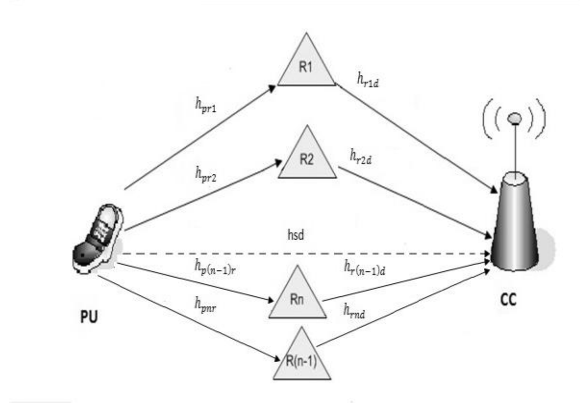
Where the gamma function $\Gamma(.)$ has both Rayleigh and Guassian distributions. The fading magnitude of the communication path and channel mean power is given by $h_{xy} = \gamma$, $\Omega_{xy} = E(|h_{xy}|^2) = \bar{\gamma}$, respectively. N at node *n* is Additive White Gaussian Noise (AWGN) with power spectral density N_0.

The shape parameter m is in the range of $\frac{1}{2}$ $to\ \infty$, the Nakagami distribution becomes Rayleigh distributions for m=1. All the links from the PU to the cognitive relay stations and from the cognitive relay stations to the cognitive centre are independent and identically distributed. The probability density function of the $|h_{xy}|^2$ over Nakagami channel is given by (Simon *et al.*, 2004):

$$f\left(|h_{xy}|^2, m, \Omega_{xy}\right) = \left(\frac{m}{\Omega_{xy}}\right)^m \frac{|h_{xy}|^{m-1}}{\Gamma(m)} \exp\left(\frac{-m|h_{xy}|^2}{\Omega_{xy}}\right) \quad (2)$$

B. Network Description

The cognitive radio network, where the SUs , being acting as the cognitive relays (passive radiators) form the cooperative cognitive radio network as shown in the **(Fig. 1).** Cognitive relay's concept in cognitive radio network not only improves the receiver parameters but it also combats the problems of hidden node as well as severe fading.



PU: Primary User
CC: Cognitive Center/Receiver
R: Cognitive Relay

Fig. 1: Cooperative Cognitive Radio Network

We have assumed a centralized sensing scenario. The cognitive relay stations observe the radio spectrum for PU's activity. As the PU gets active, the cognitive relay stations receive its transmitted signal and retransmits the amplified version of the received energy towards the cognitive receiver. The cognitive receiver acst as the Fusion Center (FC). Energy detector at cognitive receiver makes the final decision about the presence or absence of PU by comparing the received test static with the predefined decision threshold.

C. Single Cognitive Relay Setup

(Fig. 1) shows the single cognitive relay setup. Here, we have three nodes, primary transmitter, a cognitive relay station and cognitive receiver. The two hop communication takes place between the primary transmitter and the cognitive receiver. During time slot 1, the signal x from the primary transmitter is received at cognitive relay. The signal received at the relay station is given by:

$$y_{relay} = \alpha h_{sr} x + N_r \quad (3)$$

The primary user is active when the indicator $\alpha = 1$, whereas $\alpha = 0$, indicates no PU's activity in the Equation (3). h_{sr} represents channel gain and N_r shows the additive noise at cognitive relay station.

The cognitive relay station uses amplify-and-forward relaying scheme for forwarding the received energy towards the cognitive receiver. The amplified version of the received signal at cognitive relay is forwarded to the cognitive receiver during the time slot

2. The amplification factor of the cognitive relay depends on channel gain h_{sr}, as we are using variable gain relay. The amplification factor is given by:

$$\rho_r = \sqrt{\frac{E_r}{E_p|h_{sr}|^2 + N_o}} \quad (4)$$

Where E_p in the Equation (4) is the transmitted signal strength from the PU to the relay station and E_r represents the power limit at the cognitive relay station. At the second hop, the signal received at the cognitive receiver is given by:

$$y_{cr} = \rho_r \, y_{relay} \, h_{rcr} + N_1 \quad (5)$$

Where N_1 in the Equation (5) represents the AWGN noise at cognitive center and ρ_r is the amplification factor.
The SNR of the signal using relay station is given by:

$$\gamma = \frac{\gamma_{pr}\gamma_{rcr}}{\gamma_{pr} + \gamma_{rcr}} \quad (6)$$

Where γin the Equation (6) is represented in the Equation (7) as below:

$$\gamma = \frac{1}{N_0}\left(\frac{E_p E_r |h_{pr}|^2 |h_{rd}|^2}{\Omega_{pr} E_p + N_0 \quad \frac{E_r}{\Omega_{pr} E_p + N_0} \quad |h_{rd}|^2 + 1}\right) \quad (7)$$

In order to compare the performance of diversity techniques MRC and SLC, we incorporate a direct path communication between primary transmitter and cognitive receiver. The total end-to-end SNR using single relay and direct path can be given as in the Equation (8) as below:

$$\gamma = \gamma_{cr} + \gamma_{relay} \quad (8)$$

Here, the orthogonal communication paths between the primary transmitter and the cognitive receiver are assumed.

In the cognitive receiver, the energy detector performs spectrum sensing. The received energy first passes through Band Pass Filter (BPS), which removes the noise signal from the desired signal. This filtered signal is now squared at the squaring device and is then passed to the integrator. The integrator observes the received energy over an observation period of T and is then normalized to the noise variance. The detector then compares the output of the integrator with predefined threshold and decides about the presence or absence of PU by using the binary hypothesis.

D. Multiple Cognitive Relays setup

In the multiple cognitive relays setup, n number of cognitive relays collaborates for spectrum sensing. All the communication links are assumed as i.i.d Nakagami-m fading channels. As we have two hop communication between primary transmitter and cognitive receiver so at first hop, all the cognitive relays receive signal from primary transmitter over independent fading links. The signal received at k^{th} relay is given by the Equation (9) as below:

$$y_{relay\ (k)} = \alpha h_{srelay\ (k)} x + N_{relay\ (k)} \quad (9)$$

Where $k = 1,2,3,\dots,N$ and $N_{relay\ (k)}$ is the additive white Gaussian noise at k^{th} relay.
At second hop, the cognitive relays forward the magnified version of the received energy towards the cognitive receiver as given by the Equation (10):

$$\rho_{relay\ (k)} = \sqrt{\frac{E_{relay\ (k)}}{E_p|h_{srelay\ (k)}|^2 + N_o}} \quad (10)$$

Time Division Multiple Access (TDMA) has been assumed as the transmission protocol. All the communication paths, i.e., between (primary transmitter-cognitive relay) and the (cognitive relay-cognitive receiver), are orthogonal. We have assumed two diversity techniques at the cognitive receiver. The receiver uses the diversity techniques MRC or SLC to get the final output signal. The signal is integrated either through MRC or SLC and is given to the energy detector where the output is compared with decision threshold.

The total end-to-end SNR is given by the Equation (11) as below:

$$\gamma_{total} = \sum_{k=1}^{n} \frac{\gamma_{prelay\ (k)}\gamma_{relay\ (k)cr}}{\gamma_{prelay\ (k)} + \gamma_{relay\ (k)cr} + 1} \quad (11)$$

Where, $\gamma_{prelay\ (k)}$ and $\gamma_{relay\ (k)cr}$ in the Equation (11) are the channel gain coefficients from the PU to the relay stations and from the relay stations to the cognitive receiver, respectively.

Energy Decoders

(Fig. 2) shows the block diagram of energy detector. Here, the received signal is given to noise pre-filter or bandpass filter in order to filter out undesired signals from the original information signal. The output of the bandpass filter is squared at squaring device. The output of the square law device is then integrated over the time T and normalized to the noise variance. The time bandwidth product, $TB = u$, is an integer value. The output of an integrator is given by the Equation (12) as below (Urkowitz, 1967):

$$v = \frac{1}{T}\int_{t-T}^{t} y_{(r)}{}^2 dr \quad (12)$$

The output Y of the integrator is compared with the decision threshold and decision about the presence or absence of PU is made. The energy detector follows a binary

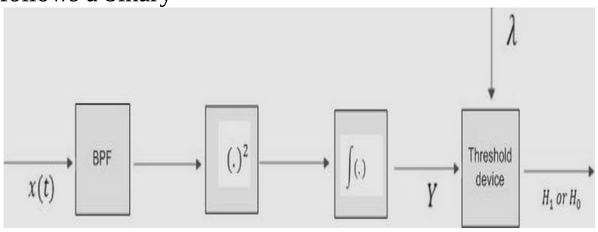


Fig. 2: Block diagram of Energy Detector

hypothesis to decide about the presence or absence of the primary user's activity. The binary hypothesis is given as below in the Equation (13):

$$\begin{cases} H_o : y_{cr} = N & \alpha = 0 \\ H_1 : y_{cr} = hx + N & \alpha = 1 \end{cases} \quad (13)$$

The Probability Density Function (PDF) of the output Y of an integrator is given by (Digham *et al.*, 2003) as shown in the Equation (14) below:

$$f_y\,(Y) = \begin{cases} \frac{1}{2^u\,\Gamma(u)} \cdot y^{u-1}.\,e^{-\frac{y}{2}} & ,H_0 \\ \frac{1}{2}\cdot\left(\frac{y}{2\gamma}\right)^{u-\frac{1}{2}} \cdot e^{\frac{-2\gamma+y}{2}}.\,I_{u-1}\left(\sqrt{2\gamma y}\right) & ,H_1 \end{cases} \quad (14)$$

Where $\Gamma(a)$ is the gamma function and $I_s\,(a)$ is the s-th order modified Bessel function of the first kind in the Equation (14).

AWGN channel these probabilities can be given as in the Equations (15) and (16):

$$P_d = p\left(y > \frac{\lambda}{H_1}\right)$$

$$P_d = Q_u\left(\sqrt{2\gamma}, \sqrt{\lambda}\right) \quad (15)$$

and

$$P_f = p\left(y < \frac{\lambda}{H_o}\right)$$

$$P_f = \frac{\Gamma(u, \lambda/2)}{\Gamma(u)} \quad (16)$$

Where λ in the Equations (15) and (16) is the decision threshold, $Q_u(.)$ in the Equation (15) is the generalized Marcum-Q function, and $\Gamma(.)$ in the Equation (16) is the incomplete gamma function.

Diversity techniques for cooperative cognitive radio network perform better over energy detector. We consider the performance comparison of two cooperative diversity reception schemes *i.e* , MRC and SLC.

A). Energy Detector with Square Law Combining

In SLC scheme, the squared and integrated version of received signal from all n cognitive relays is combined at cognitive receiver. If the signal from cognitive relay is Y_j , then the output signal combined at the cognitive receiver is given by the Equation (17) as below:

$$Y_{SLC} = \sum_{j=1}^{n} Y_j \quad (17)$$

Here j shows number of diversity feeders, Y_j represents signal from j^{th} cognitive relay in the Equation (17). The output Y_{SLC} in the Equation (17) acts as the test signal at the cognitive receiver. All the Nakagami fading paths are i.i.d. This output is then compared with the decision threshold value. When the output is greater than the decision threshold, hypothesis H_1 is selected else hypothesis H_o., as given in the Equation (14).

The total SNR for SLC diversity scheme is given by the Equation (18) as follows:

$$\gamma_{total} = \sum_{j=1}^{n} \gamma_j \quad (18)$$

Where γ_j in the Equation (18) is the SNR from j^{th} cognitive relay. Since we have assumed i.i.d so the average SNR can be given as in the Equation (19):

The probability of detection P_d and the proba

$$\overline{\gamma} = m\overline{\gamma_j} \quad (19)$$

The probability of false alarm is independent of SNR, therefore, it remains the same as given in the AWGN. However, the probability of detection depends on SNR and the signal face fading over n fading channels, so it can be evaluated using the Equation (20):

$$\overline{P}_{dSLC} = \int_0^{\infty} P_d\,(\gamma_{SLC}, \lambda) f(\gamma_{SLC}) d\gamma_{SLC}. \quad (20)$$

Where, $f(\gamma_{SLC})$ is the PDF of SNR over Nakagami fading channel.

B). Energy Detector with Maximal Ratio Combining

In MRC diversity scheme, the cognitive relays forward their amplified signal to the cognitive receiver.

The MRC combiner then combines all the received data. All the links are iid Nakagami fading. In MRC diversity reception, the received signals, $\{Y_j(t)\}_{j=1}^{n}$, where n shows number of diversity links are combined and weighted to obtain the final Equation (21) as given below:

$$Y_{MRC} = \sum_{j=1}^{n} h_j^* . Y_j \qquad (21)$$

The energy detector is then used to determine the output of MRC's combiner as test static. This Y_{MRC} as given in the Equation (21) is then compared with decision threshold in the energy detector.

The SNR at the MRC combiner is given by the Equation (22):

$$\gamma_{MRC} = \sum_{j=1}^{n} \gamma_j \qquad (22)$$

Where, γ_j is the SNR from j^{th} cognitive relay in the Equation(22).

3. RESULTS AND DISCUSSION

This section presents the simulation results. Receiver performance parameters, the probability of detection and probability of false alarm are simulated and compared. These probabilities have different effects on the spectrum's sensing performance. The probability of false alarm gives wrong detection about PU's activity and results in the lower spectrum utilization. However, the probability of detection gives accurate result about the PU's activity. $P_d \; vs \; \lambda \; (Decision \; Threshold)$ is plotted for both the MRC and SLC diversity schemes. Decision threshold is in the range of 0 to 70. All the communication links from the primary transmitter to the cognitive receiver via cognitive relay are Nakagami-m fading channels. The time bandwidth product is set to the value 2. The Nakagami-m parameter is varied from the value 1 to 3. The Nakagami parameter (m), shows channel quality and fading characteristics. The greater the value of m, the lower be the channel fading severity. **(Fig. 3)** shows the performance comparison of energy detector using diversity schemes SLC with MRC. Here, single relay scheme along with direct path has been deployed. With the increase in decision threshold, the probability of detection decreases. The Nakagami shape parameter m is varied from 1 to 3. It can be revealed from the graphs that MRC performs better than SLC. **(Fig. 4)** shows the scenario where multiple cognitive relays are deployed. Here, the number of cognitive relays is increased to 3. It can be seen from the plots that the probability of detection increases as the number of cognitive relays increases. Similarly, P_d increases as fading severity index m increases from 1 to 3. However, the best detection can be achieved using MRC when channel severity changes.

(Fig. 5) shows the performance variations of probability of detection, P_d, with the probability of false alarm, P_f. The plot in the **(Fig. 5)** clearly shows that the MRC is superior over SLC diversity scheme. It is shown that probability of detection increases for larger values of Nakagami Parameter. From the **(Fig. 5)**, It can also be seen that the number of cognitive relays as well as a greater value of m causes an increase in the probability of detection.

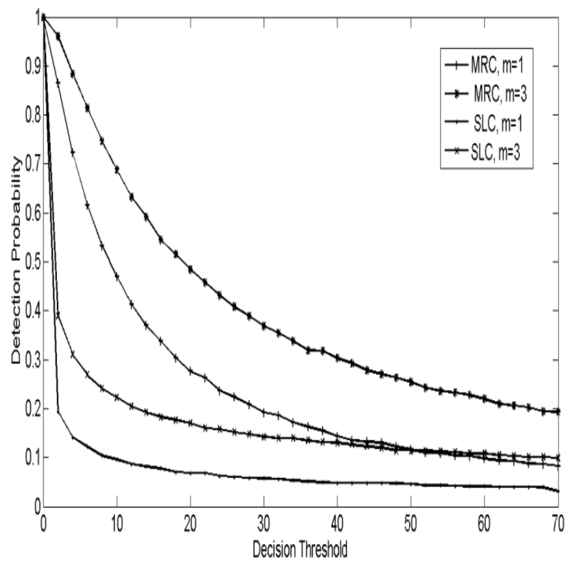


Fig. 3: Detection probability for MRC and SLC Schemes with n=1 and direct path over Nakagami fading channels (m=1 and m=3)

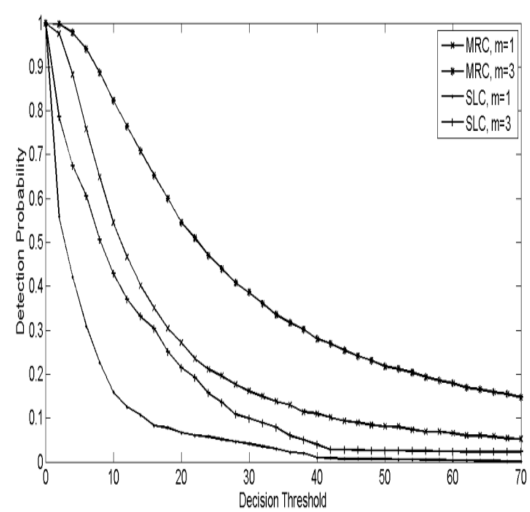


Fig. 4: Detection Probability for MRC and SLC Schemes with n=3 over Nakagami fading channels (m=1 and m=3)

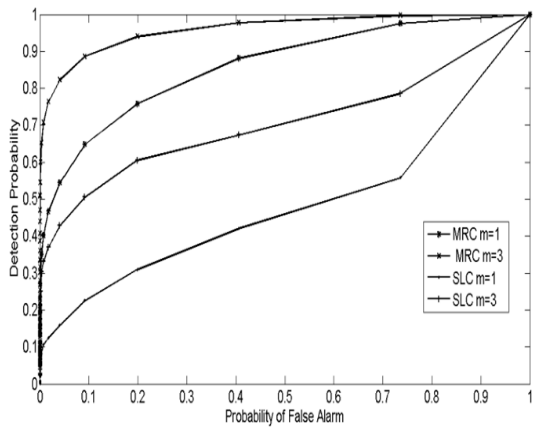


Fig. 5: Detection probability variations with probability of false alarm for n=3 relays using MRC and SLC Schemes.

4. CONCLUSION

Diversity reception techniques, MRC and SLC, in the energy detector are analyzed and simulated. These techniques are simulated over Nakagami fading channels. The obtained results help in computing the performance parameters of the energy detector, probability of false alarm and probability of detection over diversity reception techniques. MRC performs better than the SLC at both $m = 1$ and $m = 3$. However, MRC requires more transmission bandwidth than SLC, due to the reason that MRC passes complex data to the cognitive center, whereas, SLC forwards the real data towards the cognitive center.

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