

Performance of Cooperative Spectrum Sensing in Log-normal Shadowing and Fading under Fusion Rules

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Abstract

The performance of a cognitive radio (CR) user is sometimes limited due to severe fading or shadowing. In order to detect the primary user (PU) more accurately, we allow the CR users to cooperate by sharing their information. In this paper we investigate performance of single CR user and cooperative CR user based spectrum sensing (CSS) using energy detector (ED) in channels such as Log-normal shadowing, Rayleigh and Nakagami fading channels. Hard decision combining fusion rule (OR-logic, AND-logic and MAJORITY-logic) is performed at fusion center (FC) to make the final decision about the presence of PU. The performance of single CR user based spectrum sensing scheme has been assessed in terms of missed detection (P_m) and false detection probabilities (P_f). The performances of energy detector for different values of average SNR are characterized through complementary receiver operating characteristic (ROC) curves. Comparison among fusion rules has been investigated for a wide range of average SNR values in Rayleigh and Nakagami fading channels. A simulation model has been developed to evaluate performance of CSS in different fading environments. The performance of CSS has also been studied for various data fusion rules in Log-normal shadowing channel.

Keywords: *Cognitive radio, energy detection, fading channels, fusion rules, detection probability*

1. Introduction

Cognitive radio (CR) technique has been proposed to solve the conflicts between spectrum scarcity and spectrum under utilization [1]. It allows the CR users to share the spectrum with primary users (PUs) by opportunistic accessing. The CR user can use the spectrum only when it does not create any disturbance or interference to PUs. Therefore, spectrum sensing is the key of cognitive radio technology since it needs to detect the presence of PUs accurately and quickly. In many wireless applications, it is of great interest to check the presence and availability of an active communication link when the PU signal is unknown. In such scenarios, one appropriate choice consists of using an energy detector (ED) which measures the energy in the received waveform over an observation time window [2]. Spectrum sensing is a hard task because of shadowing, fading and time-varying nature of wireless channels [3]. Due to the severe multipath fading, a cognitive radio may fail to detect the presence of the PU. The detection performance of a CR can be primarily determined on the basis of two metrics: probability of false alarm, which denotes the probability of a CR user declaring that a PU is present when the spectrum is actually free, and the probability of detection, which

denotes the probability of a CR declaring that a PU is present when the spectrum is indeed occupied by the PU [4]. Cooperative spectrum sensing improves the detection performance where all CR users sense the PU individually and send their sensing information in the form of 1-bit binary decisions (1 or 0) to Fusion center (FC). The hard decision combining rule (OR, AND, and MAJORITY logic) is performed at FC using a counting rule or voting rule to make the final decision regarding whether the PU is present or not [5-9]. However, the existing works only examined the collaborative spectrum sensing with OR-logic fusion, using ED in Log-normal shadowing and the Rayleigh fading channel [6, 7]. Comparison among hard decision fusion rules for the case of cooperative spectrum sensing has been investigated in a Suzuki fading channel [5]. We note that the analytical expression for probability of detection in Rayleigh and Nakagami fading channel was given in [10, 11]. The performance of single CR user based spectrum sensing in fading channels such as Rayleigh, Nakagami, Weibull has been studied in [12]. The performance of cooperative spectrum sensing with censoring of cognitive radios in Rayleigh fading channel has been evaluated in [13, 14].

Contribution of the paper: In this paper, we have presented a new simulation model to study the performance of single CR and cooperative CR based spectrum sensing (CSS), using energy detector, over Log-normal shadowing, Rayleigh and Nakagami fading channels. Results obtained via our simulation test bed for the case of Log-Normal shadowing channel match exactly with the results obtained in the paper [6] under same scenario. Similarly, simulation results for the case of single CR user based spectrum sensing in Rayleigh and Nakagami fading channel match exactly with the theoretical results shown in paper [11]. The performance of CSS has been evaluated for different number of CR users in Log-normal shadowing, Rayleigh and Nakagami faded channels through complementary receiver operating characteristic (ROC) curves (plot of Q_m vs. Q_f). In particular, the performance of hard decision fusion rules under Log-normal shadowing, Rayleigh and Nakagami fading channels has been made.

The rest of the paper is organized as follows. In Section 2, the system model under consideration is described. It briefly describes the probabilities of detection and false alarm over additive white Gaussian noise (AWGN) channel, and fading channels. Our simulation model is presented in Section 3. Results and discussions are presented in Section 4. Finally we conclude in Section 5.

2. System Model

The energy detection method is the common method for detection of unknown signals in noise [2]. The block-diagram of an energy detector is shown in Figure 1. The input band pass filter (BPF) selects the center frequency f_c , and bandwidth of interest, W .

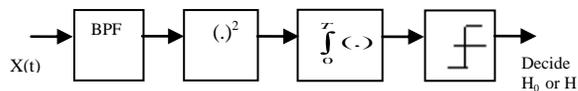


Figure 1. Block Diagram of an Energy Detector

The output of BPF filter is passed to a squaring device to measure the received energy. Then an integrator is placed to determine the observation interval, T . Finally, output of the integrator, Y , is compared with a detection threshold, λ to decide whether the signal is present or not. We assume that each CR user employs same energy detector and use the same threshold (λ).

Table 1. Notations and Descriptions

Description	Symbol
Signal waveform	$s(t)$
Noise waveform which is modeled as a zero-mean white Gaussian random process	$n(t)$
One-sided noise power spectral density	N_{01}
Signal energy, E_s	$E_s = \int_0^T s^2(t)dt$
Signal-to-noise ratio (SNR)	$\gamma = \frac{E_s}{N_{01}}$
Average SNR	$\bar{\gamma}$
One-sided bandwidth (Hz), i.e., positive bandwidth of low-pass (LP) signal	W
Time-bandwidth product	$m = TW$
Carrier frequency	f_c
Probability of detection	P_d
Probability of false alarm	P_f
Probability of missed detection	$P_m = 1 - P_d$
Hypothesis 0 corresponding to no signal transmitted	H_0
Hypothesis 1 corresponding to signal transmitted	H_1
A Gaussian variate with mean μ and variance σ^2	$N(\mu, \sigma^2)$

The received signal $x(t)$ can be represented as

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

According to the sampling theorem, the noise process can be expressed as [15],

$$n(t) = \sum_{i=-\infty}^{\infty} n_i \sin c(2Wt - i), \quad (2)$$

where $\sin c(x) = \frac{\sin(\pi x)}{\pi x}$ and $n_i = n(\frac{i}{2W})$. One can easily check that

$$n_i \sim N(0, N_{01}W), \text{ for all } i. \quad (3)$$

The noise energy can be approximated over the time interval $(0, T)$, as [2, 11]:

$$\int_0^T n^2(t)dt = \frac{1}{2W} \sum_{i=1}^{2m} n_i^2, \quad (4)$$

If we define $n'_i = \frac{n_i}{\sqrt{N_{01}W}}$, then the decision statistic Y can be written as [2, 11]:

$$Y = \sum_{i=1}^{2m} n_i'^2 \quad (5)$$

Y can be viewed as the sum of the squares of $2m$ standard Gaussian variates with zero mean and unit variance. Therefore, Y follows a central chi-square (χ^2) distribution with $2m$ degrees of freedom. The same approach is applied when the signal $s(t)$ is present with the replacement of each n_i by $n_i + s_i$ where $s_i = s(\frac{i}{2W})$. The decision statistic Y in this case will have a non-central χ^2 distribution with $2m$ degrees of freedom and a non centrality parameter 2γ [2, 11]. We can describe the decision statistic in short-hand notations as:

$$Y \sim \begin{cases} \chi_{2m}^2, & H_0, \\ \chi_{2m}^2(2\gamma), & H_1. \end{cases} \quad (6)$$

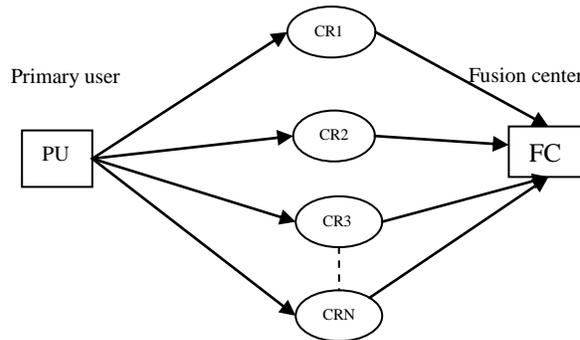


Figure 2. Block Diagram of Cooperative Spectrum Sensing

2.1. Non-fading Environment (AWGN Channel)

In non-fading environment the probabilities of detection and false alarm are given by the following formulas [2, 11].

$$P_d = P(Y > \lambda / H_1) = Q_m(\sqrt{2\gamma}, \lambda) \quad (7)$$

$$P_f = P(Y > \lambda / H_0) = \Gamma(m, \lambda/2) / \Gamma(m) \quad (8)$$

where $\Gamma(\dots)$ is the incomplete gamma function [17] and $Q_m(\dots)$ is the generalized Marcum Q-function [16]. If the signal power is unknown, we can first set the false alarm probability P_f to a specific constant. By equation (8), the detection threshold λ can be determined. Then, for the fixed number of samples $2TW$ the detection probability P_d can be evaluated by substituting λ in (7). As expected, P_f is

independent of γ since under H_0 there is no primary signal present. When h is varying due to fading, equation (7) gives the probability of detection as a function of the instantaneous SNR, γ . In this case, the average probability of detection (P_d) may be derived by averaging (7) over fading statistics [6],

$$P_d = \int_{\mathcal{Q}_m(\sqrt{2\gamma}, \sqrt{\lambda})} f_\gamma(x) dx \quad (9)$$

where $f_\gamma(x)$ is the probability density function (pdf) of SNR under fading.

2.2. Log-normal Shadowing

The linear channel gain may be modeled by Log-normal random variable e^X where X is a zero-mean Gaussian random variable with variance σ^2 . Log-normal shadowing is usually characterized in terms of its dB-spread, σ_{dB} which is related to σ by $\sigma = 0.1 \ln(10) \sigma_{dB}$ [6].

2.3. Rayleigh Fading Channel

If the signal amplitude follows a Rayleigh distribution then the SNR γ follows an exponential PDF given by [11]:

$$f(\gamma) = \frac{1}{\gamma} \exp\left(-\frac{\gamma}{\bar{\gamma}}\right) \quad \gamma \geq 0, \quad (10)$$

The average P_d in this case, \bar{P}_{dRay} , can be evaluated by substituting (10) in (9), here $f_\gamma(x) = f(\gamma)$.

$$\bar{P}_{dRay} = e^{-\frac{\lambda}{2}} \sum_{k=0}^{m-2} \frac{1}{k!} \left(\frac{\lambda}{2}\right)^k + \left(\frac{1+\bar{\gamma}}{\bar{\gamma}}\right)^{m-1} \left(e^{-\frac{\lambda}{2(1+\bar{\gamma})}} - e^{-\frac{\lambda}{2}} \sum_{k=0}^{m-2} \frac{1}{k!} \left(\frac{\lambda \bar{\gamma}}{2(1+\bar{\gamma})}\right)^k \right) \quad (11)$$

2.4. Nakagami Fading Channel

If the signal amplitude follows a Nakagami distribution then PDF of γ follows a gamma PDF given by [11]:

$$f(\gamma) = \frac{1}{\Gamma(M)} \left(\frac{M}{\bar{\gamma}}\right)^M \gamma^{M-1} \exp\left(-\frac{M}{\bar{\gamma}} \gamma\right) \quad \gamma \geq 0, \quad (12)$$

where M is the Nakagami parameter. The average P_d in the case of Nakagami channel (\bar{P}_{dNak}) can be evaluated by substituting (12) in (9), here $f_\gamma(x) = f(\gamma)$.

$$\bar{P}_{dNak} = \alpha \left[G_1 + \beta \sum_{n=1}^{m-1} \frac{(\lambda/2)^n}{2n!} {}_1F_1(M; n+1; \frac{\lambda}{2} \frac{\bar{\gamma}}{M+\gamma}) \right] \quad (13)$$

where ${}_1F_1(.,.;.)$ is the confluent hyper geometric function ($\equiv \Phi(.,.,.)$) [17, section 9.2],

$$\alpha = \frac{1}{\Gamma(M) 2^{M-1}} \left(\frac{M}{\bar{\gamma}}\right)^M, \quad (14)$$

$$\beta = \Gamma(M) \left(\frac{2\bar{\gamma}}{M+\gamma}\right)^M e^{-\lambda/2}, \quad (15)$$

and

$$G_1 = \frac{2^{M-1}(M-1)!}{\left(\frac{M}{\gamma}\right)^M} \frac{\bar{\gamma}}{M+\gamma} e^{-\frac{\lambda}{2} \frac{M}{M+\gamma}} \left[\left(1 + \frac{M}{\gamma}\right) \left(\frac{M}{M+\gamma}\right) \right]^{M-1} \times L_{M-1}\left(-\frac{\lambda}{2} \frac{\bar{\gamma}}{M+\gamma}\right) + \sum_{n=0}^{M-2} \left(\frac{M}{M+\gamma}\right)^n L_n\left(-\frac{\lambda}{2} \frac{\bar{\gamma}}{M+\gamma}\right) \quad (16)$$

where $L_n(\cdot)$ is the Laguerre polynomial of degree n [17, section 8.970]. We can obtain an alternative expression for \bar{P}_{dRay} when setting $M=1$ in (13) and this expression is numerically equivalent to the one obtained in (11).

2.5. Fusion Rule

Let N denote the number of users sensing the spectrum. Each CR user makes its own decision regarding the presence of the PU, and forwards the binary decision (1 or 0) to fusion center (FC) for data fusion as shown in Fig.2. The PU is located far away from all CRs. All the CR users receive the primary signal with same local mean signal power, i.e. all CRs form a cluster with distance between any two CRs negligible compared to the distance from the PU to a CR. For simplicity we have assumed that the noise, fading statistics and average SNR are the same for each CR user. We consider that the channels between CRs and FC are ideal channels (noiseless). Assuming independent decisions, the fusion problem where k out of N CR users are needed for decision can be described by binomial distribution based on Bernoulli trials where each trial represents the decision process of each CR user. The generalized formula for overall probability of detection, Q_d for the k out of N rule is given by [5]:

$$Q_d = \sum_{l=k}^N \binom{N}{l} P_d^l (1 - P_d)^{N-l} \quad (17)$$

where P_d is the probability of detection for each individual CR user as defined by equations (7) & (9).

The OR-fusion rule (i.e. 1 out of N rule) can be evaluated by setting $k=1$ in equation (17):

$$Q_{d,OR} = \sum_{l=1}^N \binom{N}{l} P_d^l (1 - P_d)^{N-l} = 1 - \binom{N}{0} P_d^0 (1 - P_d)^{N-0} \Big|_{l=0} = 1 - (1 - P_d)^N \quad (18)$$

The AND-rule (i.e. N out of N rule) can be evaluated by setting $k=N$ in equation (17):

$$Q_{d,AND} = \sum_{l=N}^N \binom{N}{l} P_d^l (1 - P_d)^{N-l} = (P_d)^N \quad (19)$$

Finally, for the case of MAJORITY-rule (i.e. $N/2$ out of N) the

$Q_{d,MAJ}$ is evaluated by setting $k = \lfloor N/2 \rfloor$ in (17).

3. Simulation Model

The simulation is developed in MATLAB using the following system parameters: Time-bandwidth product, $m = 5$, average SNR, $\bar{\gamma} = 10$ dB and $Q_f = 0.1$. To obtain the fading channel power distribution one can rely on the amplitude/envelope distribution. Let us assume that each multipath component (MPC) obeys an instantaneous fading

amplitude/envelope of $a = |h|$ with PDF $P_a(a)$. The instantaneous power of the said fading channel is thus given as $g = a^2$ with PDF $P_g(g)$; its average $\bar{g} = E\{g\} = E\{a^2\}$ is often normalized to unity, i.e. $\bar{g} = 1$, using a simple PDF transformation, one can relate the PDF of the channel power with the one of the envelope which is given by [18]:

$$P_g(g) = \frac{1}{2\sqrt{g}} P_a(\sqrt{g}) \quad (20)$$

And inversely

$$P_a(a) = 2a.P_g(a^2) \quad (21)$$

3.1. Probability of Detection Simulation in Non-fading (pure AWGN) Channel

- i. Generate a BPSK signal $s(t)$ with 1, -1 up to $2TW$ samples and generate AWGN signal $n(t)$ with zero mean, variance $N_{01}W$ i.e., $N(0, N_{01}W)$, here $N_{01} = E_s / \gamma$.
- ii. Received signal is $x(t) = s(t) + n(t)$.
- iii. Now $x(t)$ is the input to BPF and output of squaring device is $x^2(t)$ and passes through integrator. Then the output of integrator Y is $Y = \sum_{i=1}^{2m} n_i'^2$ (from equation (5)).
- iv. Detection threshold (λ) can be obtained for each specific value of P_f (from equation (8)).
- v. Compare Y with detection threshold (λ).
- vi. If Y is greater than λ , binary decision '1' which indicates PU is present otherwise binary decision '0' which indicates PU is absent.
- vii. The steps (i) to (vi) have been repeated for N number of CRs.
- viii. Now each CR user has its own 1-bit binary decision (D), let $H = D_{CR1} + D_{CR2} + D_{CR3} \dots + D_{CRN}$, then OR-logic fusion (if $H \geq 1$), AND-logic fusion (if $H = N$) MAJORITY-logic fusion (if $H \geq N/2$) are performed at FC.
- ix. The steps (i) to (viii) have been repeated a large number of times and then the average values of Q_d and Q_m have been estimated.

3.2. Probability of Detection Simulation in Log-normal Shadowing

- i. To generate log-normal shadowing channel gain h , the procedure mentioned as in sub section 2.2 of section 2, is followed.
- ii. Now the received signal is $x(t) = h * s(t) + n(t)$.
- iii. Then the steps from (iii) to (ix) as in subsection 3.1 of 3 are followed.

3.3. Probability of Detection Simulation in Rayleigh Fading Channel

- i. Envelope/amplitude of channel h follows a Rayleigh distribution. To generate Rayleigh distribution, we have to find the Rayleigh parameter that can be found by considering second moment of Rayleigh distribution set to unity.
- ii. Generate two Gaussian random variables X_1 and X_2 with mean zero and variance 0.5, $|h| = \sqrt{X_1^2 + X_2^2}$ gives Rayleigh distribution.

- iii. Now the received signal is $x(t) = h * s(t) + n(t)$.
- iv. Then the steps from (iii) to (ix) as in subsection 3.1 of 3 are followed.

3.4. Probability of Detection Simulation in Nakagami Fading Channel

- i. Envelope/amplitude of channel h follows a Nakagami distribution. Nakagami distribution can be generated from Gamma distribution. To find the Nakagami parameters (M, w), second moment of Nakagami distribution is set to unity. Fix the value of M as 1, 2 and 3 and find other parameter w .
- ii. If the random variable $Y \sim \text{gamma}(u, v)$ then we get $h \sim \text{Nakagami}(M, w)$ by setting $u=M, v = w/M$ in $Y \sim \text{gamma}(u, v)$ and $h = \text{square root}(Y)$.
- iii. Now f the steps (iii) and (ix) as in subsection 3.1 of 3 are followed.

4. Results and Discussion

Using the above mentioned simulation testbed (in MATLAB), the performance of above single CR and cooperative CR user based spectrum sensing schemes have been evaluated.

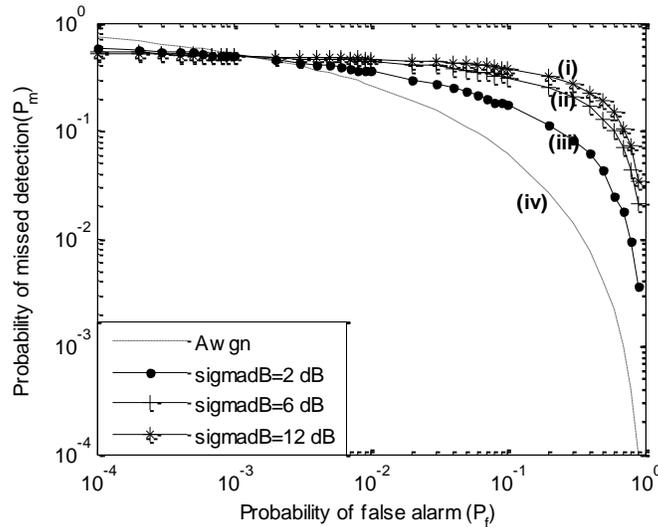


Figure 3. Complementary ROC (P_m vs. P_f) under log-normal Shadowing with Different dB-spreads ($\bar{\gamma} = 10$ dB, $m = 5$). AWGN curve is Provided for Comparison

Figure 3 shows complementary ROC curves for three different dB spreads. A plot for non-fading (pure AWGN) case is also provided for comparison. Comparing the AWGN curve with those corresponding to shadowing, we observe that, as increase in dB-spreads from 2 dB to 12 dB, probability of missed detection increases [curves (i) to (iii)]. Spectrum sensing is difficult in the presence of shadowing. Moreover, as shadowing becomes more intense (higher dB-spread), the received signal strength decreases due to some obstacles in the environment and hence energy detector's performance degrades.

Figure 4 shows the complementary ROC curves under AWGN, Rayleigh and Nakagami fading scenarios. We observe that Rayleigh fading degrades performance of energy detector

significantly. To achieve $P_m=0.01$, probability of false alarm is greater than 0.9, which results in poor spectrum utilization. Analytical results for the case of Rayleigh fading channel which are obtained from equation (14) are presented here for comparing with our simulation results. Different values of Nakagami parameter, $M=1$ and 3 are considered. Rayleigh fading channel characteristics would be achieved in a Nakagami fading channel if M is set to 1 [curve (i)]. Increase in Nakagami parameter $M=1$ to 3, significantly decrease the probability of missed detection [curves (i) to (ii)]. We can say that the performance of energy detector in Nakagami fading channel (particularly for $M=3$) is better than the performance in Rayleigh fading channel ($M=1$). Analytical results for the case of Nakagami fading channel which are obtained from equation (16) are presented here for comparing with our simulation results.

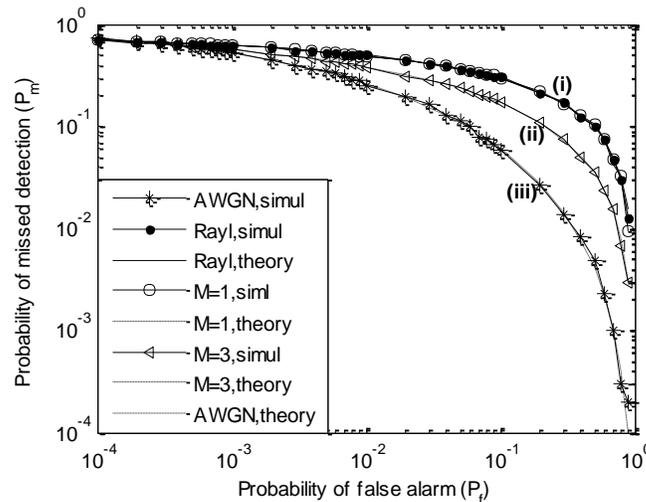


Figure 4. Complementary ROC (P_m vs. P_f) under Rayleigh and Nakagami Fading ($\gamma=10$ dB, $m=5$). AWGN Curve is Provided for Comparison

Figure 5 shows the performance comparison of single user’s energy detection based spectrum sensing in the presence of shadowing, Rayleigh and Nakagami fading channels. Nakagami parameter and shadowing dB-spread are assumed to be $M=3$, $\sigma_{dB}=2$ dB, respectively. Comparing the AWGN curve with those corresponding to fading, we observe that spectrum sensing is difficult in the presence of shadowing, Rayleigh and Nakagami fading channel. The performance of energy detector is the best in Nakagami fading channel than performance in Log-normal shadowing and Rayleigh fading channel.

Figure 6 and Figure 7 show complementary ROC (Q_m vs. Q_f) curves for different number of cooperative CR users under Log-normal shadowing ($\sigma_{dB}=2$ dB) and Rayleigh-Nakagami fading respectively. Non-fading AWGN curve is also shown for comparison (AWGN and $N=1$ curves matched with curves in [6],[11]). We can observe in these figures that fusing the decisions of different CR users cancels the effect of shadowing or fading on the detection performance effectively. Moreover, with increase in N [curves (i) to (v) in both figures), cooperative spectrum sensing outperforms AWGN local sensing and single CR user based sensing. This is due to the fact that for larger N , with high probability there will be a user with a channel better than that of the non-fading AWGN case.

Figure 8 shows the probability of detection (Q_d) vs. $\bar{\gamma}$ under Log-normal shadowing, Rayleigh and Nakagami fading scenarios for different number of cooperative CR users. Nakagami parameter and shadowing dB-spread are assumed to be $M=2$, $\sigma_{dB}=2$ dB, respectively. We have chosen Q_f as 0.1 and $m=5$ for each curve in this figure. We observe that there is an excellent improvement in performance of CSS with increase in N and average SNR. In particular, for a probability of detection equal to 0.9, single user ($N=1$) spectrum sensing in Nakagami fading channel requires $\bar{\gamma} \approx 12$ dB while cooperative sensing with $N=3$ only needs approximately 7 dB for individual CR users. The Log-normal shadowing with 2 dB- spreads performs better than Nakagami ($M=2$) fading channel in both cases of single and cooperative CR user based sensing as average SNR increases from 0 dB to 20 dB.

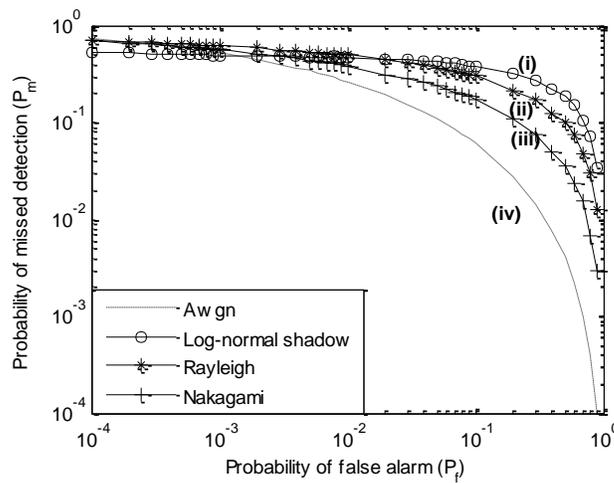


Figure 5. Complementary ROC (P_m vs. P_f) under Different Fading Channels ($\bar{\gamma}=10$ dB, $m=5$). AWGN Curve is Provided for Comparison

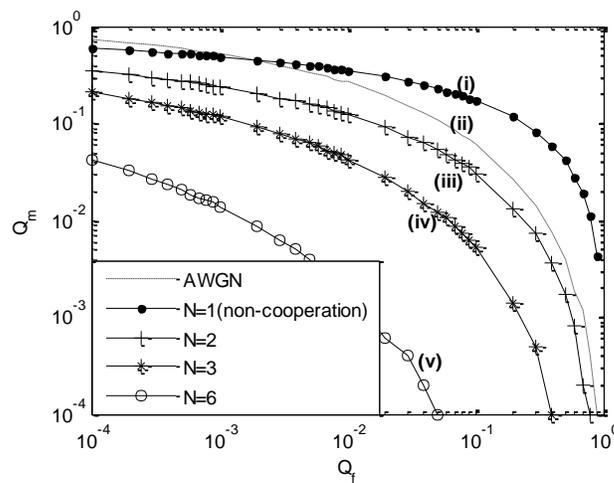


Figure 6. Q_m vs. Q_f under log-normal Shadowing ($\sigma_{dB}=2$ dB) for Different Number of Cooperative CR users ($\bar{\gamma}=10$ dB, $m=5$), OR Rule

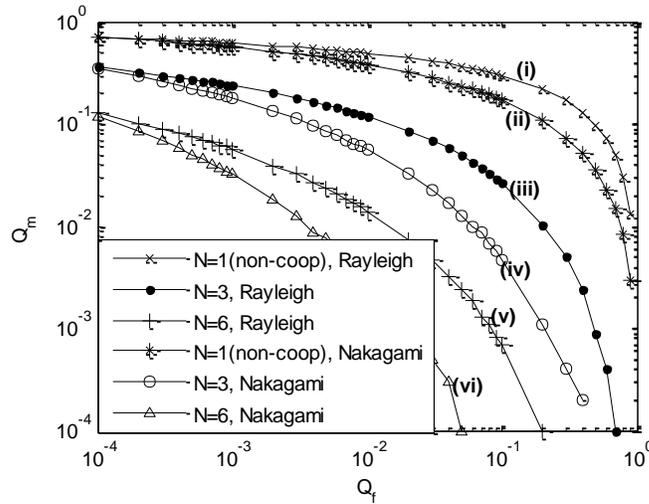


Figure 7. Q_m vs. Q_f under Rayleigh and Nakagami Fading ($M=3$) for Different Number of Cooperative CR users ($\bar{\gamma}=10\text{dB}$, $m=5$), OR Rule

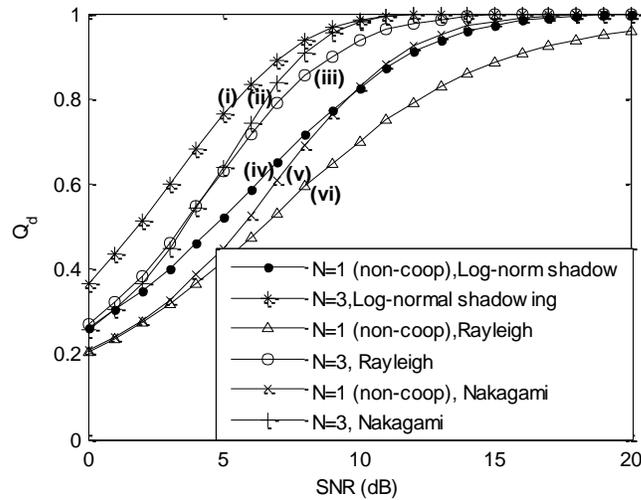


Figure 8. Q_d vs. $\bar{\gamma}$ under Different Fading Channel ($M=3$) for Different Number of Cooperative CR Users ($Q_f=0.1$, $m=5$), OR Rule

Figure 9 shows the performance of hard decision fusion rules and their comparison based on complementary receiver operating characteristics (ROC) curves for 3 cooperative CR users under Log-normal shadowing channel. We have chosen $\sigma_{dB}=2$ dB, $m=5$ and average SNR $\bar{\gamma}=10$ dB. We observe that for a particular value of $Q_f=0.1$, probability of missed detection (Q_m) is 0.005, 0.1 and above 0.8 for OR-logic fusion, MAJORITY and AND-logic fusions respectively. We can say that OR-rule performs better than MAJORITY and AND-logic fusions (curves (i), (iii) & (iv) respectively). The curve (ii) for non-cooperation case ($N=1$) is provided for comparison purpose.

Figure 10 shows the performance of hard decision rules and their comparison based on Q_d vs. average SNR $\bar{\gamma}$ for 3 cooperative CR users under Rayleigh and Nakagami fading channel ($M=3$), $m = 5$ and $Q_f = 0.1$. In case of performance of CSS in Nakagami fading channel, for a particular value of average SNR i.e., 6 dB, probability of detection is above 0.8, 0.35 and 0.01 for OR-logic, MAJORITY-logic and AND-logic respectively. We can say that OR-rule performs better than MAJORITY and AND-logic fusions [curves (i), (iii) and (v) respectively]. Similarly, the performance of CSS under OR-logic fusion outperforms the other fusion rules such as MAJORITY and AND-logic fusions [curves (ii), (iv) and (vi) respectively] in Rayleigh fading channel. Under all cases of logic fusions we observe that the performance of CSS in Nakagami fading channel is better than the performance in Rayleigh fading channel.

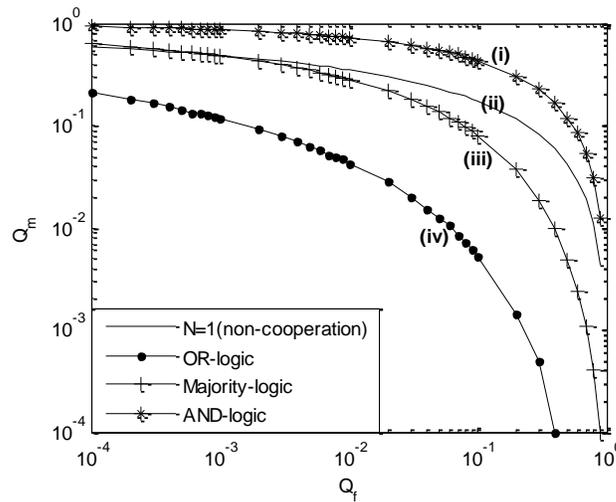


Figure 9. Performance of Hard Decision Fusion Rules via Q_m vs. Q_f under Log-normal Shadowing ($\sigma_{dB}=2$ dB) for $N=3$ CR Users

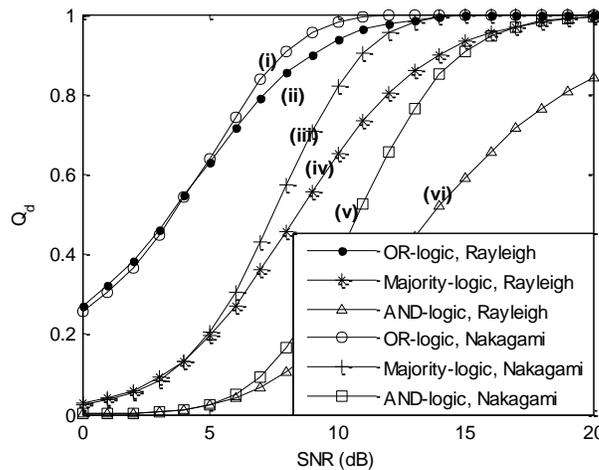


Figure 10. Performance of Hard Decision Fusion Rules via Q_d vs. $\bar{\gamma}$ under Rayleigh and Nakagami Fading Channel ($M=3$) for $N=3$ CR Users

5. Conclusion

We have investigated the performance of single CR and cooperative CR based spectrum sensing schemes using energy detection under different fading channels. We develop a simulation model for the evaluating the performance in terms of miss detection and false alarm probabilities. The performance of CSS also has been investigated via probability of detection versus different average SNR values in Log-normal shadowing, Rayleigh and Nakagami fading channels. The performance of CSS has been investigated for different data fusion rules (OR, MAJORITY and AND-rules) using our simulation testbed and the performance has been compared with each other through complementary ROC. Finally we have shown that cooperative spectrum sensing using energy detection performs better for OR-logic fusion rule as compared to MAJORITY and AND- logic fusions under same average SNR conditions in Rayleigh and Nakagami fading channel. The above study is useful in designing a cooperative cognitive network.

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