Research Article

On Performance of Weighted Fusion Based Spectrum Sensing in Fading Channels

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Cognitive radio (CR) is a promising technology for efficient utilization of underutilized spectrum since it is able to detect the occupancy of primary users (PUs) in the different parts of the spectrum. As the sensing channel uncertainties limit the reliability of the spectrum sensing decision, cooperation among multiple CR users is often used to improve the spectrum sensing decision. In this paper, the performance of single CR user based spectrum sensing and cooperative CR user based spectrum sensing (CSS) has been assessed in several channels such as AWGN, log-normal, Hoyt (or Nakagami-q), Rayleigh, Rician (or Nakagami-n), Nakagami-m, and Weibull channels. The performance of two spectrum sensing schemes based on assigning weights to CR users such as (a) weighting according to sensing channel preference and (b) weighting according to the value of decision statistic is evaluated. The performance comparison between two weighting schemes under several fading channels has been made. The performance of proposed CSS has been illustrated through complementary receiver operating characteristics (CROC) for different fading channels. The effects of weighting factors (k and R_f) on overall missed detection performance are shown. The performance of CSS with OR-logic fusion as a special case is also presented for comparison purpose.

1. Introduction

Cognitive radio (CR) techniques have been proposed to overcome spectrum scarcity by exploiting underutilized spectrum [1]. It allows the CR users to share the spectrum with primary users (PUs) by opportunistic access. Cognitive radio is defined as a wireless radio device that can adapt to its operating environment through sensing in order to facilitate efficient communications. The CR user can use the spectrum only when it does not create any disturbance or interference to PUs. Thus sensing of vacant spectrum is very important for successful operation of cognitive radio network. Due to the severe multipath fading, a CR may fail to notice the presence of the PU. Therefore, spectrum sensing is an important aspect of CR technology since it needs to sense the PUs accurately and quickly [2, 3]. Spectrum sensing is a hard task because of shadowing, fading, and time-varying nature of wireless channels [4]. The performance of single CR user based spectrum sensing has been studied in several channels such as additive white Gaussian noise (AWGN), log-normal shadowing, Rayleigh, Nakagami-m, and Weibull in

[5] where the Nakagami-m and Weibull distribution provide flexibility in describing the fading severity of the channel and consider special cases such as the well known Rayleigh fading for a certain value of the fading parameter. Cooperative spectrum sensing (CSS) improves the detection performance where all CRs sense the PU individually and send their sensing information in the form of 1-bit binary decisions (1 or 0) to fusion center (FC) [6, 7]. The hard decision fusion rules such as OR-logic, AND-logic, and Majority logic can be performed at FC to make the final decision regarding whether the PU is present or not. The performance of CSS using EDs has been studied in channels such as log-normal shadowing, Hoyt (or Nakagami-q), Rayleigh, Nakagami-m, Rician (or Nakagami-n), and Weibull in [8–11]. Hoyt distribution [12–14], also known as Nakagami-q distribution (q being the fading severity parameter), allows us to span the range of fading distribution from one-sided Gaussian ($q = 0$) to Rayleigh fading ($q = 1$) and is used extensively for modeling channels which are more severe than Rayleigh fading wireless links. Rician distribution also known as Nakagami-n distribution is used extensively for modeling less severe

than Rayleigh fading wireless links. Weibull fading has been proved to exhibit excellent fitting for indoor [15] and outdoor [16] environments. Comparison among hard decision fusion rules for the case of CSS has been investigated in a Suzuki fading channel [17]. In most of the existing work on CSS, each CR is treated in the same manner, while fusing decisions from a number of participating CRs, through the sensing channel of the CRs, may be under fading with different level of severity. Thus we require a scheme where decisions from CRs are assigned appropriate weights. The weighted cooperative spectrum sensing (WCSS) scheme performance has been investigated in [18–21].

However, the existing works examined the CSS using different weighting schemes in log-normal shadowing and Rayleigh and Nakagami-m fading channels only [22]. In this paper, we extend performance analysis of CSS in Hoyt, Rician and Weibull fading channels. We note the analytical expression for probability of detection at CR level in Rayleigh and Nakagami-m fading channels [2]. We develop a simulation test bed to assess the probability of detection at CR equipped with energy detector under several types of fading in sensing channel. Further we compare results (specifically, Rayleigh and Nakagami-m) obtained via our simulation model with the results obtained using the expressions developed in [2]. Thus we verify our simulation testbed. The performance of single CR user and cooperative CR user based spectrum sensing has been assessed in terms of complementary receiver operating characteristics (CROC) in various fading channels. The performance comparison of CSS among fading channels using two weighting schemes, namely, weighting based on channel preference and weighting based on decision statistics, has been evaluated. The performance of weighting schemes is also compared with the performance of CSS without weighting (OR-logic fusion). The effects of weighting factors on overall missed detection performance at FC are also highlighted in this paper. More precisely, our contributions in this paper are as follows:

(i) evaluation of cooperative spectrum sensing (CSS) using two weighted based schemes;

(ii) performance evaluation has been extended in Hoyt, Rician and Weibull fading channels in addition to Rayleigh, Nakagami-m, and log-normal shadowing in sensing channel;

(iii) the performance in several fading channels as mentioned above has been compared;

(iv) CROC has been obtained for CSS as well as single CR based sensing in several fading channels;

(v) the weighting schemes based CSS are compared with conventional OR-logic based fusion without weighting;

(vi) a simulation test bed has been developed in MATLAB and validated to evaluate the performance as indicated above.

The rest of the paper is organized as follows. In Section 2, the system model under consideration is described and we briefly describe the probabilities of detection and of false
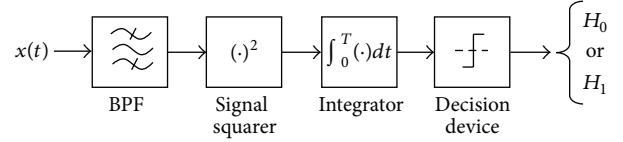

FIGURE 1: Block diagram of an energy detector.

alarm over additive white Gaussian noise (AWGN) channel, shadowing and fading channels, and weighting schemes. 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

We consider a network of N cognitive radio (CR) users, one primary user (PU), and one fusion center (FC). A CR user, which is using an energy detector (ED) with a detection threshold (λ), makes hard binary decision (either "1" or bit "0") over fading or shadowing sensing channel. All CR users use the same threshold (λ). The distance between any two CR users is less than the distance between a PU and a CR user or the distance between a CR user and the FC. Each CR user is having one ED as shown in Figure 1.

An energy detector receives a signal $x(t)$ as defined below at input and gives a binary decision regarding the presence or absence of the PU. The received signal $x(t)$ at ith CR user can be represented as

$$x_i(t) = \begin{cases} n_i(t), & H_0, \\ h_i s(t) + n_i(t), & H_1, \end{cases} \quad (1)$$

where h_i is the sensing channel gain of ith CR user. The noise $n_i(t)$ is modeled as a zero-mean white Gaussian random process and H_1 and H_0 are the two hypotheses associated with the presence and absence of a PU. The noise energy at ith CR user can be approximated over the time interval $(0,T)$, as [2, 3]

$$\int_0^T n_i^2(t)\, dt = \frac{1}{2W} \sum_{j=1}^{2u} n_{i,j}^2, \quad (2)$$

where u is the time-bandwidth product and

$$n_{i,j} \sim N(0, N_{01}W), \quad \forall j. \quad (3)$$

The decision statistic at ith CR user, Y_i, can be written as

$$Y_i = \sum_{j=1}^{2u} n_{i,j}'^2, \quad (4)$$

where $n_{i,j}' = n_{i,j}/\sqrt{N_{01}W}$. Y_i can be viewed as the sum of the squares of $2u$ standard Gaussian variates with zero mean and unit variance. Therefore, Y_i follows a central chi-square (χ^2) distribution with $2u$ degrees of freedom. The same approach can be applied when the signal $s(t)$ is present, by replacing each of $n_{i,j}$ with $n_{i,j} + s_j$ where $s_j = s(j/2W)$ for a given h_i.

Thus, the decision statistic Y_i conditioned on h_i will have a noncentral Chi-square $\chi^2(2\gamma_i)$ distribution with $2u$ degrees of freedom and a noncentrality parameter $2\gamma_i$ [2, 3]. The actual statistics of Y_i have to be found appropriately by averaging the statistics with probability density function (PDF) of fading coefficient (h_i).

2.1. Analysis of Detection and False Alarm Probabilities.
In this section we study probability of detection and probability of false alarm in nonfaded, that is, AWGN channel and faded environments. The probabilities of detection and false alarm for non-faded case are presented in Section 2.1.1, while the same parameters are presented for a general case of fading in Section 2.1.2.

2.1.1. Non-Fading Environment (AWGN Channel, i.e., $h_i = 1$).
In nonfading environment, that is, when the sensing channels are corrupted by AWGN only, the probabilities of detection and false alarm at ith CR user are given by the following formulas [2, 5–7]:

$$P_{d,i} = P\left(Y_i > \lambda \mid H_1\right) = Q_u\left(\sqrt{2\gamma_i}, \sqrt{\lambda}\right), \quad (5)$$

$$P_{f,i} = P\left(Y_i > \lambda \mid H_0\right) = \frac{\Gamma\left(u, \lambda/2\right)}{\Gamma\left(u\right)}, \quad (6)$$

where $\Gamma(\cdot, \cdot)$ is the incomplete gamma function [23] and $Q_u(\cdot, \cdot)$ is the generalized Marcum Q-function [24]. For simplicity, identical average SNRs ($\gamma_i = \overline{\gamma}; \forall i$) have been assumed for all CR users. If the signal power is unknown, we can first set the false alarm probability (P_f) to a specific desired level. For a given desired level of P_f, the threshold (λ) of energy detector is set which determines the detection probability (P_d) along with instantaneous SNR (γ) of sensing channel as given in (5). As expected, P_f is independent of γ_i for all i since under H_0 there is no PU signal present.

2.1.2. Fading Environment.
When h is varying due to fading, (5) gives the probability of detection as a function of the instantaneous SNR (γ). In this case, the average probability of detection ($\overline{P}_d$) may be derived by averaging (5) over fading statistics [6],

$$\overline{P}_d = \int_0^{\infty} Q_u\left(\sqrt{2\gamma}, \sqrt{\lambda}\right) f_{\gamma}(\gamma)\, d\gamma, \quad (7)$$

where $f_{\gamma}(\gamma)$ is the PDF of SNR under fading. The expression for P_f given in (6) remains the same for fading case due to independency of γ.

In the following subsequent sections, we study briefly various statistical models of several fading channels such as log-normal shadowing, Hoyt (Nakagami-q), Rayleigh, Rician, Nakagami-m, and Weibull fading channels.

2.2. Log-Normal Shadowing Channel.
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 $\sigma = 0.1 \ln(10)\sigma_{\mathrm{dB}}$ [6].

2.3. Hoyt or Nakagami-q Fading Channel.
We assume 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, that is, $f_{\gamma}(\gamma)$, may be defined as [13, 14]

$$f_{\gamma}(\gamma) = \frac{1}{\sqrt{p}} \exp\left(-\frac{\gamma}{p\overline{\gamma}}\right) I_0\left(\frac{\gamma\sqrt{1-p}}{p\overline{\gamma}}\right); \quad \gamma \geq 0, \quad (8)$$

where

$$p = \frac{4q^2}{\left(1+q^2\right)^2}; \quad 0 \leq p \leq 1, \quad (9)$$

where q is the fading severity parameter. The average P_d in this case, $\overline{P}_{d,\mathrm{Hoyt}}$ can now be evaluated by substituting $f_{\gamma}(\gamma)$ from (8) to (7).

2.4. Rayleigh Fading Channel.
If the signal amplitude follows a Rayleigh distribution, then the SNR γ follows an exponential PDF given by [11]

$$f_{\gamma}(\gamma) = \frac{1}{\gamma} \exp\left(-\frac{\gamma}{\overline{\gamma}}\right); \quad \gamma \geq 0. \quad (10)$$

The average P_d in this case, $\overline{P}_{d,\mathrm{Ray}}$, can be evaluated by substituting (10) in (7):

$$\overline{P}_{d,\mathrm{Ray}} = \exp\left(-\frac{\lambda}{2}\right) \sum_{k=0}^{u-2} \frac{1}{k!}\left(\frac{\lambda}{2}\right)^k + \left(\frac{1+\overline{\gamma}}{\overline{\gamma}}\right)^{u-1}$$
$$\times \left(\exp\left(-\frac{\lambda}{2\left(1+\overline{\gamma}\right)}\right) - \exp\left(-\frac{\lambda}{2}\right) \right.$$
$$\left. \times \sum_{k=0}^{u-2} \frac{1}{k!}\left(-\frac{\lambda\overline{\gamma}}{2\left(1+\overline{\gamma}\right)}\right)^k \right). \quad (11)$$

2.5. Rician Fading Channel.
If the signal strength follows a Rician distribution, the PDF of γ will be [2]

$$f_{\gamma}(\gamma) = \frac{K+1}{\overline{\gamma}} \exp\left(-K - \frac{(K+1)\gamma}{\overline{\gamma}}\right) I_0$$
$$\times \left(2\sqrt{\frac{K(K+1)\gamma}{\overline{\gamma}}}\right), \quad \gamma \geq 0, \quad (12)$$

where K is the Rician factor. The average P_d in the case of a Rician channel, $\overline{P}_{d,\mathrm{Ric}}$, is then obtained by substituting (12) in (7). The resulting expression can be solved for $u = 1$ using [24, Equation (45)] to yield

$$\overline{P}_{d,\mathrm{Ric}}\big|_{u=1} = Q\left(\sqrt{\frac{2K\overline{\gamma}}{K+1+\overline{\gamma}}}, \sqrt{\frac{\lambda(K+1)}{K+1+\overline{\gamma}}}\right). \quad (13)$$

For $K = 0$, this expression reduces to the Rayleigh expression with $u = 1$ [2].

2.6. Nakagami-m Fading Channel.

2.6. Nakagami-m Fading Channel. If the signal amplitude follows a Nakagami distribution, then PDF of γ follows a gamma PDF given by [11]

$$f_\gamma(\gamma) = \left(\frac{m}{\overline{\gamma}}\right)^m \frac{\gamma^{m-1}}{\Gamma(m)} \exp\left(-\frac{m\gamma}{\overline{\gamma}}\right); \quad \gamma \geq 0, \quad (14)$$

where m is the Nakagami parameter. The average P_d in the case of Nakagami-m fading channel ($\overline{P}_{d,\text{Nak}}$) can be evaluated by substituting (14) in (7):

$$\overline{P}_{d,\text{Nak}} = \alpha\left[G_1 + \beta\sum_{n=1}^{u-1}\frac{(\lambda/2)^n}{2n!}\,{}_1F_1\left(m; n+1; \frac{\lambda\overline{\gamma}}{2(m+\overline{\gamma})}\right)\right], \quad (15)$$

where ${}_1F_1(\cdot;\cdot;\cdot)$ is the confluent hyper geometric function ($= \Phi(\cdot;\cdot;\cdot)$) [24, Section 9.2],

$$\alpha = \frac{1}{\Gamma(m)\,2^{m-1}}\left(\frac{m}{\overline{\gamma}}\right)^m,$$

$$\beta = \Gamma(m)\left(\frac{2\overline{\gamma}}{m+\overline{\gamma}}\right)^m \exp\left(-\frac{\lambda}{2}\right), \quad (16)$$

$$G_1 = \frac{2^{m-1}(m-1)!}{(m/\overline{\gamma})^m}\frac{\overline{\gamma}}{m+\overline{\gamma}}\exp\left(-\frac{m\lambda}{2(m+\overline{\gamma})}\right)$$

$$\times\left[\left(1+\frac{m}{\overline{\gamma}}\right)\left(\frac{m}{m+\overline{\gamma}}\right)^{m-1}L_{m-1}\left(-\frac{\lambda\overline{\gamma}}{2(m+\overline{\gamma})}\right) \quad (17)\right.$$

$$\left.+\sum_{n=0}^{m-2}\left(\frac{m}{m+\overline{\gamma}}\right)^n L_n\left(-\frac{\lambda\overline{\gamma}}{2(m+\overline{\gamma})}\right)\right],$$

where $L_n(\cdot)$ is the Laguerre polynomial of degree n [24, Section 8.970]. We can obtain an alternative expression for $\overline{P}_{d,\text{Ray}}$ when setting $m = 1$ in (17) and this expression is numerically equivalent to the one obtained in (11).

2.7. Weibull Fading Channel.

2.7. Weibull Fading Channel. In the Weibull fading model, the channel fading coefficient h can be expressed as a function of the Gaussian in-phase X and quadrature Y elements of the multipath components [25, 26]

$$h = (X + jY)^{2/V}, \quad (18)$$

where $j = \sqrt{-1}$.

Let Z be the magnitude of h, that is, $Z = |h|$. If $R = |X + jY|$ is a Rayleigh distributed random variable, the Weibull distributed random variable can be obtained by transforming R and using (18) as

$$Z = R^{2/V}. \quad (19)$$

From (19), the PDF of Z can be given as

$$f_Z(r) = \frac{V}{S}r^{V-1}\exp\left(-\frac{r^V}{S}\right), \quad (20)$$

with $S = E(Z^V)$ and $E(\cdot)$ denoting the expectation. V is the Weibull fading parameter expressing how severe the fading can be ($V > 0$) and S is the average fading power. As V increases, the effect of fading decreases, while for the special case of $V = 2$, the Weibull PDF of Z reduces to the Rayleigh PDF. For $V = 1$ the Weibull PDF of Z reduces to the well known negative exponential PDF.

The corresponding CDF of Z can be expressed as [26]

$$F_Z(r) = 1 - \exp\left(-\frac{r^V}{S}\right). \quad (21)$$

In Weibull fading the instantaneous signal-to-noise ratio at a cognitive radio is given by [27]

$$\gamma = Z^2\frac{E_s}{N_{01}}. \quad (22)$$

It may be noted that the nth power of a Weibull distributed random variable with parameters (V, S) is another Weibull distributed random variable with parameters $(V/n, S)$ [25]. Thus γ is also a Weibull distributed random variable with parameters $(V/2, (a\overline{\gamma})^{V/2})$ where $a = 1/\Gamma(1 + 2/V)$. The PDF of γ can then be derived from (14) by replacing V with $V/2$ and S with $(a\overline{\gamma})^{V/2}$ as [28]

$$f_\gamma(\gamma) = \frac{V}{2(a\overline{\gamma})^{V/2}}(\gamma)^{(V/2-1)}\exp\left[-\left(\frac{\gamma}{a\overline{\gamma}}\right)^{V/2}\right], \quad (23)$$

where $\overline{\gamma}$ is the average SNR given as

$$\overline{\gamma} = E\left(Z^2\right)\frac{E_s}{N_{01}} = S^{2/V}\Gamma\left(1+\frac{2}{V}\right)\frac{E_s}{N_{01}}. \quad (24)$$

Here $E(Z^2)$ is the second moment of Z which can be obtained from the generalized expression for moments as [27]

$$E\left(Z^n\right) = S^{n/V}\Gamma\left(1+\frac{n}{V}\right), \quad (25)$$

where n is a positive integer and $\Gamma(\cdot)$ is the Gamma function. The average P_d in the case of a Weibull channel $\overline{P}_{d,\text{Weibu}}$ can be obtained analytically by substituting (23) in (7).

2.8. Hard Decision Fusion Rule (OR-Rule).

2.8. Hard Decision Fusion Rule (OR-Rule). Let N denote the number of CR users sensing the PU. Each CR user makes its own local decision regarding the presence or absence of PU (i.e., H_1 or H_0) and forwards the binary decision (1 or 0) to FC for data fusion as shown in Figure 2. The PU is located far away from all CR users. All the CR users receive the PU signal with the same local mean signal power. Further, the channels between CR users and FC are assumed to be 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 of each CR user. The generalized formula for overall probability of detection, Q_d, for the k-out of-N fusion rule is given by [5, 7]

$$Q_d = \sum_{l=k}^{N}\binom{N}{l}\overline{P}_d^l\left(1-\overline{P}_d\right)^{N-1}, \quad (26)$$
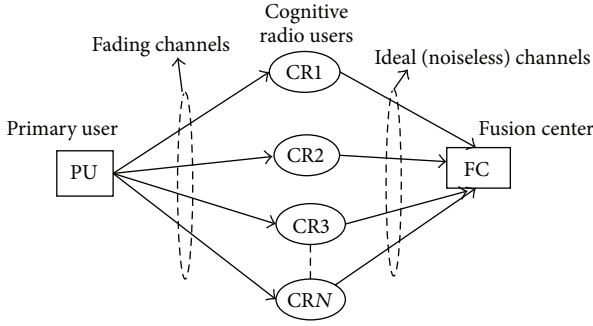
Figure 2: Cooperative spectrum sensing system.

where P_d is the probability of detection for each individual CR user as defined by generalized (5) and (7).

The OR-logic fusion rule (i.e., 1-out of-N rule) can be evaluated by setting $k = 1$ in (26):

$$Q_{d,\text{OR}} = \sum_{l=1}^{N} \binom{N}{l} \overline{P}_d^l \left(1 - \overline{P}_d\right)^{N-1}$$

$$= 1 - \binom{N}{l} \overline{P}_d^l \left(1 - \overline{P}_d\right)^{N-1} \Big|_{l=0} = 1 - \left(1 - \overline{P}_d\right)^N.$$

$$(27)$$

Equation (27) can be rewritten as

$$Q_d = 1 - \prod_{i=1}^{N} \left(1 - \overline{P}_d\right), \tag{28}$$

$$Q_m = 1 - Q_d,$$

$$Q_f = 1 - \prod_{i=1}^{N} \left(1 - P_f\right). \tag{29}$$

In conventional nonweighted fusion (hard decision fusion), the noise, fading statistics, and average SNR in sensing channel are the same for each CR user. But in a real cognitive radio system this may not be true, that is, each CR experiences different fading statistics. Under this assumption two weighting schemes are proposed [18] and explained in detail in the following subsections.

2.9. Channel Preference Based Weighting Scheme. In this paper, we assume that each CR user experiences different channel status with the PU. Though we assume fading in sensing channel, the reporting channel is assumed to be ideal as FC is considered to be situated near to CRs [6–9]. The difference in channel status of the CR users necessitates considering some of the CR users more prior in making the decision about the PU than the other CR users. Assuming that FC knows each sensing channel status and each CR user experiences different channel status, we can weight their decisions based on following certain weighting algorithm. Assume that we generate a decision at FC which is equivalent to the decision of the worse channel status CR. Then replace it with the decision of the best channel status CR. These two

generation and replacement operations are done in a way to hold two conditions: the total number of CR users must not change and decision independency is maintained. Equation (28) can be modified as

$$Q_d = 1 - \left\{\left(1 - \overline{P}_d^1\right)\left(1 - \overline{P}_d^2\right)\cdots\left(1 - \overline{P}_d^N\right)\right\}. \tag{30}$$

Let us consider an example that CR_1 user experiences a better channel with PU, say AWGN channel, and other CRs experience the same worst channel, say Rayleigh faded channel. The decision of CR_1 may be considered as decision of k CRs instead of the one and remaining $(N - 1)$ CRs as decision of $(N - k)$. This could be done by modifying (30) as [18]

$$Q_d = 1 - \left\{\left(1 - \widetilde{P}_d\right)^k \left(1 - \overline{P}_d\right)^{N-k}\right\}, \tag{31}$$

where $\widetilde{P}_d$ is the probability of detection at k number of CR users in AWGN channel and $\overline{P}_d$ is the probability of detection at $N - k$ number of CR users in faded channel. This algorithm is named as k-Gaussian and $N - k$ faded algorithm.

2.10. Decision Statistic Based Weighting Scheme. In a real cognitive radio system different CR users may have the same opinion about the presence or the absence of the PU. But decision statistic value need not be the same for all CR users. Some may have high decision statistic value, while others may have low decision statistic value. Because of this difference, the dependability on the decisions of different CRs should be different. This means that the final decision must be taken according to the preference of some CR users over the others. Let us assume that all CR users are having the same detection threshold λ value and let us define a reliability factor (R_f), R_f as the difference between the decision statistic value Y and the detection threshold value as given in [18]

$$R_f = Y - \lambda. \tag{32}$$

The reliability factor must be included in the probability of detection. For example consider 4-CR users in which one CR user (say CR_1 user) is having highest statistical value of $Y = 1.4\lambda$ and others are having the same value of $Y = 1.2\lambda$. Then the reliability factor for this network will be evaluated from the value of the decision statistic obtained from CR_1 user to give $R_f = 0.4$. The reliability factor is multiplied with probability of missed detection of CR_1 user, $\overline{P}_{m1}$ at FC; Q_d can be expressed as [18]

$$Q_d = 1 - \left[\left\{R_f * \overline{P}_{m1}\right\} \overline{P}_{m2}\cdots\overline{P}_{mN}\right];$$

$$\overline{P}_{m1,2,\dots,N} = 1 - \overline{P}_{d1,2,\dots,N}. \tag{33}$$

3. Simulation Model

The simulation is developed in MATLAB. 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

TABLE 1: Type of fading and generation.

Tape of fading coefficient (h)	Generation
Log-normal shadowing (parameter, σ_{dB})	$X \sim N(0, \sigma^2)$ where $\sigma = 0.1 \ln(10)\sigma_{\text{dB}}$ $h = e^X$
Hoyt (parameter, q)	$X \sim N\left(0, q^2/1 + q^2\right); Y \sim N\left(0, 1/1 + q^2\right)$ $h = \sqrt{X^2 + Y^2}$
Rayleigh	$X \sim N(0, 1/2); Y \sim N(0, 1/2)$ $h = \sqrt{X^2 + Y^2}$
Rician (parameter, K)	$X \sim N(s', \sigma^2); Y \sim N(0, \sigma^2)$, where $s' = \sqrt{K/(K + 1)}$ and $\sigma = 1/\sqrt{2(1 + K)}$ $h = \sqrt{X^2 + Y^2}$
Nakagami-m (parameter, m)	$X \sim \text{gamma}(r, s)$; where $r = m$; $s = 1/m$; $h = \sqrt{X}$
Weibull (parameter, V)	$X \sim N(0, 1/2); Y \sim N(0, 1/2)$ $h = \left(X^2 + Y^2\right)^{2/V}$

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 $\overline{g} = E\{g\} = E\{a^2\}$ is often normalized to unity, that is, $\overline{g} = 1$ 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]

$$P_g(g) = \frac{1}{2\sqrt{g}} P_a\left(\sqrt{g}\right). \tag{34}$$

And inversely

$$P_a(a) = 2a \cdot P_g\left(a^2\right). \tag{35}$$

The simulation is carried out according to the following steps to verify the analytical framework introduced in the previous section.

(1) Equally likely hypothesis $H \in \{H_0, H_1\}$ and primary user (PU) signal $s(t)$ are generated using uniform random variable generator.

(2) The AWGN signal $n(t)$ with zero mean variance $N_{01}W$ is generated using Gaussian random variable, where $N_{01} = E_s/\overline{\gamma}$. The sensing channel coefficient h_i at ith CR user in case of Hoyt, Rayleigh, Rician, and Weibull fading is generated using two Gaussian random variables. The Nakagami-m fading channel coefficient can be generated using Gamma distribution and Log-normal shadowing coefficient can be generated as explained in Section 2.2. In case of non-fading environment (pure AWGN), $h_i = 1$. The way of generating several types of fading coefficients (Log-normal shadowing, Hoyt, Rayleigh, Rician, Nakagami-m, and Weibull) is shown in Table 1.

(3) The received signal at ith CR user is $x_i(t) = h_i s(t) + n_i(t)$ for true hypothesis H_1 and $x_i(t) = n_i(t)$ for true hypothesis H_0.

(4) The received signal at ith CR user $x_i(t)$ is given as the input to band pass filter (BPF) and its output is

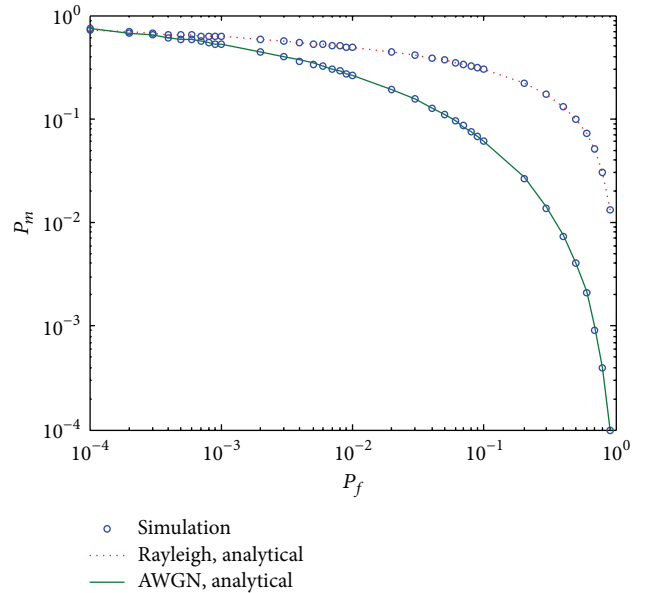
FIGURE 3: CROC curves for single CR user based spectrum sensing in AWGN and Rayleigh channel [6].

squared (i.e. $x_i^2(t)$) using squaring device and passed through an integrator. The output of the integrator is obtained as $Y_i = \sum_{j=1}^{2m} n_{i,j}'^2$ (from (4)).

(5) A predefined detection threshold λ is set at ED depending on chosen P_f (from (6)). The ED of ith CR user compares decision statistic at ith CR user Y_i with its detection threshold λ and takes a hard binary decision (1 or 0) about PU.

(6) The steps 1 to 6 have been repeated a large number of times and then the average value of P_d and P_m has been estimated.

(7) The overall probability of detection Q_d can be estimated by substituting average value of P_d in (28), (31), and (33).
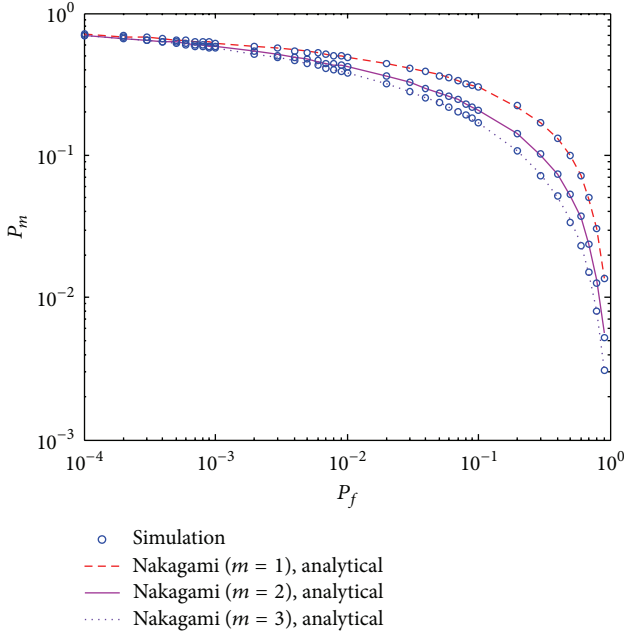
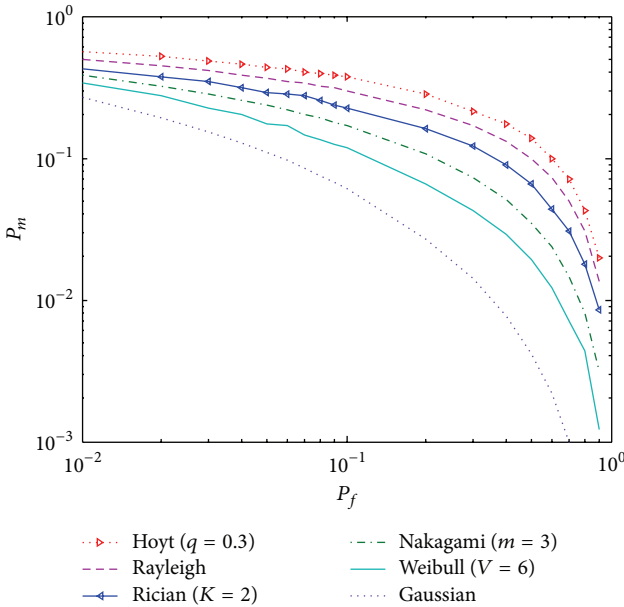FIGURE 4: Effect of Nakagami fading parameter (m) on single CR user based spectrum sensing.

FIGURE 5: CROC curves for single CR user based spectrum sensing in different fading channels.

4. Results and Discussions

Using the steps as mentioned in Section 3, we evaluated the performance of two different weighting schemes (channel preference based and decision statistic value based weighting schemes) in non-fading (AWGN) channel, in several fading channels such as Hoyt, Rayleigh, Rician, Nakagami-m, Weibull, and log-normal shadowing channel. The overall probabilities of missed detection (Q_m) and false alarm (Q_f)
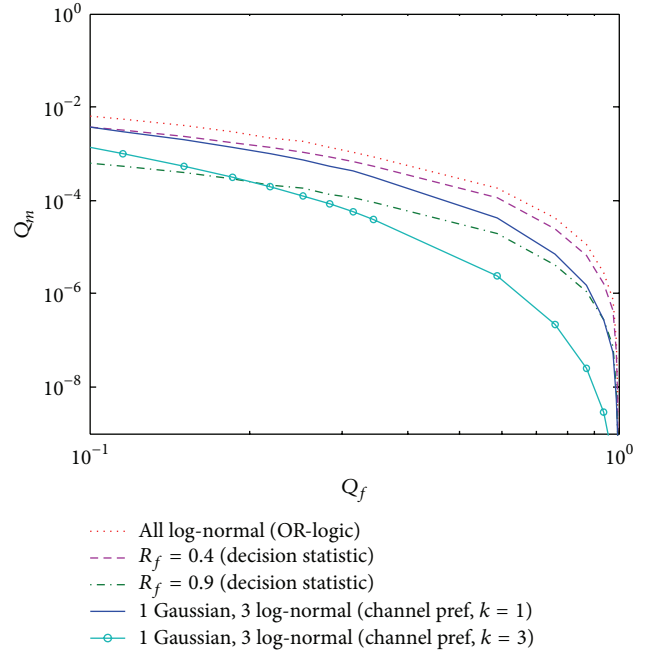

FIGURE 6: CROC curves for 4 CR users using decision statistic and channel preference based weighting schemes in log-normal shadowing (2 dB) channel.

at FC are evaluated under different channel conditions. The performance of CSS with OR logic fusion is also shown for comparison purpose. Simulation results are obtained with the following parameters, the number of CR users is $N = 4$, time-bandwidth product is $u = 5$, and the average sensing channel SNR is $\bar{\gamma} = 10$ dB. The weighting factor of channel preference based scheme, k, is considered as 1 and 3 and weighting factor of decision statistic based weighting scheme, R_f is considered as 0.4 and 0.9. Figures 3 to 5 are results of spectrum sensing using a single CR user and Figures 6 to 11 are results of cooperative spectrums sensing using weighting schemes.

Figure 3 shows the variation of missed detection probability (P_m) as a function of the false alarm probability (P_f) for single CR user based spectrum sensing. The performance is evaluated in AWGN and Rayleigh fading channel using analytical expressions and simulation. The AWGN curve is provided for comparison. As P_f increases, P_m decreases more rapidly for AWGN channel than for Rayleigh fading channel. Our simulation results match with the theoretical results.

In Figure 4, the effect of Nakagami parameter (m) on the P_m of single CR user based spectrum sensing is shown. As the Nakagami parameter m increases from 1 to 3, the probability of missed detection P_m decreases which is intuitively true as higher m indicates a less sever fading. For example, for $P_f = 0.001$, the P_m values for $m = 1, 2$, and 3 are 0.6192, 0.5776, and 0.5638, respectively.

Figure 5 shows complementary ROC curves for spectrum sensing with single CR user in the presence of Hoyt, Rayleigh, Rician, Nakagami-m, and Weibull fading channels. Hoyt, Rician, Nakagami-m, and Weibull fading parameters are
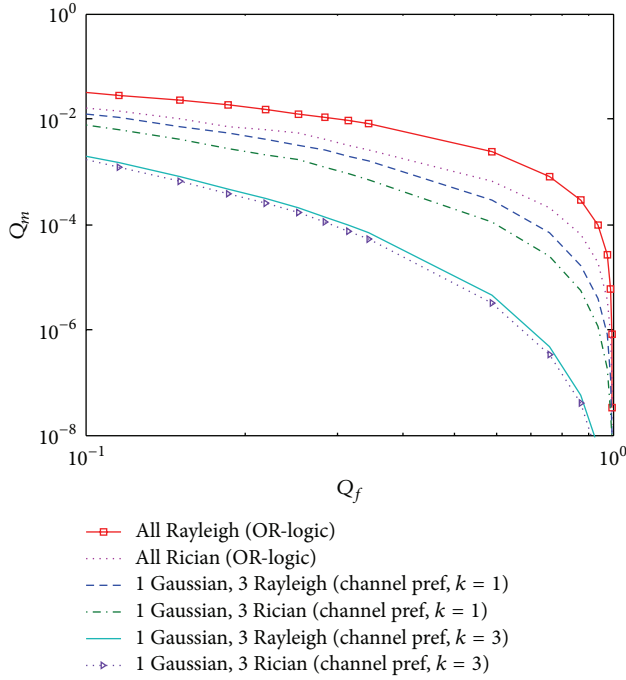
FIGURE 7: CROC curves for 4 CR users using channel preference based weighting scheme in Rayleigh and Rician ($K = 2$) fading channels.
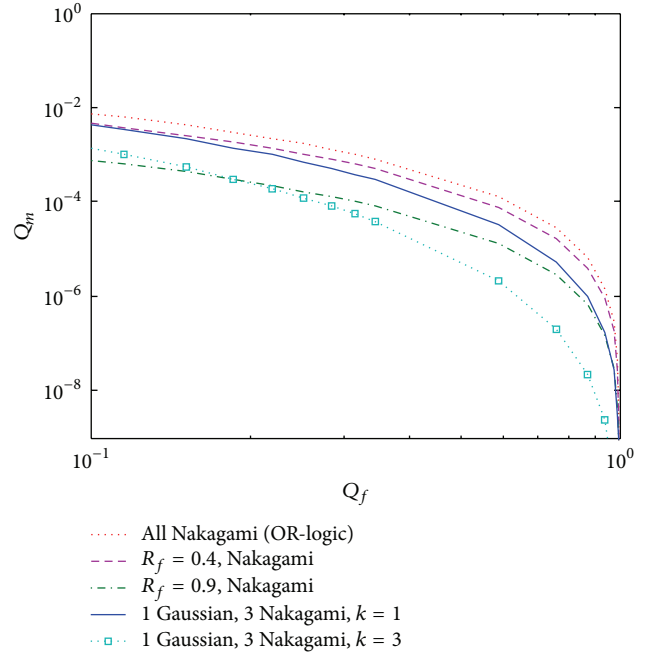

FIGURE 9: CROC curves for 4 CR users using decision statistic and channel preference based weighting schemes in Nakagami ($m = 3$) fading channel.
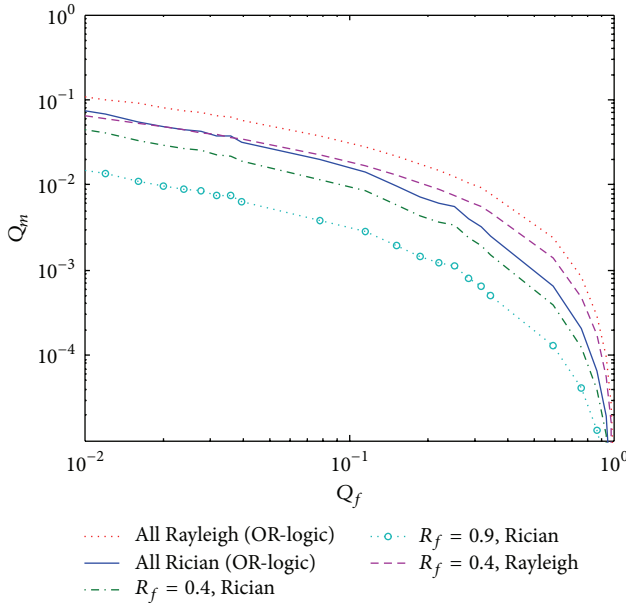

FIGURE 8: CROC curves for 4 CR users using decision statistic based weighting scheme in Rayleigh and Rician ($K = 2$) fading channels.

assumed to be $q = 0.3$, $K = 2$, $m = 3$, and $V = 6$, respectively. Comparing the AWGN curve with those corresponding to fading, we observe that spectrum sensing performance degrades in the presence of fading. The performance of energy detector is the best in Weibull fading channel among all fading channels.

Now we show the results on spectrum sensing based on weighting schemes.

In Figure 6, the performance comparison between cooperative spectrum sensing using two weighting schemes (decision statistic based and channel preference based) has been evaluated in the presence of log-normal shadowing. Two different values of weighting factor for the channel preference based weighting scheme ($k = 1$ and 3) and two different values of weighting factor for decision statistic based weighting scheme ($R_f = 0.4$ and 0.9) have been considered for this figure. The performance of conventional CSS with OR-logic fusion is also shown for comparison purpose. We observed that the performance of CSS with both weighting schemes is better than the performance of CSS with OR-logic fusion. It is observed that Q_m decreases with increase in any one of Q_f, k, and R_f. For example, at $Q_f = 0.25$, when k increases from 1 to 3, Q_m decreases from 0.0007 to 0.0001. Similarly, when R_f increases from 0.4 to 0.9, Q_m decreases from 0.0011 to 0.0002 for the same value of Q_f.

Figures 7 and 8 show the performance of CSS with channel preference based and decision statistic based weighting schemes, respectively. The performance is evaluated in both Rayleigh and Rician fading channels. It is seen from Figure 7 that as k as well as Q_f increases, Q_m decreases for both fading channels. For example, for $Q_f = 0.25$, as k increases from 1 to 3, Q_m decreases from 0.0031 to 0.0002 for Rayleigh fading channel and Q_m decreases from 0.0017 to 0.0002 for Rician fading channel as shown in Figure 7. Similarly as R_f decreases from 0.4 to 0.9, Q_m decreases from 0.0034 to 0.0011 for the same value of Q_f for Rician fading channel as shown in Figure 8. We observed that the performance of CSS in
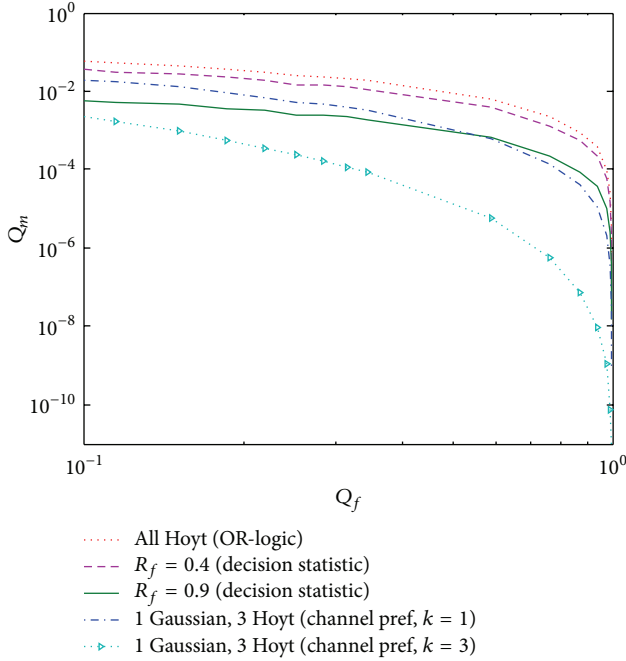
FIGURE 10: CROC curves for 4 CR users using decision statistic and channel preference based weighting schemes in Hoyt ($q = 0.3$) fading channel.

FIGURE 11: CROC curves for 4 CR users using decision statistic and channel preference based weighting schemes in Weibull ($V = 4$) fading channel.

Rician fading channel is better than the performance of CSS in Rayleigh fading channel for the same value of k and R_f due to presence of line of sight (LOS) signal component. The performance of CSS with OR-logic fusion is provided for comparison purpose.

Figures 9 and 10 show the performance comparison between two weighting schemes (decision statistic based weighting scheme and channel preference based weighting scheme) in Nakagami-m and Hoyt fading channels, respectively. Two different values of weighting factors k (1 and 3) and R_f (0.4 and 0.9) have been considered for these figures. We observe from both figures that Q_m decreases with increase in any one of Q_f, k, and R_f. For example, at $Q_f = 0.25$, Q_m decreases from 0.0007 to 0.0001 and from 0.0010 to 0.0002 as k increases from 1 to 3 and as R_f increases from 0.4 to 0.9, respectively (in Figure 9). Similarly, in Figure 10, Q_m decreases from 0.0052 to 0.0002 and from 0.0147 to 0.0025 when k increases from 1 to 3 and R_f increases from 0.4 to 0.9, respectively. The performance of CSS with channel preference based weighting scheme, for $k = 3$, is better than the performance with decision statistic based weighting scheme for $R_f = 0.9$ as seen in Figures 9 and 10. The performance of CSS with OR-logic fusion is also shown for comparison purpose. As we observe from the above curves in Figures 9 and 10, once again both the weighting schemes based fusion outperform OR-logic fusion.

In Figure 11, the performance comparison between decision statistic based weighting scheme and channel preference based weighting scheme in Weibull fading channel is shown. As in earlier case, two different values of weighting factors k (1 and 3) and R_f (0.4 and 0.9) have also been considered for this
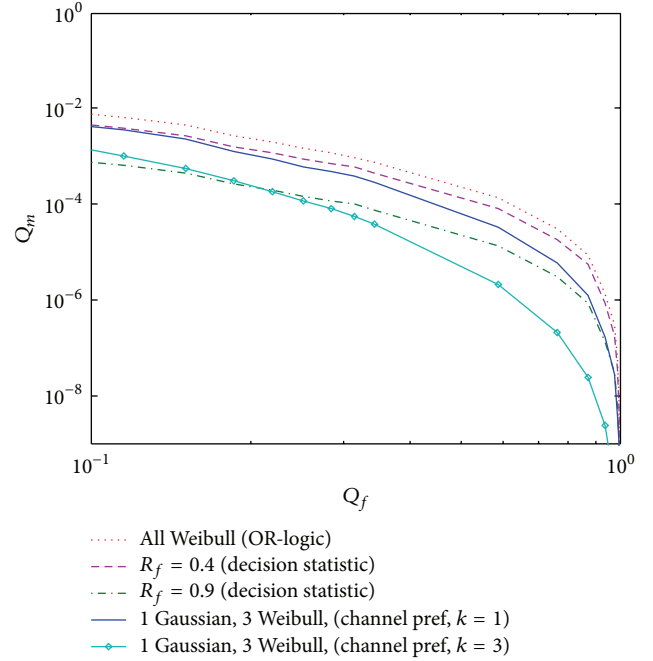
figure. As any one of Q_f, k, and R_f increases, Q_m decreases. For example, for $Q_f = 0.25$, Q_m decreases from 0.0007 to 0.0001 and from 0.0003 to 0.0001 as k increases from 1 to 3 and R_f increases from 0.4 to 0.9, respectively. The performance of CSS with channel preference based weighting scheme, for $k = 3$, is better than the performance with decision statistic based weighting scheme for $R_f = 0.9$. The performance of CSS with OR-logic fusion is also shown for comparison in this figure. Weighting schemes guarantee a better performance than OR-logic based fusion in conventional cooperative spectrum sensing scenario.

Figure 12 shows the impact of several fading channels such as Hoyt, Rayleigh, Rician, Nakagami-m, and Weibull fading on the performance of CSS using channel preference ($k = 2$) based weighting scheme. Hoyt, Rician, Nakagami-m and Weibull fading parameters are assumed to be $q = 0.3$, $K = 2$, $m = 3$, and $V = 6$, respectively. The performance of CSS in Weibull fading is better than other fading channels for the same value of k. For example, for $Q_f = 0.25$ and $k = 2$, the values of Q_m for Hoyt, Rayleigh, Rician, Nakagami-m, and Weibull channels are 1.1×10^{-3}, 8×10^{-4}, 5×10^{-4}, 3×10^{-4}, and 1×10^{-4}, respectively.

5. Conclusions

We have investigated the performance of single CR user based spectrum sensing, considering several fading in sensing channels such as Hoyt, Rayleigh, Rician, Nakagami-m, and Weibull. We have also evaluated the performance of cooperative spectrum sensing (CSS) using OR-logic fusion and two different weighting schemes such as channel preference
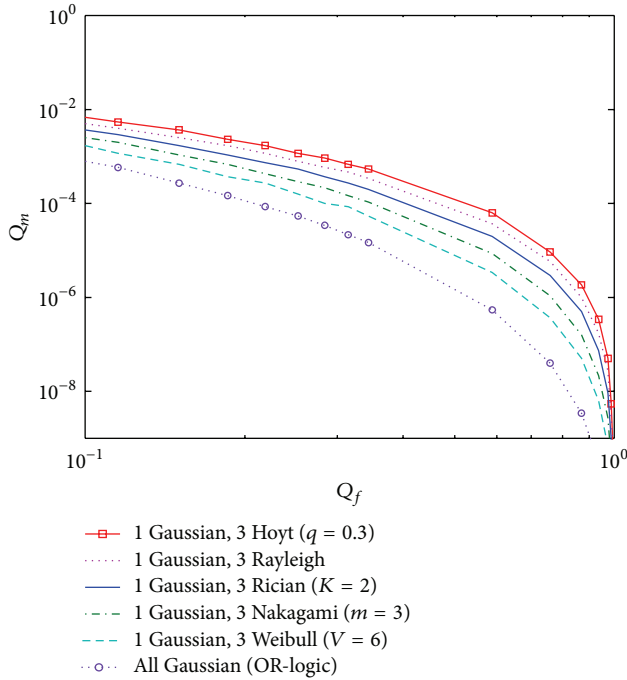
Figure 12: CROC curves for 4 CR users using channel preference based weighting scheme ($K = 2$) in different fading channels.

based weighting scheme and decision statistic based weighting scheme. The performance of CSS with channel preference based weighting scheme for higher value of k is found to be better than that with decision statistic based weighting scheme for maximum value of R_f Performance comparison of CSS with weighting schemes among fading channels has been evaluated and the performance of CSS in Weibull fading channel outperforms that of any other fading channel considered in this paper. The performances with both weighting schemes outperform OR-logic based fusion. The overall probability of missed detection decreases with increase in overall probability of false alarm and weighting factors (k and R_f). The above study is useful in designing weighted based cooperative spectrum sensing network under several fading environments in sensing channels.

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