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Performance of Cooperative Spectrum Sensing System with Multipath Fading Reporting Channel

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Abstract: *The detection of the primary user (PU) signal, or what is called the spectrum sensing, represents a serious challenge for releasing reliable cognitive communication systems. Cooperative spectrum sensing can be employed in cognitive radio networks to minimize the uncertainty in the PU detection due to transmission imperfections such as: noise, fading and shadow. Cooperative spectrum sensing can be considered as three-step process. In the first step, each secondary user (SU) performs a local detection followed by decision making independently. In the second step, all SUs forward their local decisions to a network fusion center (NFC). Third, based on the received local decisions the final decision about the PU existence is made at the NFC. In this paper, theoretical analyses for a simple cooperative spectrum sensing system with a reporting channel corrupted by both additive white Gaussian noise (AWGN) and multipath fading are presented. The error performance of the reporting channel is investigated using a discrete time channel model with a combined channel impulse response (CCIR). In the CCIR, the effect of the transmitting filter, receiving filter, and the power delay profile of the physical channel are considered to derive the composite channel impulse response. The overall probabilities of false alarm and miss detection at the NFC with optimum receiver are derived. The impacts of signal-to-noise ratio (SNR) of the sensing channel, the SNR of the reporting channel, the detection threshold, and the channel length on the cognitive radio performance are studied.*

Keywords : *Composite channel impulse response (CCIR), network fusion center(NFC), Primary user, Secondary user, Typical Urban .*

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I. Introduction

Spectrum sensing is a vital component of a cognitive communication system. Spectrum sensing enables the unlicensed secondary users (SUs) to detect the presence or absence of the licensed primary user (PU) in a specific frequency band. Furthermore, the detection of the PU signal with high accuracy decreases the interference probability between the PU and SU [1].

Energy detectors (EDs) do not require any former information about the PU signal, therefore, they are widely employed in SUs for the local spectrum sensing [2]. Moreover, energy detection is the optimum non-coherent detection technique for a Gaussian-distributed unknown signals [3].

Different schemes for cooperative spectrum sensing are proposed in [4]-[6] to enhance spectrum sensing performance. It is shown in [4] that collaboration between SUs during spectrum sensing process can reduce the PU detection time. However, channel between SUs and the NFC in [4] are considered to be noise-free, which is not the case in many realistic applications. In [5], a cluster-based cooperative spectrum sensing is proposed to mitigate the effect of channel imperfections that can be found between SUs and the network fusion center (NFC). Authors in [6], propose a cooperative spectrum sensing where the local hard decisions are transmitted to the NFC over AWGN channels.

In [7] and [8], the cooperative spectrum sensing schemes are proposed for systems with noisy channels between SUs and PU. Both proposed schemes in [7] and [8] employ a maximum a posteriori (MAP) detection at the NFC. In [8], the statistical activity patterns of the PU is employed to obtain the a priori probability which is required for MAP detection. A comparison of hard decision (HD) and soft decision (SD) based cooperative spectrum sensing schemes over imperfect reporting channels (i.e. channels between PU and SUs) is conducted in [9]. The comparison of the two approaches in [9] shows that the performance of SD based approach outperforms the HD based one. However, SD system requires higher bandwidth control channel than HD. Cooperative spectrum sensing with multiple PUs under fading channels is investigated in [10]. Authors in [11], study the performance of cooperative spectrum sensing with multiple-antenna nodes over generalized and composite fading channels. Moreover, the mixture Gamma (MG) distribution is used in [11] to approximate the probability density function (pdf) of the signal-to-noise ratio (SNR) for different fading channels. To save the time-frequency resources, SUs transmit their local decisions in the same frequency band simultaneously to the NFC [12]. Reporting error probabilities are shown in [12] for AWGN and the Rayleigh fading reporting channels. An optimum fusion rule at the NFC is obtained in[13] for cooperative spectrum sensing system with error free reporting channel.

In this paper, theoretical analyses are performed for cooperative spectrum sensing system over a multipath Rayleigh fading reporting channel. A discrete-time model system is considered where the effect of the transmitting filter, receiving filter, and the physical channel are taken into account [14]. Based on the discrete-time channel model for the reporting channel, the probability of false-alarm, and the probability of missed detection are derived. In this paper and for simplicity, the channel between the PU and each SU is assumed to be corrupted by AWGN. Each user performs a local detection utilizing an energy detector, hard decision with one bit is then made and sent as a BPSK signal over a multipath fading reporting channel to the NFC. At the NFC, the final decision about the presence or absence of the PU is made based on a certain fusion rule. At the NFC the maximum ratio combining (MRC) optimum receiver is considered. An expression for optimum fusion rule for a system with imperfect reporting channel is also presented in this paper. The rest of this paper is organized as follows. In Section II, local spectrum sensing model is introduced. Cooperative spectrum sensing model is presented in Section III. Error performance of reporting channel is derived in section IV. In Section V, analytical results are presented. Finally, conclusions are shown in section VI.

II. Local Spectrum Sensing Model

Consider a cooperative spectrum sensing system with one licensed PU, *N* unlicensed SUs, and a single NFC. In this system and for simplicity, the relative distances among SUs are considered to be smaller than their distances to the PU, thus, all SUs observe the same signal from the PU.
Based on the a above assumption, the local spectrum sensing is to decide the presence or absence of the PU based on the following two hypotheses [3]:

$$r(t) = \begin{cases} w(t), & H_0, \text{PU is absent} \\ x(t) + w(t), & H_1, \text{PU is present} \end{cases} \tag{1}$$

where *r(t)*, *x(t)*, and *w(t)*, denote the signal observed by each SU, the PU transmitted signal, and an additive white Gaussian noise (AWGN) signal, respectively. All SUs in the cognitive network perform a local detection for the PU signal using EDs. Based on the assumption that all SUs observe the same energy from the PU, the decision statistic for each ED can be described by [8]:

$$y(t) = \begin{cases} \chi_{2\mu}, & H_0, \text{PU is absent} \\ \chi_{2\mu}(2\gamma_s), & H_1, \text{ PU is present} \end{cases} \tag{2}$$

where $\chi_{2\mu}$ is the central chi-square distribution with 2μ- degree of freedom with $\mu=TW$ being the observation-time signal-bandwidth product,$\chi_{2\mu}(\gamma_s)$ denotes the non-central chi-square distribution with 2μ-degree of freedom and $2\gamma_s$ -non centrality parameter with γ_s being the SNR of the observed signal at each SU [8]. For a SU utilizing an energy detector, the average probability of false alarm, the average probability of detection, and the average probability of miss detection over a sensing channel corrupted by AWGN can be written, respectively as [1]:

$$\begin{aligned} P_f &= \Pr\{r > \lambda / H_0\} \\ &= \frac{\Gamma(\mu, \lambda/2)}{\Gamma(\mu)} \end{aligned} \tag{3}$$

$$\begin{aligned} P_d &= \Pr\{r > \lambda / H_1\} \\ &= Q_m\left(\sqrt{2\gamma_s}, \sqrt{\lambda}\right) \end{aligned} \tag{4}$$

$$P_{mis} = 1 - P_d \tag{5}$$

where λ is the energy threshold of the local ED, $\Gamma(\mu)$ denotes the gamma function, $\Gamma(\mu,\lambda/2)$ is the incomplete gamma function, and $Q_\mu(\sqrt{2\gamma_s}, \sqrt{\lambda})$ is the generalized Marcum Q function. The decision threshold, λ, is chosen to satisfy a specific probability considerations on false alarm or missed detection or both.

III. Cooperative Spectrum Sensing Model

In cognitive network, a spectrum sensing accuracy improvement can be achieved by collaboration between SUs. In general, cooperative spectrum sensing is performed according to the following three-step process [8]. First, each SU makes a local binary-decision, d_k, on the status of the PU, independently based on a local energy detection. The binary local decision can be expressed as:

$$d_k = \begin{cases} 0, & \text{PU is absent} \\ 1, & \text{PU is present} \end{cases} \tag{6}$$

Second, all SUs forward their binary decisions as a binary phase shift keying (BPSK) modulated signals to the NFC where the final decision is made. Third, the NFC makes a final decision about the presence or absence of the PU according to a predefined fusion rule. The Final decision is then sent back by the NFC to all SUs in the cognitive network. The BPSK signals are sent to the NFC over channels corrupted by multipath fading and AWGN. Thus, in this paper, transmission errors between SUs and the NFC are considered during the cooperative spectrum sensing performance analysis. Reporting channel errors may have serious impacts on the overall false alarm probability, overall miss detection probability, and optimal fusion rule at the NFC. Based on the above discussion, the false alarm probability, the detection probability, and the miss detection probability for each individual SU at the NFC can be respectively obtained as:

$$\overline{P}_f = P_f(1-P_e) + P_e(1-P_f) \tag{7}$$

$$\overline{P}_d = P_d(1-P_e) + P_e(1-P_d) \tag{8}$$

$$\overline{P}_{mis} = 1 - P_d(1-P_e) - P_e(1-P_d) \tag{9}$$

where P_e is the error probability of a system with BPSK transmission over channels corrupted by multipath fading and AWGN. The general form for the combined false alarm probability, the combined missed detection probability of the cooperative spectrum sensing at the NFC can be respectively written as [13]:

$$Q_f = \sum_{n=n_r}^{N} \binom{N}{n} \left(\overline{P}_f\right)^n \left(1-\overline{P}_f\right)^{N-n} \tag{10}$$

$$Q_m = 1 - \sum_{n=n_r}^{N} \binom{N}{n} \left(1-\overline{P}_m\right)^n \left(\overline{P}_m\right)^{N-n} \tag{11}$$

and the total sensing error portability at the NFC can be presented as:

$$Q_t(n) = 1 + \sum_{n=n_r}^{N} \binom{N}{n} \left\{ \left(\overline{P}_f\right)^n \left(1-\overline{P}_f\right)^{N-n} - \left(1-\overline{P}_m\right)^n \left(\overline{P}_m\right)^{N-n} \right\} \tag{12}$$

where n_r is the selected fusion rule at the NFC. The commonly used fusion rules are: the OR rule with n_r=1, the AND rule with ,n_r =N, and the majority rule with $n_r = \lceil N/2 \rceil$, where $\lceil . \rceil$ represents rounding the enclosed value to the nearest larger integer. In the OR fusion rule, the PU is considered to be active when one of the received local decisions at the NFC declares the existence of the PU signal. In the majority fusion rule, the NFC decides that the PU is present or active only when the majority of the received local decisions at the NFC vote for that. In the AND fusion rule, the existence of the PU signal is considered at the NFC only when all the received local decisions at the NFC claim the detection of the PU signal. Thus, for AND rule, (10), and (11) can be simplified as:

$$Q_f^{AND} = \left(\overline{P}_f\right)^N \tag{13}$$

$$Q_m^{AND} = 1 - \left(1-\overline{P}_{mis}\right)^N \tag{14}$$

In the next section, the error performance analysis of the transmission between the SU and the NFC over multipath fading and AWGN will be presented.

IV. The Error Performance Of The Reporting Channel

In practical cognitive communication systems, transmission between the SUs and the NFC might be corrupted by noise and multipath fading. These channel imperfections may cause detection errors regarding the transmitted bits from SUs leading to incorrect final decision at the NFC. In this section, the bit error rate of the NFC with the optimum receiver is obtained for BPSK modulated transmitted local decisions.

4. 1 Statistic Discrete-Time Model for a Reporting Channel

The statistical discrete time model (SDTM) combines the effect of the transmission filter, power delay profile of the channel, and receiving filter. The combined impulse response of the channel can be defined as [14]:

$$h(t) = \hbar_{Rx}(t) \otimes c_n(t) \otimes \hbar_{Rx}(t) \tag{15}$$

where $h(t)$, $\hbar_{Tx}(t)$, $\hbar_{Rx}(t)$, $c(t)$,and, $\otimes$ are the combined channel impulse response, the impulse response of the transmitting filter, the impulse response of the receiving filter, the impulse response of the multipath fading channel, and the convolution operator, respectively. The discrete version of $h(t)$ can be obtained by sampling $h(t)$ at a predefined sampling period to obtain the discrete time channel vector, i.e., $\mathbf{h}=[h(0), h(1), \ldots, h(L-1)]^T$, where T is the transpose operation, and L the discrete-time channel length. The covariance between the elements of the combined discrete time channel impulse response can be obtained as [14]:

$$E[h_n(l_1) \cdot h_n(l_2)] = \sum_{i=1}^{L} \mathrm{P}_i h_c(l_1 T_s - t_i) h_c(l_2 T_s - t_i)^* \tag{16}$$

where $h_c=\hbar_{Tx} \otimes \hbar_{Rx}$, T_s is the sampling period at the receiving filter output, P_i is the power of the i-th fading path, and t_i is the delay of the i-th fading path. The values of Pi and t_i for six-path reduced TU power delay profile are presented in[15].

4. 2 NFC with Optimum Receiver

In this subsection, the error performance of the optimum receiver at the NFC in multipath fading and AWGN is presented. As mentioned in the previous section, SUs forward their single bit local decisions to the NFC as BPSK signals over multipath fading and AWGN. Since a single bit is transmitted over multipath fading channel, the relation between the transmitted and received signals at the NFC can be represented by a single input multiple output system. Thus, the observed local decision for the n-th SUs at the NFC can be written as:

$$\begin{aligned} \mathbf{r}_n &= \mathbf{h}_n \cdot \sqrt{E_s}(2d_k - 1) + \mathbf{w}_n \\ &= \mathbf{h}_n \cdot s_n + \mathbf{w}_n \end{aligned} \tag{17}$$

where $d_k \in \{0,1\}$ is the local decision, s_n is the transmitted symbol with energy Es, $\mathbf{r}_n \in C^{L\times 1}$ is the received signal over L-multipath fading channels with $C^{L\times 1}$ being a complex column vector of length L, $\mathbf{h}_n \in C^{L\times 1}$ is the discrete-time channel vector, and $\mathbf{w}_k \in C^{L\times 1}$ is the AWGN vector with variance N_o. For the single input multiple output system described in (17), the error probability can be minimized by employing a maximum ratio combining (MRC) technique at the NFC. In this case, the transmitted BPSK symbol, s_n, can be recovered at the NFC as:

$$\hat{s}_n = \arg\min_{s_n \in \{-1,1\}} \left| \mathbf{h}_n^H \cdot \mathbf{r}_n - \left(\mathbf{h}_n^H \cdot \mathbf{h}_n \right) \cdot s_n \right|^2 \tag{18}$$

where, H is the Hermitian operator , and

$$\mathbf{h}_n^H \cdot \mathbf{r}_n = \sum_{i=0}^{L-1} \left(|h_n(i)|^2 s_n + h_n^*(i) \cdot w_n(i) \right) \tag{19}$$

$$\mathbf{h}_n^H \cdot \mathbf{h}_n = \sum_{i=0}^{L-1} |h_n(i)|^2 \tag{20}$$

Using the conditional error probability equation given in [16,eq.(9.8)] for M-ary PSK systems, the conditional error probability for system with BPSK can be written as:

$$\bar{p}_e = \frac{1}{\pi} \int_0^{\frac{\pi}{2}} \exp\left\{ -\frac{\gamma_{MRC}}{\sin^2 \theta} \right\} d\theta \tag{21}$$

where γ_{MRC} is the instantaneous SNR at the output of the MRC optimum receiver, γ_{MRC} can be written as:

$$\gamma_{MRC} = \gamma_o \cdot \mathbf{h}_n^H \mathbf{h}_n = \frac{E_s}{N_o} \cdot \sum_{i=0}^{L-1} |h_n(i)|^2 \tag{22}$$

where γ_o is the SNR at the output of the NFC receiver for an equivalent system without fading. The conditional error probability in (21) can also be written as:

$$\bar{p}_e = \frac{\gamma_o}{\pi}\int_0^{\frac{\pi}{2}} \exp\left\{-\frac{\mathbf{h}_n^H \mathbf{h}_n}{\sin^2\theta}\right\} d\theta \qquad (23)$$

The unconditional error probability for BPSK system can be found by taking the average of the conditional error probability in (23) over the instantaneous SNR γ_{MRC} [16]. Furthermore, since the scalar value $\rho=(\mathbf{h}_n)^H\mathbf{h}_n$ is a quadratic form of zero mean complex normal distributed vector $\mathbf{h}_n$, the unconditional error probability for a BPSK modulated system can be obtained by finding the characteristic function (CHF) of ρ, the result can be presented as [17]:

$$p_e = \frac{\gamma_o}{\pi}\int_0^{\frac{\pi}{2}} \{\det[\Phi]\}^{-1} d\theta \qquad (24)$$

where $\mathbf{\Phi}$ is an $L \times L$ matrix that can be written as:

$$\Phi = \begin{bmatrix} \frac{\lambda_1}{\sin^2\theta}+1 & 0 & 0 & 0 \\ 0 & \ddots & 0 & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & \frac{\lambda_L}{\sin^2\theta}+1 \end{bmatrix} \qquad (25)$$

The Probability of error at the NFC receiver can then be written as:

$$\begin{aligned} p_e &= \frac{\gamma_o}{\pi}\int_0^{\frac{\pi}{2}} \{\phi_1 \cdot \phi_2 \cdots \phi_{L-1} \cdot \phi_L\} d\theta, \\ &= \frac{\gamma_o}{\pi}\int_0^{\frac{\pi}{2}} \prod_{l=1}^{L} \phi_l \, d\theta, \end{aligned} \qquad (26)$$

where $\phi_k = \left[\frac{\lambda_k}{\sin^2\theta}+1\right]^{-1}$, and λ_i represents the *i*-th eigenvalue of the covariance matrix $\rho=E[\mathbf{h}_n(\mathbf{h}_n)^H]$ [17]. For *L*-path Equal gain power delay profile, (26) can be simplified to :

$$p_e = \frac{1}{\pi}\int_0^{\frac{\pi}{2}} \left\{1+\frac{\gamma_o}{L\sin^2\theta}\right\}^{-L} d\theta \qquad (27)$$

4. 3 The Optimum Fusion Rule over Imperfect Reporting Channel

The optimum fusion rule that minimizes the total sensing error probability can be obtained by differentiate Q_t(n) in (12) with respect to *n*, then make the derivative equal to zero, and finally solve for *n*:
The derivation of $Q_t(n)$ with respect to n can be found numerically using Newton's difference quotient [18]

$$f'(x) \approx \lim_{h\to 0} \frac{f(x)-f(x+h)}{h} \qquad (28)$$

Hence, the derivative of $Q_t(n)$ with respect to *n* is:

$$Q_t'(n) \approx \lim_{h\to 0} \frac{Q_t(n)-Q_t(n+h)}{h} \qquad (29)$$

Then, the optimum *n* value can be obtained when $Q_t(n)$=0, resulting:

$$\left(\frac{1-\bar{P}_m}{\bar{P}_f}\right)^n \cdot \left(\frac{\bar{P}_m}{1-\bar{P}_f}\right)^{N-n} = 1 \qquad (30)$$

Taking the natural logarithm for both sides of (30) leads to:

$$n\ln\left(\frac{1-\bar{P}_m}{\bar{P}_f}\right) = (N-n)\ln\left(\frac{1-\bar{P}_f}{\bar{P}_m}\right) \qquad (31)$$

After some simplification steps, the optimum fusion rule can be written as:

$$n_{opt} = \left\lceil \frac{N}{1+\beta} \right\rceil, \text{ where } \beta = \frac{\ln\left(\frac{1-\overline{P}_f}{\overline{P}_m}\right)}{\ln\left(\frac{1-\overline{P}_{mis}}{\overline{P}_f}\right)} \tag{32}$$

It is worth to mention that an optimization for fusion rule is presented in [13] for a cognitive spectrum sensing system with noise free reporting channel.

V. Analytical Results

In this section, analytical results are presented to examine the performance of a cooperative spectrum sensing under AWGN and multipath fading reporting channels. The six-path reduced typical urban (TU) power delay profile is considered in the analyses . In Fig. 1, the overall probabilities of false alarm and miss detection at the NFC with AND fusion rule are plotted as a function of threshold for different number of SUs, *N*. The SNR for the sensing and reporting channels are γ_s=10dB, and γ_o=15 dB, respectively. As shown in the figure, for a fixed threshold value, increasing the number of SUs leads to a decrease in the probability of false alarm. While, for the same threshold the probability of miss detection increases with increasing the number of SUs, *N*. Keeping in mind that both P_f and P_m are less than one, the relationship between number of users *N*, and the overall probability of false alarm or the over all probability of miss detection can be understood clearly from equation (13) and equation (14), respectively.

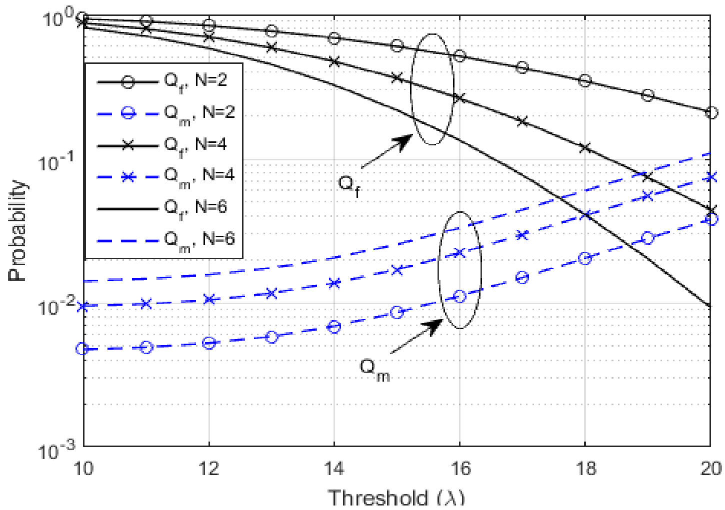

Fig. 1. The overall false alarm and miss detection probabilities as a function of threshold.

Fig. 2 shows the optimum fusion rule versus γ_o; the results in Fig. 2 are obtained for different values of threshold. Furthermore, the sensing SNR is γ_s=5dB, and the number of users is set as *N*=10. The following two observations can be made on Fig. 2. First, the optimum fusion rule depends on both threshold and SNR of the reporting channel values. For high reporting channel SNR but small threshold values the optimum rule is the AND rule. The OR rule is the optimum fusion rule for high values of both the threshold and the reporting channel SNR, this results agree with results obtained in [13] for error free reporting channel. On the other hand, the optimum fusion rule for high and low threshold values becomes closer to majority rule as the SNR of reporting channel decreases. Second, the majority rule is the optimum rule for medium threshold values regardless of the values of SNR of the reporting channel, γo.

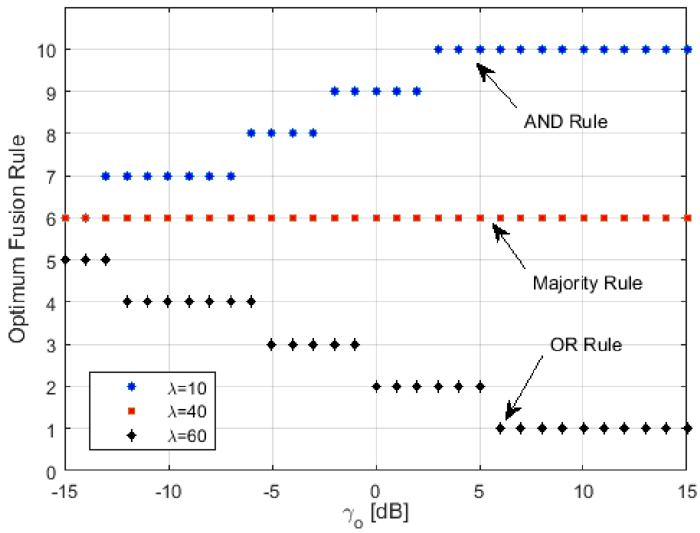

Fig. 2. Optimum fusion rule versus reporting channel SNR.

Fig. 3 illustrates the total sensing error probability versus threshold for different fusion rules. γs=10dB, and γ_o=10dB are used to obtain Fig. 3. It is clear from Fig. 3 that for fixed values of N, γs, and γ_o, the optimum fusion rule depends mainly on the threshold. Also, the optimum and the OR fusion rules are shown in Fig.3 independently for γ_s=13dB. Comparing results when γ_s=13dB with those with γ_s=10dB we can see that the sensing SNR has an impact on defining the optimum fusion rule. For example the optimum fusion rule is the OR rule at γ_s=10 and λ=40, while the OR is not the optimum rule at the same threshold when γ_s=13 dB.

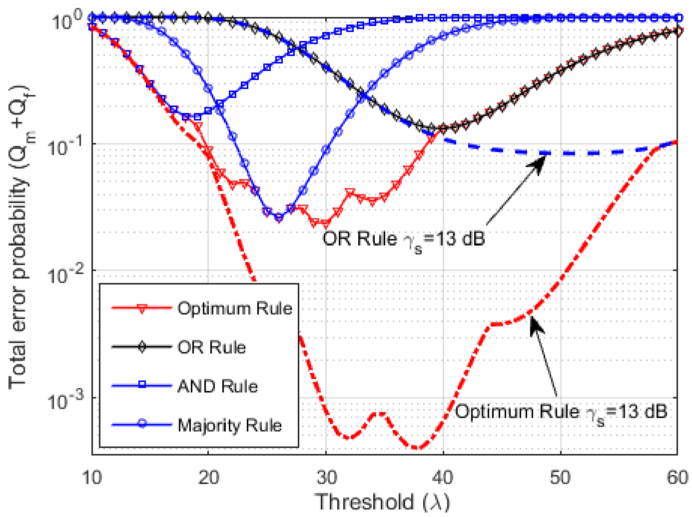

Fig. 3. Total sensing error probability versus threshold for various fusion rules.

In Fig. 4, the total error sensing probability is plotted as a function of threshold for different γ_o values. The number of users is *N*=6, the SNR of the sensing channel is set as γ_s= 10 dB, and the optimum fusion rule is employed at the NFC. There are two observation can be made on the figure. First, with the optimum fusion rule and for fixed N and γ_s values, there is an optimum threshold (λ=30) at which the total sensing error probability is the minimum. Second, the total sensing error probability decreases with γ_o; moreover, the optimum threshold is the same regardless of the γ_o value.

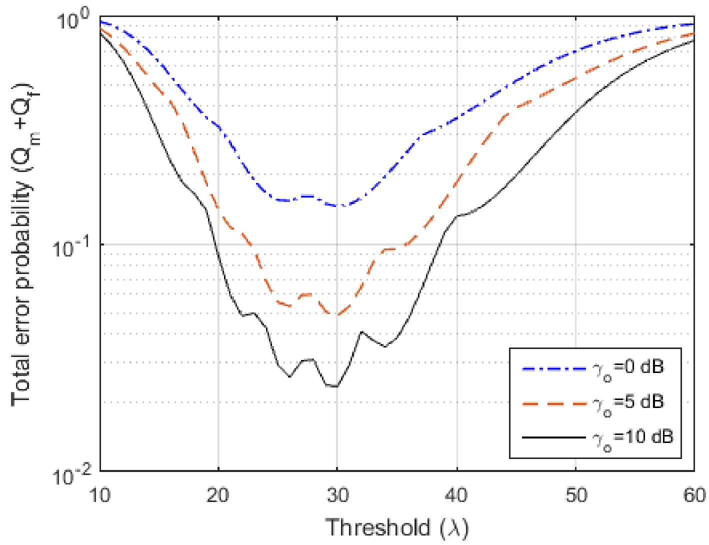

Fig. 4. Total sensing error probability as a function of threshold for different γ_o values.

Finally, in Fig. 5, the overall false alarm probability for systems with reporting channels with equal gain power delay profile and different channel lengths are compared. The equal gain power delay profile with L taps can be expressed as $\varphi_{EG}(t) = \sum_{i=0}^{L-1} P_i \delta(t - t_i)$, where $\delta(t)$ is the Dirac delta function, and Pi=1/L are the power and the delay of the i-th fading path, respectively. It is clear from the figure that the number of fading paths for equal gain power delay profile has an impact of the over all probability of false alarm; however this impact negligible for small thresholds. Moreover, the overall false alarm probability for system with equal gain reporting channel is smaller than system with typical urban reporting channel.

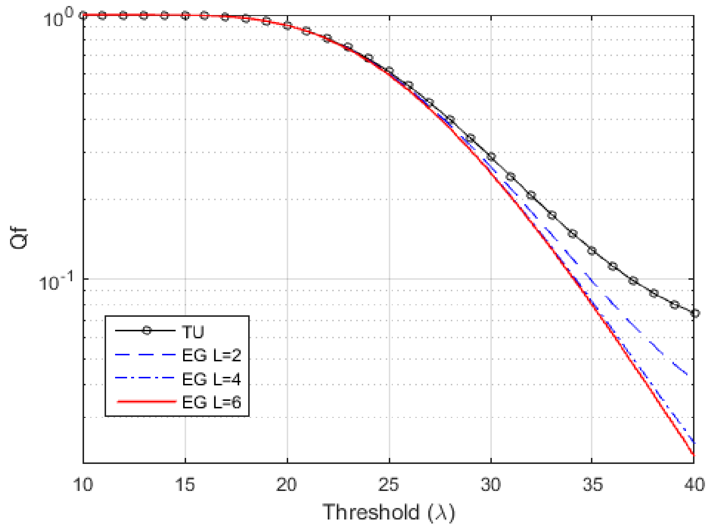

Fig. 5. Overall probability of false alarm, Q_f, versus threshold for different kinds of power delay profiles.

VI. Conclusion

In this paper, a theoretical performance analyses were presented for a cognitive radio system with cooperative spectrum sensing. The channel between SUs and PU was assumed an AWGN channel. All SUs send their local decisions to the NFC over multipath fading channel. It is shown in this paper that the performance of the reporting channel has an impact on the overall sensing error probability, and on the optimum fusion rule at the NFC. The total sensing error probability can affected by many parameters such as the SNR of reporting channel, the number of cooperative SUs, the number of fading paths , and reporting channel power delay profile.

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