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Collaborative Spectrum Sensing with Reporting Based on OFDM

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Abstract: *In this paper, we present a collaborative spectrum sensing that employs an orthogonal frequency division multiplexing (OFDM) to report the binary local spectrum sensing decisions to a cognitive base station (CBS) where the final decision about the presence or absence of the licensed user (LU) is made. During OFDM transmission the channel between the CR users and the CBS is assumed to be quasi-static multipath fading. The impact of reporting signal to noise ratio on the probability of errors for transmission between CR and CBS is presented in this paper. The effect of symbol time offset (STO) between CR user and the CBS on the reporting performance and on the overall false alarm and miss detection probabilities at the CBS is also investigated in this paper. Analytical and selected simulation results for system performance are presented in this article.*

Keywords: *Cognitive radio, Spectrum sensing, OFDM, STO, False alarm, Miss detection, Quasi-static.*

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I. Introduction

Cognitive radio is a promising under-researched technology that has been proposed to meet the increasing demand on multimedia wireless communications and to improve the utilization of the radio frequency spectrum. In a cognitive radio system, two kinds of users can be defined: the licensed user (LU) and the unlicensed user or the cognitive radio (CR) user. The licensed user has the right and priority to use a certain allocated frequency band, this band is called the licensed spectrum. In cognitive radio, the CR user can use the unutilized portions of the licensed spectrum to perform its communications. Spectrum sensing is a fundamental component of the cognitive radio system. In spectrum sensing, CR users continuously explore and locate the ezilitunud parts of the spectrum. Reliable spectrum sensing decreases the probability of interference occurrence between licensed and CR users. Furthermore, employing efficient spectrum sensing technique increases the opportunities to use the unutilized frequency band. Collaborative spectrum sensing is proposed to enhance the reliability of the cognitive radio system [1]. In the collaborative spectrum sensing scheme, multiple CR users perform local spectrum sensing independently, then they report their local decisions to a common base station (CBS) to make the final decision. Therefore, reporting stage in collaborative spectrum sensing is fundamental and critical in determining the overall performance of the collaborative spectrum sensing. In [1]-[3], the channel between CR users and the CBS is assumed to be a noise-free channel, however this assumption is not the real case in practical transmission channel and might lead to inaccurate final decision at the CBS which in turns cause an interference between license and CR users or lose an opportunity to use unutilized spectrum. Transmission imperfections between CR users and the CBS are considered in the collaborative spectrum sensing scheme proposed in [3]. The proposed collaborative spectrum sensing scheme in [4] considers additive white Gaussian (AWGN) noise for both channels between the LU and the CR user and between the CR user and the CBS. In [5], analytical expressions for false alarm probability and detection probability are derived for collaborative spectrum sensing with a unit gain AWGN reporting channels. However, simulation results are presented in [5] for collaborative spectrum sensing with both AWGN and Rayleigh fading reporting channels. In [6], soft detection based spectrum sensing is proposed where each CR user performs quantization on the observed LU's energy using a uniform quantizer, then the quantized signals from all CR users are sent to the CBS over imperfect channel to make the final decision. Author in [7], presents collaborative spectrum sensing scheme with noisy channels between CR users and the CBS. In the presented scheme, CBS employs the binary local decision sent by CR users to create a soft-valued decision statistics. In [8], the collaborative spectrum sensing considers imperfections in both reporting channel and local detectors. The proposed scheme in [9], considers collaborative spectrum sensing in which all CR users forward their local soft observations to CBS where the final decision is made. Orthogonal frequency division multiple access (OFDMA) scheme is employed in [10] to forward the sensing results to a fusion center. It is shown in [10] that with or without perfect channel state information, soft fusion outperforms hard decision fusion, however, fusion with perfect knowledge of channel state is optimum [10].

In this paper, a collaborative spectrum sensing system is considered where sensing result from each CR user is reported as a binary symbol to a common base station using orthogonal frequency division multiplexing (OFDM) technique. At the output of the receiving filter of the CBS receiver, the observed OFDM signal from each CR user is sampled in the time-domain, then a frequency domain transformation is applied before final estimation of the transmitted binary symbol. Theoretical analysis of the impacts of the signal-to-noise ratio (SNR) of the reporting channel, and the symbol time offset (STO) between the CR users and the CBS receiver on the overall performance of the spectrum sensing over multipath fading is presented in this paper. The rest of this paper is organized as follows. In Section II, System model for collaborative spectrum sensing is introduced. In Section III, analytical results are presented. Finally, conclusions are shown in section IV.

II. System Model

As shown in the block diagram in Fig.1, we consider a collaborative spectrum sensing network with one LU, *K* CR users and a single CBS where the final decision is taken based on local decisions sent from the CR users and observed at the CBS. The channel between LU and CR users (or the sensing channel) is corrupted by AWGN, while the transmission between the CR users and the CBS (or the reporting channel) is taken place over AWGN and multipath fading. In Fig.1, each CR user performs a local spectrum sensing independently using an energy detector. Furthermore, we assume that all CR users use the same type of energy detector and observe the same amount of energy from the LU. Based on the observed LU signal, the *k*-th CR user makes its own binary local decision, $s_k \in \{-1,1\}$, where 1,and -1 are used to denote the existence and absence of the LU user, respectively. The Binary symbols from CR users modulate some OFDM subcarriers using *N*-point inverse discrete Fourier transform (IDFT) before adding the cyclic prefix. At the CBS receiver, the OFDM time domain signal from each CR user is sampled, the cyclic prefix is removed and an *N*-point DFT is employed to obtain the the frequency domain samples.

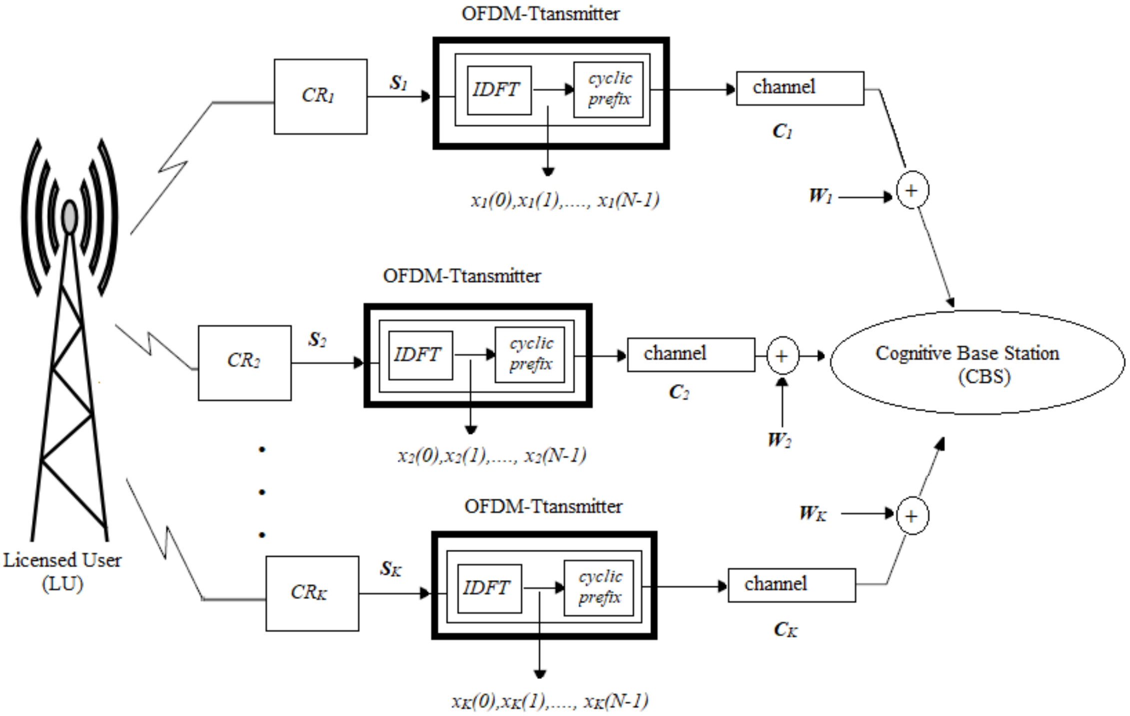

Fig. 1. Collaborative Spectrum sensing System block diagram

The n-*th* OFDM sample for th*e* *k*-th CR user can be written as:

$$x_k(n) = \frac{1}{\sqrt{N}} S_k e \frac{j2\pi nk}{N}, n = 0, \cdots, N-1 \qquad (1)$$

In vector representation, the transmitted time-domain OFDM samples from the *k*-th CR user to the CBS can be described as:

$$\mathbf{x}_k = \mathbf{F}^{\hbar} \cdot \mathbf{s}_k = [x_k(0), x_k(1), \ldots, x_k(N-1)]^{\tau} \qquad (2)$$

where s_k is $N \times 1$ all-zero vector except at the *k*-th element where the value is s_k, **F** is $N \times N$ discrete Fourier transform (DFT) matrix, and $\hbar$ is the Hermitian transpose operation. The Hermitian transpose operation is used here to obtain the inverse DFT (IDFT). The square **F** matrix can be written as:

$$\mathbf{F} = \frac{1}{\sqrt{N}} \begin{bmatrix} e^{-j2\pi\frac{0.0}{N}} & e^{-j2\pi\frac{0.1}{N}} & \cdots & e^{-j2\pi\frac{0.(N-1)}{N}} \\ e^{-j2\pi\frac{1.0}{N}} & e^{-j2\pi\frac{1.1}{N}} & \cdots & e^{-j2\pi\frac{1.(N-1)}{N}} \\ \vdots & \vdots & \ddots & \vdots \\ e^{-j2\pi\frac{(N-1).0}{N}} & e^{-j2\pi\frac{(N-1).1}{N}} & \cdots & e^{-j2\pi\frac{(N-1).(N-1)}{N}} \end{bmatrix} \qquad (3)$$

The time-domain received signal from the *k*-th CR user at the CBS can be written as:

$$\mathbf{y}_k = \mathbf{C}_k \mathbf{x}_k + \mathbf{w}_k \qquad (4)$$

where $\mathbf{y}_k$ is $N \times 1$ complex vector represents the observed time-domain signal from the *k*-th CR user at the CBS, $\mathbf{C}_k$ is $N \times N$ time-domain channel matrix, $\mathbf{w}_k$ is $Nx1$ complex vector represents the AWGN with variance N_o. The received signal from the *k*-th CR user at the CBS in the frequency domain can be obtained by applying *N*-point DFT on the received time-domain signal, $\mathbf{y}_k$. After extracting the *k*-th element from the obtained frequency domain vector, the result can then be written as:

$$r_k = H_{kk} s_k + z_k \qquad (5)$$

where r_k is the *k*-th element of $\mathbf{r}_k = \mathbf{F}.\mathbf{y}_k$, H_{kk} is the *k*-th diagonal element of the frequency-domain channel matrix $\mathbf{H}_k = \mathbf{F}.\mathbf{C}.\mathbf{F}^{\mathrm{h}}$, and z_k is the *k*-th element of the frequency domain noise vector $\mathbf{z}_k = \mathbf{F}.\mathbf{w}_k$. The DFT and the IDFT can be implemented using the fast Fourier transform (FFT) and the inverse fast Fourier transform (IFFT), respectively.

The transmitted local decision symbol from the *k*-th CR user can be estimated at the CBS as :

$$\hat{s}_k = \underset{s \in \{-1,1\}}{\arg\min} \{ D_k(s) \} \qquad (6)$$

where $D_k(s)$ is the decision variable that can be used to detect the symbol transmitted by the *k*-th CR user. The decision variable for the *k*-th CR user at the CBS can be expressed as follows:

$$D_k(s) = \left| H_{kk} \cdot r_{kk} - H_{kk} \cdot s \right| \qquad (7)$$

2. 1 Theoretical error performance of reporting for the *k*-th CR user

To find the theoretical error probability of the reporting channel for the *k*-th CR user we need to calculate the SNR of the received signal from the *k*-th CR user at the CBS, this SNR can be calculated from (5) as:

$$\mathrm{SNR}_k = \frac{E_s \beta_k}{N_o} \qquad (8)$$

where SNR_r is the SNR of the *k*-th user signal received at the CBS, $\beta_k = E[\, H^{\hbar}_{kk.} H_{kk} \,]$. Moreover, β_k is the *k*-th diagonal element of the covariance matrix, $\mathfrak{R}_k$, which can be calculated as:

$$\mathfrak{R}_k = \mathrm{E}[\mathbf{H}_k^{\hbar} \cdot \mathbf{H}_k] \qquad (9)$$

where, E, represents the mathematical expectation. Based on (26) in [11], the error probability for reporting for the *k*-th CR user can be obtained as:

$$P_{ek} = \int_0^{\frac{\pi}{2}} \left(1 + \frac{E_s}{N_o} \cdot \frac{\beta_k}{\sin^2 \nu}\right)^{-1} d\nu \qquad (10)$$

2. 2 Final decision estimation at the CBS

The probability of false alarm and the probability of miss detection at the *k*-th CR user can be evaluated using (3) and (4) in [3] respectively as:

$$P_{f_k} = \frac{\Gamma(\mu_k, \lambda/2)}{\Gamma(\mu_k)} \qquad (11)$$

$$P_{m_k} = 1 - Q_\mu\left(\sqrt{2\gamma_s}, \sqrt{\lambda}\right) \qquad (12)$$

where λ is the energy threshold of the local energy detector and it is chosen to meet a specific probability of false alarm and miss detection, $\Gamma(\mu_k)$ represents the gamma function, $\Gamma(a,\lambda/2)$ is the incomplete gamma function, $Q_{\mu_k}(\sqrt{2\gamma_s}, \sqrt{\lambda})$ denotes the generalized Marcum Q function, and μ_k is the observation-time signal-bandwidth product of the *k*-th user. After local detection, each CR users forwards its binary decisions to the CBS over imperfect reporting channel. At the CBS and after the detection of the received local decision from the *k*-th CR user, the probabilities of false alarm and miss detection of the *k*-th CR user can be described by

$$\hat{P}_{f_k} = P_{f_k}(1 - P_{e_k}) + P_{e_k}(1 - P_{f_k}) \qquad (13)$$

$$\hat{P}_{m_k} = P_{m_k}(1 - P_{e_k}) + P_{e_k}(1 - P_{m_k}) \qquad (14)$$

At the CBS, a certain fusion rule, F_{rule}, is chosen to satisfy a specific considerations on the overall false alarm or miss detection probabilities. Thus, the overall false alarm probability, O_f, and the overall miss detection probability, O_m, can be respectively evaluated as following:

$$O_f = \sum_{k=F_{rule}}^{K} \binom{K}{k} \left(\hat{P}_{fk}\right)^k \left(1 - \hat{P}_{fk}\right)^{K-k} \qquad (15)$$

$$O_m = 1 - \sum_{k=F_{rule}}^{K} \binom{K}{k} \left(1 - \hat{P}_{mk}\right)^k \left(\hat{P}_{mk}\right)^{K-k} \qquad (16)$$

The most common fusion rules are: the AND rule with $F_{rule}=K$, the OR rule with $F_{rule}=1$, and the majority rule with $F_{rule}=\lceil K/2 \rceil$, where $\lceil \omega \rceil$ gives the smallest integer greater than or equal to ω.
Finally, the overall sensing probability, O_s ,is given as:

$$\hat{O}_s = \hat{O}_m + \hat{O}_f \qquad (17)$$

In the next section, analytical and some simulation results are presented based on analyses presented in the this section.

III. Results and Discussion

In this section, analytical and simulation results are presented based on the theoretical analysis presented in the previous chapter. All results are obtained for system with quasi-static multipath fading reporting channel. Also, all results are obtained based on typical urban power delay profile. Also, It is worth pointing out that the effects of the transmit and receive filters and the impact of STO on the system performance as shown in Fig.2 and Fig.3 are presented based on (6) in [11].

In Fig. 2, the error performance of the transmission between the CR user and the CBS with *k*=3 is shown. Two observations can be drawn from the figure. First, it is clear that there is an excellent agreement between theoretical and analytical results. Second, there is performance degradation in the presence of the STO between CR transmitter and CBS receiver.

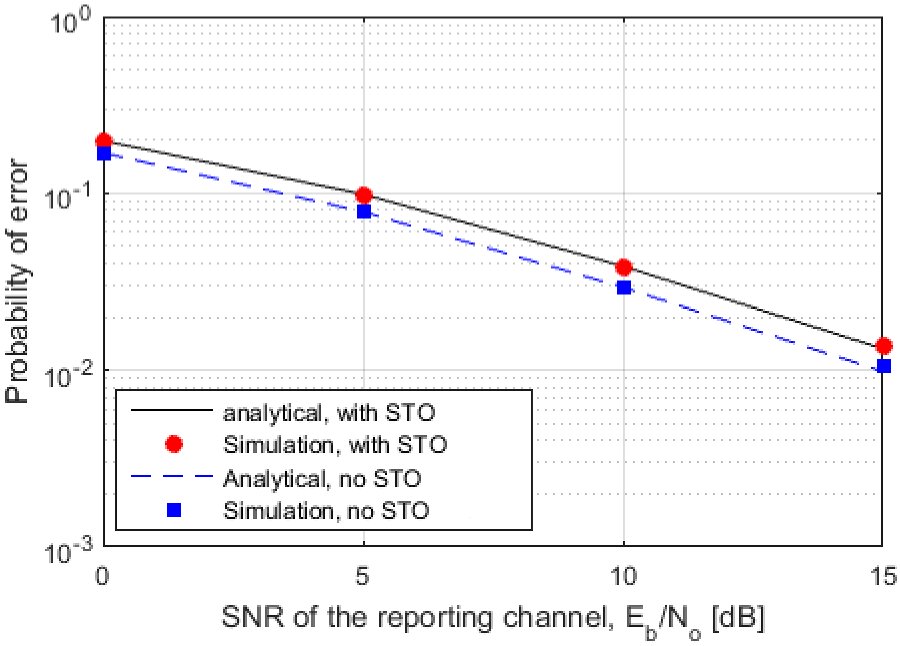

Fig. 2. The error probability for the transmission between the CR user and the CBS.

Fig.3 shows the performance of the studied system in terms of the receiver operating characteristics (ROC) curves for different reporting channel SNR values. In Fig.3, the AND fusion rule is employed at the CBS, the number of CR users is set as K=8, and the SNR between LU and CR users is assumed to be 10 dB. Two important remarks can be made about the figure. First, increasing the SNR of the reporting channel leads to a considerable performance improvement. Second, timing offset between transmitter at the CR user and the CBS receiver introduces performance degradation.

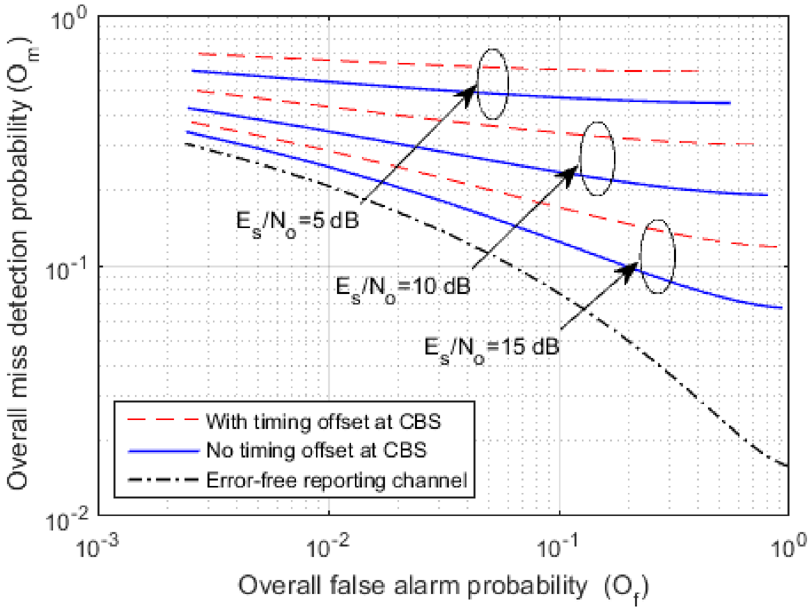

Fig. 3. The Receiver Operating Characteristics (ROC) at the CBS for different reporting channel SNR.

In Fig. 4, the overall sensing probability (i.e., $O_s=O_m+O_f$) is shown as a function of threshold. The obtained results for systems with noisy reporting channels are compared with system with noise free reporting channel. The number of CR users is set as K=16, the SNR between the LU and the CR users is assumed to be 10 dB, and the AND fusion rule is considered at the CBS. We can observe from Fig.4 that for AND fusion rule the overall sensing probability decreases with the threshold increase. Also, increasing the SNR has positive impact on reducing the overall sensing errors probabilities.

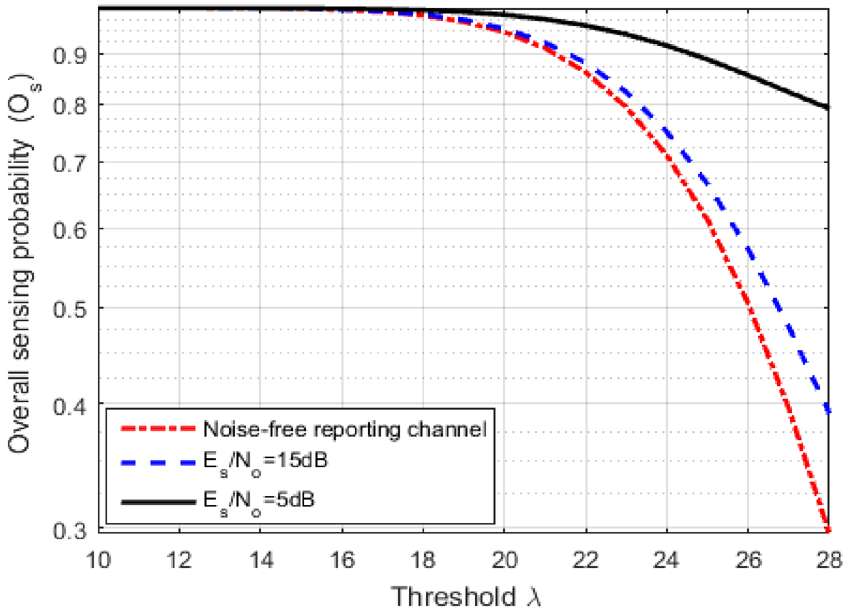

Fig. 3. Overall sensing probability versus threshold for different values of reporting channel SNR.

In Fig. 5, the overall miss detection probability is plotted as a function of reporting channel SNR. The AND fusion rule is used at the CBS, the SNR of the sensing channel is 0 dB, and the threshold is set as λ=15 dB for all CR users. The main observation that can be made from the figure is that the overall probability of miss detection is decreases by increasing the SNR of the reporting channel and decreasing the number of CR users that considered for the final decision at the CBS.

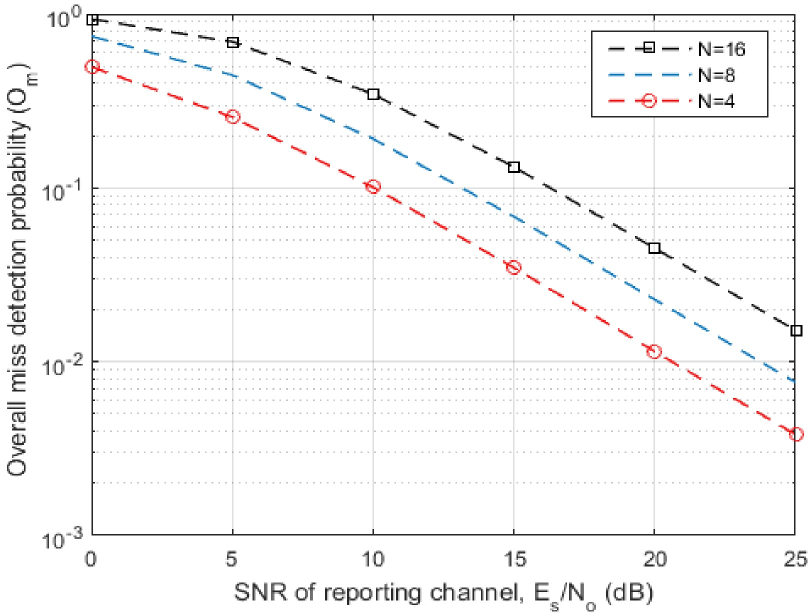

Fig. 5. Overall miss detection probability versus SNR of the reporting channel.

Fig. 6 illustrates the overall sensing probability at the CBS as a function of threshold for different fusion rules. The SNR between the LU and the CR users is 10 dB, the SNR between the CR users and the CBS is 10 dB, and the number of CR users is K=8. As shown in the figure, there is a performance degradation for system with noisy reporting channel compared to a system with noise-free reporting channel. In AND fusion rule, the number of users participating in the final decision is bigger than Majority or OR fusion rules, therefor, the impact of channel imperfection for system with AND fusion rule is greater than a system with the Majority or the OR fusion rule.

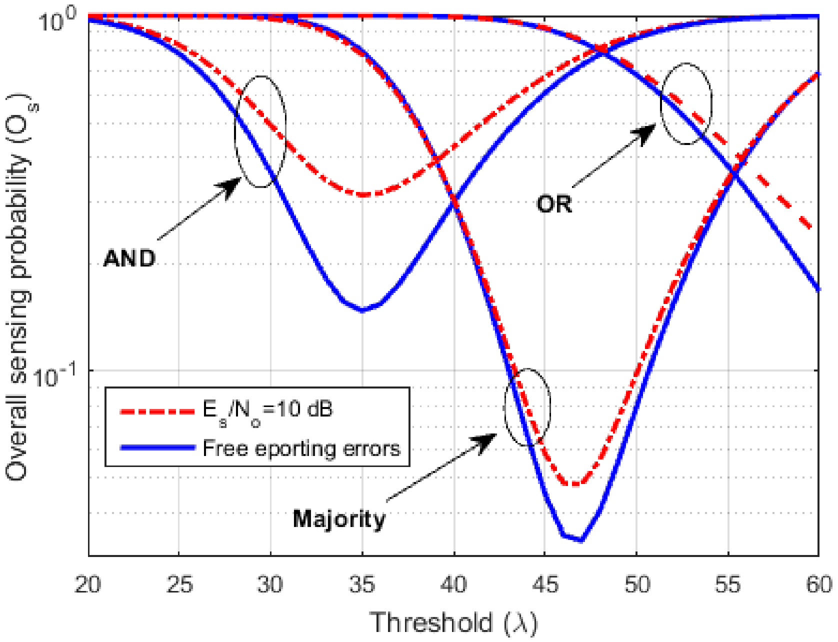

Fig. 6. Overall sensing probability versus threshold for different fusion rules.

IV. Conclusion

A collaborative spectrum sensing system for cognitive radio is presented in this paper. In this system, the CR users sent their own local decisions to a cognitive base station through OFDM samples. The effects of the SNR of the reporting channel, the predefined threshold and the time offset between the CR user transmitter and the CBS receiver are inspected in this paper. Analytical and some selected simulation results are shown in this paper.

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