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Study on Energy Detection with Diversity Receptions

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Abstract Spectrum sensing is the key technical challenge for designing the cognitive radio system which would allows the secondary users to opportunistically access the primary bands without interfering with the primary users. Spectrum sensing based on energy detector is seen as the possible candidate for cognitive radio system because of its simplicity and it requires short sensing time. This report presents the energy detection evaluation with diversity receptions over additive white Gaussian noise (AWGN) channel. It starts with the no diversity case, and presents weighted gain combining and selection gain combining cases. The detection performances are evaluated in terms of probability of detection versus the SNR by considering the OFDM signal as the primary signal.

Key words cognitive radio, signal detection, spectrum sensing, energy detector, IEEE 802.22, WRAN

1. Introduction

Currently, the spectrum resources are not being utilized effectively due to numerous factors. One of these is caused by the drawbacks of the current static spectrum allotment policy. To tackle this problem, the well known cognitive radio (CR) system which would enable flexible, efficient and reliable use of the radio spectrum by adapting the radio's operating characteristics to the environment in real time has been developed [1]– [3]. Today, the CR system is an important consideration in the major spectrum debates in the federal communications commission (FCC) in the United States (US). At the same time, the research community in Japan has also shown strong interest in this system for ubiquitous and spectrum access aspects. However, the ministry of internal affair and communications (MIC) in Japan has not yet released any rules for not only unlicensed but also licensed operation of the CR. Unlike in Japan, the FCC has drafted the first rule for a secondary system based CR to operate in the frequency bands allocated to the television (TV) systems [4] because the usage of the spectrum in these bands is not so high. For example, the IEEE 802.22 working group (WG) in US has been launched to develop a standard of a fixed wireless regional area network (WRAN) which aims at providing wireless broadband access to the rural areas where the need for broadband service has not yet been met due to the physical limitations and economic reality of wire-line solutions, with the performance comparable to those of existing fixed broadband access technologies such as DSL and cable modem [5], [6]. The IEEE 802.22 WG is formulating the WRAN system to operate in the TV bands by opportunistically accessing those bands that are not currently used by TV systems.

The coexistence between the cognitive WRAN and TV system on the same frequency band, time and location poses many challenges. One of which is that the secondary users must be capable of scanning the primary signals so as to recognize and use only vacant channels, and without any impact on the operation of the primary systems. In this sense, the spectrum sensing is seen as an essential function of the CR system for detection of the presence or absence of the primary signals. To implement CR system without interfering to the primary system, the IEEE 802.22 WG specified the requirements of spectrum sensing of digital TV (DTV) signals as; the probability of miss detection should not exceed 0.1 subjected to a 0.1 probability of false alarm when the signal-to-noise ratio (SNR) is very low [5]. Various techniques have already been developed to detect the spectrum of the primary signal. For example, an energy detector is the simplest technique which can be constructed in practice [7]– [10] and a cyclostationary detector is known as a powerful technique exploiting signal's cyclostationary property [11]– [18]. Matched filter is usually assumed as the optimal detector if the primary signal is known. This filter has to precisely demodulate the primary signal by performing synchronization. However, in practice these parameters may not be known by the cognitive radio receiver. An alternative method is to rely on energy detector. Energy detector estimates the received sig-

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nal energy over an observation time window and compares it with a threshold γ, to decide if a signal is present ($\mathcal{H}_1$) or not ($\mathcal{H}_0$). A simple square and average device may be used to estimate the energy. The threshold γ can be calculated based on probability of false alarm (P_{FA}). Therefore, the knowledge of noise power is needed to determine the threshold. Although energy detector is simplest technique but its detection performance degrades in shadowing and fading environment. For example, simulation results of [19], [20] report this problem. In order to improve spectrum sensing, several authors have recently proposed collaborative sensing among secondary users [21]– [24]. More importantly, the detection performance can be improved when low complexity diversity schemes such as weighted gain combining (WGC) and selection gain combining (SGC) are implemented. In this report, we present an analytical approach to derive P_{FA} and P_{D} when the WGC and SGC are implemented by using central limit theorem for large number of samples. The performance of the energy detector over additive white Gaussian noise (AWGN) channel is evaluated while the primary signal is an orthogonal frequency division multiplexing (OFDM) of japanese digital TV (ISDB-T; integrated services digital broadcasting for terrestrial television broadcasting) system.

The rest of this paper is organized as follows. In Section 2, a generality of energy detector is described. The energy detector exploiting equal gain combining (EGC) and selection gain combining (SGC(diversity techniques are addressed in Section 3. Section 4 presents the simulation results. Finally, Section 5 summarizes this paper.

2. Energy Detector without Diversity Reception

The detection problem can be modeled as two binary hypothesis,

$$\mathcal{H}_0 : x[n] = w[n], \qquad \text{signal is absent} \tag{1}$$

$$\mathcal{H}_1 : x[n] = s[n] + w[n], \qquad \text{signal is present} \tag{2}$$

where $x[n]$ is the received discrete time signal, $s[n]$ is the primary signal which may be modeled as the Gaussian process with zero mean and variance σ_s^2 while $w[n]$ denotes the complex AWGN with zero mean and variance σ_w^2. $n = 0, 1, 2, ..., N-1$ is the sample index. Without loss of generality, $w[n]$ and $s[n]$ are assumed to be independent of each other.

The decision statistic for testing whether $\mathcal{H}_0$ or $\mathcal{H}_1$ true can be determined based on Neyman-Pearson criterion. After mathematical simplification, the decision statistic of energy detector can be written as

$$\mathcal{T} = \sum_{n=0}^{N-1} x[n]x^*[n]. \tag{3}$$

From this equation, it is obviously seen that the energy detector compute the energy of the received signal and compare it to the predefined threshold γ. γ may be computed to satisfy the probability of false alarm P_{FA} (the primary signal is absent but the detector declares that the signal is present). If $\mathcal{T} > \gamma$, the signal is decided to be present and if $\mathcal{T} < \gamma$, the signal is decided to be absent. The detection performance of this detector is measured by a resulting pair of probability of detection and the probability of false alarm (P_{D},P_{FA}) or resulting a pair of probability of detection and the SNR (P_{D},SNR). Each pair is associated with the particular threshold γ that tests the decision value $\mathcal{T}$. In the cognitive radio system, the probability of false alarm should be fixed to a small value while the probability of detection should be maximized as much as possible.

If the signal is absent ($\mathcal{H}_0$), the statistical test $\mathcal{T}/(\sigma_w^2/2)$ follows the central chi-square $\mathcal{X}^2$ distribution with $2N$ degree of freedoms, as real and imaginary parts of $x[n]$ are following i.i.d Gaussian since the statistical test in (3) is the sum of the square of $2N$ Gaussian random variables. If the signal is present ($\mathcal{H}_1$), the $\mathcal{T}/((\sigma_s^2+\sigma_w^2)/2)$ follows the non-central $\mathcal{X}^2$ distribution with $2N$ degree of freedoms with non-centrality parameter η. In this case, the $s[n]$ is assumed to be complex Gaussian with zero mean and variance σ_s^2.

Using central limit theorem, the test statistic can be approximated as Gaussian distribution. That is

$$\mathcal{H}_0 : \mathcal{T} \sim \mathcal{N}(\mu_0, \sigma_0^2), \tag{4}$$

$$\mathcal{H}_1 : \mathcal{T} \sim \mathcal{N}(\mu_1, \sigma_1^2) \tag{5}$$

Using Equation (2-1-112) and Equation (2-1-125) of [25] and when $s[n]$ and $w[n]$ are complex, the mean and variance can be defined as

$$\mu_0 = N\sigma_w^2, \tag{6}$$

$$\mu_1 = N(1+\eta)\sigma_w^2 + \eta, \tag{7}$$

$$\sigma_0^2 = N\sigma_w^4, \tag{8}$$

$$\sigma_1^2 = N(1+\eta)^2\sigma_w^4 + 2(1+\eta)\sigma_s^2, \tag{9}$$

where η is defined as the ratio of the signal variance to the noise variance, denoted as the signal to noise ratio at the output of the energy detector

$$\eta = \frac{\sigma_s^2}{\sigma_w^2}. \tag{10}$$

As the number of samples N is large enough, in Equation 7 the terms η can be eliminated compared to the terms

$N(1+\eta)\sigma_w^2$ and the term $2(1+\eta)\sigma_s^2$ in Equation 9 can be eliminated compared to $N(1+\eta)^2\sigma_w^4$. Thus the mean and variance under $\mathcal{H}_1$ can be reduced to,

$$\mu_1 = N(1+\eta)\sigma_w^2, \tag{11}$$

$$\sigma_1^2 = N(1+\eta)^2\sigma_w^4, \tag{12}$$

Finally, P_{FA} and P_{D} can be determined as

$$P_{\mathrm{FA}} = \Pr(\mathcal{T} > \gamma \mid \mathcal{H}_0) = Q\left(\frac{\gamma - \mu_0}{\sqrt{\sigma_0^2}}\right), \tag{13}$$

$$P_{\mathrm{D}} = \Pr(\mathcal{T} > \gamma \mid \mathcal{H}_1) = Q\left(\frac{\gamma - \mu_1}{\sqrt{\sigma_1^2}}\right), \tag{14}$$

where $Q(z) = \int_z^\infty \frac{1}{\sqrt{2\pi}} e^{-\frac{y^2}{2}} dy$. Note that in this study the $s[n]$ and $w[n]$ are assumed to be complex signal.

3. Energy Detector with Diversity Reception

We now introduce two branches diversity reception for energy detector; gain combining and selection gain combining. The purpose of implementing the diversity techniques is to boost the detection performance of the energy detector. In diversity reception, only a single cognitive radio radio equipped with multiple antenna to capture the transmitted signal from different directions is considered. Different from cooperative sensing technique in which multiple users share the available information about the statistical test with one another or each user send the statistical test to the fusion center for deciding the presence and absence of the primary signal. In this initial study, AWGN channel is considered.

3. 1 Equal Gain Combining (EGC)

Under gain combining, the channel state estimation is not required while its performance only slightly inferior to the maximal ratio combining (MRC) but MRC technique requires channel state estimation. Thus, EGC technique is considered here. Under EGC scheme, the detector decides between $\mathcal{H}_0$ and $\mathcal{H}_1$ by comparing the sum of measured energies to a threshold. Therefore, a new decision statistic is calculated linearly as follows:

$$\mathcal{T}_{\mathrm{EGC}} = \sum_{l=1}^{L} \mathcal{T}_l, \tag{15}$$

where L is the number of diversity branches. Under $\mathcal{H}_0$, adding L i.i.d Gaussian distribution will result in another Gaussian distribution. Consequently, the mean and variance of $\mathcal{T}_{\mathrm{EGC}}$ can be computed as

$$\mathrm{E}[\mathcal{T}_{\mathrm{EGC}} \mid \mathcal{H}_0] = \sum_{l=1}^{L} N\sigma_{w,l}^2, \tag{16}$$

$$\mathrm{Var}[\mathcal{T}_{\mathrm{EGC}} \mid \mathcal{H}_0] = \sum_{l=1}^{L} N\sigma_{w,l}^4, \tag{17}$$

where $\sigma_{w,l}^2$ denotes the noise variance of lth branches. Note that the P_{FA} is independent of the SNR, thus it is the same over any fading channel. Likewise, under $\mathcal{H}_1$, $\mathcal{T}_{\mathrm{EGC}}$ conditioning on the SNR value will be a Gaussian distribution. For AWGN channel, the diversity reception scheme associated with a single user but with multiple antenna is similar to the one of the cooperative sensing technique. In this case, the mean and variance can be defined as

$$\mathrm{E}[\mathcal{T}_{\mathrm{EGC}} \mid \mathcal{H}_1] = \sum_{l=1}^{L} (N(1+\eta_l)\sigma_{w,l}^2 + \eta_l), \tag{18}$$

$$\mathrm{Var}[\mathcal{T}_{\mathrm{EGC}} \mid \mathcal{H}_1] = \sum_{l=1}^{L} (N(1+\eta_l)^2\sigma_{w,l}^4 + 2(1+\eta_l)\sigma_s^2), \tag{19}$$

From above, we can determine the P_{FA} and P_{D} as

$$\begin{aligned} P_{\mathrm{FA,EGC}} &= \Pr(\mathcal{T}_{\mathrm{EGC}} > \gamma_{\mathrm{EGC}} \mid \mathcal{H}_0), \\ &= Q\left(\frac{\gamma_{\mathrm{EGC}} - \mathrm{E}[\mathcal{T}_{\mathrm{EGC}} \mid \mathcal{H}_0]}{\sqrt{\mathrm{Var}[\mathcal{T}_{\mathrm{EGC}} \mid \mathcal{H}_0]}}\right), \end{aligned} \tag{20}$$

where γ_{EGC} denotes the selection threshold in the case of EGC, then

$$\begin{aligned} P_{\mathrm{D,EGC}} &= \Pr(\mathcal{T}_{\mathrm{EGC}} > \gamma_{\mathrm{EGC}} \mid \mathcal{H}_1) \\ &= Q\left(\frac{\gamma_{\mathrm{EGC}} - \mathrm{E}[\mathcal{T}_{\mathrm{EGC}} \mid \mathcal{H}_1]}{\sqrt{\mathrm{Var}[\mathcal{T}_{\mathrm{EGC}} \mid \mathcal{H}_1]}}\right), \end{aligned} \tag{21}$$

3. 2 Selection Gain Combining (SGC)

In this scheme, the branch with maximum decision statistic is to be selected. This is

$$\mathcal{T}_{\mathrm{SGC}} = \max_{l \in \{1,2,\ldots,L\}} (\mathcal{T}_l), \tag{22}$$

The P_{FA} can be evaluated using the cumulative distribution (CDF) of $\mathcal{T}_{\mathrm{SGC}}$ under $\mathcal{H}_0$ ($\mathrm{CDF}(\mathcal{T}_{\mathrm{SGC}} \mid \mathcal{H}_0)$), yielding

$$\begin{aligned} P_{\mathrm{FA,SGC}} &= 1 - \mathrm{CDF}(\mathcal{T}_{\mathrm{SGC}} \mid \mathcal{H}_0), \\ &= 1 - \left(1 - Q\left(\frac{\gamma_{\mathrm{SGC}} - N\sigma_w^2}{\sqrt{N\sigma_w^4}}\right)\right)^L, \end{aligned} \tag{23}$$

and P_{D} can be evaluated using the cumulative distribution (CDF) of $\mathcal{T}_{\mathrm{SGC}}$ under $\mathcal{H}_1$

$$\begin{aligned} P_{\mathrm{D,SGC}} &= 1 - \mathrm{CDF}(\mathcal{T}_{\mathrm{SGC}} \mid \mathcal{H}_1) \\ &= 1 - \prod_{i=1}^{L} \left(1 - Q\left(\frac{\gamma_{\mathrm{SGC}} - N(1+\eta_i)\sigma_{w,i}^2}{\sqrt{N(1+\eta_i)^2\sigma_{w,i}^4 + 2(1+\eta_i)\sigma_s^2}}\right)\right), \end{aligned} \tag{24}$$

4. Simulation Results

OFDM signal will be a key technology in the TV broadcasting systems. For examples, both Digital Video Broadcasting-Terrestrial (DVB-T) system and Integrated

Services Digital Broadcasting-Terrestrial (ISDB-T) system are used OFDM systems. Therefore, it is reasonable to assume that the primary users will often use OFDM transmission. Furthermore, the IEEE 802.22 WG is considering the IEEE 80.22 WRAN system based on cognitive radio to opportunistically access the spectrum of TV broadcasting. Hence, the problem of detecting OFDM signals is very relevant. In this paper, the OFDM system of ISDB-T is considered as the primary users. The ISDB-T system basically comprises of 13 OFDM segments for wideband and 1 or 3 OFDM segments for narrow band. The ISDB-T system operates in the frequency bands from 470 MHz to 770 MHz. Table 1 shows the parameters of OFDM signal for ISDB-T system in mode 3. In this report, the OFDM signal is generated with a Fast Fourier transform with size of 8192 samples and symbol length of 9216 samples after cyclic prefix is added for guard interval. In this study, we assume that the receiver has the bandwidth of 6 MHz and sampling at rate 8 MHz. Furthermore, asynchronous receiver is assumed. The number of sample is equal to 2 OFDM samples corresponding to 18432 samples.

In order to validate the central limit theorem approximation of the statistical test in a situation of a sufficient large samples size, histograms of the generated decision statistics $\mathcal{T}$ and $\mathrm{T_{EGC}}$ are compared with the theoretical probability density function (PDF) using the mean and variance defined in Equations 6,7,8,9 and 16,17,18,19, respectively. The number of trials in Monte Carlo simulation for generating decision statistics is $10,000$. Fig. 1 and Fig. 2 show this comparison. As can be seen, the histogram and theoretical curves are relatively well matched thus confirming the central limit theorem approximation.

The detection performance between no diversity and EGC diversity technique is illustrated in Fig. 3. The threshold γ were determined by fixing P_{FA} at 1% as recommended by IEEE 802.22 WG. In EGC scheme, we assume that each diversity branch has the same signal and with the same noise power. From this Figure, it is seen that the EGC outperform the case of no diversity technique. Furthermore, the

Table 1 OFDM signal of ISDB-T

Parameter	Description
QPSK	QPSK modulation
$T_{\mathrm{u}} = 1008\ \mu$s	OFDM useful symbol duration
$T_{\mathrm{g}} = T_{\mathrm{u}}/8$	OFDM guard interval
$T_{\mathrm{s}} = T_{\mathrm{u}} + T_{\mathrm{g}}$	OFDM total symbol duration
$N_{\mathrm{s}} = 2$	Number of OFDM symbols ($= 11.3\ ms$)
$N_{\mathrm{c}} = 5618$	Number of sub-carriers
$\Delta f = 0.99$ kHz	Carrier separation ($= 1/T_{\mathrm{u}}$)
$f_{\mathrm{s}} = 8.127$ MHz	Sampling frequency

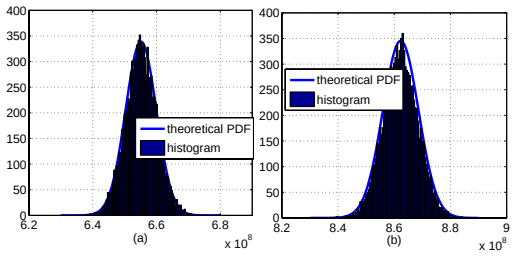

Figure 1 Histogram and theoretical PDF of $\mathcal{T}$ when $\eta = -5$ dB and $N = 2$ OFDM symbols; (a):$\mathcal{H}_0$, (b):$\mathcal{H}_1$

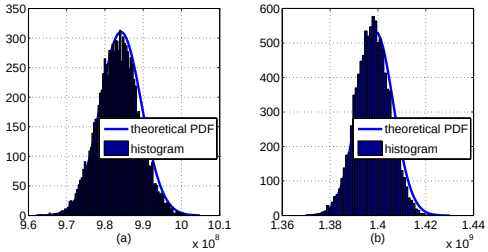

Figure 2 Histogram and theoretical PDF of $\mathcal{T}_{\mathrm{EGC}}$ when $L = 2$, $\eta_1 = -5$ dB, $\eta_2 = -2$ dB and $N = 2$ OFDM symbols; (a):$\mathcal{H}_0$,(b):$\mathcal{H}_1$

detection performance is improved as the number of diversity branches is used. This is trivial since EGC just increases the degrees of freedom of chi-square distribution proportional to the number of the diversity branches (e.g. antennas)

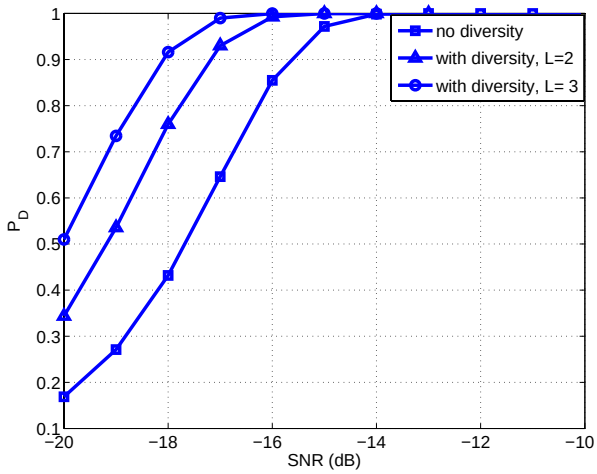

Figure 3 P_{D} vs. SNR with $P_{\mathrm{FA}} = 1\%$ in the case of no diversity and using EGC diversity technique when $\eta_1 = \eta_2$

Fig. 4 depicts the detection performance of energy detector using EGC and SGC diversity techniques. In this case only 2 diversity branches were used. For selection comn=bining technique, the branch with highest SNR is selected. Thus, to see the effect of this technique, it is necessary to assume that the SNR of 1st branch varies while the SNR of the 2nd branch is fixed. Then, η_1 varies from -20 dB to -10 dB and

η_2 is fixed at -15 dB. The P_{FA} is the same as above. Fig. 4 shows that the energy detector using EGC outperform the one using the SGC diversity technique. Performance gain of roughly 2 dB is obtained from using EGC diversity technique.

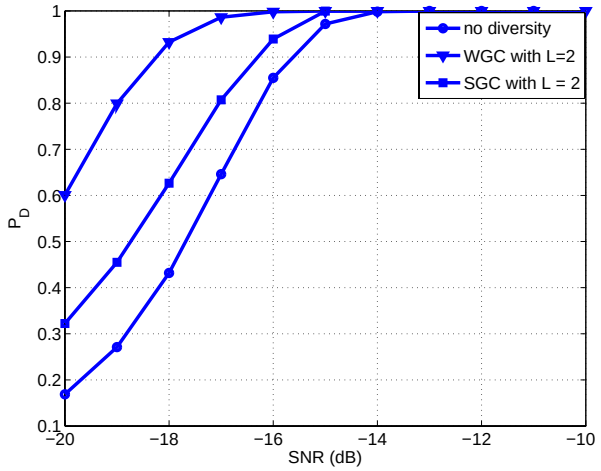

Figure 4 P_{D} vs. SNR with $P_{\mathrm{FA}} = 1\%$, η_1 varies from -20 dB to -10 dB and $\eta_2 = -15$ dB

5. Summary

This report presented the detection performance of energy detector exploiting the EGC and SGC diversity techniques. We derive the probability of false alarm and probability of detection by using the central theorem approximation. Through the simulation results, it is confirmed that the histogram and theoretical PDF of the decision statistic are relatively well matched. In comparison, the EGC technique outperforms the SGC diversity technique.

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