A closed-form of Cooperative Detection Probability using EGC-Based Soft Decision under Suzuki Fading

Thai-Mai Thi Dinh  
Faculty of Electronics and Telecommunications  
University of Engineering and Technology, Vietnam National University  
Hanoi, Vietnam  
dttmai@vnu.edu.vn

Quoc Tuan Nguyen  
Faculty of Electronics and Telecommunications  
University of Engineering and Technology, Vietnam National University  
Hanoi, Vietnam  
tuannq@vnu.edu.vn

Kumbesan Sandrasegaran  
School of Electrical and Data Engineering  
University of Technology, Sydney  
Australia  
kumbesan.sandrasegaran@uts.edu.au

Abstract—In cooperative spectrum sensing based on energy detection, several researchers have concluded that Soft Decision has better detection performance than Hard Decision. In this paper, we focus on Equal Gain Combining (EGC)-based soft decision under Suzuki fading which is a composite Rayleigh-lognormal fading. We use Moment-Generating function (MGF) to approximate Probability Density Function (PDF) of power sum of received signals at Fusion Center. Then we propose a novel method to evaluate cooperative detection performance under the effect of i.i.d Suzuki fading by using Gauss-Hermite approximation and MGF matching. Finally, we compare the results of EGC-based Soft Decision with those of Hard Decision.

Index Terms—cooperative spectrum sensing, soft decision, EGC, Suzuki fading, Gauss-Hermite integration, MGF matching.

I. INTRODUCTION

The scarcity of radio spectrum in wireless communication has become a serious problem. The radio spectrum, however, is not utilized efficiently while the demand for frequency spectrum for wireless communication services has increased significantly in last few years. Cognitive Radio (CR) proposed by Mitola [1] has been becoming an emerging technology to utilize spectrum more efficiently and alleviate spectrum scarcity. A CR network allows Secondary Users (SU), i.e. unlicensed users, to access a spectrum when it is not used by Primary Users (PU), i.e the licensed users, and without causing harmful interference to PUs [2].

To detect spectrum holes which is not occupied by PU and provide spectrum access for SUs, spectrum sensing techniques have an important and essential role. In particular, spectrum usage and PU presence is detected by SUs due to spectrum sensing techniques.

Various sensing techniques have been addressed in [3]. The authors pointed out that each method has pros and cons, in which energy detector (ED) is an appropriate candidate to enable CR functionalities because ED has low computational complexity and does not require any the transmitted signal’s prior information.

A number of studies have focused on analyzing the performance of ED over several fading channels [4-7]. With aims to enhance the detection performance of spectrum sensing under effect of fadings, the CRs do a collaboration by sending their sensing information to a Fusion Center (FC) [4], [8]. Two methods of cooperative spectrum sensing, Hard Decision and EGC-Based Soft Decision, has already been discussed in research papers [4], [5]. When utilizing EGC-Based Soft Decision, the performance of cooperative spectrum sensing gets a higher detection probability when compared with Hard Decision [5]. Motivated from this observation, EGC-Based Soft Decision under fading environment, such as Rayleigh or lognormal fading, is obtained by numerical methods [4], [9]. Up to now, based on our studies there is no published research about the EGC-based soft decision under Suzuki fading. Therefore, in this paper, we study this issue and evaluate the detection performance of cooperative spectrum sensing of the CR network under the effect of Suzuki fading.

We propose a closed-form of cooperative detection probability by utilizing MGF matching technique and Gauss-Hermite integration. Based on mathematical analysis, we investigate the detection performance of cooperative spectrum sensing under Suzuki fading.

The rest of paper is organized as follows: Section II introduces a system model of cooperative spectrum sensing. We study the detection performance of cooperative spectrum sensing under Suzuki fading in Section III. We discuss some obtained results in Section IV. Finally, in Section V, we conclude the paper.

II. MODEL OF COOPERATIVE SPECTRUM SENSING SYSTEM

A. Local Spectrum Sensing

A cognitive radio network which comprises n CRs and a Fusion Centre (FC) is shown in Fig. 1. In the case of local
spectrum sensing, each CR performs spectrum sensing individually. Each CR makes a decision based on the received PU’s signal. Hence, the spectrum sensing problem can be regarded as a binary hypothesis testing problem defined mathematically as follows,

\[
x(t) = \begin{cases} 
  n(t), H_0 \\
  h s(t) + n(t), H_1 
\end{cases}
\]

where \( x(t), s(t), h \) and \( n(t) \) denote respectively the signal received by the CR, the transmitted PU signal, the amplitude gain of the channel and the Additive White Gaussian Noise (AWGN). The signal-to-noise ratio, SNR, is determined as \( \frac{P}{N_0} \) whereas \( P \) is the transmitted power of PU, \( N_0 \) is the AWGN power spectral density and \( W \) denotes the channel bandwidth.

According to the previous work of Urkowitz [11], the average received energy, \( Y \), is compared with a threshold to make a decision (\( H_0 \) or \( H_1 \)). To assess the performance of local spectrum sensing, we take into account the following parameters: false-alarm probability \( P_f \), detection probability \( P_d \), and missed detection probability \( P_m \). In AWGN channel, \( h \) is deterministic. The false-alarm and detection probabilities are given as follows [4],

\[
P_f = P\{Y > \lambda | H_0\} = \frac{\Gamma(m, \lambda/2)}{\Gamma(m)} = G_m(\lambda) \tag{1}
\]

\[
P_d = P\{Y > \lambda | H_1\} = Q_m(\sqrt{2m\gamma}, \sqrt{\lambda}) \tag{2}
\]

Whereas, \( \Gamma(a, b) \) and \( Q_m(., .) \) denote respectively the incomplete gamma function [11] and the generalized Marcum Q-function [12]. From Equations (2) and (1), \( P_d \) and \( P_f \) are related to each other via parameter \( \lambda \). Combining these two equations, we obtain the following relationship,

\[
P_d = Q_m\left(\sqrt{2m\gamma}, \sqrt{G_m^{-1}(P_f)}\right) \tag{3}
\]

With the effect of fading and shadowing, \( h \) is varying and \( P_d \) becomes a conditional probability dependent on the instantaneous SNR \( \gamma \). As a result, the average detection probability may be obtained by averaging \( P_d \) in (3) over statistics of fading,

\[
P_{d,fading} = \int \gamma Q_m\left(\sqrt{2m\gamma}, \sqrt{G_m^{-1}(P_f)}\right) f_\gamma(x) dx \tag{4}
\]

whereas, \( f_\gamma(x) \) is the PDF of SNR \( \gamma \) under fading.

**B. Local Spectrum Sensing under Suzuki fading channel**

The Suzuki distribution was recommended by Hirofumi Suzuki in 1977 [13]. The PDF of Suzuki fading can be derived by equating the local average power of the Rayleigh faded signal to the instantaneous power of the arriving lognormal signal [14]. In Suzuki fading, there is no significant loss of power in the local multipath channel, i.e. the average power gain, \( E[|h_R|^2] \), is 1. Then, the distribution of the power gain \( p \) under Suzuki fading channel can be modeled as PDF of the product of power gain of Rayleigh channel \( |h_R|^2 \) and power gain of lognormal channel \( |h_{Ln}|^2 \),

\[
p = |h_{R-Ln}|^2 = |h_R|^2|h_{Ln}|^2 \tag{5}
\]

Using the Jacobian transformation technique, we can obtain the PDF of the composite fading channel as follows,

\[
f_{R-Ln}(p) = \int_0^\infty \frac{1}{x} f_R(\frac{p}{x}) f_{Ln}(x) dx
\]

\[
= \int_0^\infty \frac{1}{x} \left(\frac{1}{p_R} \exp\left(-\frac{p}{p_R x}\right)\right) \times \frac{1}{x \sigma_z \sqrt{2\pi}} \exp\left(-\frac{(\ln x - \mu_z)^2}{2\sigma_z^2}\right) dx \tag{6}
\]

where \( (\mu_z, \sigma_z^2) \) are the parameters of the lognormal fading. Since, \( p_R = E[|h_R|^2] = 1 \), (6) may be rewritten as,

\[
f_{R-Ln}(p) = \int_0^\infty \frac{1}{x^2} \exp\left(-\frac{p}{x}\right) \frac{1}{\sigma_z \sqrt{2\pi}} \exp\left(-\frac{(\ln x - \mu_z)^2}{2\sigma_z^2}\right) dx \tag{7}
\]

The detection probability under Suzuki fading can be obtained by substituting from (7) into (4),

\[
P_{d,Suzuki} = \int_0^\infty \int_0^\infty \frac{1}{x} \exp\left(-\frac{p}{x}\right) \frac{1}{\sigma_z \sqrt{2\pi}} \exp\left(-\frac{(\ln x - \mu_z)^2}{2\sigma_z^2}\right)
\]

\[
\times Q_m\left(\sqrt{2mp}, \sqrt{G_m^{-1}(P_f)}\right) dx dp \tag{8}
\]

A closed-form of the detection probability can be approximated as in our previous work [16],

\[
P_{d,Suzuki} = \frac{1}{\sqrt{\pi}} \sum_{i=1}^{N_p} w_i P_{d,Rayleigh}(\tau = e^{2\sigma_z a_i + \mu_z}) \tag{9}
\]

where \( a_i, w_i \) and \( N_p \) are respectively ascissas, weight factors number of samples of the Gauss-Hermite integration. \( a_i \) and \( w_i \) for different values of \( N_p \) are available in [11, Table (25.10)]. Higher value of \( N_p \) gives more accurate approximation. High accuracy is attained when \( N_p \geq 6 \).

**C. Cooperative Spectrum Sensing**

1) Hard Decision Combing: In Hard Decision method, each CR performs a local spectrum sensing and sends its individual sensing information (\( u_i = 0, 1 \)) to a FC. If \( u_i = 1 \), the hypothesis \( H_1 \) will be chosen, otherwise, hypothesis \( H_0 \) will be chosen. The FC then colligates the incoming information
to make a decision about the presence of a PU signal. For simplicity, we assume that:

- The sensing channels, i.e., links between PU and CRs are affected by i.i.d fading.
- The reporting channels, i.e., links between CRs and FC, are ideal which means information from CRs to FC is not lost or changed.
- The FC applies the Hard Decision according to \( (k\text{-out-of-}n) \) rule.

For special cases, \( k = 1 \) denotes OR rule, \( k = n \) denotes AND rule and \( k = [n/2] \) denotes Majority rule. Hence, the total probability of detection \( Q_d \) and the total probability of false-alarm \( Q_f \) when \( n \) CRs join the cooperative spectrum sensing [4] are

\[
Q_d = \sum_{i=k}^{n} C^n_i P_f^i (1-P_d)^{n-i} \quad (10)
\]

\[
Q_f = \sum_{i=k}^{n} C^n_i P_d^i (1-P_f)^{n-i} \quad (11)
\]

whereas \( P_f \) and \( P_d \) were defined in (2) and (4), respectively. The total probability of missed detection is

\[
Q_m = 1 - Q_d \quad (12)
\]

2) EGC-based Soft Decision: In this section, collaborating spectrum sensing using EGC-based Soft Decision is investigated. Fig. 2 shows a model of cooperative spectrum sensing using EGC-based Soft Decision. In this method, each CR senses energy from PU and sends it to FC. At the FC, power gains \( Y_i \) are combined to obtain the sum of power gains \( Y_0 \). Then, FC compares \( Y_0 \) to a given threshold to select the appropriate hypothesis ( \( H_0 \) or \( H_1 \)). We have the sum of energies:

\[
Y_0 = \sum_{i=1}^{n} Y_i
\]

Therefore, the PDF of combiner output given by [4]:

\[
f_{Y_0|H_0}(y) = \frac{y^{m-1}e^{-y/2}}{\Gamma(nm)2^{nm}} \quad (13)
\]

whereas, \( \gamma \) denotes instant Signal to Noise Ratio (SNR) and \( \Gamma(x) \) is the confluent hyper-geometric limit function [12]. So, we can calculate the probabilities of detection false-alarm as:

\[
Q_d = P\{ Y_0 > \lambda | H_1, \gamma_1 = l_1, \ldots, \gamma_n = l_n \} = Q_{nm} \left( \sqrt{2m\sum_{i=1}^{n} l_i}, \sqrt{\lambda} \right) \quad (15)
\]

\[
Q_f = P\{ Y_0 > \lambda | H_0 \} = \frac{\Gamma(nm, \lambda/2)}{\Gamma(nm)} \quad (16)
\]

However, the conditional probability \( Q_d \) is only a function of \( \gamma_0 = \sum_{i=1}^{n} \gamma_i \). The detection probability under fading channels can be defined as follows [4]:

\[
Q_d = \int_{\gamma_0} Q_{nm} \left( \sqrt{2m\gamma}, \sqrt{\lambda} \right) f_{\gamma_0}(\gamma)d\gamma \quad (17)
\]

whereas \( f_{\gamma_0}(\gamma) \) denotes the PDF of SNR \( \gamma_0 \).

III. PERFORMANCE OF COOPERATIVE SPECTRUM SENSING USING EGC-BASED SOFT DECISION UNDER SUZUKI FADING

As mentioned before, detection performance of Soft Decision under different fadings, such as, lognormal or Rayleigh fading, are investigated. In this section, we will deal with Suzuki fading and propose a closed-form to calculate the cooperative detection performance \( Q_d \). As shown in (17), \( Q_d \) can be calculated if the PDF of \( \gamma_0 \) is determined. With the assumption that all received SNRs, \( \gamma_i \) \( (i = 1, \ldots, n) \), have i.i.d Suzuki distribution, then \( \gamma_0 \) is the sum of \( n \) i.i.d Suzuki random variables. We use MGF matching [17] to approximate \( \gamma_0 \) as a Suzuki RV. MGF of a Suzuki RV \( \gamma_i = e^{X_i} \) with \( X_i \sim N(\mu_{x_i}, \sigma_{x_i}^2) \) can be written as [18]

\[
\Psi_{\gamma_i}(s) = \frac{1}{\sqrt{\pi}} \sum_{n=1}^{N_p} \frac{w_n}{1 + s \exp(\sqrt{2\sigma_{x_i}^2} + \mu_{x_i})} \quad (18)
\]

MGF of sum of \( n \) Suzuki RVs \( \gamma_0 = \sum_{i=1}^{n} \gamma_i \) is given as follows

\[
\Psi_{\gamma_0}(s) = \prod_{i=1}^{n} \Psi_{\gamma_i}(s) \quad (19)
\]

where \( N_p, a_n, \) and \( w_n \) denote respectively order of Gauss-Hermite integration, abscissas, weight. Terms \( w_n \) and \( a_n \) can use results in Table I when we choose \( N_p = 8 \) [19]. We match the MGF of \( \tilde{\gamma} \) with the MGF of \( \gamma_0 \) in (19) at two different points, real and positive values of \( s \), namely, \( s_1 \) and \( s_2 \) using fsolve function in Matlab. Then we obtain the estimated parameters \( (\tilde{\mu}, \tilde{\sigma}^2) \) of Suzuki RV \( \tilde{\gamma} \).

Therefore, we can rewrite PDF of \( \gamma_0, f_{\gamma_0}(\gamma), \) as follows:

\[
f_{\gamma_0}(\gamma) = \int_{0}^{\infty} \frac{1}{x^2} \exp \left( \frac{\tilde{\mu}}{\gamma} \right) \frac{1}{\sqrt{\tilde{\sigma}}} \exp \left( -\frac{(\gamma - \tilde{\mu})^2}{2\tilde{\sigma}^2} \right) d\gamma
\]

Fig. 3 illustrates an example of MGF matching of two
TABLE I
WEIGHT AND ABSCISSAS WITH \( N_p = 8 \)

<table>
<thead>
<tr>
<th>( a_i )</th>
<th>( w_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.38118</td>
<td>0.66144</td>
</tr>
<tr>
<td>1.15719</td>
<td>0.20780</td>
</tr>
<tr>
<td>1.98165</td>
<td>0.017077</td>
</tr>
<tr>
<td>-2.93063</td>
<td>0.001996</td>
</tr>
<tr>
<td>-1.98165</td>
<td>0.017077</td>
</tr>
<tr>
<td>-1.15719</td>
<td>0.20780</td>
</tr>
<tr>
<td>-0.38118</td>
<td>0.66144</td>
</tr>
</tbody>
</table>

Fig. 3. MGF matching of two i.i.d Suzuki RVs with a Suzuki RV.

i.i.d Suzuki RVs with \( \mu = 3 \text{dB}, \sigma = 0 \text{ dB} \) at two points \((s_1, s_2) = (0.4, 1)\). The estimated parameters are \( \hat{\sigma} = 0.011 \text{ dB} \) and \( \hat{\mu} = 7.7718 \text{ dB} \).

Replacing \( f_{xn}(p) \) in Equation (20) into Equation (17), we get the cooperative detection probability \( Q_{d,Su} \) under Suzuki fading as follows:

\[
Q_{d,Su} = \int_{0}^{\infty} \int_{0}^{1} \frac{1}{x} \exp \left( -\frac{p}{x} \right) \frac{1}{x \sigma \sqrt{2\pi}} \exp \left( -\frac{(\ln x - \hat{\mu})^2}{2\hat{\sigma}^2} \right) Q_m \left( \sqrt{2mp}, \sqrt{G_m^{-1}(P_f)} \right) dx dp
\]

\[
\times \left[ \int_{0}^{\infty} \frac{1}{x} \exp \left( -\frac{p}{x} \right) Q_m \left( \sqrt{2mp}, \sqrt{G_m^{-1}(P_f)} \right) dp \right]
\]

\[
\times \frac{1}{x \sigma \sqrt{2\pi}} \exp \left( -\frac{(\ln x - \hat{\mu})^2}{2\hat{\sigma}^2} \right) dx
\]

(21)

The function inside the square bracket is the cooperative probability of detection under Rayleigh channel. As presented in [6], the closed-form of \( Q_d \) under Rayleigh fading channel can be written as follows:

\[
Q_{d,Ray}(\tau) = \int_{0}^{\infty} \frac{1}{\tau} \exp \left( -\frac{p}{\tau} \right) Q_m \left( \sqrt{2mp}, \sqrt{G_m^{-1}(P_f)} \right) dp
\]

\[
e^{-\frac{\lambda}{\sigma^2} \sum_{m=0}^{\infty} -2 \left( \frac{\lambda}{\sigma^2} \right)^i} + \left( \frac{2\sigma^2 + a\tau n}{\sigma^2 n} \right)^{mn-1}
\]

\[
\times \left[ e^{-\frac{\lambda}{\sigma^2} \sum_{m=0}^{\infty} -2 \left( \frac{\lambda}{\sigma^2} \right)^i} - e^{\frac{\lambda}{\sigma^2} \sum_{m=0}^{\infty} -2 \left( \frac{\lambda}{\sigma^2} \right)^i} \right]
\]

(22)

whereas, \( \bar{\tau} \) denotes the average SNR under Rayleigh fading and \( a = 2 \).

Substituting Equation (22) into (21), we obtain the following equation:

\[
Q_{d,Su} = \int_{0}^{\infty} Q_{d,Ray}(\tau = x) \frac{1}{x \sigma \sqrt{2\pi}} \exp \left( -\frac{(\ln x - \hat{\mu})^2}{2\hat{\sigma}^2} \right) dx
\]

(23)

Let

\[
u = \frac{\ln x - \hat{\mu}}{\sqrt{2}\hat{\sigma}} \rightarrow du = \frac{1}{\sqrt{2}\hat{\sigma}} dx
\]

The probability of detection can be rewritten as follows:

\[
Q_{d,Su} = \frac{1}{\sqrt{\pi}} \int_{0}^{\infty} Q_{d,Ray}(\tau = e^{\sqrt{2}\hat{\sigma}u + \hat{\mu}}) \exp \left( -u^2 \right) du
\]

(24)

Using Gauss - Hermite integration, we can approximate:

\[
Q_{d,Su} = \frac{1}{\sqrt{\pi}} \sum_{i=1}^{N_p} w_i Q_{d,Ray}(\gamma = e^{\sqrt{2}\hat{\sigma}a_i + \hat{\mu}})
\]

(25)

Expression (25) can be considered as a closed-form of cooperative detection probability. This helps us improve the complexity of calculating and evaluating the performance of cooperative spectrum sensing using EGC-based Soft Decision under Suzuki fading.

IV. RESULTS AND DISCUSSION

Based on analysis in Section III, we used Matlab to evaluate the detection performance of cooperative spectrum sensing of a CR network using EGC-based Soft Decision as depicted in Fig. 2. In our study, we assumed that all sensing channels are under i.i.d Suzuki fading channels. Sensing information sent over reporting channels is assumed lossless.

Fig. 4 illustrates an example of detection performance of EGC-based Soft Decision under i.i.d Suzuki fading channels. In this case, we investigated the detection performance with varying number of cooperative CRs, \( n \). We consider three different values of \( n \) equal to 4, 8 and 15. Parameters of lognormal components are set \( \mu = 3 \text{dB}, \sigma = 0 \text{ dB} \). Since we consider i.i.d Suzuki channels, these parameters are the same for all channels. Black, blue and red lines are ROCs corresponding to \( n = 4, 8, 15 \). As shown in the figure, when
In this paper, we have studied EGC-based Soft Decision for cooperative spectrum sensing over Suzuki fading channel in cognitive radio. We have presented the use of MGF matching to approximate power sum of $n$ Suzuki RV's as a single Suzuki RV. Then, we proposed a closed-form of detection probability $Q_d$ under Suzuki fading to evaluate detection performance of cooperative CR network. The results obtained have shown that using the Soft Decision method is better than using the Hard Decision method.

ACKNOWLEDGEMENT

This work was supported by National Foundation for Science and Technology Development (NAFOSTED), Vietnam.

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