Cooperative Spectrum Sensing in Cognitive Radio Networks

Gourav Bansal
School of Electronics Engineering
VIT University, Vellore-632014
India

Akshay Agnihotri
School of Electronics Engineering
VIT University, Vellore-632014
India

Abstract—The entire operation of cognitive radio depends on the spectrum sensing technology. The main function of cognitive radio is to detect unused spectrum and sharing it to other user without causing harmful interference to the primary user induced by reporting phase. Basically it requires two phases: detection phase and reporting phase. In detection phase cognitive users detects the presence of primary users (Licensed user). In reporting phase cognitive user forward their detection report to fusion center. In this, we analyze the effect of ROC (Receiver Operating Characteristics) with and without dedicated reporting channel by jointly considering the signal detection and reporting phases.

Keywords—Cognitive radio, cooperative spectrum sensing, receiver operating characteristics, fusion center

I. INTRODUCTION

Cognitive radio detects the unused spectrum and shares it with the other users. The use of cognitive radio improves the efficiency of wireless spectrum resources [1], [2]. Energy detection [3], matched filter [4] detection and feature detection [5]: these three are the main categories of signal processing. In order to reduce the fading effect in wireless system, a cooperative spectrum sensing technique is used. In this technique the detection results from various cognitive users are obtained and then combined it at the fusion center together by using various logic rule such as AND fusion rule and OR fusion rule. The cooperative spectrum sensing process needs two phase: detection phase and reporting phase. For the spectrum sensing process one cannot be designed and optimized these two phases in isolation as they are not independent to each other. In detection phase cognitive users detects the presence of primary users (Licensed user) and cognitive user forward their detection report to the fusion center in reporting phase. At the fusion center the results are combined by the logic rule [6]. But there is a need to take care of time duration of both the phases as both the phases could affect each other. If the time duration of any phase is more then it will degrade the performance of overall spectrum sensing at the fusion center.

II. PROPOSED COOPERATIVE SPECTRUM SENSING IN COGNITIVE RADIO NETWORKS

A. System Description

Time duration for detection phase and reporting phases are \(\alpha\) and \(1-\alpha\) fractions respectively of one time slots. It is to be assumed that \(\alpha\) is same for all cognitive users. CUs forwards their detection report to fusion center (FC) over the orthogonal sub-channel. Sub-channels are equally divided in reporting phase, resulting in multiple time slots. These all CUs will interfere primary user (PU) potentially in the reporting phase, so in order to reduce this interference as much as possible we use a concept of selective relay based cooperative sensing scheme where all cognitive users sends their detection report to the fusion center in a selective fashion depending on the presence or absence of primary user. If CU detects that PU is absent in that case it will transmit an indicator signal with encoded cyclic redundancy code (CRC) to the FC else no signal is transmitted. At the fusion center the signal is decoded and if it is successfully decoded then it means CU detection report says that PU is absent else primary user is present. So the possibility of causing interference is reduced and controlled also as CU will interfere the PU only when it fails to detect the presence of PU.

B. Signal Model

In this model we use a Rayleigh fading and it is constant during one whole time slot. \(N_0\) is the power spectral density of the additive white Gaussian noise (AWGN) that is same for the entire receiver. Assume that \(P_p\) and \(P_s\) are the transmit power of PU and CU. Let \(H_p=H_f\) denotes the presence of PU.

Figure 1. System model of cooperative spectrum sensing
primary user and $H_p=H_0$ represents absence of it. In the detection phase, the signal received at $CU_i$ for the $k$ time slots, can be written as,

$$y_i(1) = \sqrt{P_p} h_{pi} \theta(i) + n_i(1), \quad i = 1,2,3,....,M \quad (i)$$

where index $(1)$ shows the $1^{st}$ phase of $k$ time slots, and $M$ is number of CUs. $h_{pi}$ is fading coefficient from PU to $CU_i$.

$$\theta(i) = \begin{cases} 0, & H_p = H_0 \\ x_p(1), & H_p = H_1 \end{cases} \quad (ii)$$

Where $X_p(1)$ is a complex symmetric Gaussian distribution and this is the transmit signal of PU in the $1^{st}$ phase of time slots $k$. And $\left[y_i(1)^n\right]$ is the $n$-th sample energy of signal received at $i$-th CU. Therefore the output statistic of energy detector of $CU_i$ is given by the formula,

$$T\left[y_i(1)^n\right] = \frac{1}{N} \sum_{n=1}^{N} y_i(1)^n \quad (iii)$$

where $N = \alpha T_f$, is number of samples where $f_s$ is sampling frequency and $T$ is time slot length.

Using an energy detection approach, the detection results $\hat{H}(1)$ is given by,

$$\begin{align*}
\hat{H}_0(1) & : T[y_i(1)] < \lambda_i \\
\hat{H}_1(1) & : T[y_i(1)] < \lambda_i
\end{align*} \quad (iv)$$

Each $CU$ sends a $\beta_i$ to fusion center over orthogonal sub-channel. $x_i$ is an indicator signal with encoded CRC. $\beta_i$ and $\theta(2)$ is defined as,

$$\begin{align*}
\beta_i & = \begin{cases} x_i, & \hat{H}(1) = H_0 \\
0, & \hat{H}(1) = H_1 \end{cases} \\
\theta(2) & = \begin{cases} 0, & H_p = H_0 \\
x_p(2), & H_p = H_1 \end{cases}
\end{align*} \quad (v)$$

where $X_p(2)$ is a complex symmetric Gaussian distribution and this is the transmit signal of PU in the $2^{nd}$ phase of time Slot $k$.

Signal received at fusion center is given as,

$$y_c(2) = \sqrt{P_p} h_{ic}\beta_i + \sqrt{P_p} h_{pc}\theta(2) + n_c(2) \quad (vii)$$

Where index 2 denotes the second phase. Now fusion center will decode the $\beta_i$ and do the CRC operation and if CRC checking fails means no signal is transmitted and PU is present otherwise PU is absent, and finally result is stored in $\hat{H}_c(2)$. And the $\hat{H}_c(2)$ can be written as,

$$\begin{align*}
\Lambda & = \begin{cases} H_0, & \Theta_{ic}(2) = 1 \\
H_0, & \Theta_{ic}(2) = 0 \end{cases} \quad (viii)
\end{align*}$$

Where $\theta_{ic}(2)$ is an outage event that occurs when a channel capacity is below a required data rate. Therefore $\theta_{ic}(2)$ is defined as,

$$\Theta_{ic}(2) = 1: \frac{(1-\alpha)}{M} \log_2 \left(1 + \frac{|h_{ic}|^2 |\beta_i|^2}{|h_{pc}|^2 |\gamma_p|^2 |\theta(2)|^2 + 1} \right) < \frac{1}{BT} \quad (ix)$$

$$\gamma_S = P_s / N_o, \quad \gamma_p = P_p / N_o$$

where $B$ is the frequency bandwidth. Over each time slot spectrum sensing is performed which gives data rate of initial detection results as $1/(BT)$. However it is completed during the whole reporting phase time i.e $(1-\alpha)$, so the reporting phase capacity is scaled by $(1-\alpha)$. An outage event occurs under two condition one is $\gamma_{ic} = 0$ when $\hat{H}_c(1) = H_0$ and another is small value of $|h_{ic}|^2$ which gives channel capacity below a required data rate $1/(BT)$. Now by using fusion rule $FC$ combine all $\hat{H}_c(2).$ So the final result obtained by using AND fusion rule,

$$\Lambda M \Lambda \quad H_c = \bigoplus_{i=1}^{M} \hat{H}_i(2) \quad (x)$$

By using OR fusion rule,

$$\Lambda M \Lambda \quad H_c = \bigoplus_{i=1}^{M} \hat{H}_i(2) \quad (xi)$$

III. PERFORMANCE ANALYSIS OF SPECTRUM SENSING SCHEME

In this section we have to analyze ROC by the traditional method as well as proposed scheme over Rayleigh fading channels.

a). ROC Analysis:

We check the performance of Receiver operating characteristic (ROC) with and without dedicated channel.

b). Traditional cooperative sensing with a dedicated channel:

In this the results of initial detection of CU that is encoded with CRC are forwarded to FC through a dedicated channel. At FC signal will be decoded and successfully decoded outcomes only will be combined. These successfully decoded outcomes after combined constitute a set $C$. Sample space of all possible set such that $\{C \in 0 \cup C_m\}$ where $m = 1,2,3,....,2^M-1$. $C_m$ is sub collection of non empty subset of $M$ CUs.

Case C=0: decoded operation fails at FC therefore
\[
\log_2(1 + \left|h_{ic}\right|^2 \gamma_s^T) < \frac{1}{B_d T_d}, \quad i = 1, 2, \ldots, M \tag{xii}
\]

Where \(B_d T_d\) is bandwidth time product of dedicated channel. Therefore at \(C=0\) no fusion is done at FC and degrade the performance of spectrum sensing.

\[
\overset{\wedge}{H}_c (C = \emptyset) = H_1 \tag{xiii}
\]

Case \(C=C_m\) decoded operation successfully happens so fusion is happened at FC either by AND fusion rule or OR fusion rule.

\[
\log_2(1 + \left|h_{ic}\right|^2 \gamma_s^T) > 1/ B_d T_d, \quad i \in C_m \tag{xiv}
\]

\[
\log_2(1 + \left|h_{jc}\right|^2 \gamma_s^T) < \frac{1}{B_d T_d}, \quad j \in \overline{C}_m \tag xv
\]

where \(\overline{C}_m = R - C_m\)

AND Fusion Rule
\[
\overset{\wedge}{H}_c (C = C_m) = \bigotimes_{i \in C_m} \overset{\wedge}{H}_i (1) \tag{xvi}
\]

OR Fusion Rule
\[
\overset{\wedge}{H}_c (C = C_m) = \bigoplus_{i \in C_m} \overset{\wedge}{H}_i (1) \tag xvii
\]

\(P_{d_{AND}}\) can be referred as probability of overall detection of PU presence at FC for the AND based rule,

\[P_{d_{traditional \ AND}} = \Pr\left\{ \overset{\wedge}{H}_c = H_1 \mid H_p = H_1 \right\} = \Pr\{H_c = H_1\mid H_p = H_1, C = \emptyset\} \Pr\{C = C_m\mid H_p = H_1\} + \sum_{m=1}^{M} \Pr\{H_c = H_1\mid H_p = H_1, C = C_m\} \Pr\{C = C_m\mid H_p = H_1\} \tag xviii\]

\[P_{d_{traditional \ OR}} = \Pr\{C = \emptyset\} + \sum_{i \in C_m} \Pr\{C = C_i\} \prod_{i \in C_m} P_{d_{i,i}} \tag xix\]

The probability of individual false alarm is given by,

\[
P_{f_{i,i}} = \begin{cases} P_{d_{i,i}} & \text{if } 0 < P_{d_{i,i}} < Q(-\sqrt{N}) \\ P_{d_{i,i}} - Q\left(1 - P_{d_{i,i}}\right) & \sigma_{pi}k_i \text{exp} (\varepsilon_i) \text{ otherwise} \end{cases} \tag xx
\]

Where \(k_i = \gamma_p Q^{-1}(P_{d_{i,i}}) + \sqrt{N} \gamma_p \sigma_{pi}\), \(\varepsilon_i = \frac{Q^{-1}(P_{d_{i,i}})}{\sigma_{pi}^2 k_i^2} + \frac{1}{2\sigma_{pi}^4 k_i^4}\).

\(P_{d_{OR}}\) is probability of overall detection by OR based rule,

\[P_{d_{OR}} = \Pr\{C = \emptyset\} + \sum_{i \in C_m} \Pr\{C = C_i\} \prod_{i \in C_m} P_{d_{i,i}} \tag xxx\]

\(P_{f_{i,i}}\) is probability of overall false alarm by OR based rule,

\[P_{f_{OR}} = 1 - \prod_{i=1}^{M} (1 - P_{d_{i,i}}) \tag xxxi\]

From the signal model \(P_{d_{i,i}}\) can be written as,

\[P_{d_{i,i}} = 1 - \Pr\{H_i(2) = H_0\mid H_p = H_1\} \tag xxxii\]
By using indicator signal and outage event eq. it can be further written as,
\[
P_{d_i,e} = 1 - (1 - P_{d_i}) \cdot \text{Pr}
\left[
\frac{(1-\alpha)}{M} \log_2 \left( 1 + \frac{|h_{i,c}|^2}{\sigma_i^2} \right) > \frac{1}{B_T}
\right]
\] (iii)

On solving, it can be rewritten as,
\[
P_{d_i,e} = 1 - \frac{\sigma_i^2 (1 - P_{d_i})}{\sigma_{pc}} \cdot \frac{\Lambda}{\sigma_i^2} \cdot \exp(-\frac{\Lambda}{\sigma_i^2})
\] (iv)

where 
\[
\Lambda = \left[ 2^{M/(1-\alpha)B_T} - 1 \right] / \gamma_s.
\]

Now as \(P_{d_i,e}\), The \(PF_{c,i}\) can also be written as follows,
\[
PF_{c,i} = 1 - \text{Pr}\{H_i(2) = H_0 | H_p = H_0\}
\]
\[
PF_{c,i} = 1 - \text{Pr}\{\Theta_i(2) = 0 | H_p = H_0\}
\]
\[
= 1 - (1 - PF_{c,i}) \cdot \text{Pr}
\left[
\frac{(1-\alpha)}{M} \log_2 \left( 1 + |h_{i,c}|^2 \right) > \frac{1}{B_T}
\right]
\]
\[
PF_{c,i} = 1 - (1 - PF_{c,i}) \cdot \exp(-\frac{\Lambda}{\sigma_i^2})
\] (v)

Where \(PF_{c,i}\) is probability of individual false alarm at CU\(i\) of presence of PU.

**IV. RESULT AND ANALYSIS**

In this section, we are showing the results of receiver operating characteristic (ROC) by using the traditional method and proposed scheme. The figure 2 explains the overall detection probability versus the overall false alarm probability for the traditional method, where the ROC obtained by AND has better result than OR based rule.

AND and OR fusion rule, In this figure also we are getting the better result for AND based method.

And finally the figure 4 illustrates the combined result of ROC obtained by both traditional method as well as proposed method. In this paper the parameter that we used to get the results are:
\[
\gamma_p = 5 \text{dB}, \gamma_s = 10 \text{ dB}, \alpha = 0.2, \sigma_{pc}^2 = \sigma_{id}^2 = 0.2, \sigma_{pd}^2 = \sigma_{ic}^2 = 1, M=2, R_p = 1 \text{bits/Hz}, T=25 \text{ms}, B=50 \text{ kHz}, f_s= 100 \text{kHz}, B_dT_d=1000, P_{out_{th}} = 0.01.
\]
V. CONCLUSION

In this we used a concept of proposed selective relay based cooperative sensing scheme in cognitive radio network without dedicated reporting channel. We obtained the ROC from proposed method as well as from traditional method and on comparing we found that with this proposed scheme we can save the dedicated channel resources without reducing the ROC performance. But in Fig 4 we can see that in low probability detection region the overall false alarm probability obtained from proposed method are more than that of traditional method by any fusion rule that is the disadvantage of the proposed method and in higher detection region we can see that ROC obtained from both the scheme by any fusion rule is almost identical specially in AND fusion rule. So this proposed method is good when the overall probability detection region is more than 0.9.

REFERENCES