Cooperative Spectrum Sensing: Two-sample Kolmogorov-Smirnov Test under Rician Fading Channel

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Abstract: Signal detection performance in cognitive radio architecture is enhanced by the cooperation of sensing detectors if the fading and shadowing effects exist on the channel. A cooperative spectrum sensing technique in cognitive radio networks based on two-sample Kolmogorov-Smirnov test is proposed in this paper and proposed sensing scheme is examined under Rician fading channel. The performance of the algorithm is investigated on real communication environment and real data; results show that two-sample Kolmogorov-Smirnov test based sensing offers robust and superior performance under Rician fading channel with low signal-to-noise ratio (SNR) values.

Keywords: Cognitive radio, Cooperative spectrum sensing, Two-sample Kolmogorov-Smirnov test, Rician fading channel.

I. INTRODUCTION

Cognitive radio (CR) technology was first proposed [1] to manage the frequency allocation problems due to spectrum crowding by multiple wireless devices and has been considered as the potential solution to improve the spectrum efficiency by the radios acting as secondary users and having opportunistic access to unoccupied frequency bands. CR technology offers spectrum sharing between licensed primary users (PUs) and unlicensed secondary users (SUs). A SU can use the spectrum only when the PUs are inactive and on the condition that when it does not cause harmful interference to PUs. To use the channel opportunistically, a SU first needs sensing the environment and finding the white spaces. If no PU is detected, the SU then changes its parameters to communicate on the channel. Once starting to use the channel, if a primary signal is sensed, the SU should vacate the channel immediately. Thus spectrum sensing is one of the fundamental issues of CR technology with fast and accurate signal detection.

A variety of spectrum sensing methods have been proposed such as energy detection, matched filter detection, cyclostationary feature detection, eigenvalue based detection and recently detection based on goodness of fit testing [2]-[15]. The detection performance of spectrum sensing algorithms significantly degrades due to destructive channel conditions such as fading and shadowing. Fortunately, performance degradation can be improved by the cooperative sensing among secondary users acting as sensing detectors [16, 17]. The main idea on cooperative sensing is to share the SUs’ individual sensing information by using the spatial diversity of local users and making a fused decision which is mostly more accurate than the individual decisions.

In this paper, we propose a new approach to the cooperative spectrum sensing problem named two-sample Kolmogorov-Smirnov (KS) goodness of fit (GoF) test and hard decision combining rule is performed at fusion center to make the final decision. We test the algorithm under a Rician fading channel. The novelty of this work is that some GoF tests used on spectrum sensing problem is reformulated to cooperative scheme and their performances are investigated under a fading channel.

The rest of the paper is organized as follows. In Section II, cooperative sensing basics and prior works are presented. Section III mentions GoF testing based sensing system models briefly and Section IV presents the Rician fading channel model. The proposed algorithm formulation is introduced in Section V and performance analysis and results are discussed in Section VI. Finally, the paper is concluded in Section VII.

II. COOPERATIVE SPECTRUM SENSING (CSS)

The cooperation strategies for spectrum sensing basically rely on information share/exchanges among users (or nodes). The shared/exchanged information can facilitate the detection of white spaces and increase the efficiency of the spectrum sensing.

Cooperative sensing strategies can be classified into three main categories: centralized, distributed, and relay-assisted which differ from each other by how cooperating users share/exchange the sensing data in the network [18-22]. This paper focuses on the centralized CSS where the information coming from all nodes is combined to make a final sensing decision.

The SUs called also as sensing nodes detect the primary signal’s availability independently and the detection information is then sent to a common controller which is also a SU (sometimes named as a fusion center).
fusion center (or decision center) is responsible for the final decision whether the channel is available or not for SUs’ transmissions.

In centralized CSS schemes there are mainly three types of data fusion algorithms: Hard Decision Combining, Soft Decision Combining and Quantized Soft Decision Combining [16]. In hard decision fusion, CR nodes make a local decision and send the decision to the fusion center. On the other hand, CR nodes send the entire local sensing samples to the fusion center in the case of soft decision fusion. Quantized soft decision fusion rule relies on the quantization of local sensing samples and sending only the quantized data to the center for final decision. Several centralized CSS algorithms have been proposed in literature [23-30]. Although the soft combining strategies can have better sensing performances, they need more bits on reporting to the fusion center and thus they require more control channel bandwidth.

III. GOF TESTING BASED SPECTRUM SENSING

Spectrum sensing in a CR scheme is simply to determine the primary signal transmission in a channel. A Goodness of fit (GoF) test is a statistical way of describing how well it fits a set of observations or measurements. A GoF test enables to reach the discrepancy between observed/measured values and the values expected under the model. With the help of the calculation of the discrepancy between the empirical distribution of the measurements made locally at the sensing detector and the expected distribution, and making comparison between the discrepancy and the corresponding threshold, goodness of fit test can be used as a spectrum sensing method in CR architecture.

If there is no PU on the channel, i.e., no primary signal transmission, the measurements made locally at the sensing detector are a sequence of samples drawn independently from the noise distribution. On the contrary, in the case of existence of PU, measurements made will be different from the samples taken on the situation having only noise.

Therefore, to determine the existence of primary signals on the channel, a GoF testing can be formulated to check whether the measurements are drawn independently from the noise distribution.

IV. RICIAN FADING CHANNEL

The radio signals in some communication environments may be affected (mostly fade) by some natural and medium dependent factors such as the phenomena of path loss variance with distance, shadowing (or long-term fading), and multipath (or short-term) fading. Shadowing and multipath fading can be statistically described by fading models and several statistical distributions have been proposed for fading channels models including Rician/Rayleigh fading environment.

In Rayleigh fading model, the radio signal strength is supposed to vary randomly as it passed through the fading channel, i.e., the signal fades. If a dominant line of sight exists between the transmitter and receiver in a wireless medium, Rician fading model becomes more realistic. If a direct line of sight accompanied by the diffused signal component occurs in the medium, Rician fading model based on the Rician distribution has been proposed to be a more accurate model for the fading statistics [31]. A Rician fading channel can be described by two parameters \( V \) and \( S \) where \( V \) is the ratio between the power in the dominant direct path and the power in the scattered paths and \( S \) is the total power from all paths. In receiver part, the signal amplitude is now Rice distributed with the parameters \( \alpha \) and \( \beta \) given below:

\[
\alpha = \frac{V}{\sqrt{1+V}} \tag{1}
\]

\[
\beta = \frac{S}{\sqrt{2(1+V)}} \tag{2}
\]

The resulting probability density function (PDF) is then as follows:

\[
f(x) = \frac{2(V+1)x}{S} \exp(-V - \frac{(V+1)x^2}{S}) J_0(2\sqrt{\frac{V(V+1)x}{S}}) \tag{3}
\]

where \( J_0(.) \) is the 0th order modified Bessel function of the first kind.

V. TWO-SAMPLE KOLMOGOROV-SMIRNOV COOPERATIVE SENSING

In spectrum sensing algorithms, detecting the presence of primary signal is performed by taking some samples from the channel and then making a decision based on the algorithm analysis of the measured samples. The decisions are either the presence of the signal on the channel or no signal transmission. In cooperative sensing, more detectors are used to observe the transmission condition of the environment and to make collaborative decision.

Sensing algorithm based on only one sensor is presented first and cooperation algorithm is introduced next. Let the received samples observed by the sensing detector has the cumulative distribution function (CDF), \( G(x) \). If there is no primary signal on the channel, observed samples CDF approaches to the noise distribution. In the presence of signal \( G(x) \) will be different from the previous observations. Thus, a goodness of fit test for sensing detector is considered as making the decision between two hypotheses:
\[ H_0 : G(x) = F(x) \]
\[ H_1 : G(x) \neq F(x) \]  \hfill (4)

where \( H_0 \) is the case where the received signal was drawn from a noise distribution, \( H_1 \) is the case where the transmission occurs on the channel, and \( F(x) \) is the noise CDF. If the noisy channel model is added to the hypothetical test, the sensing problem is modified to make decision about two hypotheses:
\[ H_0 : rs(t) = rn(t) \]
\[ H_1 : rs(t) = s(t) + rn(t) \]  \hfill (5)

where again \( H_0 \) is the case that “channel is idle”, and \( H_1 \) is the case that “channel is busy” with \( rs(t) \), the locally measured (or received) signal at the sensing detector; \( s(t) \), the signal coming from the primary user signal; \( rn(t) \) is the noise produced due to the existence of Rician fading channel. In the case of two-sample Kolmogorov-Smirnov testing, the statistic of the two CDFs, denoted by \( G_1(x) \) and \( G_2(x) \), respectively, is defined as:
\[ D_n(G_1, G_2) = \sup_x \left| G_1(x) - G_2(x) \right| : -\infty < x < \infty \]  \hfill (6)

where \( G_1(x) \) and \( G_2(x) \) are the CDFs of the first and second n-valued i.i.d. samples vectors. Thus, the statistic is determined by the largest absolute difference between two CDFs.

The statistic is evaluated practically by the calculation of the maximum vertical distance between \( G_1(x) \) and \( G_2(x) \) shown as the relation:
\[ D^* = \max_i \left| G_1(x_i) - G_2(x_i) \right| \]  \hfill (7)

for a set of uniformly spaced sample points. The significance level \( \alpha^* \) of the measured value \( D^* \) is formulated using the relation:
\[ \alpha^* = P(D > D^*) = \Psi \left[ \sqrt{N} + 0.12 + \frac{0.11}{\sqrt{N}}D^* \right] \]  \hfill (8)

where
\[ \Psi(x) = 2 \sum_{m=1}^{\infty} (-1)^{m-1} e^{-2m^2x^2} \]  \hfill (9)

and
\[ N = \frac{N_1N_2}{N_1 + N_2} \]  \hfill (10)

The null hypothesis \( H_0 \) is accepted at a significance level \( \alpha \) if \( \alpha^* = P(D > D^*) \geq \alpha \) and rejected if \( \alpha^* \) is less than \( \alpha \).

Here the significance value \( \alpha \) is an input of the test which is used to determine the probability of false alarm under the null hypothesis and formulated as:
\[ \alpha = P(D > \zeta \mid H_0) \]  \hfill (11)

where \( \zeta \) is a certain threshold value.

As a summary, the null hypothesis \( H_0 \) is accepted if the two-sample KS statistic is less than a predefined threshold, otherwise the hypothesis \( H_1 \) is accepted.

The proposed two-sample KS test-based cooperative spectrum sensing algorithm is carried out by the following steps:

1. The individual CR sensing detectors initially collect samples from the channel in “no signal transmission” case, i.e., noise samples.
2. The detectors then take samples from the channel for sensing the medium.
3. Each node then computes the CDFs of samples taken from StepII and StepIII, respectively and calculates the statistic value \( D^* \) and decides for a certain threshold value \( \zeta \) for the intended false alarm probability.
4. Each sensing node makes its decision independently depending on the comparison of \( D^* \) and \( \zeta \) values. The decision is either \( H_0 \) or \( H_1 \). If \( D^* < \zeta \), the individual decision is \( H_0 \), i.e., “the channel is free”; otherwise the decision is \( H_1 \), i.e., “the channel is occupied by the primary user.”
5. All CR nodes send their sensing information in the form of one-bit binary decisions (1 or 0) to the fusion center. OR-rule hard decision combining is performed at fusion center to make the final decision about the presence of primary user.

VI. PERFORMANCE EVALUATION

A. Cooperative Sensing Setup

For the performance analysis of the proposed method, we have used a test bed for implementing the cooperative sensing algorithm. The test bed includes GNU Radio platform which is an open source software toolkit providing a library of signal processing blocks for implementing the cognitive radio applications [32] and Universal Software Radio Peripheral 2 (USRP2) architecture which is a flexible low-cost cognitive radio hardware developed by Ettus Research [33]. USRP2 provides radio front-end functionalities with an FPGA and it allows making signal processing operations on a computer using GNU Radio and general purpose tasks including demodulation, interpolation, digital up-down conversions in it.

We used real primary signals for the performance evaluation. Real signal samples are produced by a transmitter design which is a combination of GNU Radio and USRP2. The transmitter produced primary signal in the form of OFDM with 40 sub carriers at a centre frequency of 433 MHz. The CR sensing nodes are also formed using GNU Radio and USRP2. We have used 4
CRs responsible for collecting data on the channel independently and making their own decisions. One of the sensing nodes also serves as fusion center and combines all the sensing information coming from the other CR nodes to make the final decision.

B. Results

We have used OFDM signals as a primary user transmission and we assumed that the transmitted signal is noise-free. To simulate the Rician fading channel, we have also produced and transmitted noisy signal samples based on Rician distribution.

Thus, when there is no primary signal transmission, the only signal on the channel is noise; and when the primary signal transmission exists on the channel, the sensed samples are the addition of primary signal and noise.

First, to determine the performances of the proposed method and existing methods without cooperative operation, we set the target probability of false alarm value to 0.1 (i.e., \( P_f = 0.1 \)).

Table I shows probability of detection \( P_d \) values of proposed two-sample KS method (TSKS) and other methods (KS-one-sample KS, ED-Energy Detection, ST-Student’s t-distribution, and AD-Anderson Darling based sensing) under Rician fading environment in a low SNR value (SNR=8dB).

<table>
<thead>
<tr>
<th>Detector</th>
<th>TSKS</th>
<th>KS</th>
<th>ED</th>
<th>ST</th>
<th>AD</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_d )</td>
<td>0.95</td>
<td>0.56</td>
<td>0.64</td>
<td>0.38</td>
<td>0.1</td>
</tr>
</tbody>
</table>

It is seen on Table I that the proposed method outperforms the existing methods. Since Anderson Darling based sensing has the worst performance under the Rician channel, the proposed two-sample KS method is compared with the other three ones.

Next, Table II shows the performance of hard decision rules (AND-rule, OR-rule, and MAJORITY-rule) as the collaborative probability of detection \( P_d \) and probability of false alarm \( P_f \) vs. average SNR based on the proposed method with 3 sensing nodes under Rician channel.

<table>
<thead>
<tr>
<th>Average SNR</th>
<th>AND-rule ( P_d ) and ( P_f )</th>
<th>OR-rule ( P_d ) and ( P_f )</th>
<th>MAJORITY-rule ( P_d ) and ( P_f )</th>
</tr>
</thead>
<tbody>
<tr>
<td>-14 dB</td>
<td>0.904</td>
<td>0.983</td>
<td>0.966</td>
</tr>
<tr>
<td>-12 dB</td>
<td>0.912</td>
<td>0.985</td>
<td>0.96</td>
</tr>
<tr>
<td>-10 dB</td>
<td>0.904</td>
<td>0.98</td>
<td>0.96</td>
</tr>
<tr>
<td>-8 dB</td>
<td>0.94</td>
<td>0.996</td>
<td>0.972</td>
</tr>
<tr>
<td>-6 dB</td>
<td>0.96</td>
<td>0.101</td>
<td>0.108</td>
</tr>
</tbody>
</table>

Figure 3 shows the Receiver Operating Characteristic (ROC) curves of the proposed cooperative two-sample KS method (TSKS) and former methods for a fixed value of SNR, -12dB, under Rician fading channel with OR-rule.

It is obviously observed from the figures 1 and 2 that two-sample KS method (no collaboration case) performance is superior to the performances of the cooperative KS, ED, and ST methods and proposed collaborative two-sample KS (TSKS) based sensing outperforms greatly and detection performance is doubled on the orders of -15 dB SNR values.

VII. CONCLUSION

In this paper, we derived two-sample KS test based cooperative spectrum sensing and investigated its performance in a Rician fading channel using the real data. The experimental results show that the proposed algorithm outperforms the existing methods and robust on the noisy
environment. It is also seen that the sampling size of the two-sample KS test algorithm has low computational complexities with low SNR values. Performance analysis of the proposed method under different fading channels is the ongoing research efforts.

REFERENCES