IMPROVEMENT OF SPECTRUM SENSING PERFORMANCE IN COGNITIVE RADIO USING MODIFIED HYBRID SENSING METHOD

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ABSTRACT. Cognitive radio (CR) is a wireless technology for increasing the bandwidth usage. Spectrum sensing (SS) is the first step in CR. There are three basic techniques in SS, energy detection (ED), matched filter (MF), and cyclostationary detection (CFD). These techniques have many challenges in performance detection ($P_d$) and computational complexity (CC). In this paper, we propose a hybrid sensing method that consists of MF and CFD to exploit their merits and overcome their challenges. The proposed method aims to improve $P_d$ and reduce CC. When MF hasn’t had enough information about PU, it switches to CFD with a reduction of CC in both MF and CFD. The proposed method is simulated under fading with cooperative and non-cooperative scenarios, measured using $P_d$ and CC ratio $C_{ratio}$. For example, at $E_b/N_0$ equal to 0dB under the Rayleigh fading channel, the $P_d$ in the proposed method increased by 38%, 28%, 28%, and 18% as compared with the modified hybrid method, traditional hybrid method, traditional CFD method, and traditional MF method in the literature, respectively.

KEYWORDS: Cognitive radio, spectrum sensing, matched filter, cyclostationary, energy detection, hybrid sensing method.

1. INTRODUCTION

Due to the large number and diversity of wireless devices and applications, the emergence of new applications, and the continuous demand for higher data rates, the Radio Frequency (RF) spectrum is becoming increasingly crowded [1, 2]. Cognitive radio (CR) has been proposed as a promising technique that provides a solution to the spectrum scarcity problem by dynamically exploiting the unused part of the spectrum band [3, 4]. A cognitive radio was defined as a radio or system that senses, and is aware of its operational environment and can dynamically adjust its radio operating parameters accordingly [5]. Cognitive radio is a wireless technology that provides the ability to share the spectrum while avoiding any imposed harmful interference to the PU [6]. The CR aims to exploit the natural resources efficiently, including frequency, time, etc. [7]. Spectrum sensing is the first step to implementing a CR system. The basic component of spectrum sensing is a primary user (PU) signal or license band, and a secondary user (SU) or cognitive user (CU) that senses the PU band to detect the activity of PU and can use its spectrum when the PU is absent [8]. The SU must not interfere in any way with the PU to succeed the cognitive radio networks [9]. Spectrum sensing techniques can be classified into two scenarios, non-cooperative and cooperative. Three basic techniques are used for spectrum sensing, these are energy detection ED, matched filter MF, and cyclostationary feature detection CFD. The ED spectrum sensing technique is more used as compared to others due to its simplicity and minimal computational complexity. However, at low signal-to-noise ratio (SNR) values, and bad channel conditions, the ED cannot differentiate between the PU signal and the noise. The matched filter (MF) maximizes the received SNR in communication systems, so it can be considered as the best detector [10]. MF has a challenge that it must know the information about the PU signal properties, i.e., packet format, pulse shaping, and the type of modulation. If the CR has incomplete information about the PU signal, then the MF cannot be used as an optimum detector. A cyclostationary detector can be used as a sub-optimal detector. CFD can distinguish between the PU signal and the noise. It has a good performance in low SNR conditions because of its noise rejection characteristic [11]. However, a cyclostationary detector has a high computational complexity since it has a long sensing time, which is not favourable in some situations [12]. To improve the performance detection, CSS (cooperative spectrum sensing) is applied. CSS could overcome fading and shadow in wireless channels. There are two basic structures of CSS, centralised and distributed [13, 14]. In CSS, SUs sense the spectrum separately and transmit their local decisions to a fusion centre (FC). By applying some fusion logic scheme, FC is responsible for the overall decision [11]. The decision fusion rules can be either hard or soft. In a hard fusion rule, every
SU makes the local binary decision independently of the activity of PU, while in the soft fusion rule, the SUs send their sensing information to the fusion centre without making local decisions. The decision is made at FC by using one of the combining rules \[15-17\]. The rest of the paper is organized as follows: Section 2 presents the literature review of the related works. Section 3 displays the theoretical background of spectrum sensing techniques. Section 4 explains the procedures of the proposed hybrid method. Section 5 shows the computational complexity of the proposed method. Section 6 illustrates the simulation results and discussions, and finally, the conclusions of the paper are drawn.

2. RELATED WORKS

Several works related to the spectrum sensing technique are proposed to improve its performance. In \[11\] traditional hybrid method based on energy and cyclostationary detectors, the cooperative scenario is proposed to improve the detection performance without taking into consideration the computational complexity. In this method, the PU signal is first scanned by ED to detect whether the PU is present or not. If ED is not certain about the detection of PU, then the PU signal is sensed by a cyclostationary detector. In \[12\], the reduction of the computational complexity in CFD is done by choosing optimum parameters. In \[13\], the hybrid method consists of two parallel paths of detectors. The first path is created from two sequential detector stages; in the first phase, ED is used to identify the PU signal existence where the signal has not been detected. Maximum–Minimum Eigenvalue (MME) is used as a second stage to detect the PU signal presence. In \[14\], the hybrid method is done by artificial neural networks (ANN). In \[15\], the hybrid method consists of five types of detectors, each one having its special functions to detect the spectrum whether it is free or occupied. In \[16\], the hybrid sensing method is proposed based on ED and cyclostationary detector with a reduced computational complexity and an improved detection performance. In \[17\], the idea of the proposed method is similar to \[12\], it reduced the computational complexity with a good performance, its process is based on the optimal parameter selection strategy for choosing detection parameters of the cyclic frequency and lag. To improve the performance of spectrum sensing techniques and solve its complexity problem, we proposed a hybrid spectrum sensing method based on matched filter and cyclostationary feature detection. This method improves the performance detection of the matched filter when it does not have sufficient information about a PU signal or at very low SNR values, and reduces the computational complexity of the cyclostationary process with an excellent performance detection. The proposed method is measured using the probability of detection \(P_d\) and computational complexity ratio under the Rayleigh multipath fading channel with cooperative and non-cooperative scenarios, and evaluated by comparing it with traditional sensing techniques (cyclostationary and MF), the traditional hybrid method in reference \[11\] and improved hybrid method in reference \[21\].

3. SPECTRUM SENSING TECHNIQUES

There are three basic techniques used for spectrum sensing, which are energy detection, matched filter, and cyclostationary feature detection. Each technique is explained in the following sections.

3.1. ENERGY DETECTOR

Energy detection (ED) is the simplest sensing technique that does not require any knowledge about the PU signal to operate. It performs the detection by comparing the accumulated energy of the received signal with a predefined threshold. The threshold depends only on the noise power \(\mathbb{E}[N^2]\). The received samples at the CU receiver are shown in the following Equation \[23\]:

\[
y(n) = H_0 x(n) + N_0(n),\]

where \(y(n)\) is the received sensed signal by the CU, \(x(n)\) is the PU signal, \(N_0(n)\) is the Additive White Gaussian Noise (AWGN) and \(H\) is the gain of the channel, and \(\theta\) is the activity pointer and has one of two values as shown in Equation \[2\]:

\[
\theta = \begin{cases} 0 & \text{for } H_0 \text{ hypothesis} \\ 1 & \text{for } H_1 \text{ hypothesis.} \end{cases}
\]

When PU is present, it is represented by hypothesis \(H_1\), while when the PU is absent, it is represented by hypothesis \(H_0\). The probabilities of false alarm \(P_f\) and detection \(P_d\) are shown in Equations \[1\] and \[3\], respectively:

\[
P_f = \Pr(En_j > \lambda \mid H_0),
\]

\[
P_d = \Pr(En_j > \lambda \mid H_1).
\]

Numerically, the threshold value can be computed for a constant \(P_f\) value, which is shown in the following Equation \[6\]:

\[
\lambda = (Q^{-1}(P_f) + \sqrt{N})2\sqrt{N}(N)^2
\]
3.2. CYCLOSTATIONARY FEATURE DETECTION

Cyclostationary feature detection is a spectrum sensing technique for detecting the PU signals by exploiting the cyclostationary features of the received signals. These features are periodicity, number of signals, their modulation type, symbol rate, and presence of interferer [23]. This method is achieved by the autocorrelation process. The autocorrelation can be computed by multiplying the received signal \(y(n)\) with its delay version. The sum of autocorrelation is compared with a pre-defined threshold to detect the activity of PU, as shown in the following equation [10].

\[
\begin{align*}
&\text{If } T_{MFD} \geq \lambda, \text{ PU signal present} \\
&\text{If } T_{MFD} < \lambda, \text{ PU signal absent}
\end{align*}
\]

4. THE PROPOSED METHOD

In this method, the design is based on the matched filter and cyclostationary techniques with an improvement in detection performance and reduction in computational complexity in both of them. The process of this method is that the matched filter receives the PU signal and senses the half number of samples by selecting one and skipping another to reduce the computational complexity in the convolution process between the incoming received signal (PU signal) and its impulse response, which is stored in the matched filter of the spectrum sensing technique. When the detector does not have a better knowledge about the PU or when the received signal is distorted due to the channel effect, it switches to the cyclostationary technique to overcome the degradation of performance detection. In the cyclostationary stage, it also senses the PU signal by using the half number of samples by sensing one signal and skipping one to reduce the computational complexity in the autocorrelation process. So, in this proposed method, we gain a high-performance detection with a reduction in computational complexity. Figure 1 shows the flowchart that explains the procedures of the proposed method. Figure 2 shows the proposed system model using the centralised cooperative network. According to [11] and [21], the probability of detection of the proposed method can be written as:

\[
P_{d,\text{proposed},i} = 1 - (1 - P_{d,\text{MF},i})(1 - P_{d,\text{cyclo},i})
\]

where \(k\) is the number of SUs in the cooperative scenario, \(P_{d,\text{proposed},i}\) is the probability of detection of the proposed method, \(P_{d,\text{MF},i}\) is the probability of detection in matched filter stage, and \(P_{d,\text{cyclo},i}\) is the probability of detection in cyclostationary stage.

5. COMPUTATIONAL COMPLEXITY OF THE PROPOSED METHOD

In this section, we compute the computational complexity in two stages (MF and CFD). Since the MF is based on the convolution process between the received and previous information of the PU signal, the computational complexity in the convolution process based on the frequency domain equals to a multiplication between two signals and we need to compute the frequency domain transformation of both the received PU signal and its impulse, then, we need to compute the multiplication between them. The computational complexity of FFT for \(N\) samples is \(O(N\log_2 N)\) according to [24], while for multiplying two signals, each
with $N$ samples, it is $o(N)$. So, the computational complexity of a traditional MF becomes:

$$C_{\text{conFFT}} = 2o(N\log_2 N) + o(N),$$

(12)

where $N$ is the number of samples. In the proposed method, we select a half of the samples by choosing one and skipping one, so the Equation (12) becomes:

$$C_{\text{conpropoFFT}} = 2o\left(\frac{N}{2}\log_2 \frac{N}{2}\right) + o\left(\frac{N}{2}\right).$$

(13)

In the second stage, the cyclostationary process is based on the autocorrelation process and its computational complexity is [22, 27]:

$$C_{\text{auto}} = \text{No. of real multiplications} + \text{No. of real additions}$$

$$C_{\text{auto}} = 4N + 4N - 2$$

(14)

The complexity of a traditional cyclostationary process is written as shown below:

$$C_{\text{cycl}} = 4N + 4N - 2 + o(N\log_2 N).$$

(15)

Since, in the proposed method, only a half of the samples was chosen for the cyclostationary process by selecting one and skipping one, the Equation (15) reduces to:

$$C_{\text{cyclproposed}} = 2N + 2N - 2 + o\left(\frac{N}{2}\log_2 \frac{N}{2}\right)$$

$$= 4N - 2 + o\left(\frac{N}{2}\log_\frac{N}{2}\right)$$

(16)

The total computational complexity of the proposed method is the addition of Equations (13) and (16), as shown in Equation (17).

$$C_{\text{Totalproposed}} = 4N - 2 + 3o\left(\frac{N}{2}\log_2 \frac{N}{2}\right) + o\left(\frac{N}{2}\right)$$

(17)
Table 1. Comparison of computational complexity.

| Method                        | Computational complexity                           |
|-------------------------------|---------------------------------------------------|
| Proposed method               | $C_{Total}^{proposed} = 4N - 2 + 3o \left( \frac{N}{2} \log_2 \frac{N}{2} \right) + o \left( \frac{N}{2} \right)$ |
| Hybrid method in [21]         | $C_{hybrid} = 2N + 2N - 2 + O(N \log_2 (N))$      |
| Traditional hybrid [11]       | $C_{hybrid}^{tradi} = 4N + 4N - 2 + O(N \log_2 (N))$ |
| Traditional Cyclostationary [21]| $C_{cycl} = 4N + 4N - 2 + o(N \log_2 N)$              |
| Traditional MF                | $C_{conFFT} = 2o(N \log_2 N) + o(N)$                |

The computational complexity ratio is defined as
the ratio of computational complexity in the proposed
method to the maximum computational complexity
(in the traditional Cyclostationary method).

$$C_{ratio} = \frac{C_{Total}^{proposed}}{C_{cycl}} \quad (18)$$

Table 1 displays the summary of the computational
complexity of the proposed method, the traditional
hybrid method in [11], the hybrid method in [21],
traditional cyclostationary, and traditional MF. It
can be noted that the complexity of the traditional
hybrid method is the same as the one of the traditional
cyclostationary method.

6. SIMULATION RESULTS AND DISCUSSION

This section shows the simulation results of the pro-
posed method in both the cooperative and the non-
cooperative scenarios. The performance is tested un-
der AWGN and Rayleigh multipath fading channels.
The results have been achieved using MATLAB 2018
on Windows 10. The performance results of the pro-
posed method are measured using the probability of
detection and computational complexity ratio and
evaluated by comparing it with: hybrid methods in
references [11] and [21], and with traditional methods
(cyclostationary feature detection (CFD) and matched
filter method MF). The simulation parameters used
are presented in Table 2. The multipath fading used
is “ITU indoor channel model (A)” with the specification
shown in Table 3 [28].

Figure 3 shows the performance curves of $P_d$ vs $E_b/N_0$ for traditional sensing methods (energy
detection, cyclostationary, and matched filter) in AWGN
using the non-cooperative scenario.

It can be seen from this figure that the matched
filter has a better performance as compared to the en-
ergy detection and cyclostationary methods, especially
at a low value of $E_b/N_0$, since it has a good knowledge
of the PU signal. For example, at $E_b/N_0$ equal to
0 dB, the probability of detection in the matched filter
is increased by 36% and 91% as compared to cyclo-
stationary and energy detection, respectively. But the performance of matched filter becomes very bad when the knowledge of PU signal becomes poor and the cyclostationary technique becomes the best technique in the detection performance. The calculation of percentage improvement in this and all below results are as shown below:

$$\text{percentage} = (\text{high value} - \text{low value}) \times 100\%.$$  

When comparing two curves at the same $E_b/N_0$ or $N$, we take the values from the curves and make sure that one curve has a value lower than the other, which is computed as shown in the above formula.

Figure 4 presents the same performance as in Figure 3, but in Rayleigh multipath fading, it can be noted that all techniques have the same detection performance as compared with Figure 3, but with a degradation in the probability of detection due to multipath fading, and the matched filter also outperforms other techniques in the case of a good knowledge of PU.

Table 3. Multipath fading properties of ITU indoor channel model (A).

| Tap | Relative delay [ns] | Average power [dB] | Doppler spectrum |
|-----|---------------------|--------------------|-----------------|
| 1   | 0                   | 0                  | flat            |
| 2   | 50                  | -3.0               | flat            |
| 3   | 110                 | -10.0              | flat            |
| 4   | 170                 | -18.0              | flat            |
| 5   | 290                 | -26.0              | flat            |
| 6   | 310                 | -32.0              | flat            |
Figure 5 illustrates $P_d$ vs $E_b/N_0$ of the proposed method in the non-cooperative scenario under Rayleigh multipath fading as compared with hybrid methods in [11] and [21] and traditional methods (cyclostationary feature detection (CFD), and matched filter detection). It can be observed that the probability of detection of the proposed method outperforms the other methods especially at low $E_b/N_0$ values, since the matched filter gives an excellent performance detection when it has the best knowledge about the PU signal. When it has a poor knowledge, it switches to the cyclostationary technique, which is a blind technique (does not need information about the PU signal) and gives a very good performance detection especially at low values of $E_b/N_0$. So, the overall detection performance of the proposed method gives an excellent detection performance with a low computational complexity. For example, at $E_b/N_0$ equal to 0 dB, the proposed method achieves an increase in detection probability of 38%, 28%, 28%, and 18% as compared with the traditional hybrid method in [11], the hybrid method in [21], traditional CFD method, and traditional MF method, respectively.

Figure 6 displays the performance curves of the average $P_d$ vs $E_b/N_0$ of the proposed method in cooperative and non-cooperative scenarios as compared to the traditional hybrid method in [11]. In the cooperative scenario, we assumed 3 CUs do the sensing and one of them is suffering from multipath fading. It can be noted that the detection performance of the
cooperative scenario has a larger improvement than non-cooperative in both methods, since the effect of fading is reduced. For instance, at $E_b/N_0$ equal to 0 dB in the proposed method, the performance detection is increased by 26% as compared with a single CU in multipath fading and increased by 20% as compared with the traditional hybrid also with a single CU in multipath fading. In all cases, the proposed method has a better performance than the traditional hybrid method.

Figure 7 shows the computational complexity ratio versus the number of samples. It can be seen that the proposed method has a lower computational complexity than the hybrid method in [21], traditional cyclostationary method, and MF, since it computes the convolution process in the MF stage or autocorrelation process in CFD with a half of the samples, and it is slightly greater than the hybrid method in [21], since this method uses an ED in the first stage. However, the proposed method outperforms the hybrid method in [21] and others in the probability of detection. For example, at $N$ equal to 100, the computational complexity ratio in the proposed method decreased by 14%, 14%, and 12% as compared to CFD, traditional hybrid in [11], and MF, respectively. So, we conclude that the proposed method has an excellent probability of detection and a very good reduction in computational complexity. Table 4 summarizes the performance of the proposed method, hybrid methods in [11] and [21], and traditional methods (ED, cyclostationary, and MF). This table shows that at very low SNR values, the proposed method is a perfect choice for spectrum sensing in terms of detection performance and computational complexity and for a very good channel environment, the ED become the best choice, but since in most cases, the channel environment is bad, the proposed method is more appropriate than others.

Table 4. Summary of performance measurement.

| Method                             | Performance detection       | Computational complexity |
|------------------------------------|------------------------------|--------------------------|
| Proposed method                    | Excellent                    | Moderate                 |
| Hybrid method in [21]              | Good                         | Low                      |
| Traditional hybrid method in [11]  | Good                         | High                     |
| CFD                                | Good                         | High                     |
| MF                                 | Very good (in best PU info)  | Moderate                 |
| ED                                 | Low                          | Low                      |

7. Conclusions

In this paper, we proposed a modified hybrid sensing method to overcome the problems of the traditional spectrum sensing technique. The proposed method is based on a combination of MF and CFD to improve the detection performance and reduce the computational complexity. The proposed method is simulated using MATLAB under Rayleigh multipath fading with two scenarios: cooperative and non-cooperative, measured using $P_d$ and $C_{ratio}$, and evaluated by a comparison with traditional and hybrid sensing methods in the literature. The simulation results show that the proposed method outperforms other methods in
the literature in terms of probability of detection and computational complexity in both channels. In future work, this method can be tested under other types of fading channels.

**LIST OF SYMBOLS**

| Symbol | Description |
|--------|-------------|
| $y(n)$ | Received sensed signal by the CU |
| $x(n)$ | PU signal |
| $\text{Noi}(n)$ | Additive White Gaussian Noise |
| $H$ | The gain of the channel |
| $\theta$ | Activity pointer |
| $H_1$ | Hypothesis when the PU is present |
| $H_0$ | Hypothesis when the PU is absent |
| $W$ | Observation window |
| $\lambda$ | Pre-defined threshold |
| $E_n$ | Accumulated energy |
| $N$ | Number of sensed samples |
| $F_s$ | Sampling frequency |
| $P_f$ | Probability of false alarm |
| $P_d$ | Probability of detection |
| $R_n^{ys}(l)$ | The discrete cyclic autocorrelation function |
| $\Delta n$ | Sampling interval |
| $S_n^{ys}(f)$ | Cyclic spectrum |
| $x_p$ | Previous information of PU signal |
| $T_{MFD}$ | The test statistic of MF |
| $P_{d,\text{proposed}}$ | Probability of detection of the proposed method |
| $P_{d,\text{MFS}}$ | Probability of detection of MF stage |
| $P_{d,\text{CFD}}$ | Probability of detection of CFD stage |
| $k$ | Number of SU |
| $C_{\text{comp,FFT}}$ | The computational complexity of traditional MF |
| $C_{\text{cycl}}$ | The computational complexity of traditional CFD |
| $C_{\text{Total,proposed}}$ | The computational complexity of the proposed method |
| $C_{\text{ratio}}$ | The ratio of computational complexity |
| $E_s/N_0$ | Signal to noise ratio per bit |

**List of abbreviations**

| CR | Cognitive Radio |
| SS | Spectrum Sensing |
| ED | Energy Detection |
| MF | Matched Filter |
| CFD | Cyclostationary Feature Detection |
| CC | Computational Complexity |
| RF | Radio Frequency |
| PU | Primary User |
| SU | Secondary User |
| CU | Cognitive User |
| SNR | Signal to Noise Ratio |
| CSS | Cooperative Spectrum Sensing |
| FC | Fusion Center |
| SU$^s$ | Secondary Users |
| MME | Maximum–Minimum Eigenvalue |
| ANN | Artificial Neural Networks |
| CAF | Cyclic Autocorrelation Function |
| CS | Cyclic Spectrum |
| FFT | Fast Fourier Transform |

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