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}, and evaluated by comparing it with traditional and hybrid methods in the literature. The simulation results show that the proposed method outperforms other methods in P_d and C_{ratio}. For example, at E_b/N_o equal to 0 dB 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 [18], 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 [19], the hybrid method is done by artificial neural networks (ANN). In [20], 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 [21], the hybrid sensing method is proposed based on ED and cyclostationary detector with a reduced computational complexity and an improved detection performance. In [22], 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 [1]. The received samples at the CU receiver are shown in the following Equation [23]:

$$y(n) = H_\theta x(n) + Noi(n), \qquad (1)$$

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

$$\theta = \begin{cases} 0 & \text{for } H_0 \text{ hypothesis} \\ 1 & \text{for } H_1 \text{ hypothesis.} \end{cases} \qquad (2)$$

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 and detection are measured by comparing the energy computed from the sensed signal on observation window W with a pre-defined threshold λ. The accumulated energy En_j can be written as shown in Equation (3).

$$En_j = \frac{1}{N} \sum_{n=1}^{N} |y(n)|^2, \qquad (3)$$

where N is the total number of sensed samples $N = WF_s$, where F_s is the frequency sampling. The probabilities of false alarm P_f and detection P_d are shown in Equations (4) and (5), respectively:

$$P_f = pr(En_j > \lambda \mid H_0), \qquad (4)$$

$$P_d = pr(En_j > \lambda \mid H_1). \qquad (5)$$

Numerically, the threshold value can be computed for a constant P_f value, which is shown in the following Equation (6) [24].

$$\lambda = (Q^{-1}(P_f) + \sqrt{N})2\sqrt{N}(N)^2 \qquad (6)$$

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 the periodicity, number of signals, their modulation type, symbol rate, and presence of interferer [25]. 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 the PU signal. If the summation is larger than the threshold, it means that the PU is present, otherwise, it is absent [11, 26]. This technique can distinguish between the signal and the noise, so it has a better performance as compared to ED. However, it has a high computational complexity, since it consumes a long sensing time. A signal is called a cyclostationary if its autocorrelation is a periodic function of time t with a given period. This type of cyclostationary detector is called a 2nd order cyclostationary detector [25]. A discrete cyclic autocorrelation function of a discrete-time signal $y(n)$ with a fixed lag l is defined in Equation (7) [21].

$$R_{yy}^{\alpha}(l) = \lim_{N \to \infty} \frac{1}{N} \sum_{n=0}^{N-1} y[n]y^*[n+l]e^{-j2\pi\alpha n \Delta n}, \quad (7)$$

where N is the number of samples of a signal $y[n]$ and Δn is the sampling interval. By applying the discrete Fourier transform to $R_{yy}^{\alpha}(l)$, the cyclic spectrum (CS) is given as [21]:

$$S_{yy}^{\alpha}(f) = \sum_{l=-\infty}^{\infty} R_{yy}^{\alpha}(l)e^{-j2\pi f l \Delta l}. \quad (8)$$

The detection of the PU signal is achieved by sensing the (cyclic frequency) of its cyclic spectrum or cyclic autocorrelation function (CAF). If the CAF is larger than the pre-defend threshold, the signal is present, otherwise, the signal is absent [25].

3.3. MATCHED FILTER

The matched filter is a coherent detection technique. This technique requires prior information about the PU signals at SU. Assuming that the PU transmitter sends a pilot stream simultaneously with the data, the SU receives the signal and the pilot stream. Matched filter detection is performed by projecting the received signal in the direction of the pilot [1]. The test statistic can be written as:

$$T_{MFD} = \sum_{N} y(n)x_p^*(n), \quad (9)$$

where x_p represents the PU signal, y represents the SU received signal. The test statistics, T_{MFD}, are then compared with a pre-defined threshold to detect the activity of PU, as shown in the following Equation (10).

$$\begin{cases} \text{If } T_{MFD} \geq \lambda, \text{ PU signal present} \\ \text{If } T_{MFD} < \lambda, \text{ PU signal absent} \end{cases} \quad (10)$$

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 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:

$$P_{d,proposedi} = 1 - (1 - P_{d,MFi})(1 - P_{d,cycoi})$$
$$i = 1, 2, \ldots k, \quad (11)$$

where k is the number of SUs in the cooperative scenario, $P_{d,proposedi}$ is the probability of detection of the proposed method, $P_{d,MFi}$ is the probability of detection in matched filter stage, and $P_{d,cycoi}$ 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 $o(Nlog_2N)$ according to [21], while for multiplying two signals, each
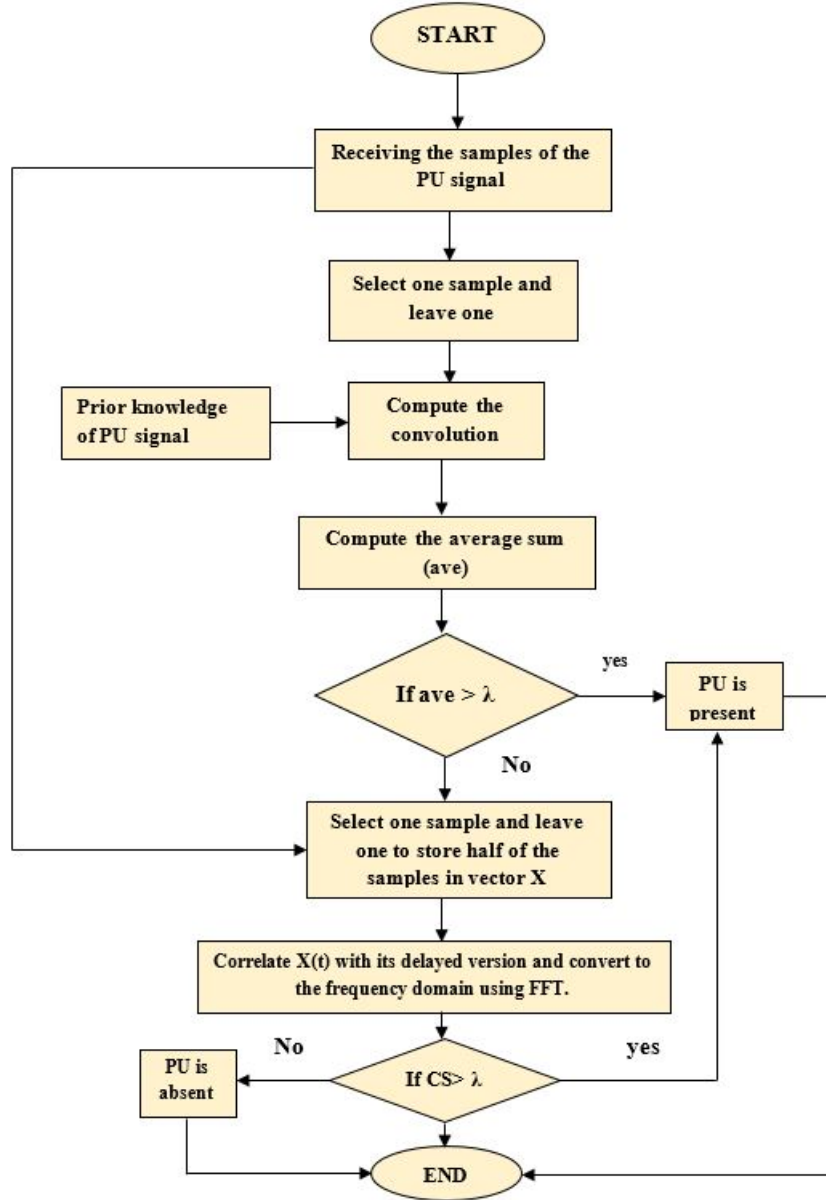
FIGURE 1. Procedures of the proposed method.

with N samples, it is $o(N)$. So, the computational complexity of a traditional MF becomes:

$$C_{conFFT} = 2o(Nlog_2N) + o(N), \qquad (12)$$

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:

$$C_{conpropoFFT} = 2o\left(\frac{N}{2}\log_2\frac{N}{2}\right) + o\left(\frac{N}{2}\right). \quad (13)$$

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

$$C_{auto} = No.\ of\ real\ multiplications$$
$$+\ No.\ of\ real\ additions$$
$$C_{auto} = 4N + 4N - 2 \qquad (14)$$

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

$$C_{cycl} = 4N + 4N - 2 + o(Nlog_2N). \qquad (15)$$

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:

$$C_{cyclproposed} = 2N + 2N - 2 + o\left(\frac{N}{2}log\frac{N}{2}\right)$$
$$= 4N - 2 + o\left(\frac{N}{2}log\frac{N}{2}\right) \qquad (16)$$

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

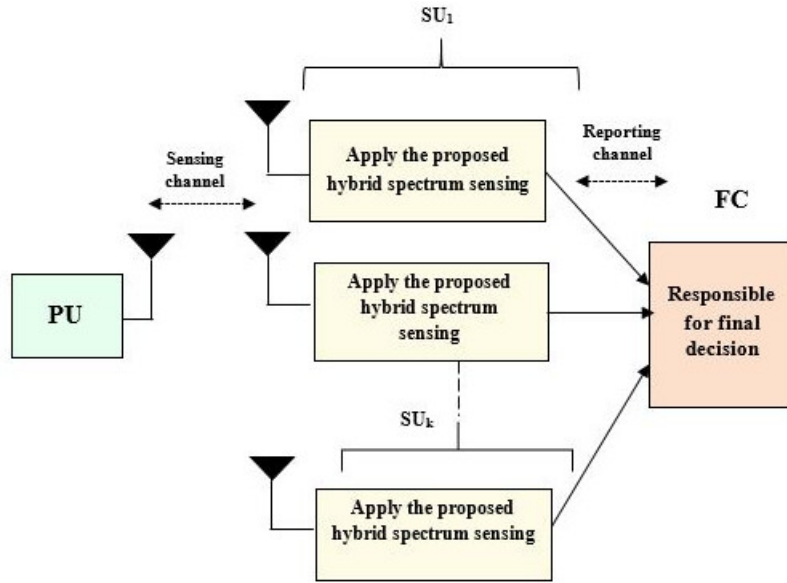$$C_{Totalproposed} = 4N - 2 + 3o\left(\frac{N}{2}log_2\frac{N}{2}\right) + o\left(\frac{N}{2}\right) \ (17)$$

FIGURE 2. The proposed system model using the centralised cooperative network.

Method	Computational complexity
Proposed method	$C_{Totalproposed} = 4N - 2 + 3o\left(\frac{N}{2}log_2\frac{N}{2}\right) + o\left(\frac{N}{2}\right)$
Hybrid method in [21]	$C_{hybrid} = 2N + 2N - 2 + O\left(Nlog_2(N)\right)$
Traditional hybrid [11]	$C_{hybridtradi} = 4N + 4N - 2 + O\left(Nlog_2(N)\right)$
Traditional Cyclostationary [21]	$C_{cycl} = 4N + 4N - 2 + o\left(Nlog_2N\right)$
Traditional MF	$C_{conFFT} = 2o\left(Nlog_2N\right) + o(N)$

TABLE 1. Comparison of computational complexity.

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

$$C_{ratio} = \frac{C_{Totalproposed}}{C_{cycl}} \quad (18)$$

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 proposed method in both the cooperative and the non-cooperative scenarios. The performance is tested under AWGN and Rayleigh multipath fading channels. The results have been achieved using MATLAB 2018 on Windows 10. The performance results of the proposed method are measured using the probability of detection and computational complexity ratio and evaluated by comparing it with: hybrid methods in

Parameters	Values
PU signal	QPSK
Carrier frequency F_c	200 Hz
Sampling frequency F_s	4000 Hz
P_f	0.001

TABLE 2. Simulation results.

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_o 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 energy detection and cyclostationary methods, especially at a low value of E_b/N_o, since it has a good knowledge of the PU signal. For example, at E_b/N_o equal to 0 dB, the probability of detection in the matched filter is increased by 36 % and 91 % as compared to cyclo-
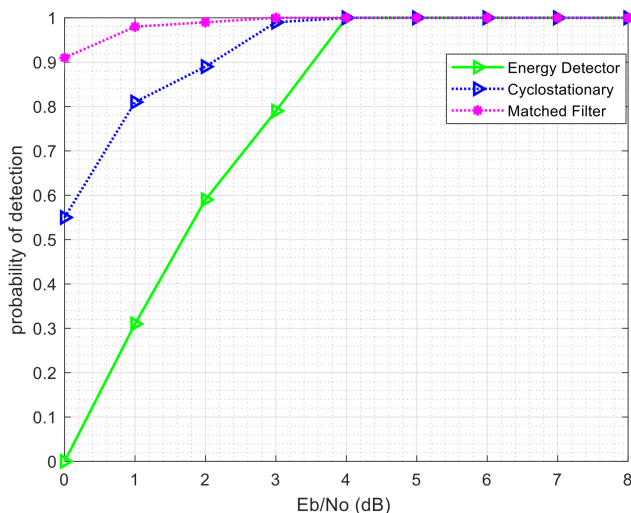
Figure 3. Performance comparison between traditional sensing techniques under AWGN and non-cooperative scenarios.
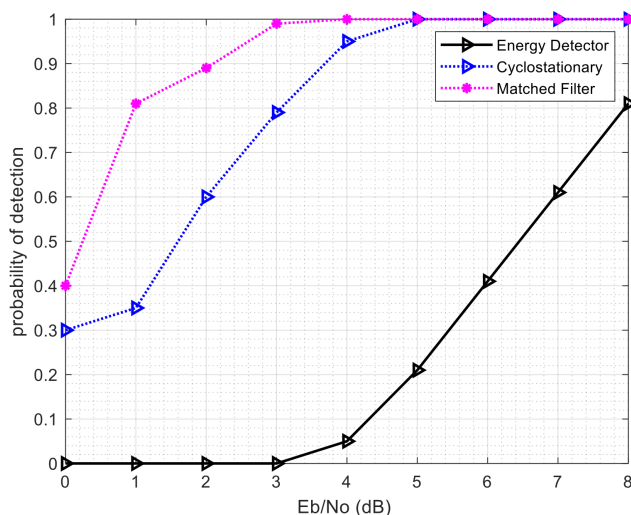

Figure 4. Performance comparison between traditional sensing techniques under Rayleigh fading and non-cooperative scenarios.

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

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

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 bellow results are as shown below:

$$percentage = (high\ value - low\ value) * 100\,\%.$$

When comparing two curves at the same E_b/N_o 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 technique in the case of a good knowledge of PU.
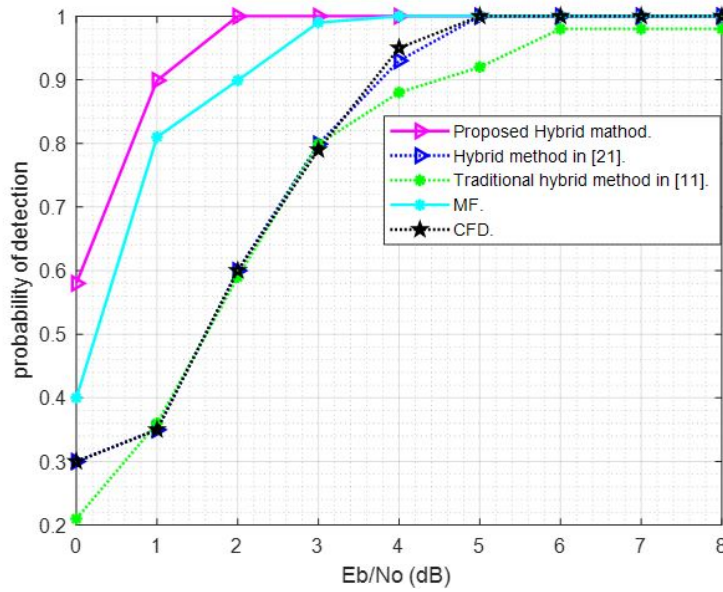
FIGURE 5. P_d versus E_b/N_o of proposed sensing methods under Rayleigh fading and non-cooperative scenario.
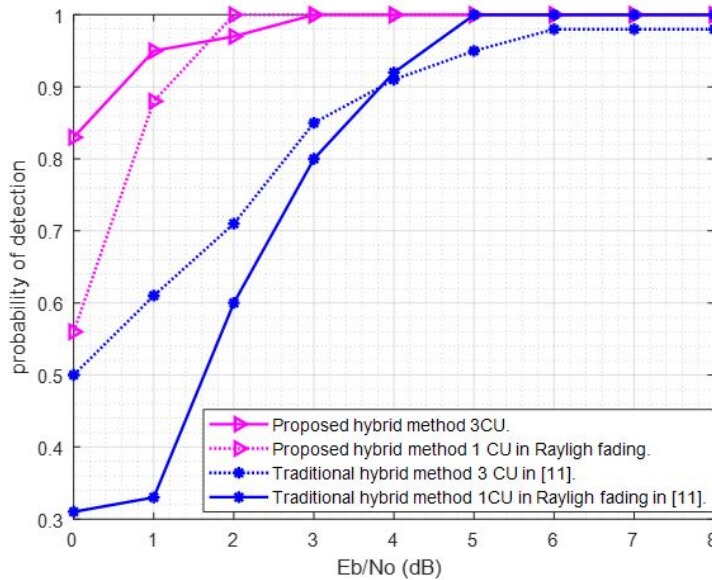

FIGURE 6. Performance comparison between the cooperative and non-cooperative scenarios in the proposed and traditional methods.

Figure 5 illustrates P_d vs E_b/N_o 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_o 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_o. 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_o 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_o 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
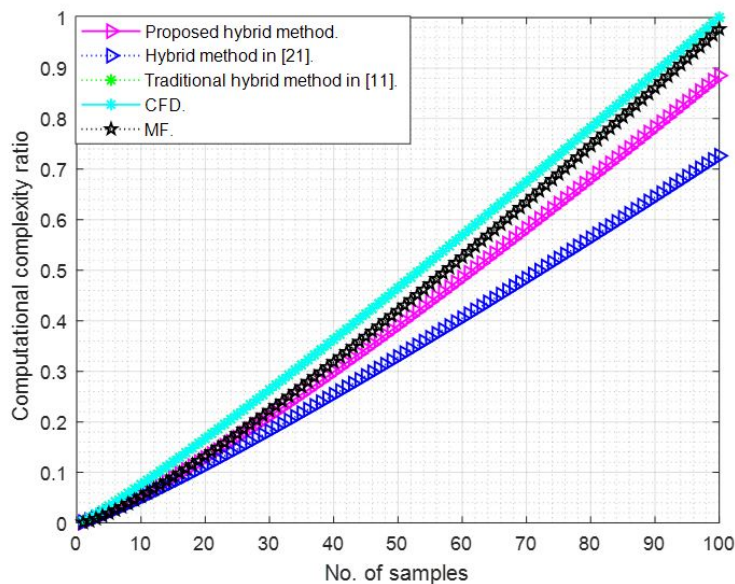
FIGURE 7. Computational complexity ratio versus the number of samples.

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 information)	Moderate
ED	Low	Low

TABLE 4. Summary of performance measurement.

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_o 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 [11], 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.

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

$y(n)$ Received sensed signal by the CU

$x(n)$ PU signal

$Noi(n)$ Additive White Gaussian Noise

H The gain of the channel

θ Activity pointer

H_1 Hypothesis when the PU is present

H_0 Hypothesis when the PU is absent

W Observation window

λ Pre-defined threshold

En_j Accumulated energy

N Number of sensed samples

F_s Sampling frequency

P_f Probability of false alarm

P_d Probability of detection

$R_{yy}^\alpha(l)$ The discrete cyclic autocorrelation function

Δn Sampling interval

$S_{yy}^\alpha(f)$ Cyclic spectrum

xp Previous information of PU signal

T_{MFD} The test statistic of MF

$P_{d,proposedi}$ Probability of detection of the proposed method

$P_{d,MFi}$ Probability of detection of MF stage

$P_{d,cycoi}$ Probability of detection of CFD stage

k Number of SU

C_{conFFT} The computational complexity of traditional MF

C_{cycl} The computational complexity of traditional CFD

$C_{Totalproposed}$ The computational complexity of the proposed method

C_{ratio} The ratio of computational complexity

E_b/N_o 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

SUs   Secondary Users

MME   Maximum–Minimum Eigenvalue

ANN   Artificial Neural Networks

CAF   Cyclic Autocorrelation Function

CS   Cyclic Spectrum

FFT   Fast Fourier Transform

ITU   International Telecommunication Union

AWGN   Additive White Gaussian Noise

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