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Spectrum Sensing of OFDM Signals Utilizing Higher Order Statistics under Noise Uncertainty Environments in Cognitive Radio Systems

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Abstract

Cognitive radio (CR) is an important issue to solve the spectrum scarcity problem for modern and forthcoming wireless communication systems. Spectrum sensing is the ability of the CR systems to sense the primary user signal to detect an ideal portion of the radio spectrum. Spectrum sensing is mandatory to solve the spectrum scarcity problem and the interference problem of the primary user. Noise uncertainty consideration for orthogonal frequency division multiplexing (OFDM) transmitted signals in severe noise environments is a challenging issue for measuring the performance of spectrum sensing. This paper proposed a method using higher order statistics (HOS) functions including skewness and kurtosis for improving the sensing performance of a cyclic prefix (CP) based OFDM transmitted signal for noise uncertainty. The detection performance of OFDM systems is measured for various CP sizes using a higher order digital modulation technique over a multipath Rayleigh fading channel for low signal-to-noise ratio (SNR) cases. In the proposed method, the CP-based OFDM transmitted signal sensing performance is measured and compared with the conventional methods under noise uncertainty environments. Through comprehensive evaluation of simulation, it is demonstrated that the sensing performance of this method significantly outperforms conventional schemes in the case of noise uncertainty in severe noise environments.

Keywords: Spectrum Sensing; Orthogonal Frequency Division Multiplexing; Skewness; Kurtosis; Cognitive Radio.

1- Introduction

Spectrum sensing in cognitive radio (CR) systems is an important issue in the modern era. The Federal Communications Commission (FCC) reported that some radio frequency bands are heavily used by licensed systems, but there are also many radio frequency bands that are only partly occupied [1]. CR is an approach for solving the scarcity problems of the frequency spectrum [2], [3]. In CR, the radio spectrum status is identified by the spectrum sensing. In recent years, numerous spectrum sensing methods have been proposed to solve spectrum sensing problems [4–6].

The energy detection based spectrum sensing method utilizes the energy of the received primary signal [7–9]. The performance of the energy detection method is not very poor for low signal-to-noise ratio (SNR) cases. Cyclostationary features have been used for detecting the signal for detecting the primary user [10]. When the primary user signal is used for sensing, matched filter detection provides the best sensing performance [11], [12]. However, spectrum sensing in the presence of noise uncertainty is not considered, and the computational complexity is very high.

The correlation based spectrum-sensing methods are very popular due to their low computational complexity and provide good performance over the fading channel [13]. The autocorrelation based spectrum sensing is classified into this category. The time domain autocorrelation property of a cyclic prefix (CP) based orthogonal frequency division multiplexing (OFDM) primary user signal was used for spectrum sensing [14–16]. The spectrum sensing of an OFDM signal under noise

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uncertainty conditions for low SNR cases is challenging. Conventional autocorrelation based methods utilize the knowledge of the CP for spectrum sensing [14], [15]. However, in practice, this is very difficult in the real cases. In addition, in [16] CP unknown case was considered. The noise uncertainty is not considered and the detection performance of OFDM transmitted signals is unsatisfactory in severe noise environments.

Higher order statistics are useful in digital signal processing, communication systems, signal detection, and a variety of other applications [17–20]. The higher order statistics, including third order statistics and fourth order statistics, are utilized for sensing OFDM transmitted signals, where the noise uncertainty cases are not considered for OFDM sensing [21]. Although some recent works considered spectrum sensing in noise uncertainty environments, the sensing performance is not very good in severe noise environments [22], [23]. However, the sensing of OFDM signals in noise uncertainty environments for low SNR cases is very important [23]. For these reasons, the major limitations of the existing spectrum-sensing methods result in their poor spectrum sensing performance for low SNR cases in noise uncertainty environments. Therefore, we were motivated for sensing OFDM transmitted signals in the case of noise uncertainty in severe noise environments.

The proposed method utilizes higher order statistics for sensing OFDM signals in noise uncertainty environments. The skewness calculation is utilized for sensing OFDM systems in noise uncertainty environments. Moreover, the kurtosis function is used for further sensing performance improvement of OFDM signals under noise uncertainty in severe noise environments. In the proposed method, the detection performance is evaluated for various CP sizes of OFDM systems under 64-QAM over multipath fading channels with additive white Gaussian noise (AWGN) in noise uncertainty environments. The proposed spectrum sensing method is compared with conventional methods [22], [23] over multipath fading channels under the effect of noise uncertainty. When the noise uncertainty effect is taken into account, the performance of OFDM detection improves dramatically when using skewness based spectrum sensing in severe noise environments. Furthermore, the sensing capability of OFDM transmitted signals increases markedly by utilizing kurtosis based spectrum sensing for low SNR cases under noise uncertainty.

The major contributions of this paper are as follows:

• Firstly, the skewness calculation is used for spectrum sensing under the effect of noise uncertainty. Furthermore, the proposed method is compared for skewness based sensing with and without noise uncertainty cases.

• Secondly, the proposed method is investigated for kurtosis function based spectrum sensing under two scenarios (with and without noise uncertainties).

• Thirdly, we have compared our proposed method with conventional methods [22], [23] in noise uncertainty environments. Simulation results demonstrated that our proposed skewness and kurtosis based spectrum sensing methods significantly improve the sensing performance.

The rest of the paper is arranged as follows. Section 2 presents a brief overview of the related work in spectrum sensing. The problem formulation of spectrum sensing is provided in Section 3. Section 4 represents the methodology of spectrum sensing. The transmitted OFDM signal is used as a primary user in the proposed method which is discussed in Section 5. The detailed explanation of the proposed method is presented in Section 6. Section 7 describes the performance evaluation of the proposed method by simulation results. Finally, the conclusion of this paper is drawn in Section 8. The notation employed in this paper is summarized in Table 1.

2- Related Work

Spectrum sensing detects the primary user’s transmitted signals in the CR systems. In the modern era, spectrum sensing for OFDM signals is very important issues in CR systems [24], [25]. The spectrum sensing method for OFDM signals under consideration of noise uncertainty is a severe challenging issue. Several spectrum sensing methods considering noise uncertainty have been proposed and investigated in recent years. Energy detection is a very popular technique that is used for spectrum sensing considering the noise uncertainty [26]. The spectrum sensing performance was very good for low SNR cases. However, OFDM systems were not considered, and only the AWGN channel was considered in this proposed method. In addition, recently, single and double threshold energy detection algorithms were implemented in [27], and a Frequency domain Goodness of Fit Test (FGoF) based spectrum sensing method was proposed to detect primary user signals [28]. The primary user detection performance was not very good in severe noise environments considering noise uncertainty and OFDM detection was not considered in those methods.

An Improved Energy Detection (IED) algorithm was proposed for spectrum sensing with an experimental hardware setup [29]. However, in low SNR environments, spectrum sensing performance degrades significantly due to noise uncertainty. In the presence of noise uncertainty, an adaptive double threshold based spectrum sensing method was recently proposed [22]. The sensing performance for low SNR cases was not very satisfactory using this method. In that case, the OFDM primary user transmitted signal was not considered. Effective energy detection was proposed in [23] to overcome the problem of OFDM signal detection considering noise uncertainty cases. However, the OFDM transmitted signal performance is not very good for large values of noise uncertainty in severe noise environments. In this paper, the proposed method improves the detection performance of the OFDM transmitted signal under both noise uncertainty and low SNR cases.

3- Problem Formulation of Spectrum Sensing

The principle of spectrum sensing is where the primary user transmitter sends data to the primary user receiver in their allotted licensed radio frequency spectrum band, while a pair of secondary users also intend to access the spectrum at the same instant. Spectrum sensing should be performed to detect the presence of the primary user receiver present within the coverage of the secondary user transmitter to protect the primary user transmission.

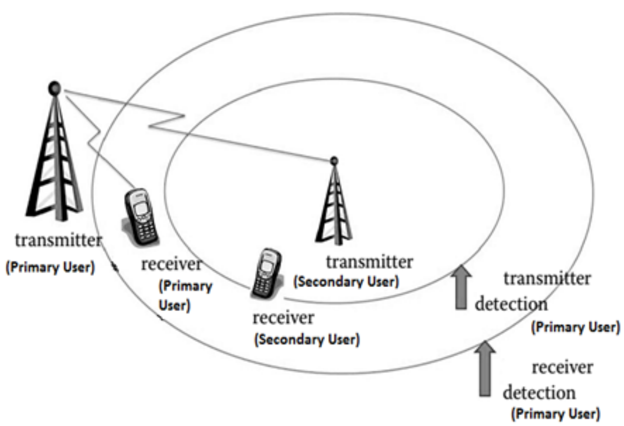

Fig. 1: Spectrum sensing principle [30].

Fig. 1 shows the principle of spectrum sensing [30]. Noise uncertainty is a very important challenge for the spectrum sensing methods. In a practical scenario, determining the noise power is very difficult. It needs to be estimated that it may contain calibration errors due to changes in thermal noise. Therefore, it is necessary to have more sensitive spectrum sensing under noise uncertainty environments in the practical situation.

In this paper, the primary user transmitted signal is an OFDM signal received at the spectrum sensing receiver. The spectrum sensing of OFDM signals is very important for modern broadcasting applications. Furthermore, spectrum sensing for OFDM signals in severe noise environments under consideration of noise uncertainty cases is challenging for modern and forthcoming wireless communication systems.

4- Methodology of Spectrum Sensing

In the proposed spectrum sensing method, there are two hypotheses that are defined by two states such as idle state, H_0, and active state, H_1, of the primary user in the spectrum sensing model. The secondary user's receiver evaluates a test statistic, T_f, based on its observed signal and compares it with a specific threshold, λ, to decide the situation between the two hypotheses.

The two hypotheses are given by

$$H_0 : T_f < \lambda \quad (1)$$

$$H_1 : T_f \geq \lambda \quad (2)$$

The spectrum sensing performance can be characterized using some important parameters. The probability of detection, P_d, indicates the primary user correctly detects its active mode [12] as

$$P_d = P\,(H_1;\, H_1) = Pr\{T_f > \lambda \mid H_1\} \quad (3)$$

Table 1: Notation used in this paper.

Parameter	***Definition***
P_d	Probability of detection
P_{fa}	Probability of false alarm
P_m	Probability of miss detection
H_0	Idle state
H_1	Active state
T_f	Test statistics
T_{f1}	Test statistics using skewness
T_{f2}	Test statistics using kurtosis
λ	Threshold
σ_w^2	Noise variance
Ω	Noise Uncertainty
N_c	CP Size
s	Number of OFDM Symbols
$S_l(y)$	Skewness function
$K_l(y)$	Kurtosis function

There are two types of errors: the probability of false alarm, P_{fa}, and the probability of miss detection, P_m.

These can be given [12] as

$$P_{fa} = P\,(H_1;\, H_0) \quad (4)$$

$$P_m = P(H_0; H_1) \tag{5}$$

In this paper, it is assumed that the primary user signal is a CP-OFDM signal received at the sensing station. The spectrum sensing of OFDM signals considering noise uncertainty cases in severe noise environments is challenging for wireless communication systems.

5- OFDM Signal

The OFDM is a multi-carrier modulation technique where the input data streams are convolutionally encoded by a 1/2-rated convolutional encoder and an interleaver is used to reduce errors that occur in bursts. Fig. 2 represents that the coded bits are digitally modulated, resulting in a complex symbol stream $X(0), X(1), \ldots\ldots, X(N-1)$. This symbol stream is converted to parallel subchannels by serial-to-parallel converter which are the frequency components. Then the frequency components are converted into time samples utilizing the inverse fast Fourier transform (IFFT).

The IFFT gives the OFDM symbol consisting of the sequence $x(0), x(1), \ldots\ldots, x(N-1)$ of length N as

$$IFFT\{X(k)\} = x(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X(k)\, e^{j2\pi kn/N} \tag{6}$$

We consider the l^{th} OFDM symbol, $x_l(n)$, as

$$x_l(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_l(k)\, e^{j2\pi kn/N} \tag{7}$$

where $1 \leq l \leq s$. s is the number of OFDM symbols and $X_l(k)$ corresponds to the l_{th} OFDM symbol at the k_{th} subcarrier. The CP is added between consecutive OFDM symbols to combat the intersymbol interference (ISI) problem of OFDM signals. Fig. 3 shows the CP insertion of the OFDM systems. The CP for $x_l(n)$ can be defined by $x_l(N-C), \ldots\ldots, x_l(N-1)$, where it consists of the last C samples of the $x_l(n)$ sequence. For each input sequence of length N, these last C samples are appended to the beginning of the sequence. This gives a new sequence, $\tilde{x}_l(n)$, of length $M = N + C$, which is the each OFDM symbol length. The resulting transmitted CP-OFDM signal $\tilde{x}_l(n)$ is converted by a parallel-to-serial converter.

The transmitted signal is filtered by the channel impulse response, $h_l(n)$, and corrupted by the additive noise, $w_l(n)$. Finally, the received signal is given by

$$h_l(n) = \tilde{x}_l(n) * h_l(n) + w_l(n) = v_l(n) + w_l(n). \tag{8}$$

where the asterisk denotes convolution and $v_l(n) = \tilde{x}_l(n)$ is used for simplicity.

6- Proposed Method

In the proposed method, the skewness calculation or kurtosis calculation is used for sensing OFDM primary user transmitted signals. Fig. 2 shows a block diagram of the proposed spectrum sensing. In this method, a noise uncertainty environment is considered which is very important for spectrum sensing method.

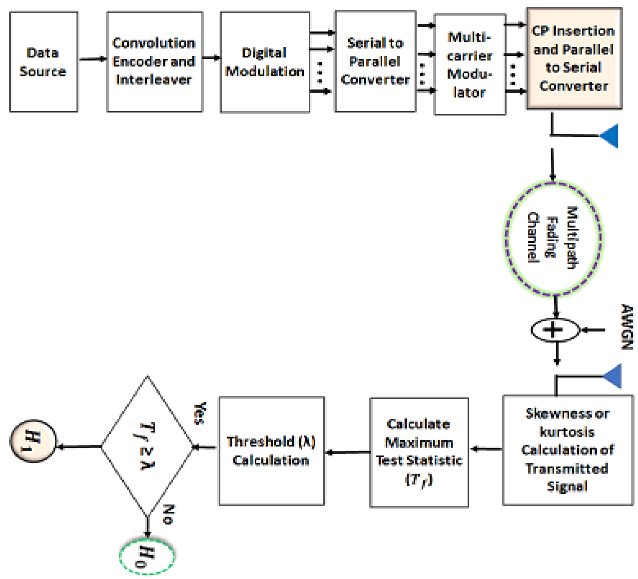

Fig. 2: Block diagram of the proposed spectrum sensing.

The OFDM signal is absent or present which is represented by H_0 and H_1 as

$$H_0 : y_l(n) = w_l(n) \tag{9}$$

$$H_1 : y_l(n) = v_l(n) + w_l(n) \tag{10}$$

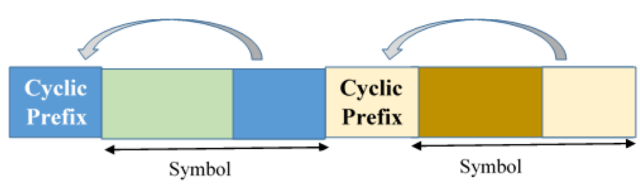

Fig. 3: CP Insertion of OFDM Signals

6-1- Skewness Function for Spectrum Sensing

Skewness, one of the third order statistics, is a statistical measure of the asymmetry of the probability distribution around the sample mean. Here, the skewness function method can be effectively utilized for OFDM signal sensing in noise uncertainty environments. The skewness function, $S_l(y)$, of a random variable, $y_l(n)$, is calculated [31], [32] as

$$S_l(y) = \frac{E[(y_l(n)-\mu)^3]}{\sigma^3} \quad (11)$$

where E{.} represents the expected value operator. In the proposed method, $y_l(n)$ is the OFDM-transmitted signal, μ is the mean of $y_l(n)$, and σ is the standard deviation of $y_l(n)$.

For a sample of variables $y_{l,1}(n)$, $y_{l,2}(n)$, ..., $y_{1,M}(n)$ the skewness can be estimated from Equation (11)

$$\hat{S}_l(y) = \frac{\frac{1}{M}\sum_{t=1}^{M}\left(y_{l,t}(n)-\hat{\mu}\right)^3}{\left(\sqrt{\frac{1}{M}\sum_{t=1}^{M}\left(y_{l,t}(n)-\hat{\mu}\right)^2}\right)^3} \quad (12)$$

$$\hat{\mu} = \frac{1}{M}\sum_{t=1}^{M} y_{l,t}(n) \quad (13)$$

where $(\hat{.})$ means an estimate and M is the number of variables. In the proposed method, M corresponds to the number of OFDM samples.

The sample skewness Equation (12) is effectively used for the test statistic calculation for spectrum sensing of OFDM transmitted signals. The test statistic using skewness function, T_{f1}, selection for the detection can be calculated by averaging the absolute value of the sample skewness function of the l_{th} OFDM symbol $\hat{S}_l(y)$

$$T_{f1} = \frac{1}{s}\sum_{l=1}^{s} |\hat{S}_l(y)| \quad (14)$$

The threshold value λ is obtained from the noise variance, σ_w^2, and the P_{fa}. The noise variance σ_w^2 is obtained as a priori information from the channel, where the technique in [33] is available for example. In the proposed spectrum sensing method, calculate the threshold value λ in the same way as that in [34] by

$$\lambda = \sqrt{-\ln P_{fa}.\sigma_w^2}. \quad (15)$$

In the proposed higher order statistics based spectrum sensing method, noise variance σ_w^2 is used for threshold calculation for OFDM transmitted signal detection. Here, we have considered that the accurate noise variance σ_w^2 is calculated. However, it is very difficult to estimate noise variance σ_w^2 perfectly for some practical applications. For this reason, it is very important to consider the influence of noise uncertainty for proposed spectrum sensing based on higher order statistics including skewness and kurtosis functions.

The noise uncertainty, Ω, is measured in dB as

$$\Omega = 10\, log10\, \Psi \quad (16)$$

where Ψ is a parameter which estimates the noise uncertainty [35], [36].

When the influence of noise uncertainty is estimated in the spectrum sensing method using skewness function, the threshold value λ is calculated by Equation (15) using $\Psi\sigma_w^2$ instead of σ_w^2.

Finally, the spectrum sensing receiver gives the final output H_0 and H_1 by

$$H_0: T_{f1} < \lambda \quad (17)$$

$$H_1: T_{f1} \geq \lambda. \quad (18)$$

6-2- Kurtosis Function for Spectrum Sensing

The kurtosis function is considered in the proposed method for OFDM transmitted signal detection. The kurtosis is a statistical measure of the peakness of the probability distribution. In the proposed method, the fourth order function can also be utilized effectively to detect the OFDM signal.

The kurtosis function, $\widehat{K}_l(y)$, for a sample of variables $y_{l,1}(n)$, $y_{l,2}(n)$,…….,$y_{l,M}(n)$ is estimated [31], [32] as

$$\widehat{K}_l(y) = \frac{1/M\sum_{t=1}^{M}\left(y_{l,t}(n)-\hat{\mu}\right)^4}{\left(1/M\sum_{t=1}^{M}\left(y_{l,t}(n)-\hat{\mu}\right)^2\right)^2} \quad (19)$$

The test statistic using kurtosis function, T_{f2}, can be obtained from the Equation (18) as

$$T_{f2} = \frac{1}{s}\sum_{l=1}^{s}\left|\widehat{K}_l(y)\right| \quad (20)$$

In the kurtosis based spectrum sensing method, the threshold value λ is calculated by Equation (15).

Furthermore, the threshold value λ is calculated by Equation (15) using $\Psi\sigma_w^2$ instead of σ_w^2 when the influence of noise uncertainty environments is considered in the kurtosis function based spectrum sensing method.

For the proposed method, the spectrum sensing gives the final output by

$$H_0: T_{f2} < \lambda \quad (21)$$

$$H_1: T_{f2} \geq \lambda. \quad (22)$$

The test statistics and threshold values for the skewness and kurtosis based spectrum sensing methods do not depend upon the OFDM primary user transmitted information, hence the proposed scheme is semi blind.

7- Simulation Result

The detection performance of OFDM primary user signals is investigated to evaluate the performance of the proposed spectrum-sensing scheme. The transmitted signals consist of a WLAN radio interface (IEEE 802.11a), which is an OFDM-based system. The simulation parameters for the proposed method are digital 64-QAM, an FFT size N of 64, a CP ratio N_c of 1/4, 1/8, 1/16, or 1/32, 150 OFDM symbols, and an SNR range of -35 dB to 0 dB. Monte Carlo simulations are conducted by averaging results over 5000 iterations. All the simulations are carried out on a multipath fading channel. The multipath fading channel consists of a five-tap impulse response with a maximum delay of 8. The simulation parameters used throughout the paper are tabulated in Table 2 (where the CP ratio is defined as $N_c = C/N$, unless otherwise stated).

The noise uncertainty is a very important parameter for spectrum sensing performance evaluation. The effect of noise uncertainty on the detection of OFDM signals is analyzed for spectrum sensing performance evaluation.

Table 2: Simulation Parameters

Parameters	***Types***
OFDM System	WLAN
Digital Modulation	64-QAM
FFT Size	64
Number of OFDM Symbols	150
Noise Uncertainty	0.5 dB and 1 dB
CP Size N_c	1/4, 1/8, 1/16 and 1/32
Channel	Multipath Rayleigh Fading with AWGN Channel
SNR Range	-35 dB to 0 dB
Higher order statistics	Skewness and Kurtosis
Number of Iterations	1500

In the proposed method, the detection performance of OFDM signals for N_c 1/4 at fixed P_{fa} 0.01 under 64-QAM is presented in Fig. 4. Here, for OFDM signal with noise uncertainty and without noise uncertainty cases are considered for sensing the primary user. In terms of noise uncertainty, which is 1 dB, the skewness function achieves the maximum P_d (≥ 0.9) at -31 dB SNR and the kurtosis function achieves the maximum P_d (≥ 0.9) at -13 dB SNR. For the skewness and kurtosis functions, the P_d for noise uncertainty 0.5 dB is slightly better than that of the noise uncertainty 1dB.

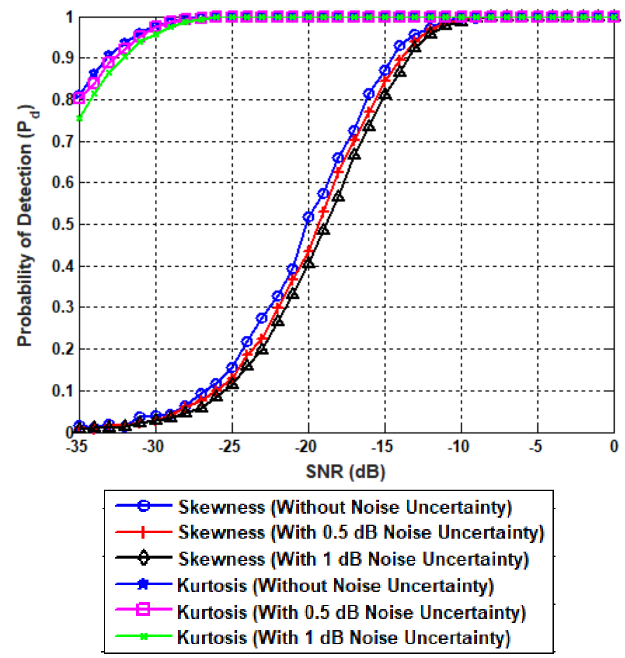

Fig. 4: Performance of the proposed spectrum-sensing method for OFDM signals under 64-QAM for N_c of 1/4 with noise uncertainty.

For without noise uncertainty case, the maximum P_d is obtained at -32 dB SNR for the skewness function and at -34 dB SNR for the kurtosis function. As a result, when the kurtosis function is used, the performance of the proposed spectrum sensing increases markedly compared with that of the skewness function.

For skewness and kurtosis functions of the proposed method, the P_d of CP-OFDM signals for N_c 1/8 in cases of 0.5 dB and 1 dB noise uncertainties are shown in Fig. 5. In the proposed spectrum sensing, FFT size (N) of 64, 64-QAM, 150 OFDM symbols, and fixed P_{fa} 0.01 are considered to measure the effect of noise uncertainty. It is observed from the plot that when the noise uncertainty is increased, the OFDM transmitted signal detection probability P_d is decreased slightly with SNR for both functions. On the other hand, the P_d of our proposed spectrum sensing method show the satisfactory results with 0.5 dB and 1 dB noise uncertainties for skewness and kurtosis functions.

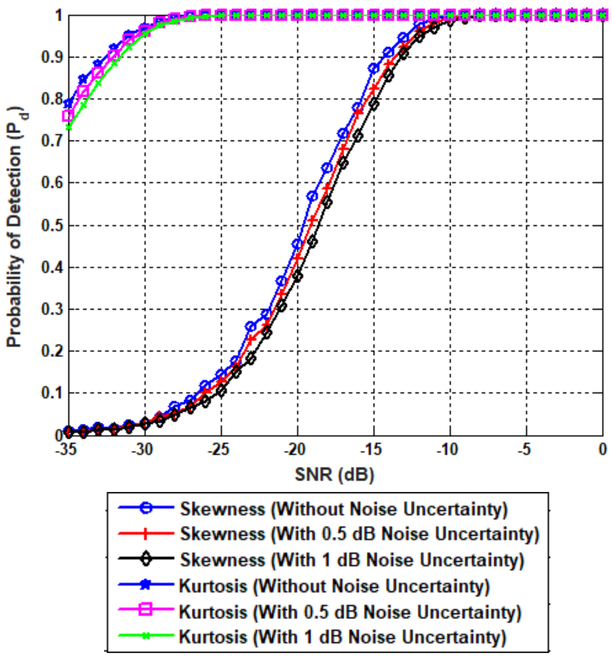

Fig. 5: Performance of the proposed spectrum-sensing method for OFDM signals under 64-QAM for N_c of 1/8 with noise uncertainty.

Fig. 6 shows the detection performance of OFDM primary user signals for N_c 1/16 under 0.5 dB and 1 dB noise uncertainty. It is clear from Fig. 6 that when the noise uncertainty is increased, the OFDM signal detection probability P_d is decreased slightly with SNR. However, the P_d of our proposed spectrum sensing method show the satisfactory results with 0.5 dB and 1 dB noise uncertainties, which is very important for spectrum sensing in CR systems.

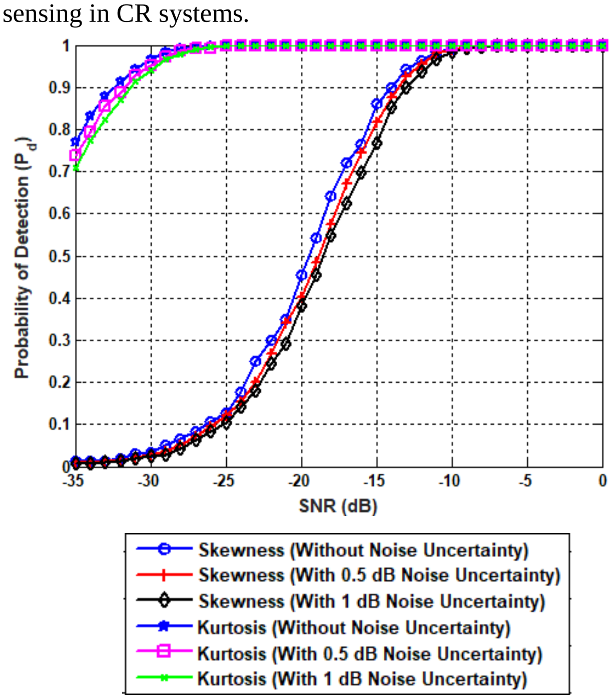

Fig. 6: Performance of the proposed spectrum-sensing method for OFDM signals under 64-QAM for N_c of 1/16 with noise uncertainty.

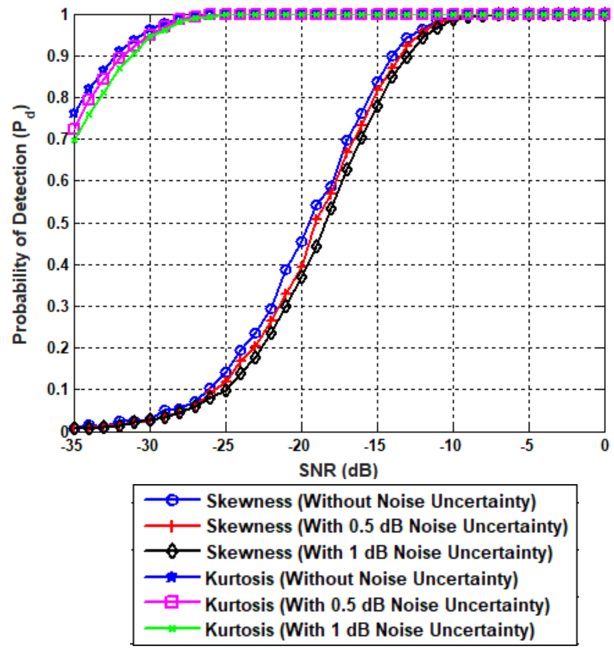

Fig. 7: Performance of the proposed spectrum-sensing method for OFDM signals under 64-QAM for N_c of 1/32 with noise uncertainty.

In Fig. 7, the noise uncertainty of 0.5 dB and 1 dB is considered in cases of the skewness and kurtosis functions to detect the OFDM signal for CP ratio N_c 1/32. It is clear from Fig. 7 that when the noise uncertainty increases, the P_d of the proposed spectrum sensing slightly decreases with SNR for skewness and kurtosis functions. However, the satisfactory P_d of OFDM transmitted signal is sustained even at 1 dB noise uncertainty in highly noisy environments.

It can be concluded from Fig. 4 to Fig. 7 that the proposed method shows the excellent P_d of OFDM primary user signal for skewness and kurtosis functions under both moderate and high noise uncertainty in highly noisy environments, which is essential for spectrum sensing in CR systems.

7-1- Performance Comparison

The proposed method is compared with an adaptive double threshold based spectrum sensing method [22] and an effective energy detection spectrum sensing method [23] in Fig. 8.

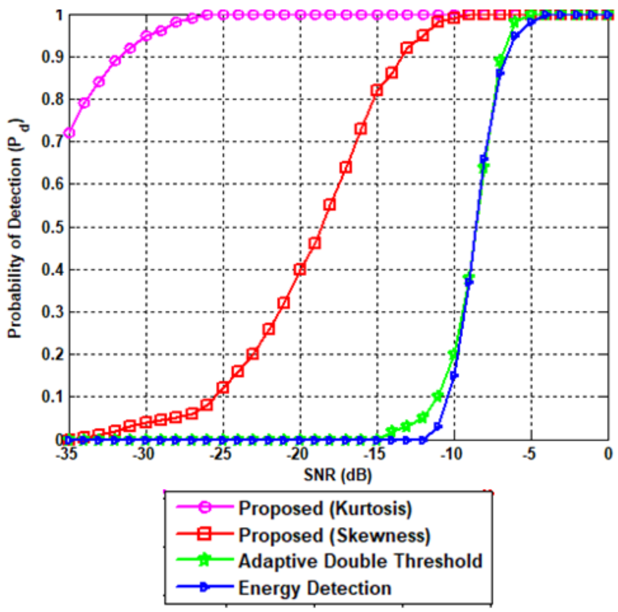

Fig. 8: Performance comparison under noise uncertainty

Here, a fixed probability of false alarm P_{fa} 0.01 and noise uncertainty 0.5 dB are considered for detection performance simulation. The results show that the sensing performance of our proposed method increases dramatically more than the conventional methods.

Table 3: Probability of detection (P_d) at fixed SNR

Spectrum Sensing Method	***SNR (dB)***	P_d
Proposed (Skewness)	-10	1
Proposed (Kurtosis)	-26	1
Adaptive Double Threshold [22]	-5	1
Energy Detection [23]	-4	1

Table 3 shows the detection performance of the proposed and conventional spectrum sensing methods under the noise uncertainty. It is clear from Table 3 that the proposed spectrum sensing scheme using skewness function offers a 5 dB SNR improvement compared with that of adaptive double threshold based spectrum sensing and a 21 dB SNR gain compared with that of energy detection. Furthermore, in the proposed method, when the kurtosis function is used for spectrum sensing, it provides a 6 dB SNR improvement relative to that of the adaptive double threshold based spectrum sensing and a 22 dB SNR gain relative to that of the energy detection of the conventional autocorrelation based spectrum sensing method. As a result, the proposed method significantly outperforms the conventional spectrum sensing methods.

8- Conclusions

The proposed method is an effective spectrum sensing scheme considering the poor sensing performance in severe noise and noise uncertainty environments. The higher order statistics, such as skewness function and kurtosis function, are exploited for sensing OFDM primary user signals. The proposed method is applicable under higher order digital modulation for various CP radios with noise uncertainty cases, which is very important for various OFDM based systems. The skewness calculation significantly improves the detection performance of the OFDM transmitted signal compared to the conventional methods, considering the noise uncertainty effect in severe noise environments. In the proposed method, the kurtosis calculation has a tendency to provide a further SNR gain relative to the corresponding skewness calculation considering the effect of noise uncertainty.

Acknowledgments

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