Spectrum Sensing Based on Higher Order Statistics for OFDM Systems over Multipath Fading Channels in Cognitive Radio

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Abstract  Spectrum sensing is an important issue in cognitive radio (CR) systems for solving spectrum scarcity problems in wireless communication systems. This paper presents a semiblind spectrum-sensing method utilizing higher order statistics including the skewness and kurtosis functions. The proposed method improves the detection performance while increasing its computational complexity, where an orthogonal frequency division multiplexing (OFDM)-transmitted signal over multipath fading channels is considered. Through comprehensive evaluation by simulations, it is shown that the proposed spectrum-sensing method significantly outperforms the conventional schemes for low signal-to-noise ratio (SNR) cases.

Keywords:  cognitive radio, spectrum sensing, higher order statistics, skewness, kurtosis, OFDM

1. Introduction

The radio frequency spectrum is a precious and limited resource. The Federal Communications Commission (FCC) reported that advances in modern technology create the potential for systems to use the radio frequency spectrum more intensively and create much more interference than in the past [1]. Cognitive radio (CR) is an approach for reducing the scarcity of the frequency spectrum for current and next-generation wireless communication systems [2], [3]. In CR, to identify the radio spectrum status as either vacant or active, spectrum sensing is used. Numerous spectrum-sensing methods for solving interference problems have been proposed recently [4]–[6].

An energy-detection-based spectrum-sensing scheme has been used in CR networks, where the presence or absence of the primary users is determined through the energy of the received primary signal [7]–[9]. Energy detection does not require prior knowledge of the transmitted signal, but the power of the random Gaussian noise is known to the receiver. The performance of the energy detection method is very poor for low signal-to-noise ratio (SNR) cases. In the cyclostationary detection method, cyclostationary features have been used to detect a signal [10]. When prior knowledge about the primary user signal is given, matched filter detection provides the optimal sensing performance [11], [12]. However, the computational complexity of the cyclostationary and matched filter detection methods is very high.

The correlation-based spectrum-sensing methods are very popular owing to their low computational complexity and provide good performance over a fading channel [13]. 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 has been used for spectrum sensing [14], [15]. The spectrum sensing of an OFDM signal for low SNR cases is challenging. Conventional autocorrelation-based methods utilize the knowledge of the CP for spectrum sensing [14]. However, in practice, this is very difficult in real cases. In addition, in [15], a CP-unknown case was considered. The detection performance of OFDM-transmitted signals is unsatisfactory in severe noise environments. Furthermore, a comb filter was used prior to the autocorrelation
for SNR improvement and large fast Fourier transform (FFT) sizes were used in [16]. The detection performance of OFDM-transmitted signals is not very good in severe noise environments. For the above reasons, the major limitation of the existing spectrum-sensing methods results in their high computational complexity and poor detection performance for low SNR cases.

Higher order statistics, which use the third or higher power of a signal, are useful for digital signal processing, communication systems, signal detection, and many other systems [17]–[20]. The proposed method utilizes higher order statistics for spectrum sensing. In this paper, we improve the detection performance of the autocorrelation-based method for OFDM-transmitted signals in severe noise environments utilizing not only skewness, which is one of the third order statistics, but also kurtosis, which is one of the fourth order statistics. The proposed method is a semiblind one. No prior information of the primary users is required for the proposed scheme, but the noise variance is used for sensing. The skewness calculation is used for sensing CP-OFDM-transmitted signals in our proposed scheme. In addition, the kurtosis function is utilized for further improving the sensing performance of CP-OFDM-transmitted signals for low SNR cases.

OFDM has been widely used in current 4G broadband wireless communication standards such as digital audio broadcasting (DAB), terrestrial digital video broadcasting (DVB-T), 3GPP LTE, Wi-Fi, WiMAX, wireless LAN (WLAN) radio interface IEEE 802.11a, g, n, and many other wireless systems. The detection of OFDM primary user signals is a challenging task. This is inherently due to the following reasons. For OFDM-based systems, various FFT sizes, CP sizes, and digital modulation schemes including binary phase shift keying (BPSK), quadrature phase shift keying (QPSK), quadrature amplitude modulation (QAM), 16-QAM, and 64-QAM are used.

In the proposed spectrum-sensing method, the detection performance is evaluated for various symbol lengths and CP sizes of OFDM systems under 16-QAM and 64-QAM over multipath fading channels with additive white Gaussian noise (AWGN). We consider a WLAN radio interface (IEEE 802.11a), which is an OFDM-based application. In the case of a multipath fading channel, many signals cannot be detected adequately using second order statistics including autocorrelation. As a result, higher order statistics including skewness and kurtosis are used for OFDM detection instead of second order statistics to overcome the low SNR detection problem. The proposed method is compared with conventional autocorrelation-based spectrum-sensing methods over multipath Rayleigh fading channels. The use of skewness markedly increases the OFDM detection performance compared with that of conventional spectrum-sensing schemes for low SNR cases. Furthermore, the use of the kurtosis function markedly increases the sensing capability of OFDM primary user signals in severe noise environments.

The rest of the paper is arranged as follows. Section 2 provides the formulation of spectrum sensing. A detailed explanation of the proposed method is presented in Sect. 3. Sect. 4 describes the simulation results of the properties of the proposed spectrum-sensing method. In addition, the OFDM-transmitted signal detection performance of the proposed spectrum-sensing method is evaluated and compared with that of conventional spectrum-sensing methods. Finally, in Sect. 5, a conclusion is drawn.

2. Formulation of Spectrum Sensing

In spectrum sensing, the secondary user must determine whether the primary user is transmitting, which implies two hypotheses. When the channel is free, only the additive noise will be observed on the secondary user side, which is the null hypothesis, $H_0$. However, if the channel is being used, the secondary user will sense the primary user signal and noise, which is the alternative hypothesis, $H_1$.

The hypothesis $H_0$ is defined as the idle state of the primary user and the hypothesis $H_1$ is defined as the active state. To determine which of the two hypotheses applies to the situation, the secondary user’s receiver evaluates a test statistic, $T_f$, based on its observed signal and compares it with a specific threshold, $\lambda$, as follows.

$$H_0 : T_f < \lambda, \text{no signal is detected} \quad (1)$$
$$H_1 : T_f \geq \lambda, \text{OFDM signal is detected} \quad (2)$$

The signal detection accuracy is determined by the probability of detection, $P_d$, that the primary user correctly detects its active mode. This can be given [12] by

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

There are two types of error: the probability of a false alarm, $P_{fa}$, which represents the false detection of the primary user, i.e., $H_1$ is determined when $H_0$ is true, and the probability of miss detection, $P_m$, which corresponds to the detection of $H_0$ when $H_1$ is true. These can be described [12] as

$$P_{fa} = P(H_1; H_0) \quad (4)$$
In this paper, we assume that the primary user signal is an OFDM signal received at the sensing station. The OFDM-transmitted signal is assumed to be received after it is passed through a multipath Rayleigh fading channel. The spectrum sensing of OFDM-transmitted signals using the conventional method is challenging for low SNR cases. However, these cases are very important for modern broadband wireless communication systems.

3. Proposed Spectrum-Sensing Method

In this paper, we propose a semiblind spectrum-sensing method that utilizes higher order statistics including the skewness and kurtosis of the primary user signal. Figure 1 shows a block diagram of the proposed spectrum-sensing method. In the proposed method, CP-OFDM signals are considered as those of the primary user.

3.1 OFDM primary user signals

The OFDM is a promising technique for high-bit-rate transmission in wireless communications systems. For an OFDM transmitter, 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. The coded bits are digitally modulated using PSK or QAM, resulting in a complex symbol stream $X(0), X(1), \ldots, X(N-1)$. Figure 1 shows that this symbol stream is converted to parallel subchannels, which are frequency components, by a serial-to-parallel converter. Then, the frequency components are converted into time samples by applying the inverse fast Fourier transform (IFFT). The IFFT gives an OFDM symbol consisting of the sequence $x(0), x(1), \ldots, x(N-1)$ of length $N$ as

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

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

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

where $1 \leq l \leq s$. $s$ is the number of OFDM symbols and $X_l(k)$ corresponds to the $k_{th}$ OFDM symbol at the $k_{th}$ subcarrier.

The CP is added to reduce the intersymbol interference (ISI) between consecutive OFDM symbols. The CP for $x_l(n)$ can be defined by $x_l(N - C), \ldots, x_l(N - 1)$, 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, $\hat{x}_i(n)$, of length $M = N + C$, which is the length of each OFDM symbol. The resulting transmitted CP-OFDM signal $\hat{x}_i(n)$ is converted by a parallel-to-serial converter.

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

$$y_l(n) = \hat{x}_i(n) * h_t(n) + w_l(n) = s_l(n) + w_l(n)$$  \(8\)

where the asterisk denotes convolution and $s_l(n) = \hat{x}_i(n) * h_t(n)$ is used for simplicity.

For $H_0$, the OFDM-transmitted signal is absent, and the OFDM-transmitted signal is present for $H_1$, which can be described by

$$H_0 : y_l(n) = w_l(n)$$  \(9\)

$$H_1 : y_l(n) = s_l(n) + w_l(n)$$  \(10\)

3.2 Spectrum sensing

In the receiving section, we use the skewness or kurtosis for sensing OFDM primary user signals.

Skewness is one of the third order statistics. It is a statistical measure of the asymmetry of the probability distribution around the sample mean. Here, the skewness function, $S_l(y_l)$, of a random variable, $y_l(n)$, is defined [21], [22] as

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

where $E\{\cdot\}$ represents the expected value operator. In our case, $y_l(n)$ is the OFDM-transmitted signal, $\mu$ is the mean of $y_l(n)$, and $\sigma$ is the standard deviation of $y_l(n)$.

From Eq. (11), for a sample of variables $y_{l,1}(n), y_{l,2}(n), ..., y_{l,M}(n)$, the skewness can be estimated by

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

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

in a practical system, where $\hat{\cdot}$ means an estimate and $M$ is the number of variables. In our case, $M$ corresponds to the number of OFDM samples.

In our proposed scheme, the sample skewness Eq. (12) is utilized for the test statistic calculation for the detection of OFDM primary user signals. The objective of spectrum sensing is to determine whether there are OFDM primary user signals. The test statistic is measured by averaging the absolute value of the sample skewness function of the $l_{th}$ OFDM symbol $\hat{S}_l(y_l)$. The test statistic, $T_{f_1}$, selection for the detection is given by

$$T_{f_1} = \frac{1}{s} \sum_{l=1}^s | \hat{S}_l(y_l) |$$  \(14\)

The threshold $\lambda$ is obtained from the noise variance, $\sigma_w^2$, and $P_{fa}$. The noise variance $\sigma_w^2$ is obtained as an a priori information from the channel, where the technique in [23] is available for example. In our case, the threshold $\lambda$ is calculated in the same manner as in [24] as

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

Finally, a cognitive controller or receiver gives the final output by comparing the threshold $\lambda$ with the test statistic $T_{f_1}$. If the test statistic $T_{f_1}$ is greater than the threshold $\lambda$, we assign the hypothesis $H_1$ as

$$H_1 : T_{f_1} \geq \lambda$$  \(16\)

Otherwise, we assign $H_0$ as

$$H_0 : T_{f_1} < \lambda$$  \(17\)

In addition, similarly to the skewness calculation, the kurtosis function is considered for OFDM-transmitted signal detection in our proposed method. The kurtosis is a statistical measure of the peakedness of the probability distribution. Here, the kurtosis function method can also be effectively exploited for sensing OFDM-transmitted signals. From Eq. (12), for a sample of variables $y_{l,1}(n), y_{l,2}(n), ..., y_{l,M}(n)$, the kurtosis function, $\hat{K}_l(y_l)$, is defined [21], [22] as

$$\hat{K}_l(y_l) = \frac{1}{M} \frac{\sum_{t=1}^M (y_{l,t}(n) - \hat{\mu})^4}{\left(\frac{1}{M} \sum_{t=1}^M (y_{l,t}(n) - \hat{\mu})^2\right)^{2}}$$  \(18\)

The sample kurtosis equation (Eq. (18)) is used for the test statistic calculation for the detection of OFDM-transmitted signals. The test statistic, $T_{f_2}$, selection for the detection is given by

$$T_{f_2} = \frac{1}{s} \sum_{l=1}^s | \hat{K}_l(y_l) |$$  \(19\)
Finally, the spectrum sensing gives the final output $H_1$ or $H_0$ by comparing the threshold $\lambda$ with the test statistic $T_{f2}$ as follows:

$$H_1 : T_{f2} \geq \lambda \quad (20)$$

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

Commonly in the above two methods, the threshold and test statistic do not depend on the prior knowledge of the information transmitted by the OFDM primary user; hence, our approach is semiblind.

The use of fifth and higher order statistics for the same purpose might be possible. Spectrum sensing performance might be improved by utilizing fifth and higher order statistics where a very large sample size is essential. However, the computational complexity of using such statistics would be greatly increased. Considering the balance between complexity and performance, therefore, we employ only the skewness and kurtosis functions in this paper.

4. Simulation Results

In this section, the properties of the proposed spectrum-sensing method are described in the first part. Then, in the second part, the performance of the proposed scheme is investigated by MATLAB simulations. Finally, in the third part, the detection performance of the proposed scheme is compared with that of conventional spectrum-sensing methods.

4.1 Properties

We utilize the skewness and kurtosis functions for sensing the OFDM-transmitted signal. Skewness measures the asymmetry of the probability distribution. Some OFDM symbols show asymmetric properties and provide a large value of the skewness function. However, some OFDM symbols show symmetric properties and the value of the skewness function is small. Therefore, large values of the skewness function are eventually expected, and these are averaged for the use of spectrum sensing. On the other hand, kurtosis measures the degree of peakedness of the probability distribution. The distribution of OFDM signals has a large difference from the normal distribution [25], [26]. This is because a high amplitude of the OFDM signal occurs in the OFDM waveform. The location of the high amplitude (peak) is unpredictable a priori when generating an OFDM signal, which is well known as a high peak-to-average power ratio (PAPR). The high amplitude creates a distribution with a long tail. In this case, the kurtosis function will have a large value. Owing to the unpredictable nature of the high amplitude, the values of the kurtosis function are also averaged for the use of spectrum sensing.

To explain the properties of the proposed spectrum-sensing method, Figure 2 shows the function calculation of OFDM-transmitted signals over a multipath fading channel at a low SNR of -20 dB. The simulation parameters are an FFT size ($N$) of 64, a CP ratio ($N_c$) of 1/4, 16-QAM, and 150 OFDM symbols.

In Fig. 2, the green color shows the autocorrelation function amplitude at a lag of $N$ for an OFDM-transmitted signal over the multipath fading channel [15]. Here, 16-QAM, an FFT size ($N$) of 64, a CP ratio ($N_c$) of 1/4, and 150 OFDM symbols are taken for the CP-based autocorrelation spectrum-sensing method simulation. The autocorrelation function at a lag of $N$ is nonzero for the presence of the CP in OFDM-based systems. In addition, the autocorrelation is highly correlated at a lag of $N$ and peak detection is possible in the presence of the CP for high SNR cases. This property was exploited for detection in the conventional CP-autocorrelation-based spectrum-sensing method [15]. The result in Fig. 2 shows that the peak detection at a lag of $N$ for each OFDM symbol is not possible for low SNR cases in the CP-based autocorrelation function spectrum-sensing method.

In Fig. 2, the red color shows the absolute value of the skewness function as a function of the number of OFDM symbols and the blue color shows the absolute value of the kurtosis function as a function of the number of OFDM symbols. For our proposed spectrum-sensing scheme, these values are used for the
test statistic selection using Eqs. (14) and (19) to detect OFDM primary user signals. Equations (14) and (19) represents the averaging of the red and blue curves, respectively. The CR receiver gives the final output by comparing the threshold $\lambda$ in Eq. (15) with the test statistic obtained using Eqs. (14) and (19). If the test statistic $T_f_1$ or $T_f_2$ is greater than the threshold $\lambda$, we assign the hypothesis $H_1$, which means that the OFDM signal is detected. Otherwise, we conclude that there is no OFDM detection. As a result, the enhancement of the amplitude improves the performance of the proposed spectrum-sensing method. For the above reason, the OFDM-transmitted signal detection using skewness and kurtosis markedly outperforms the conventional schemes using the proposed method. This feature is more emphasized especially for low SNR cases.

The higher order statistics are very effective for detection and have many applications in communication systems [20]. The skewness function is very much effective for detecting abrupt changes [27]. In [28], the kurtosis function as well as the skewness function are used to test goodness-of-fit. In the proposed spectrum-sensing method, these competencies are directly obtained.

4.2 Performance evaluation

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 ($N_c = N/C$) 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.

In the proposed spectrum sensing, the $P_d$ of CP-
OFDM signals for $N_c$ of 1/4 at $P_{fa}$ of 0.01 under 64-QAM is presented in Figure 3. Here, various OFDM symbol lengths are considered for sensing the primary user. For a very small symbol length of 100, the maximum $P_d$ ($\geq 0.9$ or 90%) is achieved at SNR of -14 dB for the skewness function and at SNR of -32 dB for the kurtosis function. For the skewness and kurtosis functions, $P_d$ for a symbol length of 200 is slightly better than that for the symbol length of 100. For a symbol length of 400, the maximum $P_d$ is obtained at SNR of -15 dB for the skewness function and at SNR of -34 dB 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. It is observable from Fig. 3 that $P_d$ increases gradually with SNR, with the rate of increase depending on the length of the OFDM symbol.

Figure 4 shows the $P_d$ of CP-OFDM signals for $N_c$ of 1/4 under 64-QAM. Here, $P_{fa}$ values of 0.001 (0.1%) and 0.01 (1%) are considered for sensing the primary user, where the performance of the proposed method is shown in the cases for the skewness and kurtosis functions again. We observe that $P_d$ increases gradually with SNR, with the rate of increase depending on the fixed $P_{fa}$. $P_d$ for the kurtosis function outperforms that for the skewness function. For the very low $P_{fa}$ of 0.1%, the maximum $P_d$ is achieved at SNR of -12 dB for the skewness function and at SNR of -31 dB for the kurtosis function. When $P_{fa}$ is 1%, $P_d$ increases furthermore. Here, the maximum $P_d$ is achieved at SNR of -14 dB for the skewness function and at SNR of -33 dB for the kurtosis function, which commonly indicate a 2 dB SNR improvement relative to that for the $P_d$ of 0.1% $P_{fa}$. These results show that when $P_{fa}$ increases, the sensing performance is significantly improved using the proposed spectrum-sensing method.

The $P_d$ of CP-OFDM signals under 64-QAM is shown for $N_c$ values of 1/8, 1/16, and 1/32 in Figures 5-7, respectively. In the proposed method, $P_{fa}$ values of 0.1% and 1% are considered for the skewness and kurtosis functions again. When $P_{fa}$ increases, the sensing performance increases with SNR using the proposed spectrum-sensing method regardless of the value of $N_c$. The detection performance for the $P_{fa}$ of 1% outperforms that for the $P_{fa}$ of 0.1%. For all cases, spectrum sensing is possible over a wide range of SNR and the $P_d$ of the kurtosis function is markedly improved compared with that of the skewness function. The good $P_d$ of CP-OFDM signals is sustained even for a very low $P_{fa}$ of 0.1% in low SNR environments.

Figures 4-7 show that when the CP size decreases, the $P_d$ of the proposed spectrum sensing slightly decreases. It happens due to the ISI caused by the multipath channel, which is not mitigated by a short CP size [16]. $P_d$ is excellent under 64-QAM for various CP sizes in severe noise environments, which is very important for OFDM-based systems.

4.3 Performance comparison

The receiver operating characteristic (ROC) curves for the proposed method and CP-autocorrelation-based spectrum-sensing method [15] under 16-QAM at
SNR of -10 dB are shown in Figure 8. The results show that $P_d$ increases markedly for our proposed method at SNR of -10 dB compared with that of the conventional spectrum-sensing method. As a result, the proposed spectrum-sensing method significantly outperforms the conventional scheme.

The proposed method is compared with the CP-autocorrelation-based spectrum-sensing method [15] and autocorrelation with a filter-based spectrum-sensing method [16] in Figure 9. The simulation parameters for the CP-autocorrelation-based sensing method are an FFT size ($N$) of 32, a CP ratio ($N_c$) of 1/4, digital 16-QAM, and a $P_{fa}$ of 0.05. Here, CP-unknown and CP-known cases are considered in the simulation to evaluate the detection performance. The CP-known case shows better performance. For the autocorrelation with the filter-based spectrum-sensing method, common parameters are used. In this method, the CP-unknown case is considered for spectrum sensing. Here, a comb filter is combined with an autocorrelation function to improve the CP-autocorrelation-based spectrum sensing. In our proposed method, we consider common parameters for performance comparison. It can be seen from Fig. 9 that the $P_d$ of the proposed method is much higher than that of the conventional scheme.

The detection performance of the proposed and conventional spectrum-sensing methods for OFDM-transmitted signals is shown in Table 1. It is clear from Table 1 that the proposed spectrum-sensing scheme using the skewness function provides an 8 dB SNR improvement compared with that of the CP-known case, a 12 dB SNR gain compared with that of the CP-unknown case, and a 9 dB SNR gain compared with that of the autocorrelation-based spectrum-sensing scheme with a filter. Furthermore, in the proposed method, when the kurtosis function is used for spectrum sensing, it provides a 16 dB SNR improvement relative to that of the CP-known case, a 20 dB SNR gain relative to that of the CP-unknown case, and a 17 dB SNR gain relative to that of the conventional autocorrelation-based spectrum-sensing method with a filter.

Here, we evaluate the computational complexity of the proposed method in comparison with the conventional autocorrelation-based spectrum-sensing method [15]. The numbers of multiplications and additions required for the function calculation utilized to calculate the test statistic are considered here. The proposed method requires $M$ OFDM samples for the skewness or kurtosis function calculation and we consider the same number of samples for the conventional method in order to measure the computational complexity in a fair comparison.

### Table 1 Probability of detection ($P_d$) at fixed SNR

| Spectrum-Sensing Method | SNR (dB) | $P_d$ |
|-------------------------|---------|-------|
| Proposed (Skewness)     | -17     | 1     |
| Proposed (Kurtosis)     | -25     | 1     |
| Autocorrelation (CP Known) | -9     | 1     |
| Autocorrelation (CP Unknown) | -5     | 1     |
| Autocorrelation (with Filter) | -8     | 1     |
The required amount of multiplications and that of additions for the skewness function calculation of the proposed method are $O(5M)$ and $O(5M)$, respectively. For the proposed method, when the kurtosis function is used, the required amount of multiplications and that of additions are $O(6M)$ and $O(5M)$, respectively. On the other hand, the required amount of multiplications and that of additions for the autocorrelation function calculation in the conventional method are $O(M)$ and $O(M)$, respectively. As a result, the computational complexity is increased for the kurtosis function calculation compared with that for the skewness function. The computational complexity of the proposed spectrum-sensing method is higher than that of the conventional autocorrelation-based spectrum-sensing method. However, the detection capabilities are significantly improved relative to those of the conventional spectrum-sensing method in severe noise environments.

5. Conclusion

We have proposed an effective semiblind spectrum-sensing method to overcome the poor detection performance in severe noise environments. Higher order statistics including the skewness and kurtosis function calculation are exploited for sensing OFDM primary user signals. The spectrum sensing using the skewness or kurtosis function can be used depending on the OFDM system application. The proposed method is applicable for various CP sizes of the OFDM-transmitted signal under higher order digital modulation schemes. The proposed spectrum-sensing method significantly improves the detection performance of the OFDM-transmitted signal for low SNR cases and achieves better detection performance compared with that of the conventional autocorrelation-based spectrum-sensing methods. The detection performance improvement is obtained at the expense of increased computational complexity due to the calculation of higher order statistics. The kurtosis calculation in the proposed method has a tendency to provide a further SNR gain relative to the corresponding skewness calculation.

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