Autocorrelation-Based Spectrum Sensing for OFDM Signals over Multipath Fading Channel in Cognitive Radio Systems

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Abstract In this paper, a spectrum-sensing method is proposed which exploits the combination of a comb filter and autocorrelation function. The proposed method improves the detection performance in severe noise environments, where a cyclic prefix (CP)-based orthogonal frequency division multiplexing (OFDM)-transmitted signal is considered. In our proposed method, the primary user information is not required for spectrum sensing. The detection performance is measured over additive white Gaussian noise (AWGN) and multipath Rayleigh fading channels for different digital modulations. A comprehensive evaluation by simulation shows that the proposed method significantly outperforms the conventional schemes at a low signal-to-noise ratio (SNR).

Keywords: CR, spectrum sensing, autocorrelation function, comb filter, OFDM, CP

1. Introduction

Cognitive radio (CR) [1] is a promising system for upcoming 5G wireless communication systems to reduce the scarcity of the frequency spectrum. Spectrum sensing is one of the most challenging issues in CR systems when searching for spectrum holes. The spectrum holes are defined as frequency bands which are allocated to licensed users, but at some locations and at some times are not utilized by them and, therefore, could be accessed by unlicensed users [2], [3]. A study by the Spectrum Policy Task Force (SPTF) of the Federal Communications Commission (FCC), however, has shown that some frequency bands are heavily used by licensed systems at particular locations and at particular times, but that there are also many frequency bands which are only partly occupied or largely unoccupied [4]. Several spectrum-sensing methods have been proposed to reduce the inefficient use of the frequency spectrum [5], [6]. All the methods have different operational characteristics, advantages, and disadvantages. Spectrum sensing can be broadly classified into two categories: cooperative spectrum sensing [7], [8] and non-cooperative spectrum sensing [9], [10]. In cooperative sensing, a group of CRs share sensing information with each other to enhance the sensing accuracy. On the other hand, when a CR acts on its own intelligence and analyses to detect the primary unused channel, that is known as non-cooperative sensing. Non-cooperative sensing is easier to implement than cooperative sensing and requires a lower computational cost. However, non-cooperative sensing may be less robust due to fading channel effects.

Non-cooperative spectrum sensing adopts three approaches, namely signal specific sensing, semiblind sensing, and blind sensing. There are several signal-specific sensing methods [6] including cyclostationary feature detection, matched filter detection, and so on. Tani and Fantacci [11] used cyclostationary features to detect a signal with noise uncertainty. When prior knowledge about the primary user signal is given, matched filter detection [12], [13] becomes the optimal sensing method. Energy detection [14], [15] is one of the most commonly used semiblind spectrum-sensing methods in CR. This is because it does not require prior knowledge on the primary user signal (which is why it is called semiblind), but it provides only a poor performance for cases with a low signal-to-noise ratio (SNR). De and Liang [16] introduced a blind spectrum-sensing method, which does not require the knowledge of the signal or of the noise power, by employing multiple receive antennas. Nagaraj [17] proposed an entropy-based blind spectrum-sensing algorithm for detection of the primary user that compares the entropy of the licensed user signal.
with an appropriate threshold. The system complexity of the method is high due to the use of automatic gain control (AGC) and an analog-to-digital converter (ADC). However, recently, unsigned autocorrelation-based blind spectrum sensing was proposed, where a band pass filter is used before the autocorrelation calculation [18]. The detection performance of the method is unsatisfactory in severe noise environments. In addition, for this method, the multipath fading effect, which is very important for real cases, was not considered.

The autocorrelation-based spectrum-sensing methods are very popular owing to their simplicity, low computational complexity, and good performance over the fading channel. Chaudhari et al. [19] utilized the time-domain autocorrelation property of cyclic prefix (CP)-based orthogonal frequency division multiplexing (OFDM) signals for detecting OFDM-transmitted signals. This method considered a fast Fourier transform (FFT) with a very small size for an OFDM signal and the probability of detection was unsatisfactory for low-SNR cases. Moreover, Chambers and Sallathurai [20] extended the spectrum-sensing method in Ref. [19] and considered large FFT sizes. On the other hand, it is known that the carrier frequency offset problem caused by large FFT sizes loses orthogonality in OFDM and degrades the detection performance of spectrum sensing [20]. Chin et al. [21] proposed a spectrum-sensing method for CP-OFDM signals over multipath fading channels, which is based on the combination of energy detection and the log-likelihood function of received samples. However, the computational complexity of this method is very high due to the use of a log-likelihood function involving several unknown parameters. In practice, the performance is severely degraded by estimating the unknown parameters, especially for low-SNR cases. This method also considered an FFT with a very small size for the OFDM signal. From the above reports, the probability of detection for low-SNR cases needs further improvement. In most cases, the major limitation of the existing spectrum-sensing methods is the detection problem for low-SNR cases.

In this paper, we set out to improve the blind spectrum-sensing detection performance at low SNRs over additive white Gaussian noise (AWGN) and multipath fading channels. The combination of comb filtering with the time-domain autocorrelation calculation is applied to sense OFDM-transmitted signals. OFDM is widely used in current and emerging wireless communication standards. The intersymbol interference (ISI) is mitigated by extending the OFDM symbol with a CP. Using the CP, OFDM reduces the dispersion effect of multipath channels encountered at high data rates and also reduces the requirement for complex equalizers [22]. When only AWGN is considered, the sensing performance is not varied with CP insertion. In contrast, when AWGN with multipath fading is considered for OFDM-transmitted signals, the sensing performance can be improved by CP insertion. Moreover, OFDM systems satisfy the requirements of CR [22]. Therefore, it is important to consider the use of OFDM-transmitted signals for spectrum sensing.

In our proposed autocorrelation-based spectrum-sensing scheme, a comb filter is used to reduce the loss of orthogonality of CP-OFDM. The autocorrelation function, which is a second-order statistical characteristic, is used for spectrum sensing. Since the calculation of the autocorrelation function has low complexity, even if the autocorrelation is combined with a comb filter, the computational complexity is still low. No prior information of the primary users is essential for our proposed scheme, but the noise variance should be used for sensing. Therefore, the proposed method is a computationally efficient semiblind scheme. We consider the CP-OFDM-transmitted signal under different channels of AWGN and multipath Rayleigh fading in detection performance simulations. The detection performance is evaluated under binary phase shift keying (BPSK) and higher-order digital modulation schemes using the proposed sensing method. We have considered an FFT with a large size for an OFDM-transmitted signal for the performance evaluation of spectrum sensing. In simulations, the proposed method is compared with autocorrelation-based [18], [19], well-known energy-detection-based [14], and entropy-based [17] spectrum-sensing methods for detecting OFDM-transmitted signals. As a result, the proposed method shows a marked performance improvement relative to these methods.

This rest of the paper is organized as follows. Section 2 outlines the system model. In Sect. 3, the proposed spectrum-sensing method is described. The performance evaluation of our proposed method by simulation is reported in Sect. 4. Sect. 5 concludes this paper.

2. System Model

Spectrum sensing in CR is practically challenging. There are two types of users, primary or licensed users and secondary or unlicensed users. The primary users have higher priority for the usage of a specific part of the spectrum, while the secondary users have lower priority. Therefore, the secondary users need to have CR capability to sense the spectrum reliably to check whether it is being used by a primary user and to change the radio parameters to exploit the unused part of the spectrum. Spectrum idles must be sensed by the secondary users for opportunistic spectrum access.
2.1 Spectrum-sensing model

We consider the simplest case of spectrum sensing, in which the channel can be used by its primary user. From a given observation, the secondary user must determine whether or not the spectrum is occupied, which implies two hypotheses, that the channel is free and that it is occupied [12],

\[ H_0 : y(n) = w(n) \]  
\[ H_1 : y(n) = h(n) * x(n) + w(n) \]

where \( y(n) \) is the signal received at the sensing station, \( h(n) \) is the impulse response of the multipath Rayleigh fading channel, \( x(n) \) is the signal transmitted by the primary user, and \( w(n) \) is the noise. The asterisk in Eq. (2) denotes convolution.

When the channel is free, only the additive noise will be observed on the secondary user side, that is, \( y(n) = w(n) \), which characterizes hypothesis \( H_0 \). However, if the channel is being used, the secondary user will sense the primary user signal \( x(n) \) plus the noise \( w(n) \), hence hypothesis \( H_1 \) will be adopted.

These two hypotheses are defined by two states of the primary user, an idle state and active state. Hypothesis \( H_0 \) is defined as the idle state and hypothesis \( H_1 \) is defined as the active state of the primary user. To decide between the two hypotheses, the secondary user’s receiver evaluates a test statistic, \( T \), based on its observed signal and compares it with a specific threshold \( \lambda \) as follows.

\[ H_0 : T < \lambda \]  
\[ H_1 : T \geq \lambda \]

The two probabilities in spectrum sensing are given as follows: the probability of detection, which indicates that the primary user correctly detects its active mode, and the probability of a false alarm, which represents false detection of the primary user, meaning that \( H_1 \) is adopted when \( H_0 \) is true. These can be described [12] as

Detection Probability = \( Pr\{ T > \lambda \mid H_1 \} \)  
False Alarm Probability = \( Pr\{ T > \lambda \mid H_0 \} \)  

2.2 Use of CP-OFDM signal

OFDM is a multicarrier modulation where the input data stream is modulated by a modulator, resulting in a complex symbol stream \( X(0), X(1), \ldots, X(N-1) \). This symbol stream

| Table 1 Some OFDM-based system parameters |
|--------------------------------------------|
| Standard Name | DVB-T | DVB-T2 | IEEE 802.11a |
|----------------|-------|--------|---------------|
| FFT Size N     | 2K, 8K | 1K, 2K, 4K, 8K | 64 |
| Subcarrier Modulation Scheme | QPSK, 16-QAM, 64-QAM | QPSK, 16-QAM, 64-QAM | BPSK, QPSK, 16-QAM, 64-QAM |
| CP Length      | 1/4, 1/8, 1/16, 1/32 | 1/4, 1/8, 1/16, 1/32 | 1/4, 1/8, 1/16, 1/32 |
| CP size (Nc)   |        |        |                |

converted to parallel subchannels, which are the frequency components, by a serial-to-parallel converter [23]. Then the frequency components are converted into time samples by taking the inverse fast Fourier transform (IFFT). The IFFT gives the OFDM symbol consisting of the sequence \( x(0), x(1), \ldots, x(N-1) \) of length \( N \), given by

\[ IFFT\{X(k)\} = x(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X(k) e^{j2\pi nk/N} \]  

where \( k = 0, 1, 2, \ldots, (N-1) \).

Then the CP is added to the OFDM symbols. The CP for \( x(n) \) can be defined by \( \{x(N-C), \ldots, x(N-1)\} \), where it consists of the last \( C \) samples of the \( x(n) \) 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 \( x'(n), -C \leq n \leq (N-1) \), of length \( N + C \). The resulting sequence is \( x'(n) = x'(-C), \ldots, x'(N-1) = x(N-C), \ldots, x(0), \ldots, x(N-1) \), which is the transmitted OFDM signal, is converted by a parallel-to-serial converter.

The transmitted signal is filtered by the channel impulse response \( h(n) \) and corrupted by the additive noise \( w(n) \). Finally, the received signal is given by

\[ y(n) = x'(n) * h(n) + w(n) \]  

3. Proposed Method

In this paper, we propose a semiblind spectrum-sensing method that utilizes the combination of a comb filter and autocorrelation calculation for the input signal. Figure 1 shows a block diagram for the proposed autocorrelation-based spectrum sensing. The proposed method is explained in detail in the following subsections.
3.1 Primary user (Transmitter)

In the proposed method, the OFDM signal is considered as the licensed user. OFDM is a method of encoding digital data on multiple carrier frequencies and is widely used for current mobile communications, named 4G. Different OFDM-based systems use different parameters according to the specific application. Table 1 shows important parameters for some OFDM based applications, where the CP size is defined as $N_c = C/N$. Therefore, in our proposed method we consider different parameters for the sensing of OFDM-transmitted signals.

In the OFDM-transmitting section, the serial data streams are digitally modulated using phase shift keying (PSK) or quadrature amplitude modulation (QAM) and passed through a serial-to-parallel data converter to split the data into a number of parallel subchannels. The data in each subchannel are the discrete frequency components of the OFDM modulator output and are applied to a multicarrier modulator that is, IFFT in Fig. 1. In the OFDM system, the IFFT takes a signal defined by the frequency components and converts it to a time-domain signal. It is perfectly valid to generate a signal in the frequency domain and convert it to a time-domain equivalent for practical use. The IFFT outputs are ordered by the parallel-to-serial converter. If the first received symbol is mixed with the second received symbol for the multipath channel, ISI is created. The CP is added to reduce the ISI between consecutive OFDM symbols and to reduce the severe effect of the multipath fading channel. Figure 2 illustrates the CP insertion in the OFDM-transmitted signal, where the tail part of the $S_0$ symbol is copied and added to the head of the $S_0$ symbol to minimize ISI. The multipath Rayleigh fading channel with AWGN is considered in our proposed autocorrelation-based spectrum-sensing method.

3.2 Spectrum sensing (Receiver)

In the receiving section, spectrum sensing is performed by the combination of a comb filter and time-domain autocorrelator. The synchronization problems of the OFDM symbol can be reduced by the comb filter [24]. In order to detect the larger FFT size for the OFDM-transmitted signal, it is necessary to compensate for the carrier frequency offset in an appropriate manner [20]. In our proposed method, we use a finite impulse response (FIR) comb filter whose frequency response consists of a series of regularly spaced notches.

The output signal of the comb filter [24], [25], $f(n)$, can be described by

$$f(n) = y(n) + g y(n - K) \quad (9)$$

where $y(n)$ is the filter input, $f(n)$ is the filter output, $g$ is a filter coefficient, and $K$ corresponds to the delay length for the filter. The comb filter output signal $f(n)$ is used as the input to the autocorrelation function.
Autocorrelation is the similarity between observations as a function of the time lag between them. Here, the autocorrelation function method can be effectively utilized for spectrum sensing. In the CP-based OFDM system, autocorrelation measures the similarity and creates a peak where similarity exists. This maximum point can be effective for spectrum sensing.

The autocorrelation function of the comb filter output, \( R_{ff}(\tau) \), and that of the noise, \( R_{ww}(\tau) \), are defined by

\[
R_{ff}(\tau) = E[f(n)f^*(n+\tau)] \tag{10}
\]

\[
R_{ww}(\tau) = E[w(n)w^*(n+\tau)] \tag{11}
\]

respectively, where \( E\{\cdot\} \) is the expectation value operator, \( \tau \) is the lag number from \(-(L-1)\) to \((L-1)\), and \( L \) is the total number of samples. In Eqs. (10) and (11), * denotes the complex conjugate. Equations (10) and (11) can be rewritten as

\[
R_{ff}(\tau) = \frac{1}{L} \sum_{n=0}^{L-1} f(n)f^*(n+\tau) \tag{12}
\]

\[
R_{ww}(\tau) = \frac{1}{L} \sum_{n=0}^{L-1} w(n)w^*(n+\tau) \tag{13}
\]
in a practical system.

In our proposed scheme, the autocorrelation functions \( R_{ff}(\tau) \) and \( R_{ww}(\tau) \) are respectively utilized for the test statistic and for the threshold selection for the detection of the primary user. The test statistic is measured by averaging the autocorrelation function \( R_{ff}(\tau) \). The threshold value is obtained from the noise autocorrelation function \( R_{ww}(\tau) \) and the false alarm probability. The objective of spectrum sensing is to decide whether there are OFDM signals or noise. Finally, a cognitive controller or receiver gives the final output by comparing the threshold with the test statistic. The threshold and test statistic values do not depend on the primary user information, hence our approach is semiblind.

3.3 Process of proposed method

We summarize the process of the proposed method as follows:

**Step 1:** Take the transmitted signal \( y(n) \) and pass it through the comb filter whose output is \( f(n) \) defined by Eq. (9).

**Step 2:** Measure the autocorrelation function \( R_{ff}(\tau) \) for \(-(L-1)\leq \tau \leq (L-1)\).

**Step 3:** Calculate the test statistic \( T \) from \( R_{ff}(\tau) \). This is described by

\[
T = \frac{1}{2L-1} \sum_{\tau=-(L-1)}^{L-1} |R_{ff}(\tau)| \tag{14}
\]

**Step 4:** Estimate the noise variance, \( \sigma_w^2 \), from a priori information from the channel where the following relation is used:

\[
R_{ww}(0) = \sigma_w^2 \tag{15}
\]

**Step 5:** Calculate the threshold value \([18]\), \( \lambda \), as

\[
\lambda = \sigma_w^2 + \frac{Q^{-1}(1 - P_{fa}) \cdot 2}{(L-1)} \tag{16}
\]

where \( Q^{-1} \) is the inverse of the complementary cumulative distribution function \( Q \) \([12]\) and \( P_{fa} \) is the false alarm probability.

**Step 6:** If the test statistic \( T \) is greater than the threshold \( \lambda \), we assign hypothesis \( H_1 \). Otherwise, we assign \( H_0 \) as follows:

\[
H_0 : T < \lambda \tag{17}
\]

\[
H_1 : T \geq \lambda \tag{18}
\]

4. Simulation Results

The performance of the proposed scheme is analyzed using two important parameters related to spectrum sensing: the probability of detection and the probability of false alarm. By MATLAB simulations, the performance is evaluated and compared with that of conventional methods. The transmitted sequence consists of a CP-OFDM signal. The simulation parameters for the proposed method are tabulated in Table 2. The spectrum sensing samples have various CP lengths and the SNR is changed from -30 dB to +10 dB. Monte Carlo simulations are commonly conducted by averaging results over 1500 iterations. The probability of a false alarm of 0.001 is considered for measuring the detection probability for different SNR values. The simulations are carried out on two different channels: AWGN and multipath Rayleigh fading. The AWGN channel is used to compare the performance of the proposed method with that of conventional methods under the same conditions. The multipath Rayleigh fading channel consists of a five-tap impulse response with a maximum delay of 8, which is used to investigate the performance of the proposed method while changing several parameters.

The FIR comb filter coefficient is commonly set as \( q = 1 \). Figure 3 shows the probability of detection of 1/4-CP-based OFDM signals for different
Table 2 Simulation parameters

| Parameters       | Types                                                                 |
|------------------|----------------------------------------------------------------------|
| Digital Modulation | BPSK, QPSK, 16-PSK, QAM, 16-QAM, 64-QAM, 256-QAM                   |
| FFT Size $N$     | 1024                                                                |
| CP Size $N_c$    | $1/4, 1/8, 1/16, 1/32$                                             |
| Channel          | Multipath Rayleigh Fading and AWGN                                 |
| Number of Iterations | 1500                                                        |

![Fig. 3](image) Probability of detection of OFDM-transmitted signals for different delay lengths of the FIR comb filter

delay lengths of the comb filter under 64-QAM over the multipath Rayleigh fading channel. It can be observed from Fig. 3 that the probability of detection is slightly better for the delay length of $N$, which is equal to the FFT size of 1024. The probability of detection does not change for different values of the delay length i.e., $N/2$, $N/3$, and $N/4$, where values are rounded to the nearest integer. From this result, in our proposed method, the delay length $N$ is considered as the delay length of the comb filter.

Figure 4 shows the autocorrelation function of the 1/32-CP-based OFDM-transmitted signal with and without an FIR comb filter over the multipath fading channel. The experimental parameters are 16-QAM, 4224 samples, and SNR = -10 dB. From Fig. 4(a), it can be observed that without the filter the peak detection by autocorrelation is not possible due to the ISI of the OFDM signals. To prevent ISI being caused by the multipath channel, OFDM systems insert a CP before each transmitted symbol. To preserve orthogonality, the end of the current symbol is transmitted before each symbol. When the length of the CP is at least equal to the length of the multipath channel, all copies of the current symbol are received before the start of the useful part of the next symbol, thus preventing ISI. The ISI is not mitigated by a short CP. On the other hand, in Fig. 4(b) when the comb filter is used prior to the autocorrelator, peak detection is possible by autocorrelation due to the presence of the CP. The comb filter is used to track the location of the ripple peaks blindly and provides an estimate of the carrier offset [24]. The comb filter also increases the SNR of the input signal [25]. These are very effective for detection and improving the performance of

![Fig. 4](image) Autocorrelation function of OFDM-transmitted signals with CP length of 1/32: (a) without FIR comb filter (b) with FIR comb filter

![Fig. 5](image) Autocorrelation function of OFDM-transmitted signals with CP length of 1/4: (a) without FIR comb filter (b) with FIR comb filter
The autocorrelation function outputs of the 1/4-CP-based OFDM signals with and without a comb filter are shown in Figure 5. Here, 16-QAM modulation, 5120 samples, and a -10 dB SNR are taken for the simulation. The ISI is mitigated by a longer CP, by which the peak value at 1024 samples can be detected without the filter as shown in Fig. 5(a). Moreover, when the combination of the comb filter and autocorrelation function is used, the amplitude of the peak is increased due to the stronger correlation as shown in Fig. 5(b). Based on this observation, the proposed method improves the detection probability of the OFDM-transmitted signals for low-SNR cases.

As shown in Fig. 2, the same samples are used repeatedly for CP-OFDM. The distance to have the same samples is $N$, which is the FFT size for OFDM. Therefore, the autocorrelation is highly correlated at $\tau = \pm N$ and gives a peak as shown in Figs. 4 and 5.

The comb filter used in Figs. 4 and 5 is simply represented by

$$f(n) = y(n) + y(n - N) \quad (19)$$

Here if we multiply the right-hand side by $1/2$ (although this is not done in practice), it is equivalent to averaging $y(n)$ and $y(n - N)$. Therefore, the comb filter provides the effect that uncorrelated AWGN components are reduced by a factor of two, resulting in the SNR improvement of the input signal. This invokes a further peak enhancement of the autocorrelation function.

The enhancement of the signal autocorrelation ensures the presence of the OFDM signal. The decision rule based on the average signal autocorrelation function, which is the test statistic, is compared with a threshold for detection. The test statistic increases with the enhancement of the signal autocorrelation. When the test statistic is less than the threshold, only noise is present. The OFDM signal can be detected when the test statistic is greater than or equal to the threshold. As a result, the enhancement of the autocorrelation improves the performance of spectrum sensing.

The effect of the proposed spectrum-sensing method for CP-OFDM-transmitted signals over the multipath Rayleigh fading channel under BPSK digital modulation is presented in Figure 6. Here, different lengths of CP are considered for sensing the primary
The high detection performance observed for positive-SNR cases evidences that spectrum sensing can perfectly distinguish a licensed user from noise. Spectrum sensing is possible for different CP lengths over a wide range of SNR, which is very important for OFDM systems. When the CP length increases, the performance of the proposed spectrum sensing increases.

Figure 7 shows the detection probability of the proposed sensing under QPSK digital modulation for different CP lengths. The simulation result shows that the length of the CP plays a significant role in the detection performance. For CP lengths of 1/8, 1/16 and 1/32, the detection performance is approximately common. However, when the CP length is 1/4, the detection probability increases. The detection probability of the proposed sensing method for 16-PSK modulation is shown in Figure 8. The detection performance for the CP length of 1/4 exceeds that for the CP lengths of 1/8, 1/16, and 1/32.

The detection probability of the proposed spectrum sensing under QAM is shown in Figure 9. The detection performance is increased gradually with the SNR depending on the CP length. The results indicate that detection may be possible at a very low SNR $\geq -13$ dB for a CP length of 1/4. As shown in Figures 10 and 11, we simulated the performance of the proposed method under 16-QAM and 64-QAM for OFDM-transmitted signals with different CP lengths.
Table 3  Detection probability at fixed SNR

| Sensing Scheme       | SNR (dB) | Detection Probability |
|----------------------|----------|-----------------------|
| Proposed Method      | -3       | 1                     |
| Unsigned Autocorrelation | 5       | 1                     |
| Entropy              | 15       | 1                     |
| Energy Detection     | 19       | 1                     |

For higher-order QAM, the sensing performance is significantly improved, especially for a CP length of 1/4 and for low SNR cases.

We have compared the performance of the proposed spectrum sensing with and without the filter over the multipath fading channel under different digital modulation schemes including BPSK, QPSK, 16-PSK, QAM, 16-QAM, 64-QAM, and 256-QAM as shown in Figure 12. For all the modulation schemes, the detection probability rises significantly with SNR. Although we have only shown the results for a CP length of 1/4, we have observed that the detection probability increases with SNR for all other CP lengths. The results show that the detection performance for BPSK, QPSK, and 16-PSK is almost the same. From our experiments, it is clear that the detection probability is higher for QAM than for PSK modulation. The primary user detection performance of our proposed method increases dramatically for higher-order QAM, which is very important for current wireless communication systems.

In digital QAM, at least two phases and at least two amplitudes are used. The autocorrelation amplitude of the signal increases with the QAM modulation order using the proposed spectrum-sensing method. When the combination of a comb filter and autocorrelation is used, the SNR improvement increases the autocorrelation amplitude, resulting in better detection performance. Fig. 12 illustrates that the detection probability (80%) is very good at low SNR (-8 dB) for 16-QAM. For 64-QAM, the maximum probability detection (≥ 0.9 or 90%) is achieved in a very low SNR environment (-10 dB). Moreover, the maximum probability of detection is achieved at -14 dB SNR for 256-QAM. For all cases, the probability of detection is improved in severe noise environments by utilizing the combination of a comb filter and autocorrelation function.

The proposed spectrum-sensing method is compared with conventional blind spectrum-sensing methods based on unsigned autocorrelation [18] and entropy [17] over the AWGN channel in Figure 13. Shaikh et al. [18] considered the OFDM-transmitted signal for energy detection and the unsigned autocorrelation for BPSK digital modulation on the AWGN channel, and thus we consider this scenario for comparison here. For the performance comparison, common parameters are used for all the blind methods at a false alarm probability of 0.001. It can be seen from Fig. 13 that the probability of detection is much higher for our proposed method than for the conventional schemes and that the maximum detection (90%) is achieved in a very low SNR environment (-7 dB). This indicates that the proposed spectrum-sensing method improves the detection performance significantly.

In the energy detection scheme, CR users sense the presence or absence of the primary users through the energy of the received primary signal. Hence, energy detection is very simple but provides a poor performance for low-SNR cases. The entropy scheme is better than energy detection for low-SNR cases but more complex [17]. The unsigned-autocorrelation-based scheme is utilized with the combination of a band pass filter and autocorrelator for spectrum sensing but does not provide a very good performance for low-SNR cases. The proposed spectrum-sensing method employs a comb filter and autocorrelator, reducing the effect of the loss of orthogonality of OFDM signals, and the SNR is improved. Table 3 shows the performance of four different blind spectrum-sensing methods for OFDM-transmitted signals. The results show that the proposed autocorrelation-based sensing scheme provides a 22 dB SNR gain compared with energy detection, an 18 dB improvement compared with the entropy-based scheme, and an 8 dB SNR improvement compared with the unsigned-autocorrelation-based blind scheme.

The proposed method is compared with the CP autocorrelation-based spectrum-sensing method [19] in
Figure 14, where the multipath Rayleigh fading channel is considered again. The simulation parameters for the CP autocorrelation based sensing method were an FFT size of 32 and a CP length of 1/4 over the multipath Rayleigh fading channel. In the proposed method, we consider an FFT size of 1024 and a CP length of 1/4. The proposed method outperforms the autocorrelation-based spectrum-sensing method with the CP. The probability of detection is improved for low-SNR cases by the comb filter. It is clear from Fig. 14 that the maximum detection by the proposed method is achieved at SNR ≥ -11 dB, whereas the maximum detection is achieved at SNR ≥ -7 dB for the conventional method. From these results, it is clear that the proposed method improves the SNR of the CP-OFDM-transmitted signal by 4 dB compared with that for the conventional method.

5. Conclusion

Taking into consideration the poor spectrum sensing performance for low-SNR cases, we have proposed a low-complexity spectrum-sensing method, where a comb filter and autocorrelator are combined and utilized for sensing OFDM-transmitted signals. The proposed method is applicable over AWGN and multipath Rayleigh fading channels under different digital modulation schemes. The effect of ISI caused by the multipath fading channel can be reduced by employing different CP lengths in OFDM systems. The comb filter is used prior to the autocorrelation calculation to reduce the effect of the significant amount of random data for the multipath fading channel. As a result, the proposed spectrum-sensing method improves the detection performance markedly and also improves the SNR compared with that for the conventional autocorrelation-based spectrum-sensing methods.

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