SPECTRUM SENSING USING COMBINATION OF COMB FILTER AND AUTOCORRELATOR IN PARALLEL FOR OFDM SIGNALS IN COGNITIVE RADIO

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Abstract - We propose an effective spectrum sensing method which exploits the combination of comb filter and autocorrelation function in a parallel form. In our proposed method, the primary user information is not required for spectrum sensing, but the noise variance is used, which corresponds to a semi blind one. A comprehensive evaluation by simulations shows that the proposed method is useful for low signal-to-noise ratio (SNR) cases.

Index Terms - Autocorrelation Function, Comb Filter, Orthogonal Frequency Division Multiplexing, Spectrum Sensing.

I. INTRODUCTION

Cognitive radio (CR) is an approach for reducing the scarcity of the radio frequency spectrum for upcoming 5G wireless communication systems [1], [2]. In CR, in order to identify the radio spectrum status being either vacant or active, spectrum sensing is used. Numerous spectrum sensing methods have been proposed during the last few years [3], [4]. In general, the spectrum sensing methods can be categorized into two groups: cooperative spectrum sensing [5] and non-cooperative spectrum sensing [6]. We mainly focus on non-cooperative spectrum sensing. Non-cooperative spectrum sensing occurs when a CR acts on its own intelligence. Non-cooperative spectrum sensing can be further classified into three classes: signal specific sensing, semi blind sensing, and blind sensing.

There are several signal specific sensing methods. For example, Tani et al. [7] used cyclostationary features for detecting the signal with noise uncertainty. When prior knowledge about the primary user signal is given, matched filter detection [8] provides the optimal sensing performance. Energy detector [9] is one of the most commonly used semi blind spectrum sensing methods, which does not require prior knowledge of the primary user signal. However, the performance of energy detector is poor for low signal-to-noise ratio (SNR) cases. De et al. [10] introduced a blind spectrum sensing method, which does not require knowledge of the signal or of the noise power. Shaikh et al. [11] proposed an unsigned autocorrelation based blind spectrum sensing method for detection of the primary user, but the method does not work effectively in severe noise environments.

The correlation based spectrum sensing methods are very popular due to their low computational complexity and provide a good performance over the fading channel. Chaudhari et al. [12], [13] proposed an autocorrelation based spectrum sensing method utilizing the time domain autocorrelation property of cyclic prefix (CP) based orthogonal frequency division multiplexing (OFDM) signals. In this method, a very small size of fast Fourier transform (FFT) was used for OFDM transmitted signals. In addition, Chambers et al. extended the spectrum sensing method in [12], [13] and used large FFT sizes in [14]. 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 [14]. Therefore, the major limitation of the existing spectrum sensing methods results in their poor detection performance for low SNR cases.

In this paper, we improve the detection performance of the autocorrelation based spectrum sensing for low SNR cases. To the best of our knowledge, no attempt has been made about this kind of approach under semi blind condition. The proposed method is a semi blind one. No prior information of the primary users is essential for our proposed scheme, but the noise variance is used for sensing. The combination of comb filter and time domain autocorrelation calculation is applied in a parallel form for sensing CP-OFDM transmitted signals. In simulations, the proposed method is compared with the autocorrelation based spectrum sensing method [13]. Several comb filters to be prepared in a parallel form are used for reducing the loss of orthogonality of CP-OFDM influenced by a multipath fading channel, while the autocorrelation functions in each parallel path are averaged and enhanced for spectrum sensing. This idea increases detection performance in spectrum sensing by improving effectively the signal-to-noise ratio (SNR) of the received signal in a merged fashion.

This paper is organized as follows. Section II describes the system model to be assumed in this paper, and the detailed explanation of the proposed method is presented in Section III. Section IV gives

simulation results. Finally, in Section V, a conclusion of this paper is drawn.

II. SPECTRUM SENSING MODEL

The primary user has higher priority on the usage of a specific part of the spectrum, while the secondary user does lower priority. In spectrum sensing, the secondary user must determine whether or not the spectrum is occupied, which implies two hypotheses. When the channel is free, only the additive noise will be observed on the secondary user side, that characterizes the null hypothesis, H_0. However, if the channel is being used, the secondary user will sense the primary user signal and the noise, which is the alternate hypothesis, H_1. In this paper, we assume that the primary user signal is a CP-OFDM signal received at the sensing station. The CP-OFDM signal is assumed to be received by being passed through a multipath Rayleigh fading channel.

The two hypotheses are defined by two states of the primary user such as idle state and active state. 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 decide the situation between the two hypotheses, the secondary user's receiver evaluates a test statistic, T(y), based on its observed signal and compares it with a specific threshold, λ, as

$$H_0 : T(y) < \lambda \tag{1}$$

$$H_1 : T(y) \geq \lambda \ . \tag{2}$$

Here the two types of errors: the probability of false alarm, P_{fa}, which represents false detection of the primary user that means to decide H_1 when H_0 is true, and the probability of miss detection, P_m, which indicates to decide H_0 when H_1 is true. These can be described [8] as

$$P_{fa} = P(H_1; H_0) \tag{3}$$

$$P_m = P(H_0; H_1). \tag{4}$$

The signal detection accuracy is measured by the probability of detection, P_d, which indicates that the primary user correctly detects its active mode. This can be described by

$$P_d = P(H_1; H_1) = Pr\{T(y) > \lambda \mid H_1\}. \tag{5}$$

III. PROPOSED SCHEME

In this paper, we propose a semi blind spectrum sensing method that utilizes the combination of comb filter and autocorrelation function in a parallel form. Fig. 1 shows a block diagram of the proposed spectrum sensing method. In the proposed method, the OFDM signal is considered as the primary user.

A. CP-OFDM Signal (Transmitter)

OFDM is a multi-carrier modulation where the input data streams are digitally modulated using phase shift keying (PSK) or quadrature amplitude modulation (QAM), resulting in a complex symbol stream X(0),X(1),……,X(N-1). This symbol stream is converted to parallel subchannels, which are the frequency components, by a serial-to-parallel converter. Then the frequency components are converted into time samples taking the inverse fast Fourier transform (IFFT). The IFFT gives the OFDM symbol consisting of the sequence x(0),x(1),……,x(N-1) of length N as

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

In our proposed method, we consider the l_{th} OFDM signal, $x_l(n)$, as

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

where $1 \leq l \leq S$ and $X_l(k)$ corresponds to the l_{th} OFDM symbol at the k_{th} subcarrier.

The CP is added to combat the inter symbol interference (ISI) between consecutive OFDM symbols. Fig. 2 illustrates the CP insertion in the OFDM transmitted signal where the tail part of the symbol 1 is copied and added to the head part of the symbol 1. 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

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

where the asterisk denotes convolution.

B. Spectrum Sensing (Receiver)

In the receiving section, spectrum sensing is performed by the combination of comb filter and

autocorrelator in a parallel form. The synchronization problems of the OFDM symbol can be reduced by the comb filter [16]. In our proposed method, we use finite impulse response (FIR) comb filters whose frequency response constructs a series of regularly spaced notches.

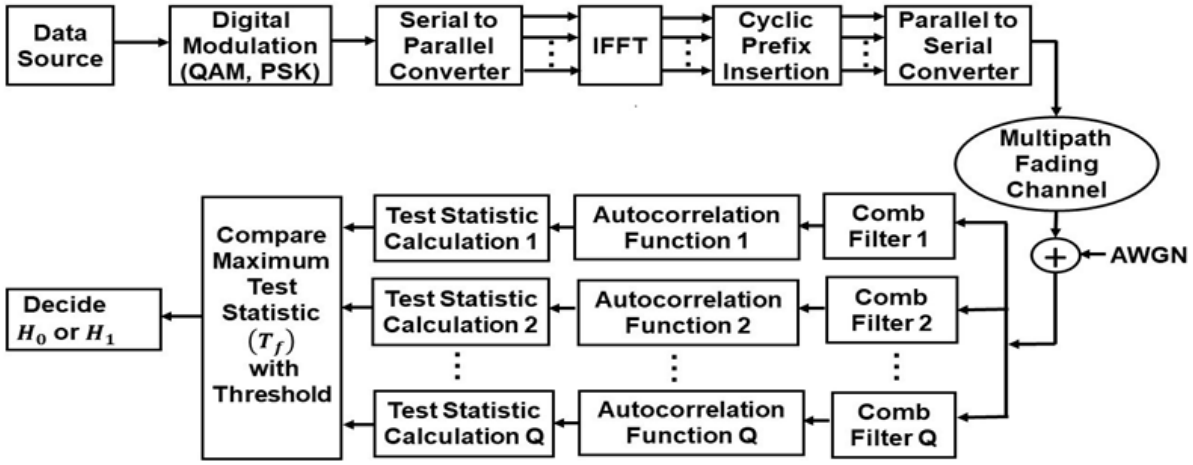


Fig. 1 Block diagram of proposed spectrum sensing method.

The filter output of the p_{th} comb filter from the l_{th} OFDM symbol input, $f_{p,l}(n)$, is described [16], [17] by

$$f_{p,l}(n) = y_{p,l}(n) + g_p y_{p,l}(n-K) \quad (9)$$

where K the delay length for each filter and g_p is the filter coefficient of the p_{th} filter, given by

$$g_p = exp\left(j2\pi p \lfloor N/Q \rfloor / N\right) \quad (10)$$

where $\lfloor . \rfloor$ is a floor function and Q corresponds to the number of comb filters used in a parallel form.

In (9), $y_{p,l}(n)$ represents the l_{th} OFDM symbol input for the p_{th} comb filter for simplicity (in practice, a sequential stream of $y_l(n)$, y(n), is received and inputted to each comb filter continuously).

The output signal of the p_{th} comb filter for each OFDM symbol is used as the input to the time domain symbol autocorrelation function.

Autocorrelation is the similarity between observations as a function of the time lag between them. Here, the autocorrelation function calculation can be effectively utilized for spectrum sensing. In the CP based OFDM system, the autocorrelation measures the similarity and creates a peak where similarity exists.

The autocorrelation function calculation of the l_{th} OFDM symbol for the p_{th} comb filter output, $R_{p,l}(\tau)$, is described by

$$R_{p,l}(\tau) = \frac{1}{M}\sum_{n=0}^{M-1} f_{p,l}(n) f_{p,l}^{*}(n+\tau) \quad (11)$$

where $1 \le p \le Q$, τ is the lag number from 0 to (M-1) and M is the number of samples. In (11), * denotes complex conjugate.

In our proposed scheme, the autocorrelation calculation of all OFDM symbols with $1 \le l \le S$ is utilized for test statistic selection for the detection of the primary user. Each test statistic, T_p, is measured by averaging each autocorrelation function, and the maximum value among all the T_ps is used as the final test statistic, T_f. The threshold value is obtained from the noise variance, σ_w^2, and P_{fa}. Finally, the cognitive controller or receiver gives the final output by comparing the threshold with the test statistics T_f. The threshold and test statistic values do not depend upon the primary user information, hence our approach is semi blind.

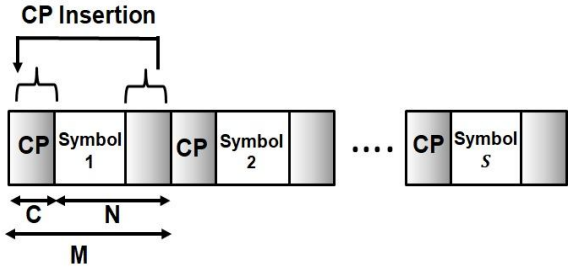


Fig. 2 Insertion of CP in OFDM Systems.

A. Process of Proposed Method

We summarize the process of the proposed method as follows:

Step 1. Take the transmitted signal $y_l(n)$ and pass it through the Q comb filters simultaneously where the output of each comb filter is $f_{p,l}(n)$ taken by (9).

Step 2. Measure the autocorrelation function for the l_{th} OFDM symbol, $R_{p,l}(\tau)$, by (11) for $0 \le \tau \le (M-1)$, in each path.

Step 3. Calculate the average of the autocorrelation for each OFDM symbol, $\bar{R}_{p,l}(\tau)$, as

$$\bar{R}_{p,l}(\tau)=\frac{1}{M}\sum_{\tau=0}^{M-1}\left|R_{p,l}(\tau)\right| \quad (12)$$

in each path.

Step 4. The test statistic T_p can be obtained by

$$T_p=\sum_{l=1}^{S}\bar{R}_{p,l}(\tau) \quad (13)$$

in each path.

Step 5. Finally, the maximum value among T_p, $1 \le p \le Q$, is used as the final test statistic T_f by

$$T_f=\left[T_p\right]_{max} \quad (14)$$

where $[\ .\ ]_{max}$ is a maximum function.

Step 6. Obtain the noise variance σ_w^2 as a priori information from the channel, where the technique in [15] is available for example.

Step 7. Calculate the threshold value λ as

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

Step 8. If the test statistics T_f is greater than the threshold λ, we assign the hypothesis H_1 as

$$H_1: T_f \ge \lambda\ . \quad (16)$$

Otherwise, we assign H_0 as

$$H_0: T_f < \lambda\ . \quad (17)$$

IV. SIMULATION RESULTS

To assess the proposed method, the performance is evaluated and compared with that of the conventional methods by MATLAB simulations. The simulation parameters for the proposed method are tabulated in Table I (where the CP ratio is defined as N_c = C/N). The SNR has been changed from -30 dB to 0 dB. The multipath Rayleigh fading channel consists of a 5 tap impulse response with the maximum delay 8.

Fig. 3 shows the P_d of CP based OFDM signals under 16-QAM digital modulation. Here, various P_{fa} including 0.001 (0.1%), 0.01 (1%), 0.1 (10%) and 0.2 (20%) are considered for sensing the primary user. We observe that the P_d is increased gradually with SNR depending on the fixed P_{fa}. For very low P_{fa} which is 0.1%, the maximum P_d (≥ 0.9 or 90%) is achieved in very low SNR environment (-13 dB). The maximum P_d is obtained at -15 dB SNR for 1% P_{fa}. In addition, when the P_{fa} is 10%, the P_d increases. Here, the maximum P_d (≥ 0.9 or 90%) is achieved in low SNR environment (-18 dB), which indicates 3 dB SNR improvement than 1% $P_{fa.}$ Finally, the primary user detection performance increases dramatically for 20% P_{fa}. It is quite observable that when the P_{fa} increases, sensing performance is significantly improved using the proposed spectrum sensing method.

Parameters	Types
Digital Modulation	16-QAM
FFT Size N	1024
Number of OFDM Symbols S	140
Probability of False Alarm P_{fa}	0.001, 0.01, 0.05, 0.1, 0.2
CP Ratio N_c	1/4
Channel	Multipath Rayleigh Fading with AWGN
Number of Comb Filters Q	3
Number of Iterations	1500

Table I Simulation Parameters

In Fig. 4, the complementary receiver operating characteristics (CROC) curves, P_{fa} versus P_m, are presented for fixed SNR cases. It is clear from Fig. 4 that the detector has low P_m (≤ 0.1) for P_{fa} 0.5 at low SNR (-23 dB). The P_m is 0.1 at P_{fa} 0.2 for SNR -20 dB, whereas, for SNR -17 dB, the P_m is almost zero at P_{fa} 0.2. The P_m declines at SNR -17 dB significantly under very low P_{fa} (≤ 0.1). It is observed from the plot that the P_m decreases when the SNR increases. In addition, if the P_{fa} increases, the P_m decreases. Therefore, the performance of the proposed spectrum sensing increases.

The proposed method is compared with the CP autocorrelation based spectrum sensing method [13] in Fig. 5. The simulation parameters for the CP autocorrelation based spectrum sensing method was the size of FFT 32, the CP ratio 1/4, 16-QAM modulation and P_{fa} 0.05. Here, CP unknown and CP known cases were considered for detection performance simulation, where the CP known case achieved better performance. In the proposed method, CP is unknown for spectrum sensing. We considered the size of FFT 1024, the CP ratio 1/4, 16-QAM modulation and P_{fa} 0.05. The proposed method outperforms both cases of the CP autocorrelation based sensing method. The P_d is improved for low SNR cases by the proposed method. When the comb filters are used prior to the autocorrelators, the peak detection is possible by autocorrelation calculation that is 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 frequency offset [16]. The comb filter also increases the SNR of the input signal [17]. These are very much effective for detection and improve the performance of spectrum sensing. It is demonstrated from Fig. 5 that

the proposed spectrum scheme offers 6 dB SNR gain than the CP known autocorrelation based and 10 dB SNR improvement than CP unknown autocorrelation based spectrum sensing scheme.

The effect of receiver operating characteristics (ROC) curves at different levels of signal strength for the proposed method and CP autocorrelation based spectrum sensing method [13] are presented in Fig. 6. It is quite observable from Fig. 6 that the P_d increases dramatically for our proposed method at SNR -10 dB as well as SNR -20 dB relative to the conventional method.

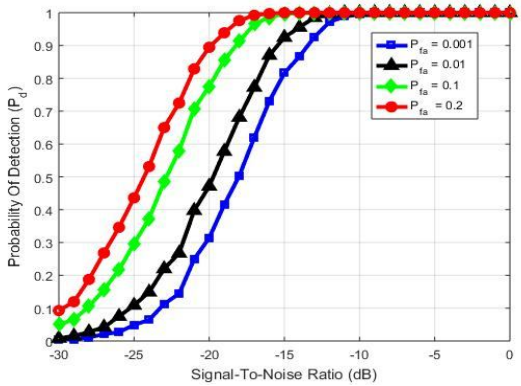


Fig. 3 Performance of the proposed spectrum sensing method for various P_{fa}.

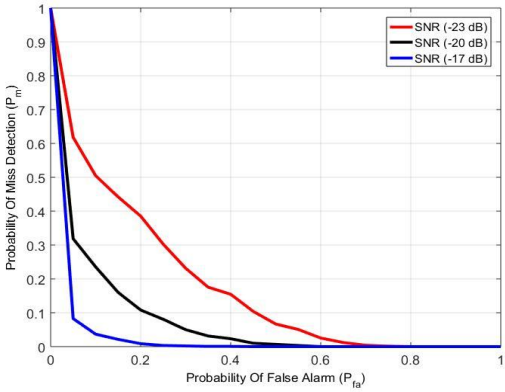


Fig. 4 CROC curves of the proposed spectrum sensing for fixed SNR cases.

CONCLUSION

We have proposed an effective semi blind spectrum sensing method to improve the detection performance in severe noise environments. The combination of comb filter and autocorrelation function is exploited in a parallel form for sensing CP-OFDM transmitted signals. The proposed spectrum sensing method improves the SNR of the received signals and achieves better detection performance than the conventional autocorrelation based spectrum sensing method.

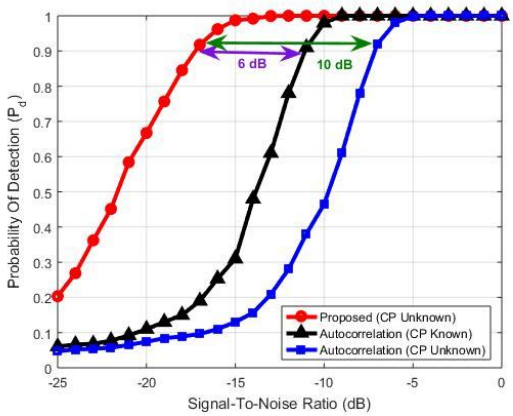


Fig. 5 Performance comparison at fixed P_{fa} 0.05.

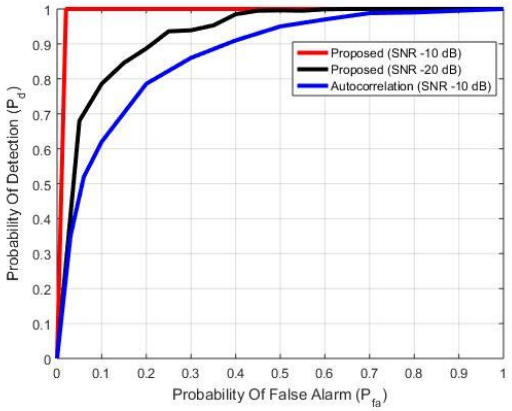


Fig. 6 Performance comparison using ROC curves for fixed SNR cases.

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