Cooperative Spectrum Sensing-Based Wideband Cognitive Radio System Design

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Abstract. Cooperative spectrum sensing can improve detection performance of cognitive radio (CR) when the channel is in severe fading and shadowing environment. In this paper, we have designed cooperative spectrum sensing-based wideband CR system including transmitter and receiver. Each CR user marks the spectrum availability through energy detection and gets the sub-basis function through doing Inverse Fast Fourier Transform (IFFT) with the product of the spectral marker vector and the random phase vector. The cooperative spectrum sensing can be realized by cascading the sub-basis functions of all the users. The simulation results have shown that the proposed system can avoid the interference caused by the primary user and outperform the spread spectrum system.

Keywords: Cognitive radio · Cooperative spectrum sensing
Basis function · Bit error rate

1 Introduction

Radio spectrum is a precious natural resource licensed by the government, most of which have been allocated to the primary users (PU). However, the researches taken by FCC have shown that some frequency bands are not used for most of the time, while other bands are only occupied in part of the time, but only a few bands are competitively used by many users [1, 2]. In order to solve the problem of spectrum resource scarcity, cognitive radio (CR) has been proposed, which is such a communication device with cognitive function and can detect to use the idle spectrum [3].

Some spectrum sensing methods have been proposed such as energy detection, correlation detection, cyclostationary feature detection and cooperative spectrum sensing, etc. [4, 5]. When the channel is in severe fading and shadowing environment, the performance of the first three methods may be very low. However, cooperative spectrum sensing can improve the overall detection performance by the collaboration of multiple CR users [6–8]. Although the spectrum sensing has been intensive study, a CR system haven't been designed, which can sense to use the idle spectrum effectively

Q. Liang et al. (Eds.): CSPS 2017, LNEE 463, pp. 533–541, 2019.
https://doi.org/10.1007/978-981-10-6571-2_65

In this paper, a cooperative spectrum sensing-based wideband CR system has been proposed. In the system, the cooperative CR users sense to sample the spectrum environment and judge whether the sub-channel is available by the adaptive threshold-based energy detection; the spectrum availability is marked as a tag vector in the frequency domain, which is multiplied by the random phase vector. The Inverse Fast Fourier Transform (IFFT) of the product generates the sub-basis function. All the sub-basis functions are cascaded to get the system basis function, which can realize cooperative spectrum sensing. The user data are modulated onto the system basis function for the transmissions in idle spectrum.

2 Adaptive Threshold-Based Energy Detection

The purpose of spectrum sensing is to detect the existence of PU signal. Considering N CR users to participate in the cooperative spectrum sensing, the sensing signal received by each user can be described as a binary hypothesis as follows

$$y_i(n) = \begin{cases} u_i(n), & H_0 \\ h_i s(n) + u_i(n), & H_1 \end{cases}, \quad i = 1, 2, \ldots, N \tag{1}$$

where H_0 and H_1 denote absence and presence of the PU, respectively, $y_i(n)$ is the signal received by the user i, $s(n)$ denotes the PU signal with mean of 0 and average power of P_s, h_i denotes the user's channel gain, and $u_i(n)$ is the noise obeying the Gauss distribution with mean of 0 and variance of σ_i^2. Energy detection value is obtained by taking the average square amplitude of M signal sampling nodes as follows

$$T(y_i) = \frac{1}{M}\sum_{n=1}^{M} |y_i(n)|^2 \tag{2}$$

According to the central limit theorem, when M is big enough, $T(y_i)$ follows the Gauss distribution approximately. We can get the means u_{i,H_0}, u_{i,H_1} and variances σ_{i,H_0}^2, σ_{i,H_1}^2 under the hypotheses H_0 and H_1 as follows

$$\begin{aligned} u_{i,H_0} &= \sigma_i^2; & u_{i,H_1} &= (1 + r_i)\sigma_i^2 \\ \sigma_{i,H_0}^2 &= \tfrac{2}{M}\sigma_i^4; & \sigma_{i,H_1}^2 &= \tfrac{2}{M}(2r_i + 1)\sigma_i^4 \end{aligned} \tag{3}$$

where $r_i = h_i^2 P_s/\sigma_i^2$ is the sensing signal-to-noise ratio (SNR) of user i. Supposing the energy detection threshold is λ_i, we can get the false-alarm probability and detection probability as follows

$$P_{f,i} = Q\left(\frac{\lambda_i - u_{i,H_0}}{\sigma_{i,H_0}}\right) = Q\left(\left(\frac{\lambda_i}{\sigma_i^2} - 1\right)\sqrt{\frac{M}{2}}\right) \tag{4}$$

$$P_{d,i} = Q\left(\frac{\lambda_i - u_{i,H_1}}{\sigma_{i,H_1}}\right) = Q\left(\left(\frac{\lambda_i}{\sigma_i^2} - r_i - 1\right)\sqrt{\frac{M}{4r_i+2}}\right) \quad (5)$$

where $Q(.)$ denotes the normal Gauss complementary integral function. Since the detection probability $P_{d,i}$ is susceptible to the noise, in order to ensure the detection accuracy, the adaptive threshold is given by

$$\lambda_i = \left(Q^{-1}(P_{d,i})\sqrt{\frac{4r_i+2}{M}} + r_i + 1\right)\sigma_i^2 \quad (6)$$

Substituting (6) into (4), the corresponding false alarm probability is given by

$$P_{f,i} = Q\left(Q^{-1}(P_{d,i})\sqrt{2r_i+1} + \sqrt{\frac{M}{2}}r_i\right) \quad (7)$$

Since different CR users are in different channel environments and their detection probabilities are different, λ_i is adaptively changed according to the environmental noise (e.g. threshold decreases with weak noise and increases with strong noise) [9]. Compared with the fixed threshold, the adaptive threshold can guarantee the detection performance of different users in different noise environment.

3 System Model Design

In this paper, the CR system adopts cooperation spectrum sensing based on the adaptive threshold-based energy detection, hence, the spectrum sensing performance can be improved greatly.

3.1 CR Transmitter Design

The CR transmitter is designed as shown in Fig. 1, whose core is the basis function generation [10]. User i for $i = 1, 2, \ldots, N$ samples the spectrum environment, calculates the energy vector $\boldsymbol{T}(\boldsymbol{y_i})$ by (2) and selects the adoptive threshold λ_i according to (6). Each element in the vector $\boldsymbol{T}(\boldsymbol{y_i})$ is compared with λ_i, and the corresponding bit value is set to be 0 (unavailable subchannel) if $T(y_i) \geq \lambda$ and 1 (available subchannel), otherwise. The generated 1-bit vector is denoted by $\boldsymbol{A_i}(\boldsymbol{\omega}) = \{A_{i1}, A_{i2}, \ldots, A_{im}, \ldots\}$ for marking spectrum hole. Random phase generator generates a random phase vector $\boldsymbol{e^{j\theta(\omega)}} = \{e^{j\theta_1}, e^{j\theta_2}, \ldots, e^{j\theta_m}, \ldots\}$, which is multiplied by the corresponding element in $\boldsymbol{A_i}(\boldsymbol{\omega})$ to get a new signal vector $\boldsymbol{B_i'}(\boldsymbol{\omega})$. $\boldsymbol{B_i'}(\boldsymbol{\omega})$ is multiplied by a scaling factor C to get $\boldsymbol{B_i}(\boldsymbol{\omega})$. The time domain signal $b_i(t)$ is obtained through doing IFFT with $B_i'(\omega)$. Updating user $i = i + 1$ and detection threshold $\lambda = \lambda_{i+1}$, detect the spectrum again.

We can obtain N users' sub-basis function $b_i(t)$ for $i = 1, 2, \ldots, N$. Cascading $b_i(t)$, we can obtain the system basis function of cooperative users as follows

$$b(t) = b_1(t) \otimes b_2(t) \otimes \cdots \otimes b_N(t) \tag{8}$$

The detected signal y_i is orthogonal with $b_i(t)$, hence, we can guarantee the orthogonality between $b(t)$ and all the y_i for $i = 1, 2, \ldots, N$. $b(t)$ is stored as a basis function for the modulation process of information data d_n. If the channel electromagnetic environment is constant over a continuous estimation time interval, a new basis function will be generated at the beginning of the time interval, and the subsequent data are modulated using the same basis function in the memory. The modulated data is emitted by the transmitting antenna. The modulation on the basis function uses bipolar modulation mode as follows

$$r(t) = \begin{cases} b(t), & "0" \\ -b(t), & "1" \end{cases} \tag{9}$$

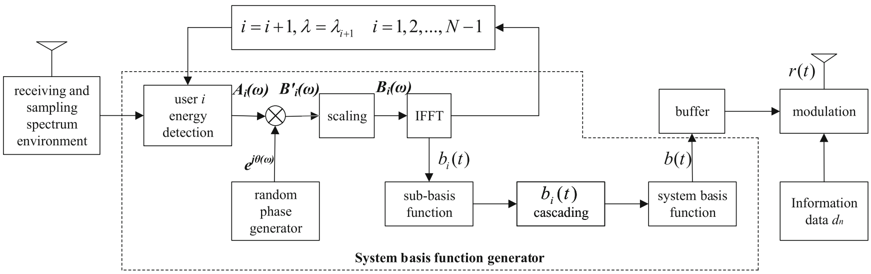

Fig. 1. CR system transmitter

3.2 Receiver Design

The CR receiver is designed as shown in Fig. 2. The receiver obtains signal $r(t)$ as well as the spectrum environment sampling of N users. The receiver can estimate the system basic function $\hat{b}(t)$ using the same system basic function generator as the transmitter.

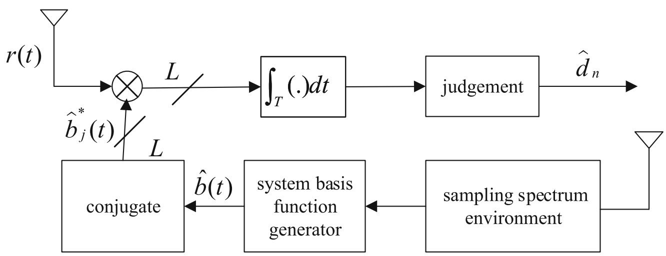

Fig. 2. CR system receiver

The receiver gets L equal interval cyclic shifts of conjugate $\widehat{b}(t)$ as $\widehat{b}_j^*(t)$ for $j = 1, 2, \ldots, L$ and then calculates the cycle correlation of $r(t)$ and $\widehat{b}_j^*(t)$ within a symbol as $z_j(t)$. Through finding the subscript l of the maximum $z_j(t)$, we can estimate the transmitted data $\widehat{d}_n$ according to the cyclic shift of $\widehat{b}_l(t)$ relative with $\widehat{b}(t)$.

3.3 System Performance Analysis

We can get frequency domain representation of the system basis function as follows

$$\boldsymbol{B}(\boldsymbol{\omega}) = \boldsymbol{B_1}(\boldsymbol{\omega})\boldsymbol{B_2}(\boldsymbol{\omega}) \times \ldots \times \boldsymbol{B_N}(\boldsymbol{\omega}) \tag{10}$$

from which we can see that for a sub-channel, if user i detects the presence of the PU in the sub-channel, the element value in the corresponding position of the vector $\boldsymbol{B_i}(\boldsymbol{\omega})$ is set to be 0, hence, the element value in the same position of $\mathbf{B}(\omega)$ is also 0, which indicates that the subchannel is unavailable [11]. The cooperative spectrum sensing satisfies the "OR Rule", and detection probability and false alarm probability are obtained as follows

$$\begin{cases} Q_d = 1 - \prod_{i=1}^{N} (1 - P_{d,i}) \\ Q_f = 1 - \prod_{i=1}^{N} (1 - P_{f,i}) \end{cases} \tag{11}$$

Assuming the average noise power is N_0, in the receiver, the interference noise obtained from the correlation of the received signal and the local basic function obeys the distribution as follows

$$n \sim (0, \quad [(N_0 + P_s(1 - Q_d))\rho + \varepsilon_s(1 - \rho)]) \tag{12}$$

where $\rho = \mathrm{Cov}\left(b(t),\ \widehat{b}_l(t)\right) \Big/ \sqrt{\mathrm{Val}(b(t)) \bullet \mathrm{Val}\left(\widehat{b}_l(t)\right)}$ denotes the cross-correlation of the basis functions $b(t)$ and $\widehat{b}_l(t)$ [12]. Using the bipolar modulation, we can get the average bit error rate (BER) of the CR system as follows

$$P_{BER} = Q\left(\sqrt{\frac{2\varepsilon_s\rho}{[N_0 + P_s(1 - Q_d)]\rho + \varepsilon_s(1 - \rho)}}\right) \tag{13}$$

Supposing the transmission $\mathrm{SNR} = \varepsilon_s/N_0$, the power ratio of PU signal to CR signal $J/E = P_s/\varepsilon_s$ and the error rate of basis function $e = (1 - \rho)/\rho \bullet 100\%$, the BER of (14) is rewritten as follows

$$P_{BER} = Q\left(\sqrt{\frac{2}{\frac{1}{SNR} + \frac{J}{E}(1 - Q_d) + e}}\right) \tag{14}$$

4 Simulations and Discussions

We assumed that each user uses energy detection with the number of sampling nodes $M = 1200$, the number of IFFT pints is 256, and the transmission power of each symbol is 10 dBW.

Figure 3 compares the false alarm probabilities of cooperative spectrum sensing with adaptive threshold, cooperative spectrum sensing with fixed threshold and non-cooperative spectrum sensing. In the figure, the number of cooperative CR users $N = 5$, the sensing SNR of users is $\{0.1\ 0.5\ 0.5\ 1.0\ 2.0\}$dB. It can be seen that the detection performance of cooperative spectrum sensing, which achieves lower false alarm probability, is better than that of the non-cooperative sensing with the same detection probability constraint. Since the adaptive threshold can change with the SNR, the detection performance of each user can be guaranteed, thus improving the overall detection performance. Figure 4 shows the BER varying with SNR with the same user number and the constant interference intensity, where we assume that $J/E = 0{-}10\,\text{dB}$, SNR = $-6{-}8\,\text{dB}$ and $P_{d,i} = 0.7$, and the basic functions generated by the receiver and the transmitter are completely same, i.e. $e = 0$. It can be seen that the simulation results are consistent with the theoretical results, and the BER can be reduced through increasing the number of cooperative users. The BER can be less than 10^{-4} when $N = 8$ and SNR $= 6\,\text{dB}$, however for non-cooperative detection (N = 1), the BER is above 10^{-1}.

Figure 5 shows the BER varying with J/E with different error rates of basis function and the constant SNR, where we assume that the SNR = 10 dB, $J/E = 0{-}10\,\text{dB}$, the number of cooperative users $N = 5$ and $P_{d,i} = 0.7$. When the distance between transmitter and receiver is short, the sampling estimations of electromagnetic environment at transmitter and receiver are nearly the same, so the generated basis functions are same. But when the distance is long, the sampling estimations

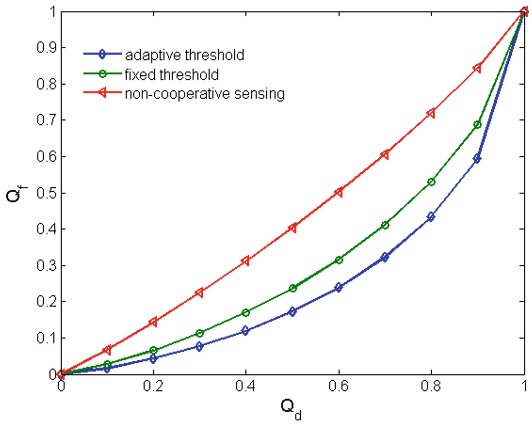

Fig. 3. False alarm probability varying with detection probability

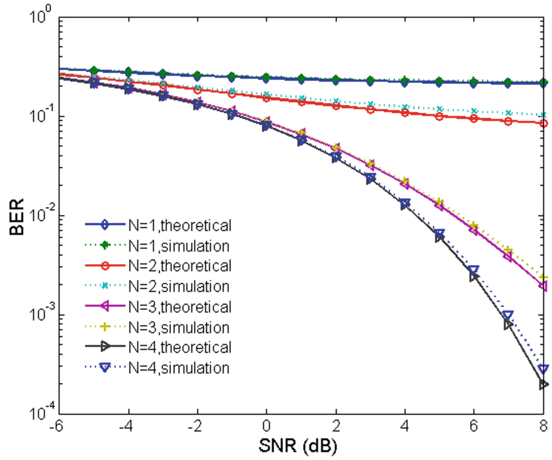

Fig. 4. BER varying with SNR

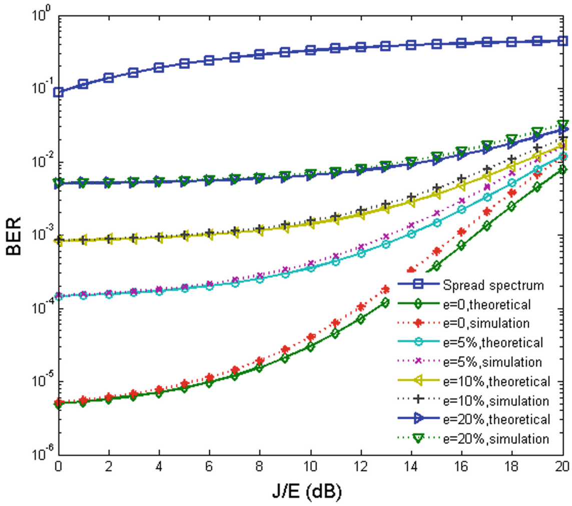

Fig. 5. BER varying with J/E

of the electromagnetic environment at transmitter and receiver are different, thus the basic functions are also different. At this time, if the receiver still uses the locally generated basis function to demodulate the signal, there would be some errors. We compare theoretical and simulated BER when the error rate is 0%, 0.5%, 10% and 20%, respectively. It can be seen that although the basis function exists error, the anti-interference ability of the designed system outperforms the spread spectrum system. That is because the CR system uses the idle spectrum to transmit data and avoid the interference caused by the PU.

5 Conclusions

Cooperative spectrum sensing can improve the detection probability of CR and reduce the interference caused by the PU. In this paper, the CR system is designed to utilize the idle spectrum resource effectively. The proposed system can realize the accurate estimation of the spectrum environment by adopting cooperative spectrum sensing based on adaptive threshold. The spectral marker vector based on spectrum estimation can generate a sub-basis function that is orthogonal to the PU signal. All the sub-basis functions are cascaded to obtain a system basis function which can realize the cooperative spectrum sensing. The communication of CR is achieved by modulating the information data to the system basis function. The proposed system can avoid the interference caused by the PU and outperform the spread spectrum system obviously.

Acknowledgments. This work was supported by the National Natural Science Foundations of China under Grant Nos. 61601221, 51404211, 91438205 and 61671183, the Natural Science Foundations of Jiangsu Province under Grant No. BK20140828, the China Postdoctoral Science Foundations under Grant No. 2015M580425 and the Fundamental Research Funds for the Central Universities under Grant No. DUT16RC(3)045, and the Open Research Fund of State Key Laboratory of Space-Ground Integrated Information Technology under grant No. 2015_SGIIT_KFJJ_TX_02.

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