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Cumulant-based blind cooperative spectrum sensing method for cognitive radio

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ABSTRACT

Spectrum sensing is a crucial technology in cognitive radio (CR). Cumulant-based or higher order statistics (HOS) based spectrum sensing methods are often considered in literature for spectrum sensing because cumulants higher than 3-order can be used as a feature to distinguish non-Gaussian signals from Gaussian noise. However, most existing cooperative spectrum sensing methods are based on the assumption that the channel gain is available, which cannot be realistic in practice. In this paper, a novel cumulant-based cooperative spectrum sensing method is proposed. The proposed method does not depend on the noise power, channel gain, or the unknown signal parameters. Additionally, the proposed method is based on Neyman–Pearson (N–P) criteria, thus it is optimal in terms of the performance of detection probability if the false alarm probability is given in advance. Simulation results and analysis are presented to verify the validity and the superiority of the proposed cooperative spectrum sensing method over the existing ones.

1. Introduction

Spectrum sensing is a crucial technology for secondary users (Sus) in cognitive radio [1]. Its main goal is how to discover the primary users (Pus). Several kinds of spectrum sensing methods have been proposed, such as energy based spectrum sensing methods, autocorrelation based spectrum sensing methods, cyclostationarity based spectrum sensing methods, and multi-cumulant based spectrum sensing methods [2]. Energy based detection methods are usually simple and have admirable performance but they depend on the accurate noise power. If the noise power is unknown, energy based detection methods would suffer the problem of SNR wall and fail to work in the worst case [3,4]. Autocorrelation based spectrum sensing methods, for example, covariance matrix based method [5], eigenvalue based method [6] and oversampling method [7], use autocorrelation values to distinguish autocorrelated signals from white noise and are immune from noise uncertainty. However, if the noise is colored or not white, their detection performances degrade greatly. Cyclostationarity based detection methods use cyclostationarity to extract signals from noise [8,9]. Cyclostationarity may come from underlying periodicities of man-made signal, such as coding, modulation and cyclic prefix. As a result, cyclostationarity can be used to distinguish the primary user signal from the noise. But cyclostationarity based methods should know the accurate cyclic frequencies in advance. In practice, because of the uncertainties in CR, such as noise uncertainty [3], signal uncertainty [10], and channel uncertainty, the noise power and cyclic frequencies may not be known exactly in advance and the noise could also be correlated. Thus, the application of energy based methods, autocorrelation based methods and cyclostationarity base methods would be limited.

Cumulants of three-order or more can be used as a feature to distinguish non-Gaussian signals from the Gaussian noise, so there are some cumulant-based spectrum sensing methods proposed already. A single-cumulant based method is first proposed in [11]. In [12], the authors further develop a multicumulant based spectrum sensing method. A sequential cumulant-based spectrum sensing method is also given in [13] and a cumulant-based goodness of fit (GoF) test spectrum sensing method is designed in [14]. However, these cumulant-based methods are mainly applied in a scenario with single CR user. Equal gain combination (EGC) scheme is simple and blind. But EGC does not exploit the rich received statistics knowledges sufficiently. Compared with EGC, other weighting combination schemes [15–17] can increase the

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detection probability but they are not blind and need to know the exact SNR of every Su, which may not be realistic in cognitive radio.

In this paper, a novel cumulant-based cooperative spectrum sensing method is proposed. The method first receives the test statistic of every Su in the network, and then calculates the estimated optimum coefficients according to Neyman–Pearson (N–P) criteria and some nonparametric approximations, and then constructs the total test statistic by linearly combining the test statistics and the estimated optimum coefficients and also establishes the threshold by using the estimated optimum coefficients, finally makes the decision by comparing the test statistic with the threshold. The main benefit of the proposed method is that it is blind. In other words, it is independent of noise power, channel gain or unknown signal parameters and only needs the known variables such as false alarm probability, the number of Sus and the received signal.

2. Conventional cumulant-based spectrum sensing method for a single Su

A typical spectrum sensing problem is usually casted as the following binary hypothesis testing problem:

$$\begin{cases} x(t) = n(t) & \mathcal{H}_0 \\ x(t) = s(t) + n(t) & \mathcal{H}_1 \end{cases} \tag{1}$$

where $x(t)$ is the received signal, $s(t)$ is the unknown non-Gaussian primary signal, $n(t)$ is the additive Gaussian noise (AGN) (maybe white or colored) with zero mean, and $\mathcal{H}_0$ or $\mathcal{H}_1$ respectively denotes the absence or presence of $s(t)$.

Given T data samples, a kth order cumulant can be estimated by [18]:

$$\hat{c}_{kx}(\boldsymbol{\tau}) \triangleq \sum_{p=1}^{P} (-1)^{(N_p-1)}(N_p-1)!\hat{m}_{v_{1,p}x} \cdots \hat{m}_{v_{N_p,p}x} \tag{2}$$

where P is the number of partitions of the set $x(t), \ldots, x(t+t_{k-1})$, N_p is the number of parts in partition p, $v_{i,p}$ is the number of elements in part i of partition p, and $\hat{m}_{v_{1,p}x}$ represents the sample kth order moment [18]:

$$\hat{m}_{kx}(\boldsymbol{\tau}) \triangleq \frac{1}{T} \sum_{t=0}^{T-1} x(t)x(t+\tau_1) \cdots x(t+\tau_{k-1}) \tag{3}$$

Define a $1 \times N$ vector of cumulant estimators $\hat{\mathbf{C}}_{kx}(\boldsymbol{\tau}) \triangleq \left[\hat{c}_{k_1x}(\tau_1), \ldots, \hat{c}_{k_Nx}(\tau_N)\right]$, the test statistic Δ_c of cumulant-based detection method is:

$$\Delta_c = T\hat{\mathbf{C}}_{kx}(\boldsymbol{\tau})\hat{\boldsymbol{\Sigma}}_c^{-1}\hat{\mathbf{C}}'_{kx}(\boldsymbol{\tau}) \tag{4}$$

where $\hat{\boldsymbol{\Sigma}}_c$ is the estimated covariance matrix of $\hat{\mathbf{C}}_{kx}(\boldsymbol{\tau})$.

According to [12], the distributions of test statistic Δ_c are:

$$\Delta_c \sim \begin{cases} \chi_N^2 & \mathcal{H}_0 \\ \chi_N^2(T\mathbf{C}_{kx}(\boldsymbol{\tau})\boldsymbol{\Sigma}_c^{-1}\mathbf{C}'_{kx}(\boldsymbol{\tau})) & \mathcal{H}_1 \end{cases} \tag{5}$$

Hence, given FAP P_{fa}, the threshold γ of cumulant-based detection method is $\gamma = \chi^2_{N,P_{fa}}$, where $\chi^2_{N,P_{fa}}$ is the chi-square value with N degrees of freedom at P_{fa} level. Hence by comparing the test statistic Δ_c with the threshold γ , one can decide whether a primary signal is present or not.

3. Proposed cumulant-based spectrum sensing method for multiple Sus

The cumulant-based cooperative spectrum sensing method is proposed in this section. Due to the uncertainties in CR, the cooperative methods should be preferred to be blind. The EGC scheme is simple and blind. But EGC does not exploit the rich information of the received statistics sufficiently. In order to solve this problem, a new blind cooperative method is proposed here. The method first receives the test statistic of every Su in the network, and then calculates the estimated optimum coefficients according to N-P criteria and some nonparametric approximations, and then constructs the total test statistic by linearly combining the test statistics and the estimated optimum coefficients and also establishes the threshold by using the estimated optimum coefficients, finally makes the decision by comparing the test statistic with the threshold. The system block diagram is depicted in Fig. 1.

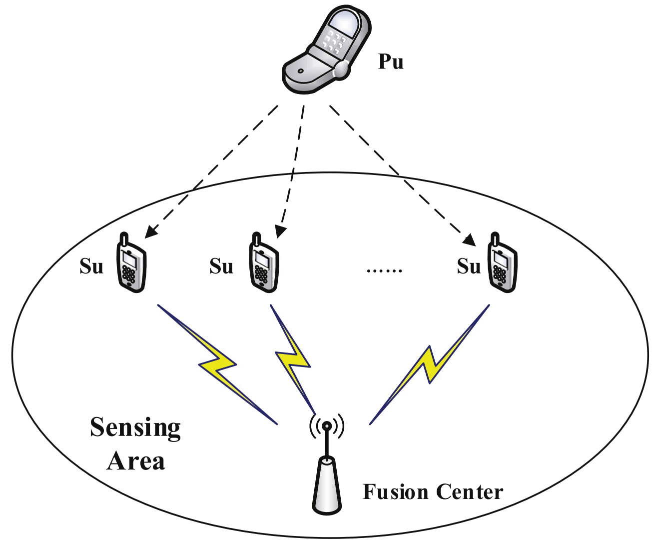

Fig. 1. System block diagram of the proposed method.

Hereinafter, the superscript ^{i} denotes the ith user in the CRN. So the distributions of the ith CR users test statistic become

$$\Delta_c^{(i)} \sim \begin{cases} \chi_N^2 & \mathcal{H}_0 \\ \chi_N^2(T\mathbf{C}_{kx}^{(i)}(\boldsymbol{\tau})\boldsymbol{\Sigma}_c^{(i)^{-1}}\mathbf{C}_{kx}^{(i)'}(\boldsymbol{\tau})) & \mathcal{H}_1 \end{cases} \tag{6}$$

The non-central Chi-square distribution can be approximated by the normal distribution according to the following formula [19, (26.4.28)]:

$$P(\chi'^2|v,\lambda) \approx P_n(x),\, x = \frac{(\chi'^2/\alpha)^{1/3} - [1 - 2(1+\beta)/9\alpha]}{\sqrt{2(1+\beta)/9\alpha}}$$
$$\left[\alpha \triangleq v + \lambda,\, \beta \triangleq \lambda/(v+\lambda)\right] \tag{7}$$

where $P(\chi'^2|v,\lambda)$ denotes the probability density function (PDF) of non-central chi square distribution with non-central parameter λ and v degrees of freedom and $P_n(x)$ denotes the PDF of normal distribution. Hence, let

$$\Delta^{(i)} \triangleq \sqrt[3]{\Delta_c^{(i)}} \tag{8}$$

under $\mathcal{H}_0$, according to (7) we have $\alpha = N$, and $\beta = 0$, and $\Delta^{(i)}$ has the following approximate distribution:

$$\frac{\Delta^{(i)}}{N^{\frac{1}{3}}} \sim \mathcal{N}\left\{1 - \frac{2}{9N}, \frac{2}{9N}\right\} \tag{9}$$

under $\mathcal{H}_1$, let $\lambda^{(i)} \triangleq T\mathbf{C}_{kx}^{(i)}(\boldsymbol{\tau})\boldsymbol{\Sigma}_c^{(i)^{-1}}\mathbf{C}_{kx}^{(i)'}(\boldsymbol{\tau})$, according to (7), we have $\alpha = N + \lambda^{(i)}$, $\beta = \lambda^{(i)}/(N + \lambda^{(i)})$ and $\Delta^{(i)}$ has the following approximate distribution:

$$\frac{\Delta^{(i)}}{(N+\lambda^{(i)})^{\frac{1}{3}}} \sim \mathcal{N}\left\{1 - \frac{2(1+\frac{\lambda^{(i)}}{N+\lambda^{(i)}})}{9(N+\lambda^{(i)})}, \frac{2(1+\frac{\lambda^{(i)}}{N+\lambda^{(i)}})}{9(N+\lambda^{(i)})}\right\} \tag{10}$$