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Cyclostationarity-based cooperative spectrum sensing over imperfect reporting channels

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ABSTRACT

Reliable detection of weak primary user signals is a crucial problem for cognitive radio networks. To address the above issue, cooperative spectrum sensing (CSS) methods based on cyclostationary detection (CD) have been introduced in the literature. In this paper, a soft decision-based CSS method based on the second-order CD at secondary users (SUs) is proposed. The proposed scheme aims to maximize the deflection criterion at the fusion center (FC), while the reporting channels are characterized by Rayleigh fading. To this end, a fusion rule which does not require to know the noise variances of sensing channels is developed. Since the fusion rule assumes the perfect knowledge of channel state information (CSI) of reporting links, it has theoretical significance and provides an upper bound for the performance of cyclostationarity-based CSS. We have also proposed a more practical suboptimum fusion rule and studied its detection performance in the presence of uncertainties in noise variance and channel power gain estimations. Furthermore, in order to be able to evaluate the performance of the CSS, an analytic threshold estimation method has been proposed. Extensive simulation results have been illustrated the robustness of the proposed method compared to the existing cyclostationary detectors.

1. Introduction

Cognitive radio (CR), first introduced by Mitola in 1999 [1], provides a way to use the valuable radio spectrum in an efficient manner. These radios are actually unlicensed wireless devices that temporarily utilize the unused primary spectral bands [2,3]. However, the first step in opportunistic access to the licensed spectrum is the detection of unused spectral bands [4]. In addition, CR should vacate the primary band as soon as a primary user (PU) starts transmitting. Briefly speaking, reliable PU detection in low SNR regime is one of the main challenges to cognitive radio networks.

Although cognitive radios should reliably detect the presence of PUs, it has been shown that the local spectrum sensing may not provide enough reliability in fading environments [5]. To address this problem, cooperative spectrum sensing (CSS) methods were proposed in the literature to improve the detection performance of secondary networks [6–8]. However, most existing scenarios assume that all the cooperating users use the commonly adopted energy detection (ED) technique for their local sensing. Nevertheless, despite the simplicity, quickness and no requirements of pre-knowledge about the PU's signal, the ED method has some challenging issues. For example, it cannot differentiate PUs from secondary users (SUs), and requires to know the noise variance to ensure proper detection performance [9]. Even though the cyclostationary detection (CD) method can solve these problems [10–12,8,13–16], there are rather limited developments in CSS strategies based on CD.

Recently, soft decision-based CSS methods based on ED at SUs have been introduced in the literature [6,17–20]. These methods assume that the perfect knowledge about the noise variances of sensing channels are available at the fusion center (FC). However, in practice, this assumption may be unrealistic. Therefore, the CSS methods based on local ED may be very susceptible to noise uncertainties and thus their performance can be dictated by the accuracy of the noise power estimate. Furthermore, in these studies, it is assumed that the perfect knowledge of noise variances and channel states of reporting links are available at the FC.

To overcome the above issues, CSS based on CD has been proposed in the literature [8,21,22]. Cyclostationarity-based detection methods exploit inherent cyclostationary properties of digitally modulated signals and have acceptable performance in very low SNRs [11,8]. Since CD can distinguish PUs from SUs and also is robust against noise uncertainty, the CD-based CSS can achieve an acceptable detection performance in low-SNR conditions, while the performance is not degraded due to the noise uncertainty problem at cognitive radios. Despite the advantages of CD over ED-based spectrum sensing, there are rather limited researches on CD-based CSS, mostly because of its complicated analytical expressions and also complexities that may arise in implementing the CD algorithms.

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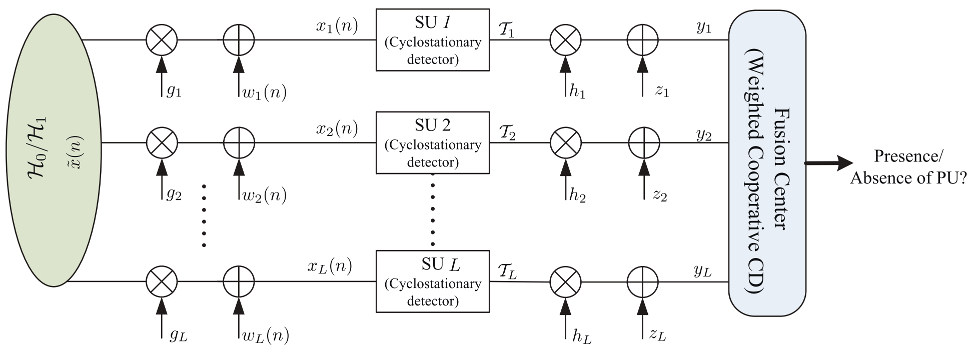

Fig. 1. System model for the cyclostationarity-based cooperative spectrum sensing over imperfect reporting channels.

The main objective of this paper is to develop a cyclostationarity-based CSS framework for reliable detection of PUs when the reporting and observation channels are under fading. To this end, we first provide an overview of the Dandawaté–Giannakis's algorithm [11,8] as the local sensing method. This statistical test does not require any specific assumption about the distribution of PU signals. Based on this local sensing method, we then propose a weighted soft combination method based on deflection criterion maximization at the FC and show that our approach achieves better detection performance compared to the conventional cooperative detectors. Note that our proposed method does not require any prior knowledge about the noise variances of sensing channels or their fading statistics. Since the proposed weighted soft combination method requires the knowledge of some parameters that may be unknown at the FC, we further simplify it heuristically, while showing a comparable performance to the previous one.

Because there is not a closed-form expression for the probability density function (PDF) of the proposed decision statistic, we first derive its characteristic function and then propose a numerical inversion method for evaluating the corresponding distribution function. Simulation results show that the proposed analytical threshold setting procedure provides adequate accuracy for performance analysis purposes.

The remainder of this paper is organized as follows. System model is presented in Section 2. The local sensing strategy and the proposed cooperative spectrum sensing method are described in Section 3. Performance of proposed scheme is investigated in Section 4. Finally, conclusions are drawn in Section 5.

2. System model

It is assumed that the base-band discrete-time received signal for ith SU, $x_i(n)$, $i = 1, 2, \ldots, L$, at a time instance n is given by:

$$x_i(n) = \varrho g_i \tilde{x}(n) + w_i(n), \quad n = 1, \ldots, M, \tag{1}$$

where L refers to the number of SUs existing in the network, g_i denotes the channel fading coefficient between PU and ith SU, and $w_i(n) \sim \mathcal{CN}(0, \delta_i^2)$ with δ_i^2 as the variance of the complex additive Gaussian noise. Note that δ_i^2 and g_i are generally unknown. Moreover, $\varrho = 0$ and $\varrho = 1$ correspond to null (inactive PU) and alternative (active PU) hypotheses, respectively. We assume that the PU is either active or inactive during the sensing duration. The signal transmitted by PU is denoted by $\tilde{x}(n)$. Without loss of generality, $\tilde{x}(n)$, g_i and $w_i(n)$ are assumed to be independent of each other. Furthermore, conditional independence of spatially distributed SUs is assumed [8].

After the decision statistic $\mathcal{T}_i$ at the ith SU is computed, it is transmitted to the FC through an independent reporting channel that experiences flat fading. Hence,

$$y_i = h_i \mathcal{T}_i + z_i, \quad i = 1, \ldots, L, \tag{2}$$

where $z_i \sim \mathcal{N}(0, \sigma_i^2)$ and h_i is a real-valued fading envelope with $h_i > 0$, which is assumed to be constant during the sensing period. Without loss of generality, we assume that the fading channels have unit powers (i.e. $E\{h_i^2\} = 1$). In many cognitive radio scenarios, the envelope of the fading channel and the noise variance can be estimated in advance. Thus, at the first step, the quantities $\{h_i\}_{i=1}^L$ and $\{\sigma_i^2\}_{i=1}^L$ are assumed to be perfectly known to the FC. Then, the impact of presence of uncertainties in the estimations of the above quantities is studied. The whole system model is depicted in Fig. 1.

3. The proposed cyclostationarity-based cooperative sensing method

In this section, we consider the proposed CSS method which is based on the second-order cyclostationary detection at each SU.

3.1. Overview of non-cooperative cyclostationary detection method

In this section, we only present the key steps of Dandawaté–Giannakis's algorithm and omit details. For more detailed background on this algorithm and its implementation, the readers are referred to [11,12,8].

Assume that we want to test for the presence of the cyclostationarity at a candidate cycle frequency α (known prior or can be estimated [11,23]) in the received signal $x(n)$. For a given set of time lags $\{\tau_i\}_{i=1}^N$, the estimated cyclic autocorrelation vector $\hat{\mathbf{r}}_{xx^*}$ is defined to be [11]

$$\hat{\mathbf{r}}_{xx^*} \triangleq [Re\{\hat{R}_{xx^*}^{\alpha}(\tau_1)\}, \ldots, Re\{\hat{R}_{xx^*}^{\alpha}(\tau_N)\}, Im\{\hat{R}_{xx^*}^{\alpha}(\tau_1)\}, \ldots, Im\{\hat{R}_{xx^*}^{\alpha}(\tau_N)\}], \tag{3}$$

in which

$$\hat{R}_{xx^*}^{\alpha}(\tau_i) \triangleq \begin{cases} \dfrac{1}{M}\displaystyle\sum_{n=1}^{M} x(n)x^*(n+\tau_i)e^{-j2\pi n\alpha}, & \tau_i \geq 0 \\ (\hat{R}_{xx^*}^{\alpha}(-\tau_i))^*, & \tau_i < 0 \end{cases} \tag{4}$$

denotes the estimated cyclic autocorrelation function (CAF) at the time lag τ_i and the cycle frequency α. It has been proven that subject to certain mixing conditions, $\sqrt{M}\hat{\mathrm{r}}_{xx^*}$ is asymptotically (i.e. as $M \to \infty$) distributed as $\boldsymbol{u} \overset{\text{def}}{=} \sqrt{M}\hat{\mathrm{r}}_{xx^*} \overset{D}{\sim} \mathcal{N}(\boldsymbol{\mu}, \boldsymbol{\Sigma}_{xx^*})$, where $\boldsymbol{\mu}=\mathbf{0}$ under $\mathcal{H}_0$, and $\boldsymbol{\mu}= \sqrt{M}\mathbf{r}_{xx^*}$ under $\mathcal{H}_1$ [8]. Here, $\overset{D}{\sim}$ denotes the convergence in distribution, and $\mathcal{N}(\boldsymbol{\mu}, \boldsymbol{V})$ denotes the multivariate normal distribution with mean vector $\boldsymbol{\mu}$ and covariance matrix $\boldsymbol{V}$. The