Signal Processing 97 (2014) 183–194

Contents lists available at ScienceDirect

Signal Processing

journal homepage: www.elsevier.com/locate/sigpro

Rao test based cooperative spectrum sensing for cognitive radios in non-Gaussian noise ☆

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ARTICLE INFO

Article history:
Received 9 August 2013
Received in revised form
23 October 2013
Accepted 28 October 2013
Available online 13 November 2013

Keywords:
Cognitive radio
Cooperative spectrum sensing
Rao detection
Decision fusion
Non-Gaussian noise

ABSTRACT

In this paper, we address the problem of spectrum sensing in the presence of non-Gaussian noise for cognitive radio networks. A novel Rao test based detector, which does not require any *a priori knowledge* about the primary user (PU) signal and channels, is proposed for the detection of a primary user in non-Gaussian noises that are molded by the generalized Gaussian distribution (GGD). The statistic of the proposed Rao detector is derived and its detection performance is analyzed in the low signal-to-noise ratio regime and compared to that of the traditional energy detection. Furthermore, the Rao-based detection is extended to a multi-user cooperative framework by using the "*k*-out-of-*M*" decision fusion rule and considering erroneous reporting channels between the secondary users and the fusion center due to Rayleigh fading. The global cooperative detection and false alarm probabilities are derived based on the cooperative sensing scheme. Analytical and computer simulation results show that for a given probability of false alarm, the Rao detector can significantly enhance the spectrum sensing performance over the conventional energy detection and the polarity-coincidence-array (PCA) method in non-Gaussian noises. Furthermore, the proposed cooperative detection scheme has a significantly higher global probability of detection than the non-cooperative scheme.

1. Introduction

In traditional fixed spectrum allocation method, most of the licensed radio spectral bands are under-utilized in time and space domains, leading to a low utilization efficiency of the frequency spectrum. Cognitive radio (CR) has emerged as a key technology that can improve the spectrum utilization efficiency in next generation wireless networks through dynamic management and opportunistic use of radio resources. In this approach, unlicensed (secondary) users (SUs) are allowed to opportunistically access a frequency band allocated to licensed (primary) user (PU), providing that the PUs are not temporally using their spectrum or they can be adequately protected from the interference created by the SUs. Hence, the radio spectrum can be reused in an opportunistic manner or shared at all time, resulting in increased capacity scaling in the network. One of the most important challenges in CR systems is to detect as reliably as possible the absence ($\mathcal{H}_0$ = null hypothesis) or presence ($\mathcal{H}_1$ = alternative hypothesis) of PU in complex environments characterized by fading effects as well as non-Gaussian noise.

Several spectrum sensing methods and algorithms have been proposed for single-user and cooperative detection under the white Gaussian noise (WGN) assumption, see e.g. [1–3]. In practice, however, the problem is more challenging

☆ This work was supported by the Scholarship Funds of Nanjing University of Technology and the National Natural Science Foundations of China under Grant 61372122.
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http://dx.doi.org/10.1016/j.sigpro.2013.10.032

as we need to detect the various PU signals impaired by non-Gaussian noise and interference, as pointed out in [4]. Non-Gaussian noise impairments may include man-made impulsive noise, co-channel interference from other SUs, emission from microwave ovens, out of band spectral leakage, etc. [5,6]. Furthermore, the performance of a spectrum detector optimized against Gaussian noise may degrade drastically when non-Gaussian noise or interference is present because of the heavy tail characteristics of its probability density function (PDF) [7,8]. In view of these problems, it is desirable to seek useful solutions to spectrum detection in practical non-Gaussian noises and to evaluate the detection performance.

Several standard models are currently available from the literature to fit non-Gaussian noise or interference distributions, such as the generalized Gaussian distribution (GGD) and the Gaussian mixture distribution (GMD). The GGD is a parametric family of distributions which can model both "heavier" and "lighter" than normal tails through the selection of its shape parameter. In particular, it has been widely used to model man-made noise, impulsive phenomena [5], and certain types of ultra-wide band (UWB) interference [9].

Spectrum sensing for CR networks in the presence of non-Gaussian noise has been addressed by several researchers recently [11–13]. However, the implementation of these detectors remains challenging as they require *a priori* knowledge of various side information, such as the variances of the channel gain between the PU and the SU and the PU signal [11], the cyclic frequency of the PU signal [12] or the variance of the receiver noise at the SU [13], which may not be readily available in practice. To overcome this limitation, [14] gives an easily implementable and nonparametric detector, namely polarity-coincidence-array (PCA), but the performance of PCA is worse than that of the energy detection when shape factor β is between 1.4 and 2. The use of the generalized likelihood ratio test (GLRT) which incorporates unknown parameter estimation to the traditional likelihood ratio test, has been proposed for local spectrum sensing in non-Gaussian noise [15]. The GLRT is an optimal detector, but it needs to perform the maximum likelihood estimation (MLE) of the unknown parameters under each hypothesis. As such, it suffers from a large computational burden.

The Rao test is an approximate form of the GLRT which only needs to estimate the unknown system model parameters under $\mathcal{H}_0$. Therefore, it has a simpler structure and lower computational complexity than the GLRT [16,17]. Although Rao test has been applied to weak signal detection in non-Gaussian noises in [16,17], its application to spectrum sensing has been limited to Gaussian noise [18]. Recently, several researchers have proposed Rao detector for signal detection in non-Gaussian noise for practical systems, but the analysis is based on the noise PDF molded by GMD considering only one or a few unknown parameters. Based on the theories of GLRT and Rao test, we use the GGD model to describe the background noise and investigate the Rao test based spectrum sensing problem in non-Gaussian noise for CR systems with unknown complex-valued PU sinal, complex-valued channel gain and noise variance. We also analyze the effect of the GGD shape parameter on Fisher information matrix (FIM) and the Rao based detection performance under the GGD noise with different shape parameters.

Multi-user cooperation is a commonly used technique in spectrum sensing due to its capability of overcoming the harmful fading and shadowing effects by employing the spatial diversity. Many recent works have exploited cooperation for improving the performance of spectrum sensing in the presence of Gaussian noise [19,20]. In these literatures, the reporting channels between SUs and FC have been assumed error-free, which is not practical. In [21,22], the detection performance has been analyzed by considering reporting errors, but the local probabilities of detection and false alarm and the cross-over probability have been assumed identical for all SUs for the reason of analytical simplicity. Furthermore, multi-user cooperation for spectrum sensing in the presence of non-Gaussian noise has not yet received much attention.

In our preliminary work [23], we have considered cooperative spectrum sensing for a CR sub-network comprised one fusion center (FC) and multiple SUs, which together seek to detect the presence/absence of a PU over a given frequency band. Each SU employs a Rao detector, which does not require any *a priori* knowledge about the PU signal and channel gains except the PDF of noise (with or without unknown variance), to independently sense the PU signal in the presence of a non-Gaussian noise characterized by the GGD. By simulations we have shown that the Rao detector outperforms the energy detector under the GGD noise with shape factor $\beta \in (0, 2]$.

In this paper, our major contributions include: (i) We derive the detection performance in terms of the probabilities of detection and false alarm for the energy detector and the Rao detector in the low SNR regime. We also analyze the detection performance when the degree of non-Gaussianity and the number of samples vary under different SNRs. (ii) We analyze and compare the performances of the two detectors in terms of the asymptotic relative efficiency (ARE) for GGD noise with various degrees of non-Gaussianity. (iii) We propose a cooperative scheme based on the local decisions of the SUs and the "k-out-of -M" decision rule. We analyze the global detection and false alarm probabilities for a more practical scenario for spectrum sensing under non-Gaussian noise where the SUs in general have different local probabilities of detection and false alarm as well as cross-over probability of erroneous reporting channels. (iv) Through theoretical analysis and numerical simulations, we show that the Rao detector can significantly enhance the local detection performance over the conventional energy detection in non-Gaussian noise and the proposed cooperative spectrum sensing scheme has a significantly higher global probability of detection than the non-cooperative one.

The rest of the paper is organized as follows. The CR system and GGD noise models under consideration are presented in Section 2. The local Rao-based detector used by the SUs is derived and analyzed in Section 3, while the theoretical performance analysis of Rao detector and energy detector for non-Gaussian noise is derived in Section 4. The cooperative spectrum sensing scheme implemented at the FC over error-free/erronous reporting channels is discussed