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Cooperative spectrum sensing using fuzzy membership function of energy statistics

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ABSTRACT

This paper proposes a novel cooperative spectrum sensing method in cognitive radio based on the fuzzy membership functions which are quantized using a near-optimal quantization scheme with low computational complexity. A membership function is obtained in a Secondary User (SU) using an ordinary energy detection method and its output is sent to a Fusion Center (FC) after quantization through a noiseless reporting channel, where the final decision is made. The FC combines the received information using some fuzzy rules such as algebraic product to make a final decision about the absence/presence of a primary user. The simulations results reveal that, under quantization, the proposed cooperative spectrum sensing schemes considerably improve the performance of system.

1. Introduction

Increasing the demand for wireless services with higher rate and the traditional fixed spectrum policy have caused that the spectrum scarcity is a challenging problem in the wireless communication systems. One proposal for alleviating the spectrum scarcity is the use of Cognitive Radio (CR) technology [1]. In this technology, the unlicensed users known as Secondary Users (SUs), sense the spectral environment and adjust transmission parameters to opportunistically use the available spectrum bands. One challenge faced in a CR system is that the SUs must reliably detect weak primary signals of possibly different types and, realize the spectrum holes for their transmissions and vacate the frequency band as soon as the Primary Users (PUs) start their transmission [2,3]. In order to improve the reliability of spectrum sensing and alleviate some practical concerns of spectrum sensing such as multipath fading and hidden PUs, Cooperative Spectrum Sensing (CSS) has been proposed [4]. In recent years, the CSS schemes have been extensively studied in CR networks [5–8]. For example, in [8] an energy-efficient and time-saving one-bit CSS scheme with two-stage decision has been proposed. Zhao has also proposed a two-stage entropy-based CSS method using two-bit decision in [7].

In centralized CSS, each SU forwards its local sensing results to a Fusion Center (FC). The FC combines the received local information and makes a final decision to detect the absence/presence of the PU. The combination of sensing results at the FC can be categorized by soft and hard combination techniques. In the hard combination schemes, the SUs send quantized sensing data to the FC, while in the soft combination, the SUs forward their original sensing data without quantization [9]. Although the soft combination schemes have a better performance in the detection of PUs signals, they require a wideband channel for transmitting the observations. The hard combination schemes, on the other hand, cause information loss and performance degradation and reduce the communication overhead between the SUs and the FC. In the simplest hard combination method, each SU sends one-bit information to the FC regarding the local decision about the absence/presence of the PU. The restriction of the SU output to one bit (0 and 1) certainly causes a substantial information loss. In this paper, we apply the fuzzy logic decision making for combination of sensing results at the FC. In the proposed method, a function called membership function maps the local observation to a value between 0 and 1 which mitigates the information loss compared to the hard combination schemes.

In contrast to the classical detection problem, the decision making in a fuzzy logic detection problem is not restricted to the likelihood of an event; nevertheless, it is still restricted to the degree of membership to two classes corresponding to the absence/presence of a signal. The fuzzy logic has widely used in signal detection, telecommunication systems and CR networks [10–14]. In [12], the fixed detection threshold is replaced with a soft continuous threshold implemented as a membership function which is chosen so that it maps the observation set to a false alarm space corresponding to the false alarm rate. In [15], the authors

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have used a membership function to map the observation space to a continuous real value space between 0 and 1 for distributed fuzzy Constant False Alarm Rate (CFAR) detection in Weibull clutter by using the maximum likelihood and ordered statistics CFAR detectors as local detectors.

Throughout this paper, we address the centralized cooperative spectrum sensing using the fuzzy set theory concepts. We employ the membership function for mapping the observation space of each SU to a value between 0 and 1 representing the degree of assurance about the presence or the absence of the PU. To reduce the bandwidth of the dedicated control channel, all values of the membership functions should be quantized into several bits before transmitting to the FC. In [16,17], several optimal quantization techniques have been presented in the signal detection process. There is some literature on the quantization scheme in CSS [18,19]. In [18], a locally optimal multi-bit quantization scheme based on the deflection criterion has been proposed. In [19], the authors have presented a quantization scheme based on the Lloyd-Max-Based quantization method [20]. However, to perform these quantization schemes, the prior knowledge of the PU signal is needed, which is not always available in a CR network. Another problem of these methods is their high complexity in comparison with the uniform quantization.

In the proposed method, since the probability distribution of the operating values of the proposed membership function tends to the uniform, using the uniform quantization scheme can be almost optimal. The quantized values of membership functions of SUs are sent to the FC and are combined via several fuzzy rules such as algebraic product, algebraic sum, intersection and union to make a final decision about the absence/presence of a PU. We compare the performance of the proposed algorithm with some classical rules such as Optimal Soft Combination (OSC) and Equal Gain Combination (EGC) using the Receiver Operating Characteristic (ROC) curves that captures the relations of the probability of detection, the probability of false alarm, and the SNR in curves via Monte Carlo simulations. The simulation results show that the proposed algorithm with algebraic product rule performs well similar to the OSC scheme. Although, the OSC scheme performs slightly better than the proposed algorithm with algebraic product rule, the OSC is based on the instantaneous SNR's at the SUs which may be impractical in certain environments. Moreover, in contrast to the OSC and EGC schemes, using the uniform quantization is close to optimal in the proposed method.

The rest of the paper is organized as follows. Section 2 provides an overview of the system model and the background. Local spectrum sensing using fuzzy membership function is presented in Section 3. In Section 4, we derive the final test statistic in the FC using some fuzzy fusion rules. In Section 5, we derive the optimal fusion rule based on the Neyman-Pearson criterion. Simulation results are presented in Section 6. Finally, Section 7 provides conclusions.

Notations: Throughout this paper, we use boldface letters to denote vectors. A Gaussian random variable with mean m and variance σ^2 is represented by $x\sim\mathcal{N}(m, \sigma^2)$. We use $\mathbb{E}[.]$ as the expectation operator, and $\mathbb{P}\{.\}$ for representing the probability of the given event. Moreover, $(.)^T$ stands for the transpose of a matrix or vector and $Q\,(.)$ denotes Q-function which calculates the tail probability of a zero mean unit variance Gaussian variable, i.e. $Q\,(x) = \int_x^\infty 1/\sqrt{2\pi}\exp(-t^2/2)dt$.

2. System model and background

In this work, we consider a homogeneous CR network in the sense that all the SUs use the same protocol for local spectrum sensing. The network consists of M secondary users indexed by $\{i = 1, \ldots, M\}$ that monitor the frequency band of the interest. We use a centralized manner in the cooperative spectrum sensing in which each SU sends its sensing data to a fusion center. The spectrum sensing problem for the ith SU can be represented by a binary hypothesis test as follows

$$\begin{cases} H_0: & y_i(t) = w_i(t), \\ H_1: & y_i(t) = h_i(t)s(t) + w_i(t), \end{cases} \tag{1}$$

where H_1 and H_0 are the hypotheses of the presence and absence of the PU's signal, respectively. $y_i(t)$ and $w_i(t)$ are the received signal and an additive complex white Gaussian noise with covariance σ_i^2 at the ith SU respectively, and $s(t)$ is the transmitted signal from the PU. $h_i(t)$ denotes the coefficient of the channel between the ith SU and the PU, which is assumed to be constant during the detection interval. Moreover, we assume that the sensing channels corresponding to the SUs are independent. We also assume that $s(t)$ and $w_i(t)$ are independent.

The channel coefficient h_i is a constant in the non-fading additive white Gaussian noise (AWGN) channels and a random variable in the fading channels. In the case of Rayleigh fading channel, $\left|h_i\right|$ follows a Rayleigh distribution with probability density function (pdf) as

$$f_{|h_i|}(r) = \frac{2r}{\Omega_i}\exp\left(-\frac{r^2}{\Omega_i}\right) \quad r \geq 0 \tag{2}$$

where $\Omega_i = \mathbb{E}[\left|h_i\right|^2]$ is determined based on the average SNR at the *ith* SU.

Under the assumption of attenuation due to shadowing, the received signal power in dB unit, follows a normal distribution. In this case, the pdf of h_i is given by [21]

$$f_{h_i}(r) = \frac{\varsigma}{\sqrt{2\pi}\sigma_{\nu_i} r}\exp\left[-\frac{\left(20\log_{10}r - m_{\nu_i}\right)^2}{2\sigma_{\nu_i}^2}\right] \tag{3}$$

where $\varsigma = 20/\ln 10 = 8.6859$, and $\sigma_{\nu_i}^2$ and m_{ν_i} are the variance and the mean of $\nu_i \triangleq 20\log_{10}h_i$ respectively which follows the Gaussian distribution. dB-spread as $\sigma_{dB} = 0.1\exp(10\sigma_{\nu_i})$ is usually used to characterize the log-normal shadowing.

The performance of detecting H_1 against H_0 is typically characterized by the ROC curves that capture the relations of the probability of detection and the probability of false alarm. In CR networks, the probability of detection measures how well the SUs can detect the presence of the PU. Therefore, a larger detection probability indicates a less interference between the PU and the SUs. The probability of false alarm indicates the chances on which the detector recognizes the presence of the PU when none is actually present; thus smaller false alarm probability indicates higher spectrum efficiency.

3. Local spectrum sensing using fuzzy membership function

In this section, we form a fuzzy membership function for local spectrum sensing. As will be seen, using fuzzy membership function, the SUs can transmit their quantized test statistics to the FC with better quality considering the limitation in bandwidth. Moreover, using the fuzzy membership function in the SUs, we can employ well-known fuzzy fusion rules for efficiently combining the received test statistics of SUs in the FC.

In particular, we start with energy detection (i.e., radiometry) as the first step to establish the membership function, which will be explained as follows.