Spectrum Sensing using Frequency domain Entropy estimation and its FPGA implementation for Cognitive Radio

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Abstract

Spectrum sensing is an important module in cognitive Radio (CR) technology. This paper presents a spectrum sensing technique based on entropy estimation of the received signal in frequency domain. This approach is extended for cooperative sensing using different fusion rules. Performance of the algorithm is analyzed using Monte-Carlo methods. The performance of proposed entropy based detection is compared with energy based detection technique. Simulation results reveal that, entropy based detection algorithm can detect signals of signal-to-noise ratio upto -24dB using five nodes for detection probability \( P_d \geq 0.9 \) and false alarm probability \( P_f \leq 0.1 \). Sensing algorithm of single node is successfully implemented in Virtex4 FPGA.

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Keywords : Cognitive Radio Networks; Cooperative spectrum sensing; Entropy detection; Energy detection; Signal to noise ratio; Field Programmable Gate Array (FPGA).

1. Introduction

The Radio spectrum is an indispensable natural resource for evolution of future generation wireless systems. However, due to rigid licensing policies, radio spectrum has become scarce. On the other hand, the recent statistical studies on radio spectrum usage have shown that the pre-allocation of spectrum bands to specific wireless communication applications lead to poor utilization of spectrum in terms of frequency, time and geographical space [1]. Cognitive radio (CR) has emerged as a promising technology to resolve the impending spectral scarcity and under utilization of allocated spectrum [2].

Spectrum sensing is the essential component in the CR functions. The primary objective of spectrum sensing is to provide more spectrum access opportunities to secondary users (SU) without interference to the Primary user (PU) or licensed network users. Several signal processing techniques are being used for spectrum sensing [3]. Popular methods among them are based on Matched filtering, Energy detection, and Cyclostationary feature detection. But the detectors based on matched filtering approach needs knowledge of signals a priori. In case of energy detection, performance of the algorithm is often reduced at low Signal to Noise Ratio (SNR). In case of Cyclostationary detection, the observation time required for sensing is more and thus reduces the transmission opportunities to the CR users. In general entropy of the received signal reduces if the received signal is a modulated signal [5]. In this paper,

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we have used this concept for signal detection in noisy and fading environment, where the characteristics of the
noise and signal are unknown.

The performance of the detection process is evaluated using two main parameters: probability of detection \( (P_d) \)
and probability of false alarm \( (P_f) \). In practice, performance of single CR is often compromised with multi-path
fading and shadowing in the channel. To mitigate the impact of these issues, cooperative sensing has been shown to
be an effective method to enhance the detection performance by exploiting spatial diversity [7]. Cooperative
detection is being classified into centralized, distributed, and relay assisted methods [6]. Since entropy of the time
domain signal remains constant at low SNR, entropy based techniques in time domain cannot detect the signal
reliably and accurately [4]. To overcome this problem, in this work, entropy estimation is carried out in frequency
domain for local sensing and extended for centralized cooperative spectrum sensing. Finally, the performance of
the algorithm based on entropy detection is compared with energy detection technique. Digital Video Boardcasting-
Terristrial (DVB-T) and Quadrature phase shift keying (QPSK) signals with additive white Gaussian noise (AWGN),
Rayleigh fading and shadowing are considered as licensed or primary user (PU) signals. We also implemented the
proposed algorithm based on entropy estimation in a Xilinx Virtex-4 (XC4VSX35-FFG668-10) Field Programmable
Gate Array (FPGA) for signal detection.

The main contributions of this work are (i) spectrum sensing is carried out based on entropy of the received signal
in frequency domain, (ii) this is extended for cooperative detection with different types of fusion rule, (iii) the performance of entropy based detection is compared with energy detection technique, and (iv) FPGA
implementation of entropy based detection algorithm for single node detection.

The rest of the paper is organized as follows. Section 2 presents both single node and cooperative
sensing algorithm. Section 3 describes the simulation results. Section 4 presents implementation details of sensing
algorithm in FPGA followed by conclusions in section 5.

2. Spectrum Sensing Algorithm

2.1. Single node Sensing Algorithm

The fundamental problem of spectrum sensing in CR is to discriminate between the following two hypotheses \(H_0\) (signal is absent in the channel) and \(H_1\) (signal is present in the channel).

\[
H_0 : r(n) = w(n), \\
H_1 : r(n) = hs(n) + w(n), n = 0,1,..............N-1.
\]  

Where \(r(n)=[r(0), r(1), ..........., (N-1)]\) is the received signal sequence of CR user, \(N\) is the sample size, \(s(n)\) is
PU’s transmitted signal, \(w(n)\) is the AWGN in the channel, and ‘\(h\)’ is the channel gain.

2.1.1. Entropy Based Detection:

Entropy of the received signal is estimated in frequency domain using histogram method [4]. The
histogram of the received sequence is obtained by dividing the range of values into \(L\) (a design parameter) no. of
bins, with bin size as, \((R_{\text{max}} - R_{\text{min}})/L\). \(R_{\text{max}}\) and \(R_{\text{min}}\) denote the maximum and minimum value of \(R(k)\), and \(R(k)\) is
the squared magnitude of Fast Fourier Transform (FFT) coefficients of received signal \(r[n]\). Let \(f_i\) denote the
number of samples in \(i^{th}\) bin with \(\sum_{i=1}^{L} f_i = N\). Then the probability of samples accumulated in \(i^{th}\) bin is \(p_i = f_i/N\).

The estimated entropy for the received signal can be expressed as [5],

\[
\phi(r) = - \sum_{i=1}^{L} \frac{f_i}{N} \log_{b} \frac{f_i}{N}.
\]  

2.1.2. Cooperative Sensing Algorithm

The cooperative sensing algorithm is based on the idea of cooperative detection with different types of fusion
rule. The cooperative detection process is divided into three stages: local sensing, fusion rule, and decision
making. In the first stage, each CR user senses the channel independently and estimates the entropy of the received
signal. In the second stage, the entropy estimates are combined using different fusion rules. In the third stage,
the centralized decision is made based on the fusion results.
Based on estimated entropy of received signal and threshold ($\lambda_\phi$) value, the detector uses the following decision rule,

$$\phi(r) \leq \lambda_\phi, \text{Decides} H_1$$
$$\phi(r) < \lambda_\phi, \text{Decides} H_0$$

The threshold can be expressed as [5]

$$\lambda_\phi = H_L + Q^{-1}(1 - P_f)\sigma_w$$  \hspace{1cm} (3)

Where $H_L$ is the theoretically estimated Gaussian noise entropy, $\sigma_w$ the noise variance, and $Q(.)$ is the complementary distribution function of the standardized Gaussian, evaluated at $(1 - P_f)$. In this work, both detection technique performances are analyzed using Monte-Carlo methods.

2.1.2. Energy Based Detection:

In general, Neyman-Pearson (NP) criterion is being used in Energy detection technique. The optimal NP test is to compare the log-likelihood ratio with a predetermined threshold ($\lambda_e$) as [6],

$$\log \left( \frac{P(r_0, r_1, \ldots, r_{N-1}) | H_1}{P(r_0, r_1, \ldots, r_{N-1}) | H_0} \right) \overset{H_1}{\gtrsim} \lambda_e$$  \hspace{1cm} (4)

Where $P(r | H_1)$, $P(r | H_0)$ are the probability density functions of $H_1$ and $H_0$ respectively. Obviously, the log-likelihood ratio depends on the distribution of the signal to be detected. In this detection scheme, noise is assumed to be independent and identically distributed (iid) with zero-mean and circularly symmetric complex Gaussian with variance equal to one. Under such conditions, the test statistic can be approximated as [6],

$$\left\| r \right\|^2 \overset{n_{H_1}}{\gtrsim} \sum_{n=0}^{N-1} |r[n]|^2 \overset{n_{H_0}}{\lesssim} \lambda_e$$ \hspace{1cm} (5)

where $\left\| r \right\|^2$ is the norm of the received signal sequence, threshold ($\lambda_e$) depends upon $P_f$ [7].

2.2. Cooperative Sensing Algorithm:

Single node sensing performance is unreliable and increases the misdetection probability due to non line of sight (NLOS) communication, receiver uncertainty, and hidden terminal issues in the medium. To mitigate the impact of these issues, multinode or cooperative sensing is being used [7]. Fig. 1 represents an overview of centralized cooperative sensing model. In this model, Fusion center (FC) makes the global decision by aggregating the received local sensing information and informs the global decision to all cooperating CR users.

![Figure 1: Cooperative spectrum sensing model](image_url)
Assuming that there are $M$ cooperating nodes and the received signals of all nodes are independent. For each node the channel coefficient $h_m$ is of nonzero mean, and unit variance complex Gaussian random variables, then the hypothesis test (1) becomes,

$$H_0 : r_m(n) = w_m(n), m = 0,1,...M-1$$

$$H_1 : r_m(n) = h_m s_m(n) + w_m(n), n = 0,1,...N-1$$

(6)

Cooperative sensing can be classified based on soft and hard decision fusion techniques.

2.2.1. Soft decision fusion:

Most commonly used soft decision techniques are usually weighted gain combining (WGC) or equal gain combining (EGC). Due to shadowing, fading, and receiver uncertainty some nodes have a better location dependent SNR than other nodes. Therefore, the FC will give different weights to different nodes based on SNR. The FC generates a global decision based on threshold test. In the case of energy detection, the cumulative detection probability for WGC as [7],

$$C_G = \sum_{m=0}^{M} y_m w_m > \lambda_e$$

Where $y_m$ and $w_m$ is the energy measurement and weight of $m^{th}$ node. In case of entropy based detection, the cumulative detection probability for WGC can be expressed as

$$\varphi_G = \sum_{m=0}^{M} \varphi_m w_m < \lambda_\varphi$$

(7)

(8)

2.2.2. Hard decision fusion:

Commonly used hard decision techniques in cooperative detection are OR and AND fusion logics. In case of OR logic, the FC decides $H_1$ if any one of the nodes in the cooperative network reports about presence of signal. The sum of the binary bits is at least equal to one. i.e.,

$$\sum_{m=0}^{M-1} [y_m] \geq 1$$

The detection probability of OR fusion is

$$C_{d=OR} = 1 - \prod_{m=1}^{M} (1 - P_{d,m})$$

(9)

Where $P_{d,m}$ is the detection probability of the $m^{th}$ CR user (or $m^{th}$ node). In case of AND logic, the FC decides $H_1$ if and only if all the nodes in the cooperation have decided $H_1$. The sum of the binary bits is equal to number of nodes in the cooperation. i.e.,

$$\sum_{m=0}^{M} [y_m] = M$$

The detection probability of AND fusion is

$$C_{d=AND} = \prod_{m=1}^{M} P_{d,m}$$

(10)

3. Simulation results

In order to evaluate the performance of proposed spectrum sensing algorithm, both DVB-T and QPSK signals are considered under AWGN and Rayleigh fading channel environment with desired $P_d$ and $P_f$. The simulation parameters are listed in Table. 1. The entropy detector estimates the entropy of the received signal within the desired frequency band and compares it with a suitable threshold as per eqn (2) and (3). In the case of energy detection, the energy of the received signal is computed in the observed time period and compared it with a pre-computed threshold [7]. Since the non existence of closed form solution for $P_d$ and $P_f$, the performance of the
algorithm is analyzed using Monte Carlo method. The consequences of shadowing and channel fading are also considered in our simulation. Fusion logics such as AND, OR rules for hard decision and WGC, EGC for soft decision are considered for simulation. Different number of CR nodes (varies from 3 to 7) are used in the simulation for cooperative sensing and for each node the SNRs are varied from -30 dB to -10dB.

Table 1: Specifications for simulation

| PU signal       | DVB-T, QPSK          |
|-----------------|----------------------|
| Channel Bandwidth (W), Observed time | 6MHz, 5.4 μsec |
| Channel type    | AWGN, Rayleigh fading |
| $P_f, P_d$ values (desired) | 0.1, 0.9 |

Fig. 2 represents single node detection complementary ROC curves for energy and entropy detection using DVB-T signal with sample size of 64 and 256, no of bins ($L$) as 15. It is observed that the entropy detection technique has less misdetection probability compared to energy detection with fourfold increase in sample size. But, at higher probability of false alarm (from $P_f = 0.5$ to 0.8) the energy detection shows better performance. In general, the detection probability increases as the sample size increases. But, as the sample size increases, the transmission opportunities of CR users reduces [9]. Thus, entropy detection has an advantage of improving performance at lower...
using the entropy detection technique is able to detect the signal with 10 dB more noise level. From this table, it is observed that at required $P_d$ and $P_f$ ($P_f \leq 0.1$ and $P_d \geq 0.9$), the proposed algorithm is able to detect noisy DVB-T signals with SNR upto -18 dB. Whereas, in the case of QPSK signal, the algorithm is able to detect noisy signals with SNR upto -12 dB.

Table 2: The least $SNR$ achieved with required $P_d$ for different $P_f$ using single node ($M=1$)

| Signal type, Sample length (N) | $P_f=0.1$ | $P_f=0.01$ |
|-------------------------------|-----------|------------|
| DVB-T, $N=64$                 | -18dB     | -16dB      |
| QPSK, $N=64$                  | -12dB     | -9dB       |

Table 3: The least $SNR$ achieved with required $P_d$ and $P_f$ using different no. of nodes ($M$) (EGC fusion)

| Detection method, $P_f=0.9$, $P_f=0.1$ | $M=3$ | $M=5$ | $M=7$ |
|----------------------------------------|-------|-------|-------|
| Energy detection                       | -12dB | -14dB | -16dB |
| Entropy detection                      | -22dB | -24dB | -26dB |

4. Hardware Implementation

The spectrum sensing algorithm based on entropy estimation for single node detection is implemented in Xilinx Virtex-4 (XC4VSX35-FFG668-10) FPGA. The hardware in loop (HIL) simulation is carried out for verification of the algorithm in FPGA. Fig. 6 represents the spectrum sensing architecture along with HIL simulation based on entropy of the received signal. The architecture consists of an FFT square unit, Histogram unit, Entropy estimator, Threshold unit, and a Decision unit. DVB-T signals of different SNR under AWGN and Rayleigh fading environment are generated in MATLAB and are considered for evaluation. The FFT square unit will transform the signal into frequency domain. The square magnitudes of the FFT are fed into the histogram unit which calculates the frequency of each bin. Fig. 7 describes the architecture of entropy estimator using system generator for DSP tool, which calculates the entropy as per eqn. (2) by considering the frequency of each bin. Threshold is calculated as per eqn. (6). Based on the entropy and threshold value, decision unit decides either $H_1$ or $H_0$. The decision ‘1’ and ‘0’ represents signal presence ($H_1$) and signal absence ($H_0$) respectively in the desired frequency band.

Hardware and software co-simulation results are matched with MATLAB simulation results for DVB-T signals with different SNR at desired performance level. Hardware resources required for implementing the entropy detector using sample size of 64 and binwidth ($L$) = 15 are estimated to be of 1512 slices, 1366 flip flops, 3 BRAM, 1870 LUTs, 68 IOB’s, and 12 Embedded multipliers. The maximum frequency of operation for the detector is...
126.236MHz with sample size of 64. Moreover, it is observed that as the number of bins ($L$) increases the resource requirement for detector increases.

Figure 6. FPGA implementation of Entropy detector

Figure 7. System Generator architecture of Entropy estimator

5. Conclusions

In this paper, we have proposed a detection algorithm based on entropy estimation in frequency domain. The performance of this approach is evaluated and compared with energy detection techniques at detection probability ($P_d$) = 0.9 and false alarm probability ($P_f$) = 0.1. The comparison was carried out both for single node detection and cooperative detection. Simulation results show that entropy estimation technique can detect the noisy DVB-T signal of SNR up to -18dB at required $P_d$ and $P_f$ ($P_f \leq 0.1$ and $P_d \geq 0.9$) with single node of sample size 64. Using cooperative sensing method with (5 node in cooperation) entropy detection technique can detect the noisy DVB-T signal of SNR up to -24dB at required $P_d$ and $P_f$ whereas energy detection detects only up to -14dB. Proposed algorithm for single node detection is also implemented in Xilinx virtex-4 FPGA successfully. The implementation of optimum cooperative sensing based on entropy detection is under development to enhance the system performance.

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