Efficient Two Stage Spectrum Sensing for Cognitive Radios

Fidel Wasonga[1] and Thomas O Olwal[1]
[1]*Department of Electrical Engineering*
Tshwane University of Technology
Pretoria, South Africa
fiwaso23@gmail.com and OlwalTO@tut.ac.za

Adnan M. Abu-Mahfouz[1,2]
[2]*Meraka Institute*
Council for Scientific and Industrial Research
Pretoria, South Africa
A.AbuMahfouz@ieee.org

Abstract **-** The growth of wireless communication in recent years has resulted to spectrum scarcity and increase in the number mobile users. However, the major concern in wireless communication is spectrum scarcity on fixed spectrum. Technologies such as cognitive radios (CR) have emerged to address the issue of spectrum scarcity in wireless communication. The principle which CR is using to address spectrum scarcity is by utilizing opportunistic spectrum access method. In this method CR allows the secondary users (SU) to opportunistically utilize spectrum by sensing the absence or presence of the primary users (PU) on the spectrum that it will assign to the SU. Thus, before CR allows the SU to utilize the spectrum it must first carry out the process of spectrum sensing (SS). This process of SS can either be done by exerting single stage or two stage SS techniques. Nevertheless, this process is not an easy task, due to several factors such as noise, co-channel interferences and attenuation which have a negative effect on the accuracy, reliability and efficiency of CR. Thus, in this work literature review on single stage and two stage (dual stage) SS techniques was carried out to determine how the efficiency, accuracy and sensing time on SS can be improved.

Index Terms **-** spectrum sensing, cognitive radio, spectrum holes, secondary user, primary user, single stage

I. INTRODUCTION

Wireless communication users and devices have drastically increased in the past years, due to the demand for more applications and faster data rates. Hence, wireless communication spectrum has become scarce. Furthermore spectrum scarcity has drastically been increased, by fix spectrum assignment by communication authority such as Independent Communication Authority of South Africa (ICASA) [1]. To combat the challenge of spectrum scarcity and underutilization a creative technique was developed.

The technique that was developed to address the issue of spectrum scarcity was CR. This technique provided a contemporary solution for exploiting available spectrum [2]. In this technique, SU are able to ingress on PU spectrum if the PU is not utilizing the spectrum [3]. Nonetheless, CR must firstly perform the process of SS in order to prevent interferences or collision between PU and SU.

Consequently SS is the most significant process in the design of CR. To sense spectrum in CRs, there are three rudimental techniques namely; energy detection (ED), match filter detection (MFD), and cyclostationary feature detection (CFD) which are all also considered as single stage techniques [4][3].

Among the above mentioned single stage methods, ED is considered to be uncomplicated, having low sensing time and a reasonable SS technique [4]. In ED SS technique, the desired frequency band is searched and tests are carried out to contrast the energy measured with a set fixed ED threshold to determine the absence or presence of PUs[5]. However, ED technique operation is not sturdy to noise and low SNR conditions thus affecting the reliability and performance of CR[6]. Furthermore ED SS technique cannot distinguish noise from other signals.

To overcome the challenges of single stage ED technique MFD technique was developed. In this technique unknown signal is corresponded to the known signal [6][7]. However, this single stage SS technique needs dedicated receivers for each PUs signal which results into system complexity [8].

Another single stage SS technique was developed by the name of CFD. In this technique, the properties of wireless communication signals are utilized in this SS technique to perform sensing. The properties of wireless communication signals that are exerted in this technique are such as; sequences, repeating codes, hopping sequences, cyclic prefixes, and pulse trains [9]. This is due to these properties exhibiting periodicity or cyclostationary characteristics based on the mean and autocorrelation function. Therefore this periodicity characteristic is used for signal recognition and detection. This technique is better compared to ED and MFD due to the following characteristics; ability to differentiate noise from PUs signal, ability to differentiate different types of signals and operates well in low SNR state [10] [8] [9]. Nonetheless this single stage SS technique has high computational complexity and an elevated sensing time compared to single stage ED SS technique [10].

Therefore, due to the downside of a single stage SS technique, a two stage SS technique was considered to obtain the trade-offs of merits and demerits between single stage SS technique [11]. This technique simply involved the collaboration of single stage spectrum sensing techniques, for instance ED and CFD.

Nonetheless there are numerous convectional two stage SS collaboration techniques which will be discussed further in the section III. According to literature based on two stage SS sensing technique, the technique offers the following benefits compared to its single stage counterpart; maximization of probability of detection, less detection times and promising performance in low SNR conditions [10] [12][13]. With this merits of two stage SS techniques, the SS performance of CR can likely be improved drastically.

Innumerable aspects regarding different single and two stage SS techniques are illustrated in Table.1 and Table.2. The aim of this paper is to determine a suitable combination of two stage SS techniques to provide minimum sensing duration, sensing accuracy and better performance under low noise conditions. We begin by introducing single stage SS techniques in Section II, followed by Table.1 illustrating the merits and demerits of single stage SS techniques. Section III illustrates previously proposed two stage SS combination, followed by Table.2, indicating the challenges of each two stage combination. Lastly section IV provides a comparison and discussion that indicates the possible suitable combination of two stage SS.

II. SINGLE STAGE SPECTRUM SENSING TECHNIQUES FOR COGNITIVE RADIOS

In this section, we briefly introduce single stage SS techniques such as ED, MFD, and CFD.

A. Energy detection

An ED SS technique is considered to be the most basic technique due to its simplicity. CR contains ED SS sensor nodes that can act together with the surrounding environment to acquire critical radio details such as; existing PU and unoccupied/underutilized spectrum. To determine the presence or absence of PU this traditional testing hypothesis is applied [14][15];

$$\mathrm{y(t)} = x(\mathrm{t}) + h * z(t) \qquad \mathrm{N}_1 : \text{If PU is present} \qquad (1)$$

$$\mathrm{y(t)} = x(\mathrm{t}) \qquad \mathrm{N}_0 : \text{If PU is absent} \qquad (2)$$

where N_0 is the absence of PUs and N_1 the presence of PUs in the band, $\mathrm{y(t)}$ indicates the received signal, h and $z(t)$ are the gain of the channel and the PUs signal respectively which is suspected be a random Gaussian process with variance σ_z^2, $x(\mathrm{t})$ is the assumed accompaniment white Gaussian noise (AWGN) with zero-mean and variance σ_n^2 [13].

The energy of the received signal is represented with (3);

$$\mathrm{T} = \frac{1}{N} \sum_{t=1}^{N} y^2(\mathrm{t}) \qquad (3)$$

Where, N is the regarded number of samples.

Cognitive radio ED model can be further expressed using the following binary hypothesis;

$$\mathrm{d}_{ED} = \left\{ \begin{array}{l} +1 \text{ if } \mathrm{N}_1 \text{ is declared } (\mathrm{T} \geq \lambda) \\ \hline -1 \text{ if } \mathrm{N}_0 \text{ is declared } (\mathrm{T} \leq \lambda) \end{array} \right\} \qquad (4)$$

In equation 4, when the threshold is greater than T indicates the possible absence of PU and where T is greater than the threshold shows the possibility of presence of PU.

To measure the efficiency of ED SS technique two types of probabilities are used; probability of detection (P_d) and probability of false detection (P_f) [16]. In equation (5), (P_f) represents the chances that the CR indicates that the PUs exist in the band when the PU are not actually occupying the band and P_d is the probability that CR correctly identifies the existence of PUs. These measures can be calculated using the following equations;

$$\mathrm{P}_f = P\left(T \geq \frac{\lambda}{N_0}\right) = \frac{\Gamma\left(u, \frac{\lambda}{2}\right)}{\Gamma(u)} = Q\left(\frac{\lambda - \sigma_n^2}{\sqrt{2L\sigma_n^4}}\right) \qquad (5)$$

$$\mathrm{P}_d = P\left(T \geq \frac{\lambda}{N_1}\right) = Q_u\left(\sqrt{2SNR}, \sqrt{\lambda}\right) = Q\left(\frac{\lambda - \sigma_t^2}{\sqrt{2L\sigma_t^2}}\right) \qquad (6)$$

Where Γ is the incomplete gamma function, Q_u is the Marcum Q-function, λ stands for decision threshold and u time-bandwidth product [17][18]. Thus, a CR using ED SS technique can be concluded to be efficient when a high P_d is measured and a low P_f is measured. The design of ED SS can be represented by Fig 1.

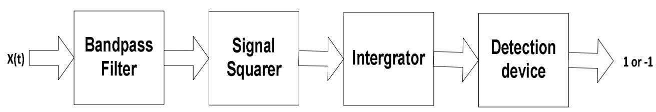

Figure 1 Energy Detection block diagram

B. Match filter detection technique

Match filter detection method is a well-known SS technique. In this technique prior knowledge of the PUs signal characteristic is needed. The characteristics of the PU signal that are applied for matching are; order, modulation type, packet format and pulse shape [19]. Thus, to determine if the PU is occupying the spectrum correlation is done between the known signal and unknown signal [19]. Similar to ED, MFD SS technique has two coherent hypotheses;

$$y(t) = \begin{Bmatrix} \sqrt{\varepsilon X_p(t)} + \sqrt{1-\varepsilon x(t)} + w(t) & : \text{if PU is present} \\ w(t) & : \text{if PU is absent} \end{Bmatrix} \quad (7)$$

Where $X_p(t)$ represents the known PU signal, ε is the fraction of energy that is added to the PU signal, and $x(t)$ the incoming PU signal. MFD can further be represented with Fig 2.

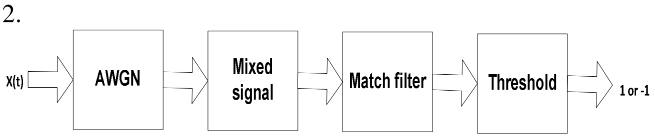

Figure 2 Match Filter Detection block diagram

C. Cyclostationary feature detection technique

CFD SS technique is a well robust technique that is capable of overcoming noise uncertainty and low SNR conditions unlike ED. In this technique the PU signal is determined by determining the features present on the PU such as periodicity [20]. By observing the varying mean and autocorrelation of the PU signal the presence of the PU can be determined, if there is no variation then it is determined that the signal is noise. This can be represented by the following equation also known as cyclic autocorrelation function (CAF) of the received PU signal where;

$$R_y^{\alpha} = E\left[Y(t+\tau)Y^*(t-\tau)e^{j2\pi\alpha t}\right] \quad (8)$$

E is the expectation operation,* the complex conjunction, and α cyclic frequency [20].
The process of CFD technique can be illustrated by the Fig.3;

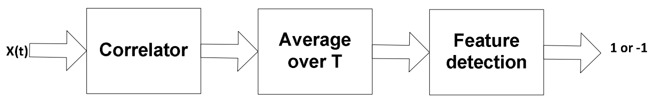

Figure 3 Cyclostationary Feature Detection block diagram

The Table 1 shows a summary of merits and demerits of the above discussed single stage SS techniques.

Table 1 Merits and demerits of single stage spectrum sensing techniques

Single stage SS techniques	**Merits and Demerits of single stage SS techniques**	
	Merits	***Demerits***
Energy Detection	• Simple to implement • Requires no prior knowledge of PU signal • Very less sensing time	• Poor performance under low SNR conditions • Difficulty in selecting appropriate threshold • Difficulty in distinguishing noise and PU • Very low sensing accuracy
Match Filter Detection	• Robust under low SNR conditions • Low sensing time	• Requires prior knowledge of PU • High computational complexity • Requires large number of receivers
Cyclostationary Feature Detection	• Robust under low SNR conditions • Able to distinguish noise and PU • High sensing accuracy • Can differentiate different type of signals	• Large sensing times • High computational complexity

III. TWO STAGE SPECTRUM SENSING

In this section, we will study previously proposed two stage SS techniques.

A. Combined ED and CFD SS techniques

Recently various SS methods combing ED and CFD techniques have been proposed in [3][6][9][13][18].

In[4], combination of ED and CFD or MFD technique was proposed. For the coarse sensing stage and fine sensing stage ED and CFD SS techniques was exerted respectively. CFD SS technique would only be activated in [3], if the threshold falls in between the threshold limits similar to [13][18]. The proposed combined ED and CFD SS technique in [13][18] contained bi-threshold, but however in [2] it contained an additional MFD SS technique. To perform SS in [3], the band and power of the PU would be examined notwithstanding of prior knowledge or NO prior knowledge of PU waveform. If in the analysis, the PU waveform is known, MFD SS technique would be activated and if otherwise combined ED and CFD would be activated.

Sequential Unconstrained Minimization Technique for threshold optimization (SUMT) was proposed in [13] for threshold optimization which was is in contrast with [18], where CFD was exerted to iteratively estimate the noise level that would assist in fixing ED threshold to provide better SS performance under low SNR conditions.

B.FFT two-stage SS technique

Fast Fourier Transform based ED was proposed in [9], whereby in the coarse sensing stage FFT-ED based on flat-top window was applied followed with a FFT-ED that contains a window that is able to minimize the extension of the processed spectrum, allowing focusing to be done on the processed spectrum. The aim of a flat top window was to expand the spectrum, after which CR node could easily detect the PU signal by power values obtained from FFT point by FFT-ED. To accurately determine the presence or absence of PU, raised –cosine window was applied to perform in-depth sensing and to suppress the extension of the spectrum after which CR node can make a decision

C. Fuzzy logic based two stage SS technique

A fuzzy logic based two stage SS technique was proposed in [17]. The proposed technique is similar to SS techniques applying ED in the first stage containing bi-threshold. However, in the fine sensing stage a fuzzy logic scheme is applied. Fuzzy logic is only activated when ED SS technique is uncertain or inaccurate. A similar approach applying fuzzy logic was proposed in. However, in [21] two different parameters was exerted for decision making, that is energy and power spectral density [PSD].

D. Maximum –minimum Eigen value [MME] and covariance [CAV] two stage SS technique

MME and CAV based SS technique was proposed in [22]. The proposed technique exerts the advantages of ED, MME and CAV SS techniques to accurately determine the presences or absence of PU. Due to the simplicity of ED, SS is done within a short period during high signal to noise [SNR]. MME and CAV are applied in the fine sensing stage to overcome the shortfalls of ED during noise power uncertainty [18]. However, this technique tends to have a longer SS time. A similar approach was done in [21]. The technique applied in [21] was a combined MME for the fine sensing stage. For the coarse sensing stage ED was applied, and in this stage comparison was done between the measured energy (E) with the threshold. If the E was greater than the threshold the channel would be declared occupied if otherwise the second stage would be activated. Also in this stage, comparison would also be made between the threshold and the test statistics.

E. Waveform [WD] and ED two stage using Realtek Software defined Radio [RTL – SDR

A WD and ED SS technique was proposed in [23], in the proposed method SS was done based on the availability of PU signal pattern. The fine sensing stage was only activated if the PUs signal was known, hence minimizing the sensing time in contrast to other two stage SS techniques [19]. To capture the PU signal Realtek (RTL2832U) SDR was applied to determine the availability of underutilized spectrum. RTL-SRD was applied instead of USRP spectrum analysers due to less complexity and cost. Compared to [5][8][11] which incorporate on the coarse sensing stage ED, RTL-SRD technique utilizes WD. In this stage WD performs test statistics and comparison with the threshold to determine the presence or absence of PU. If the test statistics is significant than the threshold then it is declared the PU is present, if otherwise ED is activated to determine if it is noise since the signal is unknown.

F. Pipelining two stage spectrum sensing technique

A pipelining based two stage spectrum sensing technique was proposed in [24]. The aim of the proposed technique was to provide low spectrum sensing time. To achieve that, the entire spectrum bandwidth was divided into equally sized partitions called coarse sensing blocks (CSB). The process of determining the presence or absence of PU, the energy of each block was compared with a pre-set threshold. If the energy is greater than the pre-set threshold, the two stage detector would declare that the channel is occupied if otherwise it would be declared that the channel is idle. Moreover, the idle channel would be further examined and allocated to the SU if it is determined that is unoccupied. Nonetheless the band is further divided into sub – bands called fine sensing blocks (FSB). While finessing process is performed, coarse sensing process is also carried out simultaneously hence the name pipelining. However, in [24] the authors have not given any information on which SS techniques are applied on the proposed two stage SS technique.

IV. COMPARISON AND DISCUSSION

In this paper, study was conducted on previously proposed two stage SS methods. Based on the study it was observed that numerous two-stage SS techniques tend to have a relatively high computational complexity, very low, low and medium sensing accuracy, and poor performance under uncertain noise condition. However, it can be concluded that for better sensing times and sensing accuracy ED SS technique must be exerted in the coarse sensing stage followed by a feature detection technique on the fine sensing stage.

This can be examined in table 2 that shows the comparison between previously proposed two stage SS techniques.

Table 2 Comparison of two stage SS techniques

Two stage spectrum sensing Techniques	**Two stage SS techniques features**			
	Sensing time duration	***Sensing accuracy***	***Performance Under Noise***	***Computational complexity***
ED and CFD [3]	low	medium	medium	high
FFT [9]	very high	medium	very poor	very high
Fuzzy logic [17]	very high	low	very poor	very high
MME and CAV [22]	low	very low	good	very high
WD and ED [23]	high	low	good	very high

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