A Low-Cost Modified Energy Detection-Based Spectrum Sensing Algorithm with GNU Radio for Cognitive Radio

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***Abstract*—Spectral efficiency persists as an issue with the increasing demand for interconnectivity and applications involving IoT. In this work, we present a low cost, modified energy detection algorithm to perform spectrum sensing for possible use in space constrained and energy limited applications. Modifications are made to the theoretical energy detection algorithm and then implemented in GNU Radio utilizing a more economical commercial-off-the-shelf SDR. The proposed algorithm eliminates the need for an exclusive FFT block as part of the RX chain in GNU Radio and works without requiring a large sample rate. The spectrum sensing results presented demonstrate and validate energy detection methods using this low-cost, accessible experiment.**

Keywords—GNU Radio, Software Defined Radio, Energy Detection, Spectrum Sensing

I. Introduction

It is a widespread fact that constant limitations for radio spectrum availability stemming from rapidly growing demand of wireless devices and applications makes it more crowded or approaching saturation [1]. Evidence provided by the Federal Communication Commission (FCC) demonstrates shortage of the critical and expensive spectrum resource and it has recommended policy changes to accommodate growing spectrum demands in both the private and public sectors. [1]-[3]. In many cases, the lack of spectrum may not necessarily be due to an unavailability of bandwidth, but because some spectrum resources may be reserved exclusively for restricted use only by licensed users called primary users (PUs)

Recently, methods like cognitive radio schemes aim to increase spectral efficiency by re-allocating the spectral resources of the PU when they are idle [2]. In 2022, with the partial release of 5G networks and current research on 6G networks, potential hazards and new red flags about spectrum use have come to light [4]. This increases the impetus to revisit the study on cognitive radio schemes to effectively utilize the spectrum holes. Current research in this area utilizes challenging detection methods and expensive hardware. This research aims to propose a low-cost spectrum sensing scheme that uses a slightly modified energy detection algorithm.

Despite few limitations, the Energy Detection method is still popular due to its reduced computational complexity, speed of operation and no requirement of knowledge of modulation or error correction scheme used. Successful spectrum sensing using energy detection has been demonstrated in the past [4]-[7]. In [5] two relatively expensive SDRs were used, and a histogram method was proposed to determine the threshold for energy detection. In [6], a low-cost method was used in the analysis, yet the hardware utilized for this study is 400% more expensive than the hardware reported in this manuscript. Our research approach aims to improve the algorithm in [7] by using inexpensive commercial-off-the-shelf (COTS) software defined radios (SDRs) and a modified energy detection algorithm. This algorithm can be used in

The proposed energy detection algorithm removes the need for an in-line exclusive FFT operation in the RX chain and is implemented on a cost effective as well as robust SDR called ADALM Pluto. The proposed algorithm is instead directly applied in real-time to the incoming data. Removal of the exclusive FFT block eliminates the added algorithm step of moving from time-domain into frequency-domain and back. Additionally, this method also uses lower number of samples in its threshold computation thereby having the potential to improve the computational speed and overall system power consumption. This spectrum sensing functionality was achieved with an approximate cost reduction of 75%.

Such a cost-effective spectrum sensing implementation using modified energy detection algorithm can be used in several real world applications like autonomous driving, IoT, etc. Furthermore, it can also help with partial softwarization of autonomous driving systems that utilize wideband chaotic signals as shown in [8] or to support PHY layer algorithms like scheduling signal transmission to multiple users [9].

The rest of the paper is organized as follows. Section II gives background information for spectrum sensing. Section III details the experiment workflow and blocks used for algorithm. Section IV explains the construction of the testbed to perform energy detection-based spectrum sensing. Section V presents the experimental results, and a conclusion is provided in Section VI.

II. Background

A. Overview

Since the initial stages of research on cognitive radio by Joseph Mitola in 1999, the number of wireless devices and applications have exponentially grown [1]. It was predicted that by the year 2020 there would be 12.2 billion devices connected to the internet. [5]. With the advent of IoT, current residential/commercial wireless networks include multiple interconnected devices like television, alarm system, thermostat, remote controllers, garage control units, cell phones, etc. As aforementioned, this generates a continuous demand for resource-effective use of the limited spectrum available. One of the ways to effectively utilize the spectrum is to re-use the idle portion of licensed spectrum purchased by the primary users (PUs) to allocate for spectrum demand by secondary user (SU) applications leading to the concept of cognitive radio.

B. *Spectral Utilization Efficiency*

The use of wireless technology is at an all-time high where everyone uses electronic devices to communicate in countless ways. This increases the demand for allocating and using the radio frequency spectra, thereby adding an overhead on the spectrum availability. To encourage efficient use of spectrum, the concept of cognitive radio (CR) has been introduced. The core of CR utilizes fundamentals like spectrum sensing, spectrum decision, spectrum sharing and spectrum mobility in a radio environment. Resulting algorithms can detect and reallocate a portion of the spectrum called white space which essentially is not currently being used by the PUs and can instead be used for SU applications. When licensed users require the spectrum back, CR can detect their activity through spectrum sensing and return the licensed spectrum back to the PU resulting in spectrum efficiency. The availability of a low-cost and low complexity SDR employing energy detection would be ideal for SUs due to their limited resource constraints.

C. *Cognitive Radio*

Cognitive radio is a hybrid technology involving software defined radio (SDR) as applied to spread spectrum communications. Cognitive radios are highly useful for their flexibility and ability to enhance spectral efficiency. They can rapidly upgrade, change their transmission protocols and schemes, listen to the spectrum as well as quickly adapt to different spectrum policies [6]. The cognitive ability of the CR algorithm is due to its key ability to detect appropriate communication parameters via spectrum sensing and make efficient decision for spectrum use [7]. Detection performance is evaluated through the following metrics: probability of false alarm, which denotes the probability that the CR detects that the spectrum is occupied when it is free, probability of missed detection, which denotes the probability of declaring that the spectrum is free by CR when the spectrum is actually in use by the PU [8].

D. *Energy Detection*

Energy Detection based spectrum sensing tries to detect the presence of energy in a frequency band of interest. This detection is achieved by comparing the output of an energy detector with a threshold value that is dependent upon the noise power in that frequency band [10]. Fig. 1 shows us the energy detection model of a received signal.

Energy detection does not require any a priori information of the received signal and is favored due to its reduced complexity and its ability to be executed in both time and frequency domains [4], [6]. Typically, the decision statistic of an energy detector can be calculated from the squared magnitude of the FFT averaged over N samples of the received SU signal. This process is modeled in Equation 1, where w(n) is additive white noise. The energy of the received signal samples is compared with a fixed threshold to test the presence or absence of PUs. Let Ho be the hypothesis that the PU is absent while let $H1$ be the hypothesis that the PU is present. Using the received signal sample at time 'n', denoted by y(n), this can be mathematically formulated as a binary hypothesis testing shown in equation 2.

$$y(n) = \{w(n) \qquad H_0, PU\ Absent\}$$

$$y(n) = \{w(n) + s(n) \qquad H_1\ , PU\ Present\} \tag{1}$$

$$T(y) = \frac{1}{N}\sum_{n=1}^{N}|y(n)|^2 \tag{2}$$

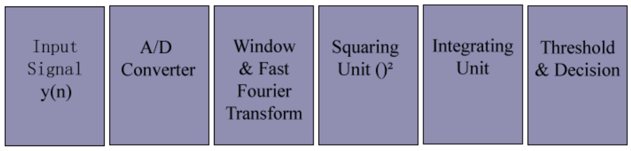

Figure 1. Energy Detection Model of Received Signal

In [10] a review was done on spectrum mobility in CR networks, which is considered another crucial part in the cognitive cycle, and it also discussed various hand off algorithms. Each step of the cognitive cycle is discussed in detail. We focus on spectrum sensing in this research, which is the first step of the cognitive cycle. The method presented here is popular due to its simplicity and has contributed to successful energy detection-based spectrum sensing [4]. In [11] two USRP devices were used, and a histogram method was proposed to determine the threshold for energy detection. This method uses expensive hardware to improve performance of energy detection. In [6], a low-cost method was used in its analysis, yet the hardware utilized for this study is 400% more expensive than the hardware reported in this manuscript. Energy Detection was tested for Real Time Video Transmission in [12] in which a predetermined threshold was calculated and utilized for energy detection with GNU Radio to improve the theoretical energy detection method.

In our research, we calculate the threshold based on real-time noise power and calculations were performed using Radio blocks inside GNU. This research approach aims to improve the algorithm in [13]. In [14], the researchers used USRP B200 to improve the theoretical energy detection method. The retail price for USRP B200 is around $950 whereas our ADALM (Analog Devices Adaptive Learning Module) Pluto SDR used in this research costs about 25% of that. Our implementation in GNU Radio improves previous research by implementing an algorithm that takes real time measurements with a lower sample rate, and hardware, which is a fraction of the cost of existing methods.

III. TEST IMPLEMENTATION

To build a cognitive radio, a combination of software and hardware is used to execute the processes in the cognitive cycle. In this section we describe the software, hardware and algorithm used in our test implementation.

A. *Software: GNU Radio*

GNU radio has been used along with radio frequency hardware to implement cognitive radio test beds as well as without hardware in stand-alone mode for such purposes. We use GNU Radio for our experiment since reconfigurability is a core and desired feature offered by it [7]. Applications written in the GNU radio using the Python scripting language inter-links and provide a communication path between different real-time signal processing blocks implemented via C++ modules [5].

B. Hardware: Software Defined Radio

Out of the several hardware platforms supported by GNU radio, in our research we use the software defined radio (SDR) due to their cognitive ability, ease of upgrade, widespread use as well as reconfiguration features by incorporating various transmission channels [8]. Several SDRs with varying frequency ranges, costs, and characteristics are available in the market. Since, we are proposing a cost-effective approach, in this research, we use a lost cost SDR called the Analog Devices Adaptive Learning Module (ADALM) Pluto SDR. It offers vast frequency range, compatibility with GNU Radio, ability to operate in full duplex mode, and user friendliness.

Fig. 2 shows a block diagram of the test bed used in this research where the energy detection algorithm is implemented via GNU Radio running on a host computer and the SDR acts as a SU but is also connected via the GNU Radio.

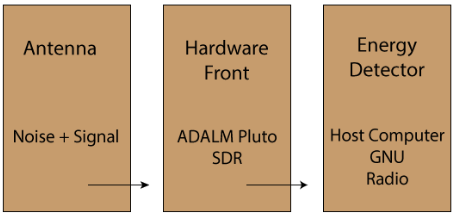

Figure 2. Block Diagram of Test Bed

C. Algorithm Calculations

Calculating the threshold value for energy-based spectrum sensing in the receive flow graph is a mathematically involved task especially with real-time data. It is necessary to execute the theoretical analysis and numerical calculations based on the real-time, practical conditions. Using the definition of signal to noise ratio, SNR,

$$SNR = \frac{\sigma_s^2}{\sigma_w^2} \tag{3}$$

where σ_s^2 is our signal power and σ_w^2 is our noise power, calculating SNR requires computation of σ_s^2 and σ_w^2. Using our test hypothesis from Equation 1, the energy detection algorithm is a semi-sightless detection under the assumption of no deterministic knowledge about the signal. Let us assume that we only know the average power of the signal, then the Decision model, D(y), can be written as follows:

$$D(y) = \begin{cases} \frac{1}{N}\sum_{n=0}^{n-1} y(n)s(n) > \gamma & under\ H_1 \\ \frac{1}{N}\sum_{n=0}^{n-1} y(n)s(n) < \gamma & under\ H_0 \end{cases} \tag{4}$$

In equation (4), D(y) is the decision variable and γ is our threshold. We must first estimate σ_w^2 using real-time measurements. The measured received noise power under no signal transmission is -115dB, which quantifies as a purely noise environment. This gives $\sigma_w^2 = 0.000036478$.

Next, we set our desired P_{fa} at 0.2. Using the desired number of samples as 5x10^6, we calculate the threshold 'γ' as follows:

$$\gamma = \left(\frac{Q^{-1}(P_{fa})}{\sqrt{N}} + 1\right)\sigma_w^2 \tag{5}$$

Substituting in the values set for P_{fa} and σ_w^2 earlier, we get $\gamma = .0000364$ as the calculated threshold. This threshold 'γ' is set in the energy-based spectrum sensing receive flow-graph to perform signal detection. Now, the probability of detection is calculated as follows:

$$P_d = Q\left(\gamma - \frac{\mu}{\sigma}\right) \tag{6}$$

In equation (7), using our gaussian assumption,

$$\mathcal{N}\left(\left((1 + SNR)\sigma_{w,}^2\right), \frac{(1+2SNR)\sigma_w^4}{N}\right), \tag{7}$$

the mean μ and standard deviation σ can be calculated respectively using

$$\mu = (1 + SNR)\sigma_{w,}^2 \tag{8}$$

and

$$\sigma = \frac{(1+2SNR)\sigma_w^4}{N} \tag{9}$$

Using above calculated values, we get, $\mu = .00005614$ and $\sigma = .0000000235$. This algorithm is a modified version of the Neyman-Pearson detector using real-time measurements for threshold calculation. Using the calculated real-time values we build the energy detector.

IV. CONSTRUCTION OF THE PROPOSED ENERGY DETECTOR

For this energy detection-based spectrum sensing experiment, a robust energy detector is needed. The energy detector is a part of the decision unit for cognitive radio and compares the measured energy with a threshold value to decide whether the channel is occupied by PU [15]. This detector provides a flexibility of an RF transceiver working over a range of frequency bands. The result is, a SDR proficient of supporting a variety of waveforms and modulation schemes, a packet processing engine for protocol and routing functionality, and a general-purpose processor for implementation of spectrum policies and algorithms. Fig. 3 shows the proposed architecture in the form of a simple block diagram. For this experiment, our signal source is a cosine wave generated in GNU Radio and is transmitted from the ADALM Pluto SDR to the receive antenna of the same ADALM Pluto SDR. As the signal is received, we build an energy detector in GNU radio and a decision is made regarding the presence or absence of a primary user (PU).

Our PU is representative of the received signal source and our SU is represented by the ADALM Pluto SDR. An TECHTOO WiFi 2.4GHz 18dBi High Gain Yagi Directional Antenna is used for testing at 2.4GHz and a HYS YAGI Antenna High Gain 9dBi UHF 70cm Base Antenna is used for testing in the 400-470Mhz band.

For this experiment, we developed a system that consists of host computer with GNU Radio Module 3.7.11 and our ADALM Pluto SDR. The host computer is a personal computer running a Linux Operating System, Ubuntu 18.04. The host computer connects to the SDR via a USB 2.0 connection to perform signal processing tasks.

For a theoretical energy detector, the energy threshold for the received signal is observed [16]. However, this system is not adaptive in the sense that it does not modify its system characteristics like ϵge or p based on the degradation of the active radio channel. In a condition of high noise variance as well as decreased SNR, this method is bound to fail [7]. In [17], recent work displays an extensive algorithm and considers the SNR wall. Our proposed algorithm can be seen in Fig. 3.

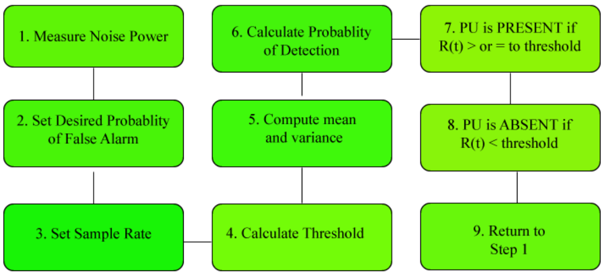

Figure 3. Proposed Algorithm for Energy Detection

V. Experimental Results

The energy detection spectrum sensing in cognitive radio was implemented successfully with GNU Radio signal source as a primary user and ADALM Pluto SDR receiver acting as a secondary user. The detection algorithm was implemented in GNU radio on the receiver side according to the receiver flow graph given in Fig. 6 in Appendix A. The grey GNU radio blocks indicate the path used for threshold calculations. The transmitted frequency is set at 2.4 GHz but it is also adjustable for transmission to a value in the range within the ADALM Pluto SDR. This transmitted signal is received by the receiver, which is tuned to the transmitter frequency, processed using GNU radio and GMSK demodulated.. The code was written in python, where the threshold was calculated and is used in the threshold block of GNU radio receiver side flow graph to decide the detection of the input signal. If the signal is present, energy of the signal becomes higher than the threshold and the detected output becomes one. If the signal transmission stops, then the energy of the signal becomes less than threshold and detected output becomes zero. This shows that the signal is acting as a primary user and the successful operation of the energy-detection based spectrum sensing.

Fast Fourier Transforms (FFT) and scope plots are used to observe the signals at each point. The energy detector was also tested under noise condition with no signal; results show that noise is detected as no signal present by setting the detection output flag to ‘0’. Fig. 4 shows the result of the energy detector when the signal transmission is underway in black. The detector output is one and energy of the received signal was measured at the output when the signal transmission is taking place. Fig. 4 also shows the energy detector under a noise only test in grey. The detector output shows 0, as expected for the case of no PU transmission he received signal is represented with FFT plot in GUI of GNU radio companion. The results of the energy detector were tested and verified by varying the frequencies of transmission.

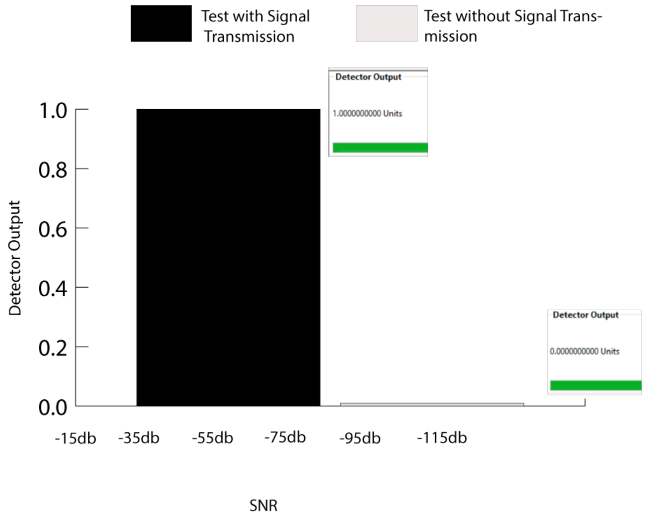

Figure 4. Detector results showing successful energy detection.

To study the receiver operating characteristics (ROC) curve, we analyzed the data obtained from GNU Radio using Matlab and compared it against the theoretical values. It can be seen from Fig. 5 that our data from the energy detection algorithm on GNU Radio is validated via a close match to the algorithm utilizing theoretical energy detection threshold.

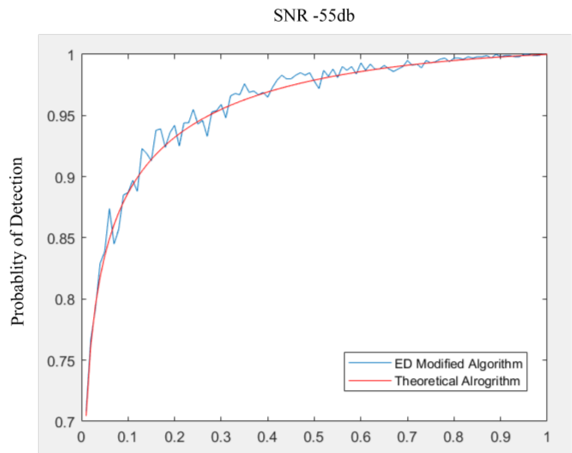

Figure 5. ROC showing probability of detection (Pd) vs probability of false alarm (Pfa).

Our proposed algorithm slightly increases the probability of detection for increasing various values of probability of false alarm at an SNR of -55dB but a much finer resolution of Pfa will give more insight.

VI. Conclusion

In this paper, we propose a cost effective, user friendly and robust energy detector using a GNU radio acting as a primary user and an ADALM Pluto SDR as the secondary user. The threshold was calculated based on real-time data and analyzed in Matlab. Successful energy detection results via a comparison to a threshold are provided. This method was shown to have an improved probability of detection utilizing a lower sample rate, inexpensive hardware and capable of operating over a large range of frequencies.

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Appendix A

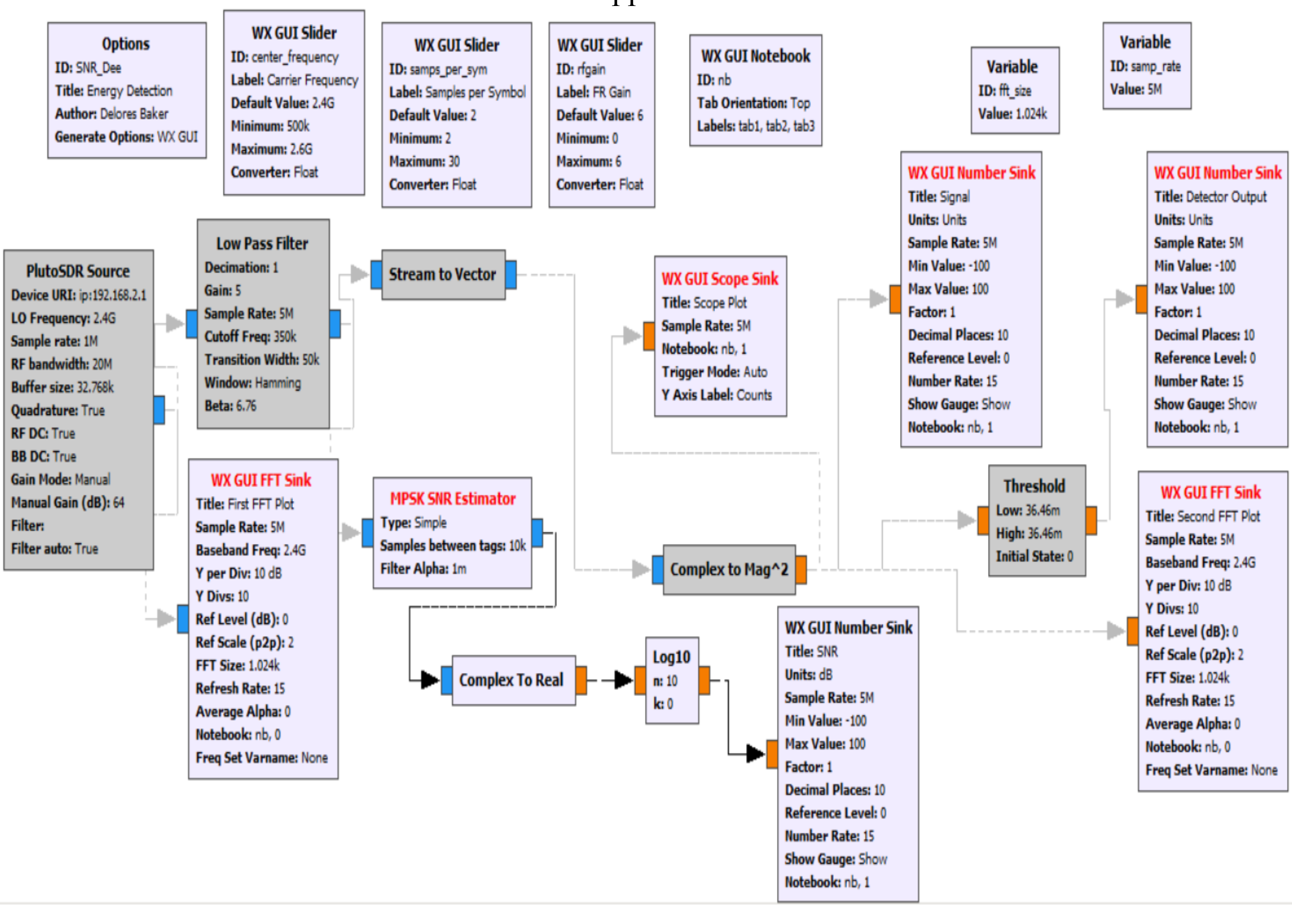

Figure 6. Receiver side Flowgraph for GNU Radio