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Original Research Article

Development of an Energy Detector for Cognitive Spectrum Sensing in Simulink Using a Software Defined Radio

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ABSTRACT

The aim of this work is to develop an energy detector that will function as a spectrum sensing cognitive radio that can be able to sense or detect the presence or absence of a primary user of a particular frequency channel. An Energy detector was modelled in Simulink and interfaced with a software defined radio to perform real time spectrum sensing, signal prediction and spectrum management decision. To detect the presence or absence of a primary user, the Energy detector measures the estimated noise power of a received signal over a specified duration and bandwidth with a sampling rate of 3 MHz and it then performs a threshold estimation of the received signal and then compares the signal level with the ambient noise level in the transmission channel occupied by a primary user. It then generates a 1/0 decision to indicate primary user present or absent in real time. Testing was done in real time so as to demonstrate the efficiency of the energy detector. The energy detector in MATLAB-Simulink interfaced with the software defined radio forms the Spectrum sensing cognitive radio. It was implemented and it performed spectrum sensing in real time and it was used to detect the presence or absence of a primary user in a selected radio frequency channel.

1. INTRODUCTION

Communication governing bodies that regulate the use of the Radio Frequency spectrum such as the Nigeria Communication Commission (NCC) have assigned various bandwidths to various communication infrastructure that make use of the spectrum. The Nigerian Communications Commission is responsible for radio spectrum regulation in Nigeria. The primary tool of spectrum management by the government in all of these countries is a licensing system through bidding. Spectrum are apportioned into blocks for specific uses, and licenses are assigned for these blocks to specific users or companies (Mohammed, 2015). These assigned bandwidths are fixed to the respective infrastructure.

The radio frequency spectrum span between 3 kHz to 300 GHz and as a result of this, there appears to be a problem of spectrum scarcity as new applications and services arise from time to time. Bandwidths need to be assigned to these new applications, however bandwidths of the RF spectrum have already been assigned to other applications. Example of these applications are the TV band, the GSM band, the ISM band and the satellite communication band etc. Regulatory authorities oversee, control and license the broadcasting and communication services that use the RF spectrum. They police the airwaves to ensure there are no illegal signals being transmitted. The competition to transmit in parts of the spectrum used for services like radio, DTV and mobile communications is fierce, and these bodies aim to make sure that only authorized signals are broadcast. However, most of these services do not utilize the spectrum assigned to them all the time, so this have led to the phenomenon of spectrum holes or spaces at certain period whereas new applications are contending for available free spectrum for usage. This one-time allocation of the radio spectrum that gives exclusive right of using the spectrum to only the licensed users has been seen as the major cause of both spectrum underutilization and spectrum artificial scarcity (Haykin, 2005; Akyildiz, et al., 2006). Hence, researchers in communications came up with the technology of cognitive radio.

A cognitive radio is a communication system that can adapt itself to statistical changes in an operating environment in such a way that it is able to change its modulation technique, its transmitter power and carrier frequency, by this it engages both cognitive intelligence/capability and re-configurability. One of its most important capability is that it scans the environment network, and discovers different spectrum holes and makes inferences and adapts to the environment. The software defined radio (SDR) is the platform upon which Cognitive radio is built. A software defined radio is a radio that performs modulation, demodulation and filtering of signals on software regardless of the hardware part. The technology and development of Software Defined Radio was first proposed by (Mitola,1995).

Cognitive radio follows a procedure in its operation known as the cognitive circle. The circle consists of four aspects. They are spectrum sensing, spectrum decision, spectrum sharing and spectrum mobility. Amongst these four steps, spectrum sensing is said to be a very fundamental part to the functionality of the cognitive radio. In spectrum sensing the cognitive radio uses its ability to sense any part of the spectrum within its frequency range of signal detection and then it can know when to use the spectrum for its transmission and reception.

Through the deployment of a cognitive radio, a particular frequency band that is not occupied by its primary user at a particular location and at a particular time can therefore be used as a communication channel for another services pending when that frequency band is again reoccupied by its primary user. The temporary user is termed the secondary user.

In this work an energy detector is developed and implemented in Simulink platform to function as a spectrum sensing cognitive radio that can perform spectrum sensing of any signal between the frequency range of 24 MHz to 1766 MHz that is the frequency range of operation of the RTL-SDR (Realtek software defined radio). The cognitive radio will be able to detect when a primary user is present and then quickly exit the band to avoid interference and it should be able to detect when the primary user is absent in other to utilize the channel for communication as a secondary user.

2. METHODOLOGY

2.1. Definition of Spectrum Sensing Parameters using Energy Detection Techniques

An energy detection approach is a common way of spectrum sensing to decide whether unknown signals exist or not. The receiver (sensing node) does not need any knowledge of the primary users' signal. The energy € of signal x(t) can be measured by applying Rayleigh's energy theorem as follows (Tabassam, et al., 2011):

$$\mathrm{E} = \int_{-\infty}^{\infty} |x(t)|^2 \, d(t) \quad < \infty \tag{1}$$

If the energy of the signal satisfies (2.1) and the Fourier Transform X(f) of x(t) exists. Then,

$$\int_{-\infty}^{\infty} |x(t)|^2 \, d(t) \quad = \quad \int_{-\infty}^{\infty} |x(f)|^2 \, (f) \tag{2}$$

There is preservation of the energy of a signal in both time domain and frequency domain as shown in (2.2) but the frequency domain representation is more flexible. The signal detection & analysis makes no difference in which domain it is measured.

(Wang & Liu, 2011) analysed the following hypothesis model for spectrum sensing,

Assume the hypothesis model for a signal received by an energy detector,

$$\mathrm{H_0 : y(t) = \; n(t)} \tag{3}$$

$$\mathrm{H_2 : y(t) = h.x(t) + \; n(t)} \tag{4}$$

$\mathrm{x}(t)$ is the primary user's signal to be detected at the local receiver of a secondary user, $\mathrm{n(t)}$is the additive white Gaussian noise, and h is the channel gain from the primary user's transmitter to the secondary user's receiver. $\mathrm{H_0}$ is a null hypothesis, meaning there is no primary user present in the band, while $\mathrm{H_1}$ means the primary user's presence. The detection statistics of the energy detector can be defined as the average (or total) energy of N observed samples.

$$\mathrm{T = \frac{1}{N} \sum_{t=1}^{N} \; |y(t)|^2} \tag{5}$$

The decision on whether the spectrum is being occupied by the primary user is made by comparing the detection statistics T with a predetermined threshold. The performance of the detector is characterized by two probabilities: the probability of false alarm $\mathrm{P_F}$ and the probability of detection $\mathrm{P_D}$. $\mathrm{P_F}$ denotes the probability that the hypothesis test decides $\mathrm{H_1}$ while it is actually $\mathrm{H_0}$, i.e.

$$\mathrm{P_F} = P_r(T < \lambda | H_0) \tag{6}$$

While $P_D$denotes the probability that the test correctly decides H_1 ,i.e.,

$$\mathrm{P_D} = P_r(T > \lambda | H_1) \tag{7}$$

A good detector should ensure a high detection probability $\mathrm{P_D}$ and a low false alarm $\mathrm{P_F}$, or it should optimize the spectrum usage efficiency (e.g., QOS of a secondary user network) while guaranteeing a certain level of primary user protection. To this end, various approaches have been proposed to improve the efficiency of energy detector-based spectrum sensing. Figure 1 shows the block diagram describing energy detection in frequency domain.

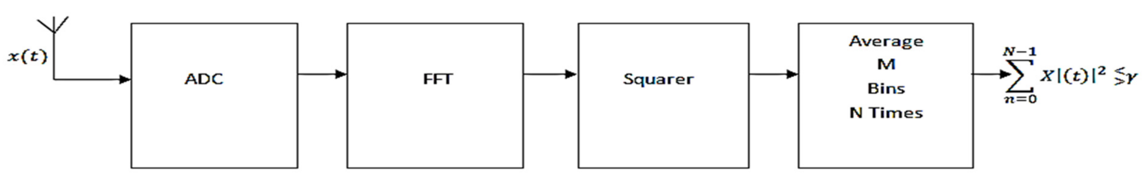

Figure 1: Block diagram of energy detection in frequency domain

Miftahabdullahi, (2015) defined the parameters for spectrum sensing as follows:

H_o: hypothesis that Primary User (PU) is absent and only noise present

H_I: hypothesis that Primary User (PU) is present plus noise present

Y[n]: the received signal

W[n]: the received noise energy

X[n]: received energy of primary user

Pmd: probability of missed detection

Pd: probability of detection

Pfa: probability of false alarm

T: test statistic

$\boldsymbol{\lambda}$: threshold setting

σ_w^2: noise covariance

σ_x^2: signal covariance

From first principles, the spectrum sensing problem can be formulated mathematically as a Binary hypothesis test (BHT) problem with the following two hypotheses:

$$\mathrm{H_o} : \mathrm{y[n] = w[n]} \quad \mathrm{n = 1,2 \ldots \ldots \ldots . . N} \tag{7}$$

$$\mathrm{H_1} : \mathrm{y[n] = x[n] + w[n]} \quad \mathrm{n = 1,2 \ldots \ldots \ldots . . N} \tag{8}$$

Where $\mathrm{H_o}$ is a null hypothesis which states that the received signal y[n] corresponds to noise samples w[n] only; meaning no PU signal in the sensed spectrum band.

$\mathrm{H_1}$ indicates the contrary; that a licensed user is present, making the received signal

$$\mathrm{y[n] = x[n] + w[n]} \tag{9}$$

Ideally spectrum detection would mean hypothesis H1 for primary user (PU) present and hypothesis H0 otherwise. But due to mistakes in spectrum sensing and the stochastic nature of spectrum utilization in practice, some new terms will be defined to handle this drawback in mistaken detection. The terms are missed detection (md) and false alarms (fa).

Based on these definitions, the performance of any spectrum algorithms can be summarized by means of two probabilities:

Probability of missed detection given by:

$$\mathrm{P_{md}} : \mathrm{P(H_o \mid H_1)} \tag{10}$$

or complimentarily, the probability of detection,

$$P_d = \mathrm{P}(H_1 \mid H_1) = 1 - P_{md} \tag{11}$$

And probability of false alarm,

$$P_{fa} = \mathrm{P}(H_o \mid H_1) \tag{12}$$

In practice, large Pd and low Pfa values are desirable with some trade-off, necessary

The analog and digital integrator produces an output known as the decision test statistics. The test statistic is compared with the threshold to make the final decision on the presence or absence of the primary signal. However, the test statistic may not always be the integrator output, but a function that is in correspondence with the integrator output (Urkowitz, 1967).

A decision statistic for energy detector is (Cabric, et al., 2003):

$$\mathrm{T} = \sum_n (Y[n])^2 \tag{13}$$

Where Y[n] is the received signal and n is the number of samples contained in the signal.

2.2. Design Parameters

The spectrum sensing cognitive radio system block diagram is shown in Figure 2. The main design parameters of the energy detector are the number of samples and threshold. Although the performance of the energy detector depends on SNR and noise variance as well, designers have very limited control over them because these parameters depend on the behaviour of the wireless channel.

2.2.1. The RTL-SDR Receiver segment

The receiver segment consists of the RTL-SDR receiver block and a low-pass IIR filter block. The RTL-SDR receiver block has two inputs that are used to configure the RTL-SDR hardware, the input to tune the centre frequency of the receiver and the input to set the RF tuner gain. For this work, the centre frequency will be set to the particular frequency band of interest. The RF tuner gain is chosen such that its value will increase the quality of the received signal. The higher the tuner gain, the better the quality of the received signal, however the gain should not be too high in other not too overdrive the amplifier in the tuner. A tuner gain of 35 has been found to be adequate to tune the RTL-SDR for better reception quality.

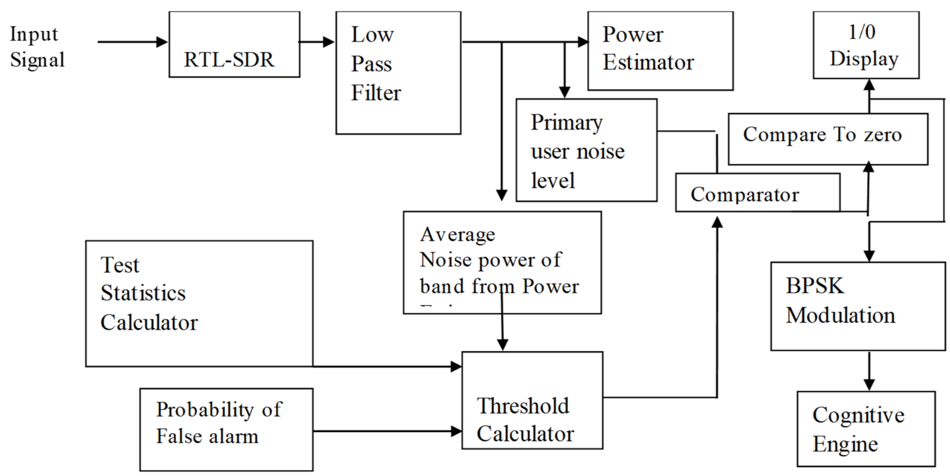

Figure 2: spectrum sensing cognitive radio system block diagram

2.2.2. Working parameters for the RTL-SDR receiver

The sampling rate chosen is 3MHz. This means the spectrum analyzer will have a bandwidth of f_s MHz, that is 3 MHz. This means that it will show spectral activity in the range:

$$\left(fc - \frac{fs}{2}\right) \text{ to } \left(fc + \frac{fs}{2}\right) \text{ Hz} \quad (14)$$

f_c is the centre frequency of the RTL-SDR. Centre frequencies chosen within the TV spectrum of 470 MHz to 870 MHz frequency band will begin with 471.5 MHz up until 868.5MHz in the frequency range of 3MHz.

The tuner gain chosen is 45 dBm. The is chosen this high, in other to amplify the signal and to differentiate it from background noise. The accepted gain values for the RTL-SDR is between 0 to 50dBm. Figure 3 shows the receiver segment of the energy detector model in Simulink.

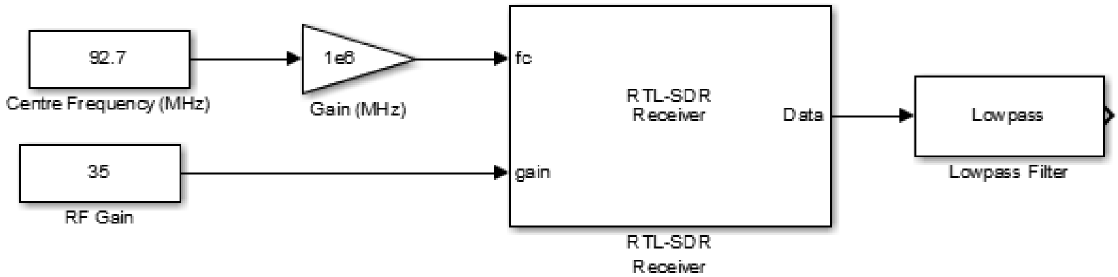

Figure 3: Receiver segment of the energy detector model in Simulink

2.2.3. The RTL-SDR power estimator segment

The power estimator segment outputs the noise power of the particular frequency band in which the RTL-SDR is tuned to. It is made up of the RMS calculator block that calculates the magnitude amplitude square of the received signal to determine the noise power present in the band and a dB converter that converts the noise power to dB value. The value of the maximum noise power gotten is used as one of the parameters to set the threshold. Figure 4 shows the power estimator segment of the energy detector in Simulink.

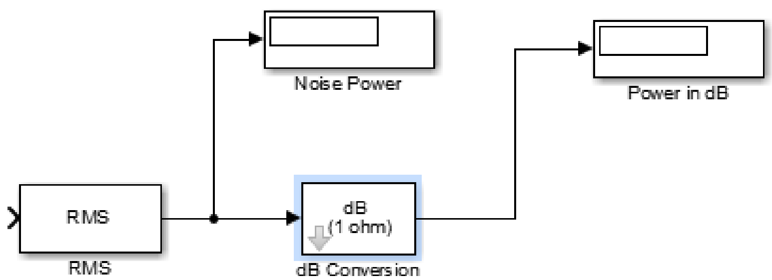

Figure 4: Power estimator segment of the energy detector model in Simulink

2.2.4. The test statistics calculator segment

The test statistic is compared with the threshold to make the final decision on the presence or absence of the primary signal. In digital implementation, after proper filtering, sampling, squaring and integration, the test statistic of energy detector is given by (Attapattu, Tellambura and Jiang 2014):

$$\Lambda = \sum_{n-1}^{N} |y(n)|^2 = \sum_{n-1}^{N} (e_r(n)^2 + e_i(n)^2) \quad (15)$$

where $e_r(n) = \theta h_r S_r(n) - \theta h_r S_i(n) + w_r(n)$ (16)

$$e_i(n) = \theta h_r S_i(n) - \theta h_r S_r(n) + w_i(n) \quad (17)$$

Given that the transmitted signal of the primary user, denoted S, is a complex signal. It has

real component S_r and imaginary component S_i i.e S = $S_r + jS_i$

If the received signal is sampled, the nth (n = 1,2,..) sample , y(n) can be given as

$$y(n) = w(n) \quad :H_0 \quad (18)$$

$$x(n) + w(n) \quad :H_1 \quad (19)$$

where x(n) = hs(n), h is channel gain (a complex value), and w(n) = $w_r(n) + jw_i(n)$ is the noise sample which is assumed to be circularly symmetric complex Guassian (CSCG) random variable with mean zero ('E[w(n)] = 0) and variance $2\sigma_w^2$ (Var [w(n)] = $2\sigma_w^2$). 'E[.] and Var[.] are expectation and variance operations, respectively. The channel gain denoted as h = h_r + jhi is constant within each spectrum sensing period.

Equation (3.4) may be rewritten as,

$$y(n) = \theta x(n) + w(n) \quad (20)$$

where x(n) is the actual signal to be sensed, ɵ = 0 for H_o and ɵ = 1 for H_1

As the Parseval's theorem or Rayleigh's energy theorem, the test statistic of digital implementation is equivalent to:

$$\boldsymbol{\Lambda} = \sum_{K=1}^{N} |Y(K)|^2 \quad (21)$$

where $Y(K)$ is the frequency domain representation of y(n).

The test statistics of an analogue energy detector may be given as (Atapattu, Tellambura and Jiang 2014):

$$\boldsymbol{\Lambda} = \frac{1}{T} \int_{t-T}^{t} y(t)^2 \, dt \quad (22)$$

However, in a heavy-traffic multi-user network, by using the hypothesis H_1, the test statistics may be defined as

$$\boldsymbol{\Lambda} = \sum_{n-1}^{n0-1} |y(n)|^2 + \sum_{n=no}^{N} |y(n)|^2 \quad (23)$$

where there is only noise signal in the interval [1, n_0 – 1]. Moreover, for the analysis of parameter optimization or noise estimation error, $\boldsymbol{\Lambda}$ is usually normalized with respect to the sample number N and the noise variance $2\sigma_w^2$ as (Mariani et al., 2011)

$$\boldsymbol{\Lambda} = \frac{1}{2\sigma_w^2 N} \sum_{N-1}^{n} |y|^2 \quad (24)$$

The test statistics calculator modelled in Simulink comprises of a kaiser window function to allow the required band of frequencies, a magnitude squarer, FFT block, a summer block, and a magnitude block to get the magnitude of the output complex signal. The Figure 5 shows the test statistics calculator for the energy detector in Simulink.

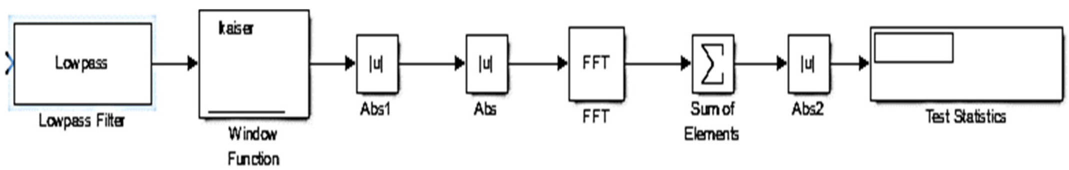

Figure 5: Test Statistics calculator for the energy detector in Simulink

2.2.5. The Threshold calculator segment

A pre-defined threshold is required to decide whether the target signal is absent or present. This threshold determines all performance metrics, P_d, P_f and P_{md}. Since it varies from 0 to 1, selection of operating threshold is important. The operating threshold thus can be determined based on the target value of the performance metric of interest (Atapattu, Tellambura and Jiang 2014).

When the threshold increases (or decreases), both P_{fa} and P_d decrease (or increase). For known N and, $2\sigma_w^2$ the common practice of setting the threshold is based on a constant false alarm probability P_{fa}, e.g., $P_{fa} \leq 0.1$. The selected threshold based on P_{fa} can be given by using (Attapattu, Tellambura and Jiang, 2014):

$$\boldsymbol{\lambda}_f = (Q^{-1}(P_{fa}) + \sqrt{N}) * \sqrt{N 2\sigma_w^2} \quad (25)$$

where Q is a Gaussian function.

The performance metrics used in setting the pre-defined threshold are a selected probability of false alarm, the average noise power of a well-known band in which the signal to be sensed is located, the width of the number of frame samples contained in the signal. These three afore-mentioned performance metrics are fed into a product block to output a value that will be fixed as threshold for spectrum sensing. The normalized test statistics is compared with the threshold value and the difference is taking for spectrum prediction. Figure 6 shows the threshold calculator for the spectrum predicting segment of the energy detector.

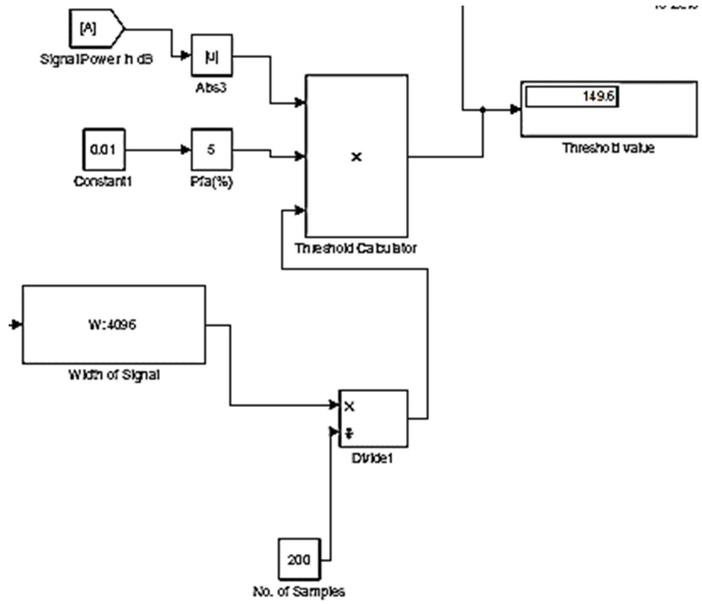

Figure 6: Threshold calculator of the energy detector for the spectrum predicting segment

Using the hypothesis model for a signal received by an energy detector (Wang and Liu 2011),

$$H_0 : y(t) = n(t) \tag{26}$$

$$H_2 : y(t) = h.x(t) + n(t) \tag{27}$$

y(t) is the received signal at the local receiver of a secondary user, $x(t)$ is the primary user's signal to be detected, $n(t)$is the additive white Gaussian noise, and h is the channel gain from the primary user's transmitter to the secondary user's receiver. H_0 is a null hypothesis, meaning there is no primary user present in the band, while H_1 means the primary user's presence.

The decision on whether the spectrum is being occupied by the primary user is made by comparing the detection statistics T with a predetermined threshold. The performance of the detector is characterized by two probabilities: the probability of false alarm P_F and the probability of detection P_D. P_{Fa} denotes the probability that the hypothesis test decides H_1 while it is actually H_0, i.e.,

$$P_{Fa} = P_r(T > \lambda | H_0) \tag{28}$$

While $P_D$denotes the probability that the test correctly decides H_1 ,i.e.,

$$P_D = P_r(T > \lambda | H_1) \tag{29}$$

A good detector should ensure a high detection probability P_D and a low false alarm P_{Fa}

2.2.6. Spectrum predicting segment for spectrum sensing cognitive RTL-SDR

This segment consists of a difference compare block that compares the value of the test statistics to the derived pre-defined threshold, the difference of both data is gotten and fed into a compare to zero block. If the test statistics is greater than the predefined threshold, a 1 is displayed giving hypothesis H_1 meaning primary user present but if the test statistics is lesser than the pre-defined threshold a 0 is displayed giving hypothesis H_0 meaning primary user absence. Figure 7 shows the spectrum predicting segment of the energy detector in Simulink.

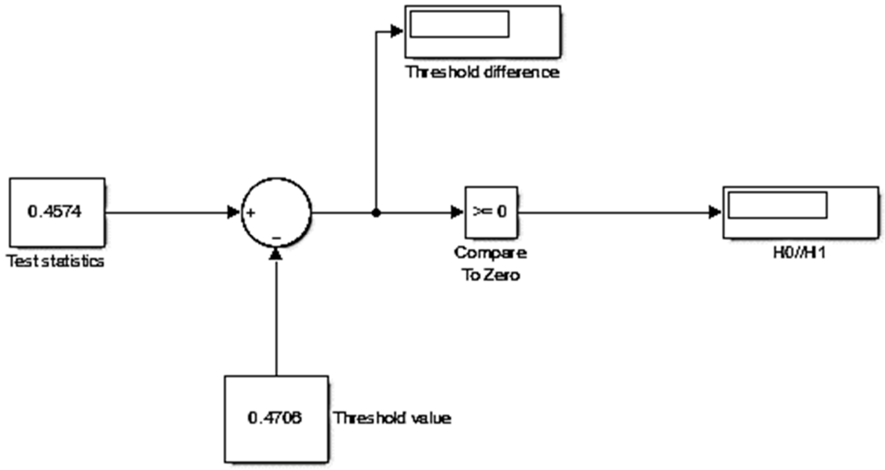

Figure 7: Spectrum Predicting segment of the energy detector in Simulink

2.2.7. Transmission of H_o/H_1 through BPSK to cognitive engine

A Binary Phase Shift keying (BPSK) signal can be defined as:

$$V_{BPSK}(t) = b(t)\sqrt{2P}\cos 2\pi f c t \text{ where } 0 < t < T \quad (30)$$

where b(t) = +1 or -1, f_c = carrier frequency, T = bit duration, P = Signal Power, A = Peak value of sinusoidal carrier.

The H_o or H_1 decision from the spectrum prediction is transmitted to a cognitive engine in the case of cooperative sensing for further spectrum management. Given that it's a 1 or 0 decision output, Binary Phase Shift Keying (BPSK) is used for modulation and this modulated signal will be sent to a transmitter which will transmit the decision from the spectrum sensor to a cognitive engine or other cognitive users for spectrum management. The real time model for the Binary Phase Shift Keying (BPSK) modulation of H_o/H_1 decision in Simulink is as shown in Figure 8.

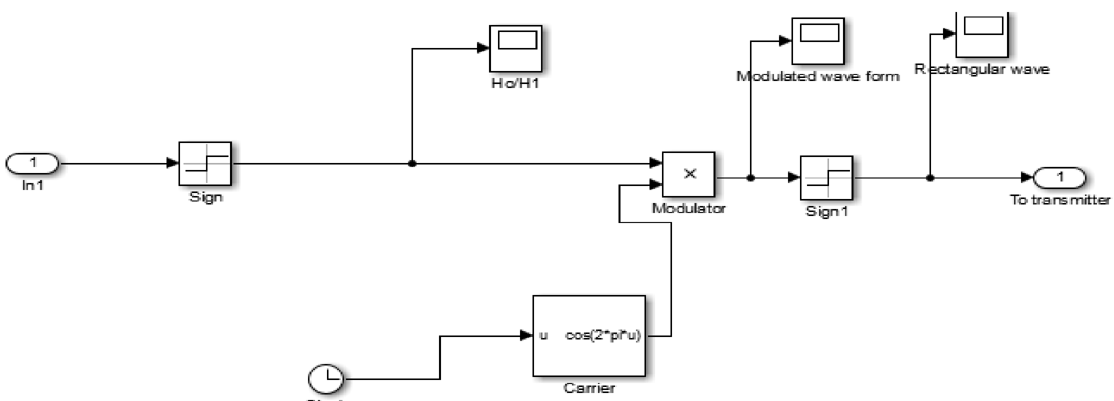

Figure 8: BPSK modulation and transmission of H_o/H_1 spectrum decision real time

3. RESULTS AND DISCUSSION

The complete system of the energy detector developed performing the function of a spectrum sensing cognitive radio is shown in Figure 9. The mode of operation of the entire system can be summarized as follows- the software defined radio (RTL-SDR) is tuned to the centre frequency of the band whose primary signal is of interest, the RTL-SDR receives the signal, performs sampling and analog to digital conversion of the signals and outputs the samples to the PC where the energy detector model in Simulink is interfaced with the RTL-SDR. The simulink model has a low pass filter which receives the sampled signal and its function is to limit the band noise and normalize the variance of the signal. The signal is then passed on to the power estimator which measures the signal energy and calculates the noise power. The received signal from the RTL-SDR after low pass filtration is also passed on to the test statistics calculator, where the signal is passed through a kaiser window to allow the required band of frequencies and then it is magnitude squared. The squared signal of allowed frequencies is then passed through an FFT block to get the corresponding coefficients, these coefficients are then summed up and the absolute value of the result is taken since the result comes out as a complex number. The absolute output of the sum is the test statistics. The width of the signal, which is the number of samples present in the signal and two other constants, that is the average noise power of a known frequency band and a selected probability of false alarm are fed into the threshold calculator, to get a set threshold. The primary user ambient noise level is compared against the set threshold, from the comparison, the difference of the two signals is taken and the output value is fed into a compare to zero block. If the output value is greater than zero, a one is displayed, predicting the presence of the primary user but if the output value is lesser than zero, a zero is displayed predicting the absence of the primary user signal. The output of 1 or 0 is then modulated unto a carrier signal using Binary Phase Shift Keying (BPSK) so that it can be transmitted to a cognitive engine for spectrum management.

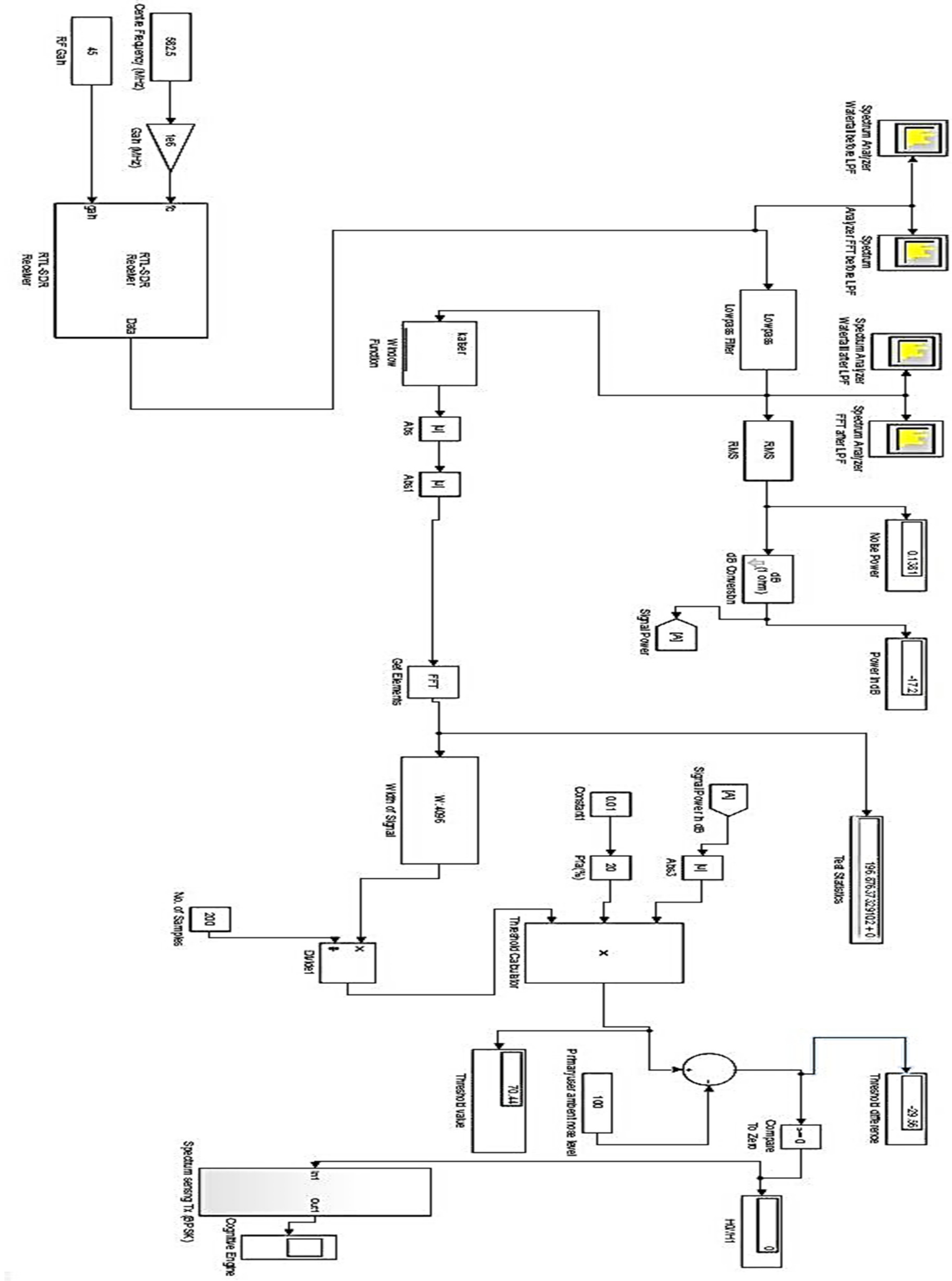

Figure 9: Complete real time model of the energy detector in Simulink

The Figure 10 and Figure 11 shows the graphical display of the energy detector when a primary user is present (H_1) and when a primary user is absent (H_o).

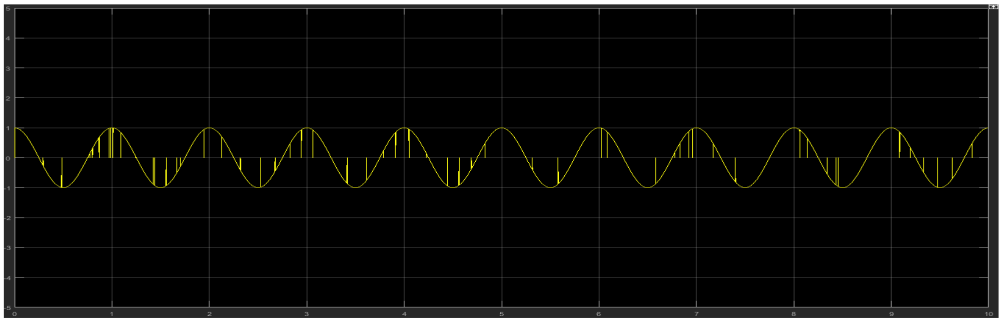

Figure 10: Graphical display of primary user present (H_1)

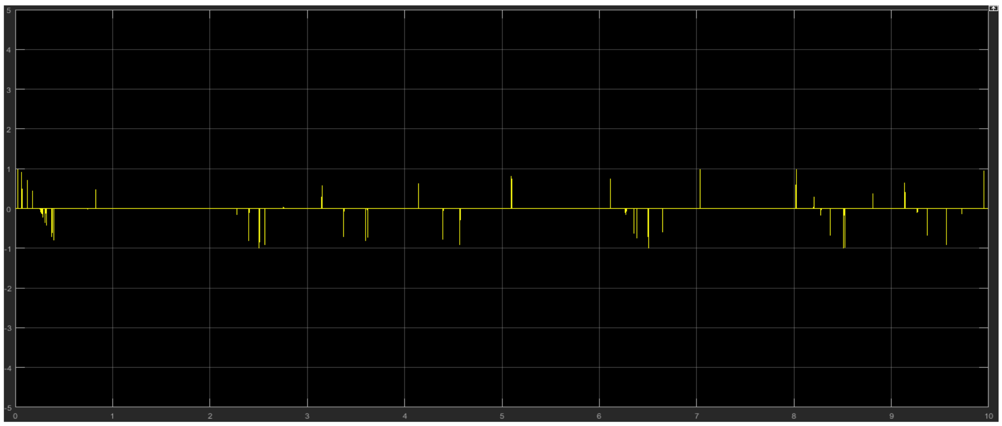

Figure 11: Graphical display of Primary user absence (H_o)

4. CONCLUSION

In this work an energy detector have been developed in Matlab-Simulink and interfaced with a software defined radio to function as a spectrum sensing cognitive radio and it was able to perform spectrum sensing between the radio frequency range of 24 MHz to 1766 MHz. Further works can be done by using this developed energy detector Simulink radio system to monitor and evaluate signals that fall within this frequency range such as FM and TV signals.

5. ACKNOWLEDGMENT

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6. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

REFERENCES

Adepetun, A., (2021). *NCC outlines ECCs' roles in promoting public safety,* s.l.: The Guardian.

Akyildiz, I.F, Lee W., Vuran M.C., Mohanty S. (2006). Next generation/dynamic spectrum access/cognitive radio wireless networks: a Survey. *Computer Networks,*50 (13) pp. 2127-2159.

Attapattu, S., Tellambura, C. and Jiang, H. (2014). Energy Detection for Spectrum Sensing in Cognitive Radio. *Springer*, 1(2), pp. 11-26.

Cabric, D., Tkachenko, A. and Brodersen, R. W.,(2003). *Spectrum Sensing Measurements of Pilot, Energy, and Collaborative Detection,* Berkeley, 6(3), pp 1-7

Faruk, N., Adediran, Y. A. and Ayeni, A. A., (2013). On the study of emperical path loss models for accurate prediction of TV signal for secondary users. *Progree in Electromagnetic Research (PIER)* 49(49), pp. 155-176.

Haykin, S. (2005). Invited Paper: Cognitive Radio Brain Empowered wireless Communications. *IEEE Journals on Selected Areas in Communications,*3(2) pp. 201-220.

Mariani, A., Giorgetti, A. and Chiani, M., (2011). Effects of noise power estimation on energy detection for cognitive radio applications. *IEEE on Communication,* 59(12), pp. 3410-3420.

Miftah, A.M. (2015). *A Estimation of Detection Threshold Spectrum Sensing in Cognitive Radio using Adaptive Fuzzy Inference System and Monte Carlo Techniques,* Zaria: Ahmadu Bello University, Zaria, Ph.D thesis.

Mitola, J. (1995). The Software Radio Architecture. *IEEE Communications Magazine,* 33, pp. 26-38.

NCC, (2023). *Emergency Communicatons Centres.* [Online]
Available at: https://ncc.gov.ng/stakeholder/corporate-matters/projects/74-emergency-communications-centres-ecc
[Accessed 15 February 2023].

Tabassam, A. A., Suleman, M. U., Kalsait, S. and Khan, S., (2011). Building Cognitive Radios in MATLAB Simulink – A Step Towards Future Wireless Technology. *Wireless Advanced,* 15(20) pp. 15-20.

Urkowitz, H., (1967). Energy Detection of Unknown Deterministic Signals. *Proceedings of the IEEE,* 55(4), pp. 523-531.

Wang, B. and Liu, R. K., (2011). Advances in Cognitive Radio Networks: A Survey. *IEEE Jornal of Selected Topics in Signal Processing,* 5(1), pp. 5-23.