Spectrum Sensing System in Software-defined Radio to Determine Spectrum Availability

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***Abstract*:** Spectrum sensing is an integral part of cognitive radio, which seeks to address the perceived spectrum scarcity that is caused by inefficient utilization of the available spectrum. In this paper, a spectrum sensing system using energy detection for analog TV and FM broadcast transmitters as well as modified Integrated Services Digital Broadcasting Terrestrial (ISDB-T) signals is implemented on a software-defined radio platform using GNU's Not Unix (GNU) radio and the N200 Universal Software Radio Peripheral (USRP). Real-time implementation and experimental tests were conducted in Metro Cebu, a highly urbanized area in the southern part of the Philippines. Extensive tests and measurements were necessary to determine spectrum availability, particularly in the TV band. This is in support of the Philippine government's efforts to provide internet connectivity to rural areas. Experimental results have so far met IEEE 802.22 requirements for energy detection spectrum sensing. The designed system detected signals at -114 dBm within a sensing time of 100 ms. Furthermore, the required $P_d\left(\geq 90\right)$ and $P_{fa}\left(\leq 10\right)$ of the standard were also achieved with different thresholds for various signal sources representing primary users.

***Keywords*:** Cognitive radio, Energy detection, GNU radio, Software-defined radio, Spectrum sensing, USRP

1. Introduction

Cognitive radio (CR) allows unlicensed users, known as secondary users, to access unused licensed frequency bands. CR is not only a solution to the spectrum scarcity foreseen for the future, but most importantly, it aims to efficiently utilize existing frequency spectrum allocation in which the primary user (PU), or licensed user, exclusively operates in a particular band. IEEE 802.22, implemented in 2004, is now the recognized standard in cognitive radio for broadband wireless access to TV bands. Also known as the Wireless Regional Access Network (WRAN) standard, IEEE 802.22 is aimed at using cognitive radio techniques in television white space (TVWS) to provide broadband connectivity to rural areas without interfering with incumbent users.

In the Philippines, the Information and Communications Technology Office (ICTO) of the Department of Science and Technology (DOST) is spearheading the government's effort to conduct tests for TV whitespace. There was successful pilot testing of the TVWS technology in February 2014 in the provinces of Bohol and Leyte, two of the areas that have the lowest internet connectivity. While reportedly the largest deployment in Southeast Asia [1], no studies so far have been conducted to quantify spectrum availability and to determine the effects of such deployment on existing primary users, i.e., analog and digital TV receivers.

Spectrum sensing is a crucial part of CR. It is universally recognized as the main enabler for CR, because it provides awareness of the radio environment. It also indicates the availability of transmission opportunities, shows who is occupying the channel, and determines the quality of the channel itself. Among the spectrum sensing techniques, energy detection (ED) was chosen for this study since it does not require any prior information about the PU signal.

In order for a CR system to be implemented, a flexible platform is required. Software-defined radio (SDR) meets all these requirements. SDR implements some or all of the radio system component hardware and software in a personal computer. This platform is introduced with the use of two Universal Software Radio Peripherals (USRPs) as hardware and GNU's Not Unix (GNU) radio for software.

This research implements the ED spectrum-sensing approach in real time on an SDR platform. The developed system is the first important step necessary to quantify spectrum availability.

2. Spectrum Sensing Using Energy Detection

Searching for spectrum availability is basically the first task of any cognitive radio system before signal transmission. This kind of detection method works best in signals that have a high signal-to-noise ratio (SNR). Making a decision between two hypotheses is the goal of spectrum sensing:

$$y[n] = \begin{cases} w[n] & : H_0 \\ s[n] + w[n] & : H_1 \end{cases} \quad \text{for n = 1,…,N} \tag{1}$$

where $y[n]$ represents the received complex signal, $s[n]$ is the transmitted PU signal, and $w[n]$ signifies additive white Gaussian noise (AWGN). The H_0 hypothesis is when no PU signal is present, whereas H_1 is when the PU is transmitting.

Spectrum sensing can be done in the time domain or the frequency domain. In this paper, it is implemented in the frequency domain. The conversion from time domain to frequency domain is done by the fast Fourier transform (FFT) block in GNU radio [2], which uses 1024-point FFT. The formula for FFT is shown in Eq. (2):

$$X(k) = \sum_{n=0}^{N-1} y[n] e^{-\frac{j2\pi kn}{N}} \tag{2}$$

where $X(k)$ is the frequency domain signal, $y[n]$ is the real value, $e^{-\frac{j2\pi kn}{N}}$ is the complex value, and N is the FFT size.

After the conversion from time domain to frequency domain in GNU radio, Eq. (3) is used to calculate the energy of the signal. This is done by calculating test statistics, T, and comparing them to the predefined threshold, which is

$$T = \frac{1}{N} \sum_{n=1}^{N} |X(k)|^2 \tag{3}$$

where T is the output of the energy detector, $X(k)$ represents the FFT values of the signal, and N is the number of bins used. Threshold γ is set where it would give the probability of false alarm, P_{fa}<10%, and probability of detection, P_d ≥90%. These thresholds determine if the signal is present or not. The performance of the energy detector can be characterized by resulting pair (P_{fa}, P_d) as the probabilities that the sensing algorithm detects the PU under $H0$ and $H1$, respectively. P_{fa} is the detection percentage when the transmitter is off. P_d, on the other hand, is the detection percentage when the transmitter is on.

$$P_{fa} = P(T > \gamma | H_0) \tag{4}$$

$$P_d = P(T > \gamma | H_1) \tag{5}$$

Eq. (4) occurs when the PU is not transmitting and T is greater than γ. On the other hand, Eq. (5) occurs when the PU is transmitting and T is greater than γ.

3. System Overview

Rapid growth in the ways and means by which people utilize different types of communication demonstrates the need to modify radio devices easily and cost-effectively. SDR technology brings the flexibility, cost efficiency, and power to drive communications forward, with wide-reaching benefits realized by service providers and product developers right through to the end users.

Current hardware-based radio devices are specific for certain functionality, and can only be modified through physical intervention. If the need to support multiple waveform standards arises, it would definitely result in higher production costs and limited flexibility. Several researchers [2-4] studied the use of GNU radio for spectrum sensing, integrating USRP and used-energy detection as their sensing mechanism.

GNU radio is a free software development toolkit. It is widely used in hobbyist, academic and commercial environments to support wireless communications research, as well as to implement real-world radio systems [5]. The applications are primarily written in the Python programming language, while the supplied, performance-critical signal processing path is implemented in C++ using processor floating point extensions. Thus, the developer is able to implement real-time, high-throughput radio systems in a simple-to-use, rapid-application–development environment.

The software comes with the GNU Radio Companion (GRC), which has a graphical environment where you can design different flow graphs depending on your application. Hundreds of blocks are already available, but for specific ones, you either design your own block using out-of-the-box modules or edit the Python-generated code of the GRC. This software provides the signal processing runtime and processing blocks to implement software radio using

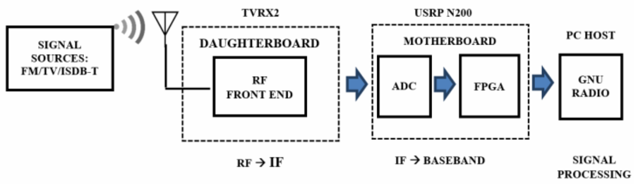

Fig. 1. Block diagram of software-defined radio.

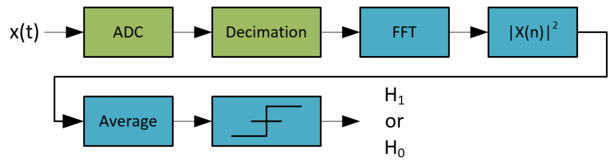

Fig. 2. Block diagram of energy detection in the frequency domain.

readily available, low-cost external RF hardware and commodity processors like USRP.

Universal Software Radio Peripheral products are computer-hosted software radios [6]. These are commonly used with the GNU radio software suite to create complex software-defined radio systems. A USRP operates on DC at 6 GHz. Such a device consists of two boards: the daughterboard and the motherboard. The daughterboard is the TVRX2, and the motherboard is the USRP N200. An RF front end filters the RF signal, and converts from RF to intermediate frequency (IF), and vice versa. TVRX2 is a receiver capable of receiving frequencies in the 50 MHz to 860 MHz range. The output signal is then connected to the USRP N200 motherboard, where it is sampled by an analog-to-digital converter (ADC) at 100 MS/s and then down-converted to baseband by a digital down-converter (DDC) implemented in the Spartan 3A-DSP 1800 field-programmable gate array (FPGA). The baseband digital signal from the USRP N200 motherboard is sent via Ethernet interface to the host computer running GNU radio software installed under Ubuntu 14.04 to further process the signal.

For the Integrated Services Digital Broadcasting Terrestrial (ISDB-T) setup, USRP1 was used as the transmitter. It operates from 400 MHz to 1 GHz. The WBX 50-2200 was used as the daughterboard and can accommodate frequency bands from 50 MHz to 2.2 GHz. The antenna used for both is the LP0410, which is a log periodic directional antenna. It allows operation from 400 MHz to 1 GHz and is compatible with any daughterboard that can operate within that range.

Unlike the USRP N200, this connects to the computer via a USB port. A block diagram of the system is shown in Fig. 1.

Fig. 3. Experimental setup of the spectrum sensing system of the modified ISDB-T.

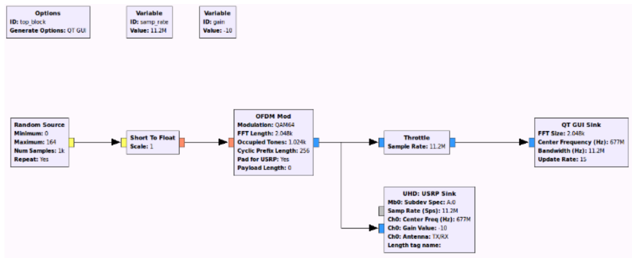

Fig. 4. Modified ISDB-T transmitter flow graph.

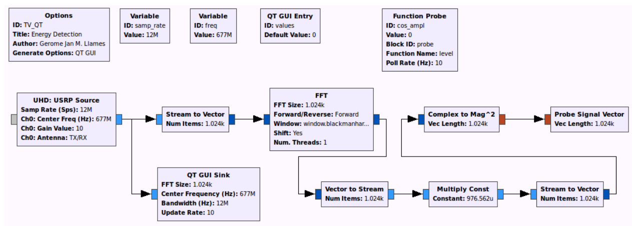

Fig. 5. Modified ISDB-T receiver flow graph.

4. Energy Detection in GNU Radio

The signals received came from various transmitters: analog TV, FM and modified ISDB-T. Fig. 2 shows a block diagram of the detector implemented in the frequency domain using 1024 points. This was chosen due to its lower complexity and because this detector only determines if the spectrum is available or not. Other researchers performed detection in the time domain [7]. Shown in Fig. 3 is the transmission and reception experimental setup of the modified ISDB-T. This modified version, unlike the original, has only one hierarchical transmission using 64 quadrature amplitude modulation (QAM). A transmission flow graph is shown in Fig. 4 [8]. The flow graph in Fig. 5 was used for reception of these signals. There were just some minor tweaks made in order for it to receive the center frequency, sampling rate, etc.

After all the processes are completed by the USRP, the data go to the computer where the GNU radio is installed via the Ethernet cable. It is converted into a vector of 1024 points.

At the same time, the output is plotted using the QT GUI Sink block. This has power spectral density (PSD), Waterfall, Time Domain, and Constellation displays. Following the conversion to 1024 points is the FFT block [5]. Next is removal of the scaling made by the FFT block itself. Then, the magnitude of the complex value is squared ($a \pm jb \Rightarrow a^2 + b^2$).

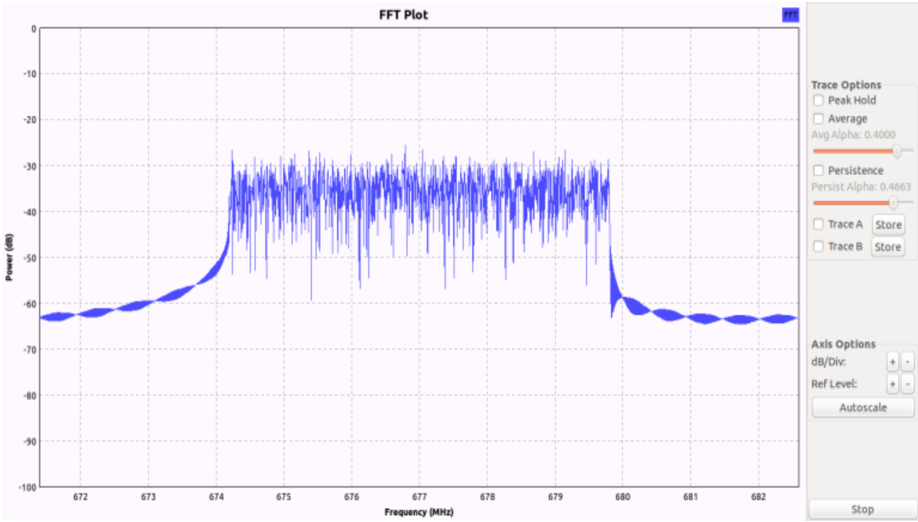

Fig. 6. Modified ISDB-T transmitted signal centered at 677 MHz.

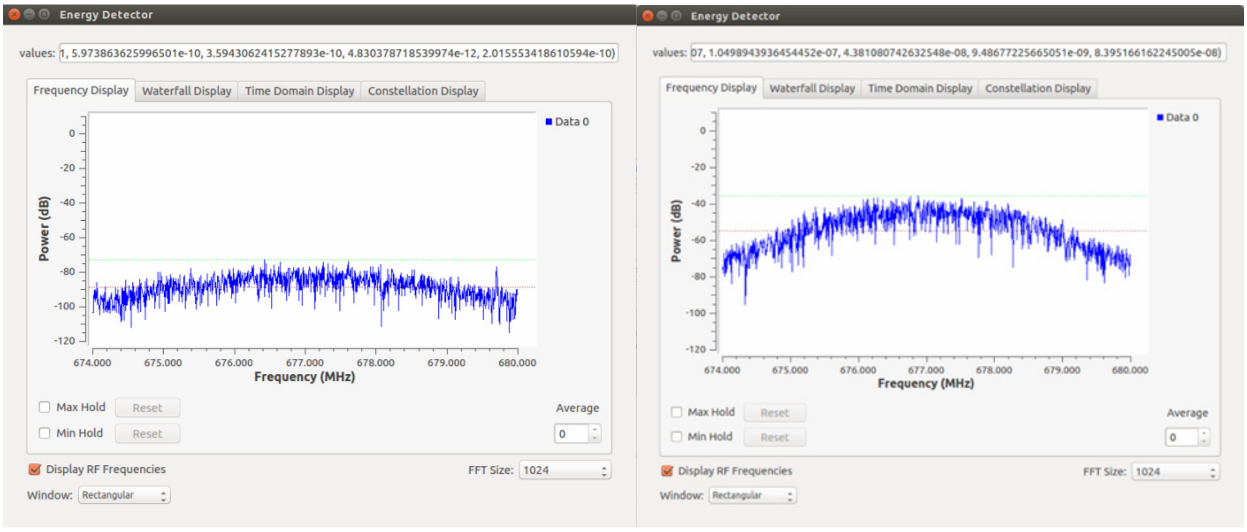

Fig. 7. Left: energy detector output if the PU is not transmitting; right: energy detector output if the PU is transmitting.

Finally, the data go into the probe signal vector block. This block gets those 1024 vectors and selects the peak values of the frequency domain, averages them, and compares them to the threshold to determine if the signal is present or not.

This additional processing is automatically done by editing the generated Python code of the GRC. Fig. 6 shows the transmitter plot in the frequency domain of the modified ISDB-T signal using GNU radio. Illustrated in Fig. 7 is the received waveform for wideband orthogonal frequency division multiplexing (OFDM) of the PU transmitter centered at 677 MHz. Shown in the left is the frequency domain representation of the energy detector if the PU is not transmitting. On the right is when the PU is transmitting.

5. Experimental Results

Signals broadcasted by different stations have different shapes in the frequency domain. Among the three types of signal, analog TV had the most different plot where, unlike modified ISDB-T and FM, its peaks are located on the sides.

Initially, three sensing methods were considered. First is averaging all the bins; second is averaging selected center bins; and third is averaging selected peak bins. The first two are straightforward processes, but the third is not. What makes this unique in all three sensing mechanisms is that it automatically searches for the peak value of a certain frequency and averages it along with a few bins on its sides. The first and second methods had very poor performance in sensing the analog TV signal. Only the third mechanism provided excellent performance with all

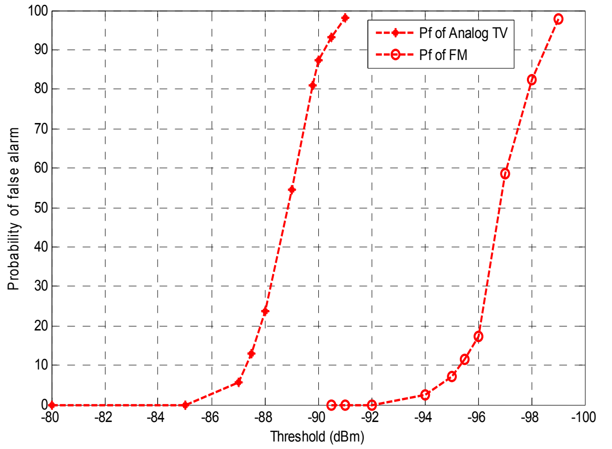

Fig. 8. Probability of false alarm of the TV and FM band from varying thresholds.

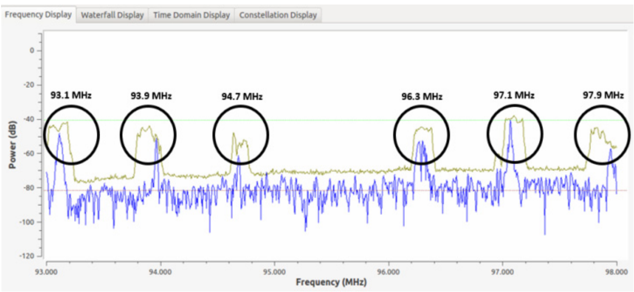

Fig. 9. 93 MHz to 98 MHz FM band in Cebu.

three signals. Therefore, it was used as the sensing technique.

5.1 Analog TV and FM as PU

The TV and FM band (54 MHz to 686 MHz) in Metro Cebu were swept. There were 14 out of 16 current operational channels received at the research location. Some of the data about the stations are also available on the National Telecommunications Commission (NTC) website [10]. This experiment was conducted from the fifth floor of the Bunzel building in the Communication & Broadcasting Engineering Laboratory Section (CBELS) of the University of San Carlos in Cebu City. The designed energy detector system was set to a TV whitespace frequency (57 MHz) and a frequency that has almost no power for FM (88.3 MHz). The threshold was varied to get a value <10% P_{fa}. This value was then used to get P_d.

To get P_{fa} <10%, the threshold for analog TV was -87 dBm and resulted in P_d >90% for the rest of the channel. The plot is shown in Fig. 8. FM on the other hand, had a lower threshold, at -95 dBm, to get <10% P_{fa}, as shown in the same figure for TV. All the FM frequencies had P_d>90% except for 89.9 MHz, which had the weakest received power. Six FM stations and an analog TV signal are shown in Figs. 9 and 10, respectively.

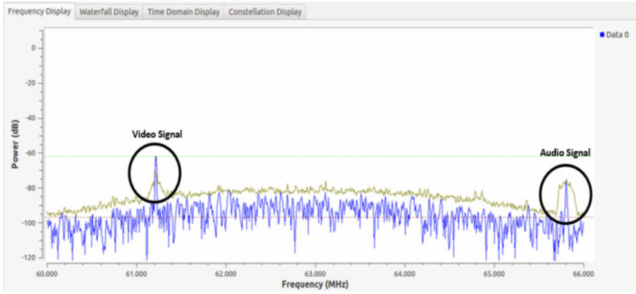

Fig. 10. 63 MHz ABS-CBN analog TV band in Cebu.

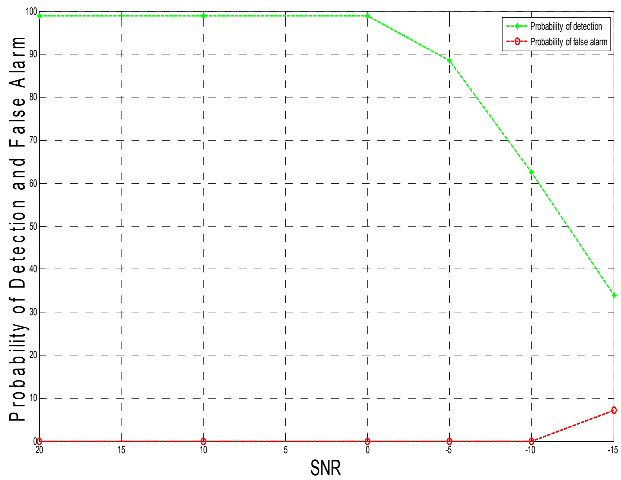

Fig. 11. Probability of detection and false alarm of the received modified ISDB-T signal over varying SNR.

5.2 Modified ISDB-T as PU

This experiment included two USRPs: USRP 1 (Tx) and USRP N200 (Rx). The former was hosted on a desktop computer in the lab, while the latter was hosted on a researcher's laptop. Tx and Rx were both tuned to 677 MHz [7]. All the parameters were held fixed for the whole setup, except for the SNR, which varied between -15 dB and 20 dB. Fig. 11 shows the plot of P_{fa} and P_d. We can see that as the SNR decreases, P_{fa} increases while P_d decreases.

The threshold was set at -85.5 dBm, which resulted in a P_d of >90% and a P_{fa} of <10%. The system starts by executing the flow graph of the transmitter, which generates the 64 QAM signal and passes through an inverse fast Fourier transform to get an OFDM segment output. Then, it passes through the USB cable interface of the computer and USRP 1. This interface allows 8 MSps at a host sample rate for 16-bit I/Q. Then, up-conversion follows inside the Altera Cyclone FPGA and DAC at 64 MSps. Finally, this IF signal is converted to RF where it is transmitted to the receiver system, which is one foot away. The log periodic is capable of receiving frequencies from 400 MHz to 1 GHz. The TVRX2, which has a maximum bandwidth of 10 MHz, then converts the received signal to IF. Then, the signal is sampled at 100 MSps by the USRP N200 ADC and down-converted to baseband in the Spartan 3A-DSP 1800 FPGA. The data pass through the

Ethernet cable at a maximum 25 MHz host sampling rate. Lastly, the data go into the GRC for the ED process.

5.3 Sensing Time

One of the requirements of the IEEE 802.22 standard is sensing time, which should not go beyond two seconds.

A study on opportunistically utilizing licensed segments of the spectrum without interfering with licensed users and other unlicensed users in the network was conducted [9], where the researcher used the time library available in Python to determine the sensing time. It gives the time the program finishes executing the code. An example of how to implement it is shown below.

```
import time
start_time = time.time()
main()
print(“--- %s seconds ---“ % (time.time() – start_time))
```

This research uses the same method. The energy detector was able to provide an output in just 100 ms.

6. Conclusions

Cognitive radio is the solution for efficient utilization of the current frequency spectrum, which is exclusive only to the PUs. In this paper, performance under ED was evaluated by sensing real-time signals for analog TV, FM, and modified ISDB-T, which determined availability for CR applications using 1024-point FFT-based ED. In the experiments performed, the threshold value was set in such a way that it would give a P_{fa} of less than or equal to 10% and a P_d of greater than or equal to 90%. In order to fulfill the requirements of the IEEE 802.22 standard, a threshold of -87 dBm for TV, -95 dBm for FM, and -85.5 dBm for modified ISDB-T was set. The system is sensitive enough to receive signals even at -114 dBm. An additional requirement of the standard is sensing time, for which the system offers 100 ms.

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References

[1] I. a. C. T. Office, "TV White Space Deployment in PH the Largest in Asia," Tagbilaran, 2014. Article (CrossRef Link)

[2] M. A. S. N. F. S. K. S. Y. a. N. H. M. Rozeha A. Rashid, "Spectrum Sensing Measurement using GNU Radio and USRP Software Radio Platform," in *ICWMC 2011 : The Seventh International Conference on Wireless and Mobile Communications*, Luxembourg , 2011. Article (CrossRef Link)

[3] A. M. N. F. S. K. S. Y. R. A. R. a. M. H. S. Mohd Adib Sarijari, "Energy Detection Sensing based on GNU Radio and USRP: An Analysis Study," in *Proceedings of the 2009 IEEE 9th Malaysia International Conference on Communications*, Kuala Lumpur Malaysia, 2009. Article (CrossRef Link)

[4] S. K. I. M. G. A. H. M. K. a. J.-i. T. Md. Abdur Rahman, "Development of Spectrum Sensing System with GNU Radio and USRP to Detect Emergency Radios," Tokyo, 2010. Article (CrossRef Link)

[5] "gnuradio.org," GNU Radio, 2006. Article (CrossRef Link)

[6] A. N. I. C. Ettus Research, "www.ettus.com," Article (CrossRef Link)

[7] W. A. N. a. A. S. Bañacia, "Simulation and FPGA Implementation of Television White Space Sensing Using Energy Detection for Cognitive Radio", *International Conference on Humanoid, Nanotechnology, Information Technology, Communication and Control, Environment and Management (HNICEM)*, Cebu City, 2015. Article (CrossRef Link)

[8] J. E. M. N. C. A. T. Donn Emile Kylee M. Megazo, Generation of a Modified ISDB-T Signal Using Software Defined Radio, Cebu, 2015.

[9] B. A. Jayawickrama, "TV White Space Cognitive Radio System Development Using Ettus Platform," 2011.

[10] J. Mitola, "Software radios-survey, critical evaluation and future directions," in *IEEE National Telesystems Conference*, 1992. Article (CrossRef Link)

[11] T. Y. a. H. Arslan, "A survey of spectrum sensing algorithms for cognitive radio applications," in *IEEE Communications Surveys & Tutorials*, 2009. Article (CrossRef Link)

[12] Z. M. H. C. G. L. a. W. W. Z. Yan, "Spectrum Sensing Access and Coexistence Test ber for Cognitive Radio Using USRP," in *4th IEEE International Conference on Circuits and Systems for Communications*, 2008. Article (CrossRef Link)

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