# Spectrum Sensing for Cognitive VHF Land Mobile Radio Communication Networks Using Energy Sensing Techniques

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***Abstract*—The 2015 migration from Very High Frequency (VHF) Analog to Digital Television (TV) created plenty of white spaces in the entire VHF TV Band (174–230 MHz). These white spaces can be used by other wireless applications and internet services whose radio spectrum is already pushed to maximum utilization and is therefore scarce for emerging wireless applications such as IP Television, high-speed wireless internet, cellular telephony, multimedia services, Zigbee, WiMax-Advanced. In this study, we implemented a VHF Land Mobile Radio System (LMRS) that can utilise the Television White Spaces (TVWS) in the upper VHF TV band for mission critical voice transmissions. We detected VHF Land Mobile Radio (LMR) transmissions in the TVWS using energy sensing techniques, with the real-time energy detector developed on the Software-Defined Radio (SDR) testbed composed of RTL-SDR device, VHF Radio and GNU Radio. We used a simulated energy detector using GNU Radio to set the evaluation benchmark. In both, the simulations and the real-time platform, a Narrow Band Frequency Modulation (NBFM) was generated and transmitted through the TVWS. The performance of the implemented real-time energy detector compared to the simulated one was lower, due to the noise distribution being not perfectly Additive White Gaussian Noise (AWGN), and thermal noise from the RTL-SDR. In addition, the transmission in TVWS was high in signal energy compared to transmission in traditional LMR frequency (approximately 10% improvement), and thus improved penetration in remote areas and thick forests.**

***Index Terms*—Cognitive Radio, VHF LMRS, TVWS, SDR, NBFM, RTL-SDR, GNU Radio, VHF Radio, Ultra High Frequency (UHF)**

## I. Introduction

TVWS can be used for wireless applications and internet services such as IP Television, high-speed wireless internet, cellular telephony, multimedia services, Zigbee, WiMax-Advanced, and Long Term Evolution (LTE) [1]. Moreover, LMRS applications can also utilise TVWS for their transmissions. By definition, the telecommunications section Title 47 of the Code of Federal Regulations (CFR) defines LMRS as a “regularly interacting group of base, mobile, associated control, and fixed relay stations intended to provide LMR communications service over a single area of operation”. Such systems are used by emergency first response organizations such as the police, fire brigade, ambulance services etc. The frequency bands that are used used by LMRS (150–174 MHz VHF and 421–512 MHz UHF) are considered to be the most congested with limited frequency availability for implementing new systems or expanding the existing systems[1]. As such, in VHF LMRS, allocation of spectrum resources is done using Time Division Multiple Access (TDMA). However, the TDMA is a static spectrum allocation since channels are permanently assigned to users or applications, leading to spectrum scarcity in the VHF LMRS for new users and applications [2]. This situation can hamper mission critical transmissions and operations. It is therefore important to identify alternative spectrum for new users and applications. As such, new solutions such as Cognitive Radio (CR) Technology are important to enable transmission and receiving of VHF LMRS services e.g., mission critical voice and data transmissions. CR that uses SDR, can opportunistically use frequency bands that are not heavily occupied by primary users.

In this research, a VHF Land Mobile CR, utilising TVWS in the upper VHF TV band for voice transmissions is proposed as a source of additional VHF LMR spectrum. The band is preferred due to its excellent propagation characteristics over long distances and can easily penetrate walls and other objects, and hence hold enormous potential for wireless applications that need long transmission range [3]. As a contribution, we ascertain TVWS availability, design VHF LMRS capable of transmitting in the TVWS, and analyse the performance of the VHF LMRS in the TVWS.

## II. Background and Motivation

Several studies in the literature have implemented spectrum sensing [4]–[7]. Patil *et al.* [4], implemented spectrum sensing using GNU Radio as a software and RTL-SDR as hardware to sense VHF frequencies used in Frequency Modulation(FM) broadcast band (88–108 MHz). However, this scenario was designed for FM broadcasting and so is not applicable in our two way VHF LMRS solution. In addition, the study did not consider TVWS utilisation. Raja [5], modelled and simulated a VHF CR environment for aeroplane air-to-ground communication systems. However, the study did not indicate transmission/non-transmission activities in the channel. The solution proposed in the study uses Amplitude Modulation(AM) signals. As such, it is not applicable to LMRS that uses NBFM signals. Additionally, the solution proposed in the

[1]https://www.fcc.gov/narrowbanding-overview

study did not consider TVWS. Amritha *et al.* [6], implemented a prototype for TVWS detection using USRP in the UHF TV band from 470–490 MHz. However, the implementation does not mention the utilization, transmission, and signal detection characteristics in the VHF TVWS. Moreover, Tang *et al.* [7], simulated a maritime CR-Automatic Identification System(AIS) VHF network scenario for spectrum sensing to detect and exploit the available AIS VHF white spaces without interfering AIS services. However, this is a simulation and therefore the solution is inapplicable to real world VHF LMRS applications. Also, the solution does not consider TVWS, which is the focus of this work. Finally, Moncayo *et al.* [8], implemented a low-cost spectrum monitoring system based on Dragonboard 410C and RTL-SDR 2832U dongle for scanning FM and analog TV occupied/unoccupied channels. However, the implementation does not explain the utilisation of the redundant channels, which is the core of this research.

In summary, all these studies include making test-beds for modelling, simulation, spectrum sensing, channel estimation etc. To the best of our knowledge, no studies have built a prototype with CR to make a real-time VHF radio transmission in the upper band of VHF TVWS as a source of additional spectrum.

## III. METHODOLOGY

This study was based in Uganda, a developing country that is located in the geographical Eastern Africa region. In this region, several studies indicate that the VHF band was vacated and pushed to UHF [9], [10]. This is evidenced in Uganda's radio spectrum allocation table, where the upper VHF band is not allocated [11]. For demonstration purposes we choose the former and idle TV Channel 5 (174–181 MHz) of the band.

*1) Designing VHF LMRS capable of transmitting in the TVWS:* In order to design a VHF LMRS capable of transmitting in the TVWS, GNU Radio platform was used to simulate VHF LMR signal, and RTL-SDR, VHF Radio and GNU Radio were used to generate and sense real-time signal transmissions.

*2) Spectrum sensing approach:* We adopted the energy detection spectrum sensing technique because of its low processing cost, simplicity, and ease of extracting input signal energy with normalized noise energy [12], [13]. In this approach, energy detection can also be used to find whether there is VHF NBFM signal transmission or not. The sensing platform is composed of SDR, python application on GNU platform, RTL-SDR dongle with VHF antenna, and VHF Radio. The presence and absence of VHF NBFM signal transmission was determined using energy as it refers to all signals as noise. A minimum amount of signal energy required for transmission was set using Equation (5). In spectrum sensing, detection of the presence or absence of the primary user signal energy in the band must follow a binary test hypothesis below;

$H_0 : y(n) = w(n)$, primary user absent.

$H_1 : y(n) = s(n) + w(n)$, primary user present.

where $y(n)$ denotes the received signal at CR nodes, $s(n)$ is the transmitted signal from the primary user/transmitter. In this study, these two hypotheses were used to decide if the VHF LMRS signal is present or not. The $w(n)$ represents AWGN, assumed to be independent and identically distributed with zero mean, variance of $\sigma^2$ and is a random process. The energy detection at the CR node was based on test statistic represented by Equation (1) [14]–[18];

$$T = \sum_{i=0}^{N} |y(n)|^2 \tag{1}$$

where, $T$ is the test statistic, $N$ is the number of observed samples $y(n)$. In conventional energy detection systems, the threshold is determined based on Constant False Alarm Rate (CFAR) given by Equation (2) [19].

$$P_{FA} = Q\left(\frac{\frac{\gamma}{\sigma^2} - N)}{\sqrt{2N}}\right) \tag{2}$$

where, $Q$ is the standard Gaussian complementary Cumulative Distribution Function (CDF), $\sigma^2$ is the variance, $N$ is the number of samples, and $\gamma$ is the threshold signal energy. The probability of detection $P_D$ is given by Equation (3) [19].

$$P_D = Q\left(Q^{-1}(P_{FA}) - \sqrt{\lambda^2/2N}\right) \tag{3}$$

Taking $Q^{-1}$ of $P_{FA}$ in Equation (2), the threshold formula for the energy detector based on the $P_{FA}$ is derived as shown in Equation (4).

$$Q^{-1}(P_{FA}) = Q^{-1}\left(Q\left(\frac{\frac{\gamma}{\sigma^2} - N)}{\sqrt{2N}}\right)\right) \tag{4}$$

Rearranging Equation (4) gives Equation (5);

$$\gamma = \left[(Q^{-1}(P_{FA}) \times \sqrt{2N}) + N\right] \times \sigma^2 \tag{5}$$

where, $\gamma$ is the threshold signal energy, $\sigma^2$ is the variance of AWGN, $N$ is the number of samples and $Q^{-1}$ is the inverse of the tail probability of the standard normal distribution ($Q$ function). In this study, some parameters were measured and used to calculate the threshold of the system such as the energy of the signal, number of samples and variance. The energy of the signal was calculated using the detection statistic of the energy detector which is the average of $N$ observed samples $y(n)$ given by Equation (6) [20];

$$T = \frac{1}{N} \sum_{i=0}^{N} |y(n)|^2 \tag{6}$$

where, $N$ is the number of observed samples $y(n)$. If the number of samples used for detection is large enough

($N > 250$), we can make use of the Central Limit Theorem to approximate the distribution of the test statistic as Gaussian, with mean and variance as stated above for each of the hypotheses [19]. Thus,

$$T = \sigma^2 \tag{7}$$

Since the spectrum sensor computes the power of each channel, the noise floor level can be defined as the lowest power level detected (weakest channel detected). Then, the decision threshold can be computed based on this value [21]. For large values of $N$, the corresponding Gaussian Probability of Misdetection ($P_{MD}$) is computed as 1 minus the $P_D$ value of the normal CDF i.e., $P_{MD} = 1 - P_D$. The input (NBFM signals from VHF LMRS) was detected by RTL-SDR and their energy computed. The result was then compared with a threshold energy to obtain the presence or absence of VHF NBFM signal transmission as shown in Fig. 1.

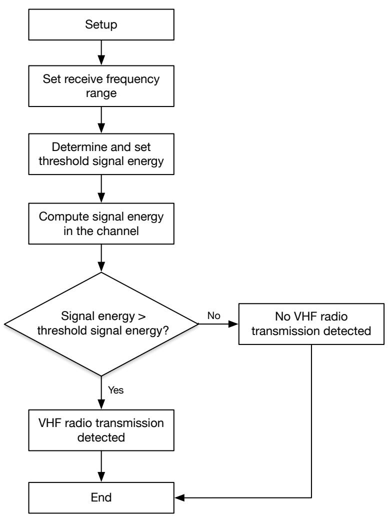



Fig. 1. Workflow of our proposed spectrum sensing approach.

*3) Simulated VHF LMR signal detection setup:* We developed signal detection blocks and connected them using python scripts to make a complete signal detection setup. The setup was then further designed and run in two cases: (1) no synthesized VHF NBFM signal transmission and (2) synthesized VHF NBFM signal transmission.

*4) Real-time VHF LMR signal detection setup:* Motorola VHF Radio was configured to transmit NBFM signal through the signal detection setup. The same parameters as in the simulation were used. The energy detector consisted of RTL-SDR connected to the developed signal processing blocks. The set up was then run in two cases: (1) no VHF NBFM signal transmission and (2) VHF NBFM signal transmission.

*5) Performance analysis of the proposed setup:* To analyse the performance of VHF LMRS in TVWS, simulated setup results were used as a benchmark to validate the real-time setup results. The metrics used are $P_D, P_{MD}, SNR$, and signal energy.

## IV. Implementation and Performance Evaluation

The implementation used an idle VHF TV channel for VHF LMRS transmissions. In general, the bandwidth of the DVB-T2 TV channels is 7 MHz. A lot of VHF radio applications do not need such a vast spectrum, e.g., voice communications, distress alerts, GPS alerts etc. For these types of applications, we considered dividing a single TVWS channel into multiple sub-channels. Our adopted sub-channel formation scheme considers each sub-channel as a 12.5 kHz-wide channel. Channel 5 is a terrestrial TV channel occupying the spectrum range of 174–181 MHz. For this channel, when our sub-channel formation proposal is applied, the first sub-channel frequency range is 174–174.0125 MHz with the centre frequency at 174.00625 MHz. In this way, our sub-channel formation can form 560 such sub-channels within Channel 5. The performance in the TVWS channel was evaluated using transmissions in real-time setup and a simulated setup as a means of validation.

### A. Simulation implementation

We synthesized a NBFM signal using GRC and AWGN added to NBFM signal and the resulting signal was passed through the setup in Fig. 2(a). The simulation parameters were set as follows. NBFM transmitted signal, AWGN channel noise, 1024 samples/FFT size, 174–174.0125 MHz frequency range, 174.00625 MHz center frequency, and 0.05 desired $P_{FA}$.

*1) Determining threshold signal energy for simulated setup:* Threshold energy for this simulation can be calculated using Equation (5). The maximum noise signal energy (peak) in the channel was first computed using the GRC blocks and displayed by WX GUI number sink, noise variance computed using Equation (6) and Equation (7) and finally the threshold was computed. The noise spikes have peak energy of 0.0274697449 units (Fig. 2(c)), and the number of samples considered for this project is 1024, By substituting the values in Equation (6), variance can be obtained; since it is approximated to be equal to test statistic T as indicated in Equation (7);

$$\sigma^2 = \frac{0.0274697449}{1024} = 2.68259 \times 10^{-5}$$

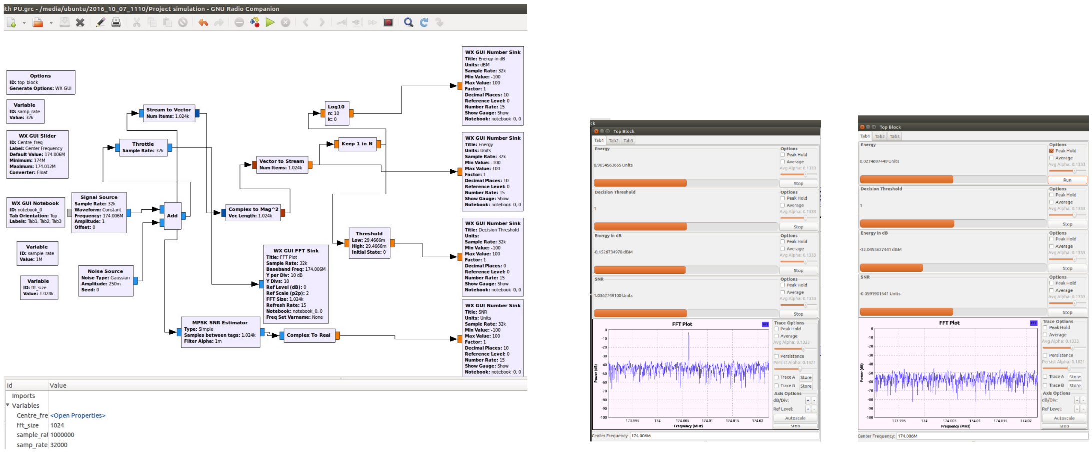
For the $P_{FA}$, IEEE standard suggests $P_{FA}$ to be less than 0.1 [22], [23]. In this study, we considered a much stricter $P_{FA}$ of 0.05 to ensure that critical VHF applications have access to the spectrum when needed.

$$\text{Therefore, } P_{FA} = 0.05,\ Q^{-1}(0.05) = 1.6449.$$

Thus, from Equation (5), the threshold signal energy, $\gamma = [(1.6449) \times \sqrt{2 \times 1024}) + 1024] \times 2.68259 \times 10^{-5} = 0.0294666329$.

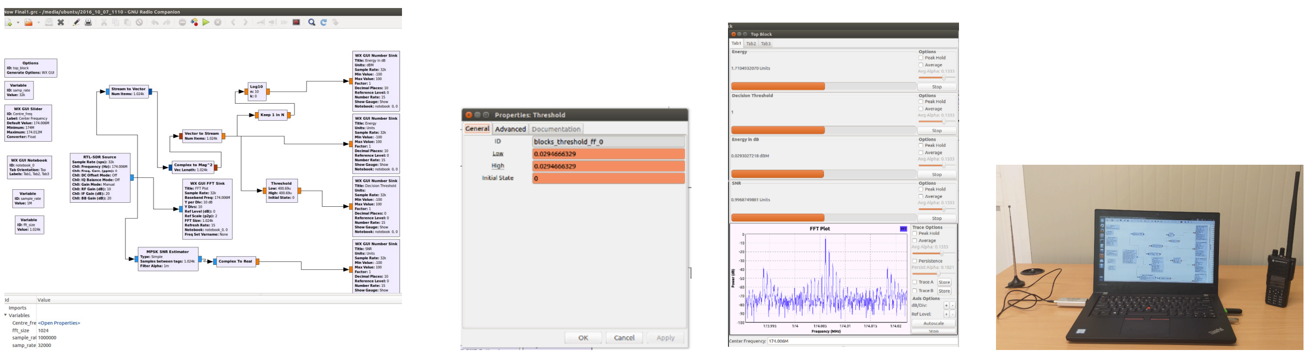
We set this value in the threshold block (Fig. 3(b)) and executed the simulation considering two different cases.

*a) No VHF NBFM signal transmission:* In this case we transmit AWGN to the system and the result is even noise spikes with very low energy and $SNR$ (in linear units) as



(a) (b) (c)

Fig. 2. (a) Simulation setup for noise signal energy detection, (b) Simulated NBFM in the channel, and (c) Peak noise energy considered for threshold determination.



(a) (b) (c) (d)

Fig. 3. (a) Setup for real-time energy detector for spectrum sensing in GNU Radio, (b) Threshold setting in the threshold block, (c) VHF LMR signal transmission in TVWS channel, and (d) Setup for real-time energy detection for spectrum sensing on RTL-SDR, GNU Radio and VHF Radio platform.

shown in Fig. 2(c). The decision threshold value is 0 indicating absence of VHF NBFM signal transmission.

*b) VHF NBFM signal transmission:* In this case, an NBFM synthesized signal is present, with high signal energy and $SNR$ compared to when there was no VHF NBFM signal transmission. The decision threshold is 1 indicating the presence of the VHF NBFM signal as shown in Fig. 2(b), thus fulfilling the test statistic conditions in Section III-1.

*2) Simulation results and analysis:* The simulation in case 2 above was then run 10 times and the noise variance, $SNR, P_D$, and $P_{MD}$ were computed: (i) noise variance was computed using Equation (7), (ii) $SNR$ was measured using $SNR$ estimator block), (iii) $P_D$ was calculated using Equation (3), and (iv) $P_{MD}$ was calculated as $(1 - P_D)$. On the results, an analysis of the plot in Fig. 4(a) shows that as the $SNR$ increases the $P_D$ also increases and vice versa. From the plot in Fig. 4(b), as the $SNR$ increases, $P_{MD}$ decreases and vice versa.

### B. Implementing real-time energy based detector in TVWS and GNU radio

In this section we designed frequency channels on the Motorola DP4801e VHF radio. The radio is configurable using Motorola Customer Programming Software (CPS). For this research, Mototrbo CPS version 16.0 build 827 was used.

Considering Channel 5 (174–181 MHz) with sub-channel 174–174.0125 MHz, using the sub-channel for transmission, the centre frequency was set as 174.00625 MHz. The use of 12.5 kHz in the VHF radio ensured narrow banding rule where the channel bandwidth is 12.5 kHz. The radio thus produced Narrow Band Frequency Modulation (NBFM) signals that were transmitted through the TVWS which were then detected by the RTL-SDR/GNU platform.

Fig. 3(d) shows the test-bed setup of the real-time energy sensor. It consists of one VHF radio (used as the transmitter), RTL SDR connected to the Laptop via USB. The laptop used was running Ubuntu 16.0 Operating System with GNU radio software version 3.7.7 installed. The laptop hardware specifications were Model: Lenovo Thinkpad T470, Hard disk space: 500GB, RAM: 4GB, Processor: Intel core i5.

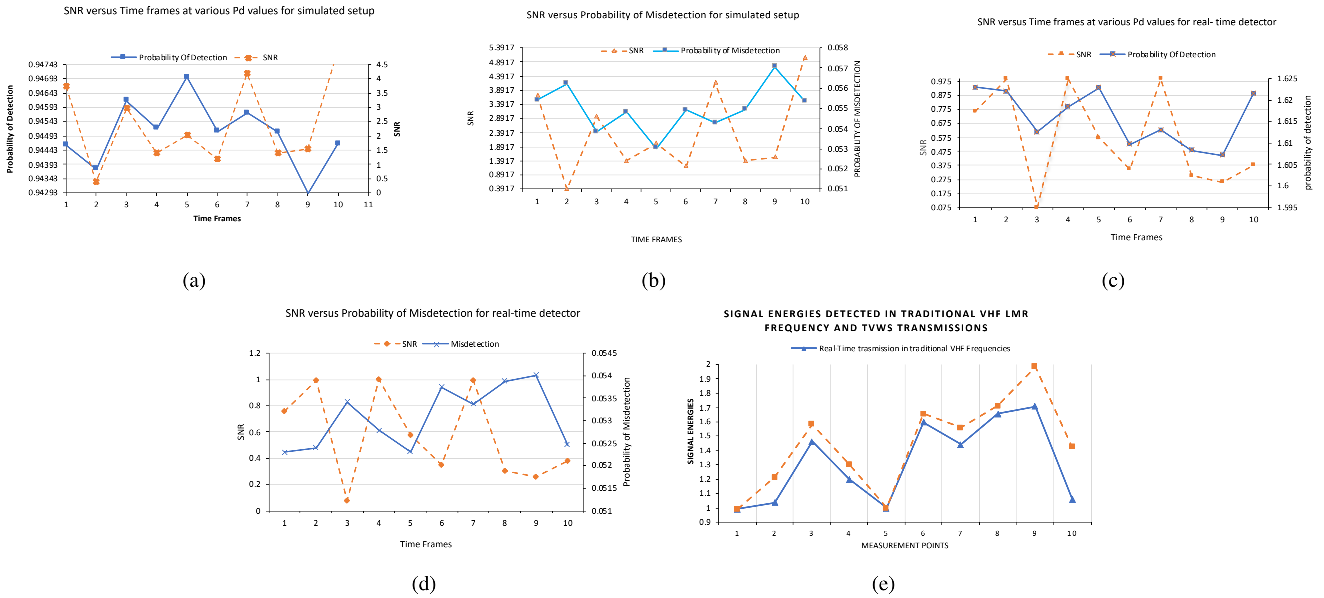



Fig. 4. (a) $SNR$ versus time frames at various $P_D$ values for simulated setup, (b) $SNR$ versus time frames at various $P_{MD}$ for simulated setup, (c) $SNR$ versus time frames at various $P_D$ values for real-time detection setup, (d) $SNR$ versus time frames at various $P_{MD}$ values for real-time detection setup, and (e) Comparison of transmissions in traditional VHFLMR frequency and TVWS frequency.

For efficient detection of VHF NBFM signal in the GNU radio companion, the RTL–SDR was configured with 174.00625 MHz centre frequency, 12.5 kHz bandwidth, 174–174.0125 MHz radio frequency range, and one channel. Spectrum sensing by the real-time detector followed the algorithm in section III-1, Fig. 1. This was achieved using GRC flow diagram in Fig. 3(a). The diagram starts with the block called RTL-SDR source block which is responsible for receiving the VHF signals and converting them into streams of data. Through this block our signal parameters of interest such as centre frequency, channel bandwidth etc. were set as described above. These parameters helped in proper analysis of the captured data stream. After this, the signal was directed into three directions, in the same order as in Section IV-A. To evaluate the performance of the real-time detector, $P_D$, $P_{FA}$, $P_{MD}$, $SNR$, frequency channel and signal energy were considered.

Threshold energy for the real-time detector was calculated using Equation (5). The maximum noise signal energy (peak) in the channel was first computed using the GRC blocks and displayed by WX GUI number sink. The noise variance and finally threshold were computed based on this. The noise spikes had peak energy of 0.00037355355 units, and considered 1024 samples. Variance is calculated in the same way as in the simulation implementation in Section IV-A1. Therefore,

$$\sigma^2 = \frac{0.00037355355}{1024} = 3.6478 \times 10^{-7}$$

$$P_{FA} = 0.05,\ Q^{-1}(0.05) = 1.6449$$

Then, threshold signal energy evaluates to;
$\gamma = \left[\left(1.6449 \times \sqrt{2 \times 1024}\right) + 1024\right] \times 3.6478 \times 10^{-7}$
$\gamma = 0.00040069.$

This threshold signal energy value was then set in the threshold block of the GRC flow diagram and sensing was achieved using the algorithm in Section III-1, Fig. 1. The experiment was then run in two different cases.

*a) No transmission from the VHF Radio:* In this case the channel was occupied by noise signal energy and the result was even noise spikes with a very low energy and $SNR$ (in linear units). The decision threshold value is 0 indicating absence of the VHF LMR signal transmission.

*b) With transmission from the VHF Radio:* In this case, the radio was tuned to the channel frequency configured in RTL-SDR and Press To Talk Button (PTT) on VHF Radio was pressed, resulting into the NBFM information signal captured by RTL-SDR. The signal was processed based on the algorithm in Section III-1, Fig. 1 and implemented in GRC. The WX GUI FFT sink displays spectrum with high signal energy and $SNR$ compared to when there was no VHF NBFM signal transmission. The decision threshold is 1 indicating the presence of VHF LMR signal transmission in TVWS as shown in Fig. 3(c), thus fulfilling the test statistic conditions in Section III-1. From Fig. 3(c), the decision threshold is 1, indicating that the VHF LMR signal transmission and the channel is occupied.

*c) Results and analysis:* The experiment was then run 10 times and the noise variance, $SNR$, VHF LMR signal energy, $P_D$, $P_{MD}$ were measured and calculated (as explained in Section III-1). An analysis of the plot in Fig. 4(c) shows that as the $SNR$ increases the $P_D$ also increases and vice versa. In comparison with the same graph in the simulation, this shows a similar trend between the two, and thus the real-time detector performs as expected. The average of the 10 results of $P_D$ values is 0.946932558, approximately 0.95, which fulfils our condition to achieve $P_{FA}$ of 0.05. From the plot in Fig. 4(d), as the $SNR$ increases, the $P_{MD}$ decreases and vice versa. This shows a similar trend in the simulation graph in Fig. 4(b), and thus the real-time detector behaves as expected.

### *C. Comparing transmissions in traditional VHF LMR frequency and VHF TVWS frequency*

Repeating the procedure in Section IV-B, with traditional LMR frequency, e.g., 153.3 MHz, and noise when there is no transmission recorded as 0.0001782223, $P_{FA} = 0.05$, and thus threshold energy being 0.00019118. By comparing the signal energies of transmissions in traditional LMR frequency and TVWS frequency, the chart in Fig. 4(e) was obtained.

From the plot in Fig. 4(e), the results indicate higher energy detected (average improvement of 0.12768 – approximately 10% improvement) when using VHF TVWS frequency than in traditional VHF LMR frequency. This implies improved penetration in thick forests or remote areas/emergency where ideal telecommunication systems are unavailable and private VHF radio communications are the only choice for delivery of mission critical voice and data services such as GPS, tracking.

## V. Conclusion

In conclusion, the CR implementations for VHF LMRS is an emerging technology and can be implemented with TVWS, RTL-SDR and the GNU radio platform. The real-time results obtained are evidence for the test-bed that was built. Moreover, the difference between the energy detector simulations and real-time test-bed results show the differences in their performances, which highlights the limitation of hardware and the channel used. Notably also, the transmission in TVWS was generally of high signal energy compared to transmission in traditional LMR frequency and thus improved penetration in remote areas and thick forests. In future work, we aim to vary the probability of false alarm and evaluate its effect on the signal sensing.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