Implementation of a real-time auto-tunable energy detector for spectrum sensing in the context of cognitive radio

E.W. Mureu, P. K. Kihatoand P.K. Langat

Abstract—With the ever increasing popularity of wireless applications, more innovative ways of enhancing spectral efficiency are needed in-order to avail more bandwidth. One such way, is to allow for secondary use of channels allocated to a licensed primary user, but which in a given time or location happen to be idle. This is on condition, that no harmful radio interference is caused to the licensed primary user, and that the secondary user should vacate the channel immediately, once the former is present.

One of the proposed technologies to enable this, is the Cognitive Radio (CR). A CR is a form of wireless communication in which a transceiver can intelligently detect which communication channels are in use and which are not, and instantly move into vacant channels while avoiding occupied ones. This is with an aim of optimizing the use of available radio-frequency (RF) spectrum while minimizing interference to other users.

A key requirement of CR is spectrum sensing which aids in the detection of the channels status. Several spectrum sensing methods exist but the energy detection method is preferred due to its simplicity and ability to sense even unknown signals. Most of the research work carried out in this area is simulation based. Where practical implementation has been done, it involved sensing of only a narrow radio spectrum band. An implementation of a wide band auto-tunable energy detector would be more useful and realistic in the context of cognitive radio.

This paper presents results of a practical real-time auto-tunable energy detector implemented in MATLAB, using the Universal Serial Radio Peripheral (USRP) N200 kit, that could perform spectrum sensing within the 10 MHz to 3.2 GHz spectrum band. The system was able to sense any desired radio band or channel within this range and detect the presence or absence of the licensed primary user signal. The performance of the implemented system was compared with that of a commercial spectrum analyzer using the probability of detection and the probability of false alarm parameters. The performances of the two systems were found to be very similar thus validating our system.

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Keywords—Cognitive Radio, Energy detector, Spectrum sensing, USRP.

I. INTRODUCTION

THEpopularity of wireless communication has continued to put a big strain on the available radio spectrum as more and more applications are developed. The result of this is scarcity of radio spectrum to support new wireless applications as most of it has already been allocated. But from the spectrum occupancy measurements that have been conducted around the world, it has been found that a good chunk of the allocated radio spectrum remains idle [1] - [5]. Therefore, study has shown that the scarcity of the radio spectrum has more to do with the approaches used to share and access the spectrum as opposed to its over utilization [6]. There is therefore need, for more innovative ways to allocate and manage radio spectrum to address this artificial shortage. The cognitive radio system is one such innovation [7]. A Cognitive radio system (CRS) is defined as a radio system employing technology that allows the system to obtain knowledge of its operational and geographical environment, established policies and its internal state; to dynamically and autonomously adjust its operational parameters and protocols according to its obtained knowledge in order to achieve predefined objectives; and to learn from the results obtained. CRS makes it possible for devices to use radio spectrum on opportunistic and secondary basis on condition that they don't cause harmful interference to the primary users [8].

One of the key functionality of the CRS is the spectrum sensing that allows the system to obtain knowledge of its operational and geographical radio environment. A number of spectrum sensing methods have been proposed [7]. Energy detection method for spectrum sensing was used in this study due to its simplicity and not requiring a prior knowledge of the Primary User signal (PU).

This study therefore proposed to implement a real-time auto-tunable energy detector for spectrum sensing in the context of cognitive radio. The system was meant to automatically tune and measure the signal power of any desired radio frequency band in real time. The measured signal was compared with the set threshold value to determine the presence or absence of the PU signal. The proposed system was implemented using a Software Defined Radio system comprising of a GNU radio and USRP N200 module. To ascertain its functionality, it was used to carry out spectrum occupancy measurement within the Digital Terrestrial Television (DTT) band which in Kenya lies between 470 MHz to 694 MHz in the radio spectrum [9]. A commercial Rigol DSA832E spectrum analyzer was used to carry out parallel spectrum occupancy measurement in-order to validate results obtained from the proposed system.

The rest of the paper is organized as follows: Section II deals with literature review, section III deals with the methodology, section IV deals with results and discussion and conclusion is presented in section V.

II. LITERATURE REVIEW

This section introduces concepts of cognitive radio system, energy detection, software defined radio, GNU radio, USRP, and the related works.

A. Cognitive radio

A Cognitive Radio (CR*)* is an intelligent wireless communication system capable of gathering knowledge of its surrounding radio environment, which it then uses to increase its communication channel reliability and to dynamically access underutilized spectrum resources.

Opportunistic Spectrum Access (OSA*)* is currently one of the main applications of CR. The CR cycle involves three processes namely; Spectrum sensing, Spectrum analysis and Spectrum decision. This study concerns itself with the spectrum sensing process of the CR. There are different spectrum sensing techniques which are used to check for presence or absence of the primary user signal in a given radio frequency band. As earlier mentioned, this study used the energy detection method of spectrum sensing due to its simplicity and ability to sense even signal whose transmission properties are not known [7].

B. Energy detection

This approach is the most common spectrum sensing scheme, due to its ease in simple implementation and low computational complexities. Furthermore, it is considered more generic as there is no need for any prior knowledge about the primary user's signal.

In order to measure the energy of the received signal, the output signal of band pass filter with bandwidth w, is squared and integrated over the observation interval T. Finally, the output of the integrator, $\mathrm{x(t)}$, is compared with a threshold, λ, that depends on the noise floor, to decide whether a primary user signal is present or not [7]. The principle of energy detector is shown in Fig. 1

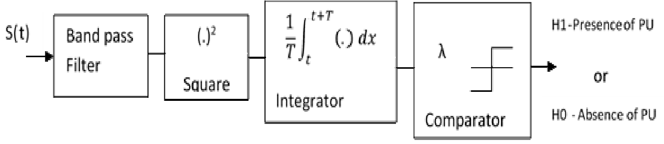

Fig. 1: The principle of energy detection

In this method, the signal is detected by comparing the output of the energy detector with a threshold that depends on the noise floor. Two hypothesis of received signal are considered. *H0* when the PU is absent and *H1*when the PU is present.

$$H1: y(n) = s(n) + u(n) \qquad (1)$$

$$H0: y(n) = u(n) \qquad (2)$$

Where *y(n)* is the received signal, *s(n)* is the PU signal and *u(n)* is Additive White Gaussian Noise (AWGN) noise with zero mean.

The PU signal is detected by comparing the output *X*of the sensing algorithm, with a decision level (threshold level,λ) as shown in Fig. 1.

Test statistics is given by

$$X = \sum_{n=1}^{N} |y(n)|^2 \qquad (3)$$

Where X is the energy of the received signal and N is number of samples.

To evaluate the performance of the spectrum sensing techniques, a number of metrics have been proposed, including the probability of detection, P_d, the probability of false alarm, P_{fa}, and the probability of miss detection, P_{md}. *Pd*is the probability that the SU declares the presence of the PU signal when the spectrum is occupied [7].

Probability of detection ($\mathrm{P_d}$) is given as:

$$P_d = \mathrm{P}(\mathrm{X} > \lambda | H_1) = Q\left(\frac{\lambda - N(\sigma_s^2 + \sigma_w^2)}{\sqrt{2N(\sigma_s^2 + \sigma_w^2)^2}}\right) \qquad (4)$$

The higher the $\mathrm{P_d}$, the better the PU protection is.

The probability of false alarm, P_{fa}, is the probability that the SU declares the presence of the PU signal when the spectrum is actually free (idle). It is expressed as:

$$P_{fa} = \mathrm{P}(\mathrm{X} > \lambda | H_0) = Q\left(\frac{\lambda - N(\sigma_w^2)}{\sqrt{2N(\sigma_w)^4}}\right) \qquad (5)$$

The lower the *Pfa*, the more the spectrum access the Secondary Users (SUs) will obtain.

The probability of miss detection, P_{md}, is the probability that the SU declares the absence of a PU signal when the spectrum is occupied. It is given by

$$P_{md} = 1 - P_d \qquad (6)$$

These three metrics measure the efficiency of the spectrum sensing techniques and can be expressed as:

$$P_d + P_{fa} + P_{md} = 1 \qquad (7)$$

Where, λ is threshold used to determine the presence and absence of PU. σ_s^2 and σ_w^2 represent signal and noise respectively. The threshold can be calculated from equation (5) as:

$$\lambda = Q^{-1}(P_{fa})\sqrt{2N(\sigma_w)^4} + N\sigma_w^2 \qquad (8)$$

There is a tradeoff between the probability of false alarm and the probability of miss detection. Miss detection of the PU activity causes interference to the PU and false alarm results in missed spectral opportunities for SUs. This tradeoff can be expressed as conservative with $P_{fa}$and aggressive with P_{md}; and a spectrum sensing technique has to fulfill the constraints on both probabilities.

C. *Software Defined Radio*

In brief, a Software Defined Radio (SDR) is a radio system which performs the required signal processing in software instead of using dedicated integrated circuits in hardware. The benefit is that since software can be easily replaced in the radio system, the same hardware can be used to create many kinds of radios for many different transmission standards; thus, one software radio can be used for a variety of applications [10].

D. *GNU radio*

GNU Radio is a free and open-source software development toolkit that provides signal processing blocks to implement software radios. It can be used with readily-available low-cost external RF hardware to create software-defined radios, or without hardware in a simulation-like environment. It is widely used in hobbyist, academic and commercial environments to support both wireless communications research and real-world radio systems.

GNU Radio performs all the signal processing. You can use it to write applications to receive data out of digital streams or to push data into digital streams, which is then transmitted using hardware. GNU Radio has filters, channel codes, synchronization elements, equalizers, demodulators, vocoders, decoders, and many other elements (*blocks*) which are typically found in radio systems. More importantly, it includes a method of connecting these blocks and then manages how data is passed from one block to another. Extending GNU Radio is also quite easy; if you find a specific block that is missing, you can quickly create and add it [11].

E. *USRP N200*

The USRP N200 offers high-bandwidth, high-dynamic range processing capability. The Gigabit Ethernet interface of the USRP N200 allows high-speed streaming capability up to 50 MS/s in both directions (8-bit samples). These features, combined with plug-and-play MIMO capability make the USRP N200 an ideal candidate for software defined radio systems with demanding performance requirements [12].

F. *Related works*

The implementation of a real-time energy detector for spectrum sensing based on software defined radio in the context of cognitive has been carried out by several authors. The authors in [13] investigated sensing performance implemented on real-time testbed of GNU Radio and USRP Software Defined Radio communication platform operating at 2.48 GHz with a bandwidth of 4 MHz In [14] the authors implemented 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 on a software-defined radio platform using GNU's Not Unix (GNU) radio and the N200 Universal Software Radio Peripheral (USRP). In [15] the authors used USRP 2901 to detect the presence of primary user based on energy detection method. Their system was implemented in LabVIEW software. The authors in [16] investigated the energy detection spectrum sensing mechanism using GNU Radio and USRP N210 operating at a center frequency of 825 MHz and within a bandwidth of 20MHz.

Similar implementations found in the related works that was reviewed concentrated had only the ability to sense only a single band. For it to be of practical importance in the context of cognitive radio, the implantation need to scan wide range of bands and do it in a repetitive manner.

This study therefore proposed to implement a real-time auto-tunable energy detector for spectrum sensing in the context of cognitive radio to fill this gap. The system could be configured to scan any band or bands of interest and do it in cyclic manner to fulfill the requirements of cognitive radio system

III. METHODOLOGY

The measurement equipment consisted of a laptop, USRP N200 device and active UHF antenna. The laptop was connected to the USRP N200 device via a Giga Ethernet switch. The GNU radio software loaded in the laptop was used to implement the software defined radio. MatLab software was used to give the Graphical User interface required for control. The necessary device drivers and supporting software were loaded and configured in the laptop to enable communication between the various devices. A MatLab script was written that could enable any desired frequency band from 10 Hz to 3.2 GHz to be scanned in the context of spectrum sensing. The script could allow the system to automatically tune to any desired frequency band, perform the spectrum sensing, output the measured signal power and depending on the threshold value, determine if PU is present or not. the energy detection was used as the method for spectrum sensing whereby the measured signal power in a given radio frequency band or channel was compared with a set threshold value.

For the purposes of testing the functionality of the proposed system, we carried out Television channel occupancy measurements on the Digital Terrestrial Television (DTT) band. In Kenya, this band is allocated frequencies between 470 MHz-694 MHz in the radio spectrum [9]. Since each TV channel occupies a bandwidth of 8 MHz, a total of 28 channels could be accommodated within this band. A threshold value was determined through measurements, for purposes of evaluating whether a channel is occupied or not. If the measured signal power within a given channel was found to be equal or greater than the threshold value, the PU was deemed to present and thus channel was occupied. Otherwise, if the measured signal power was below the threshold value, the PU was deemed to be absent and thus the channel was unoccupied. In this case, the PU is a digital TV transmitter. Using the MatLab script, the channels were scanned from the first one to the last in a repetitive manner. At each instance, the channel signal power was measured, output and stored. Table 1 show the specifications and configurations of the USRP N200 device that was used.

To validate the results obtained using the USRP based spectrum sensing module, a commercial spectrum analyzer was also used to carry out the spectrum occupancy measurements in the DTT band. The particular spectrum analyzer that used was a Rigol DSA832E which had a range of 9 KHz to 3.2GHz. Its corresponding threshold value was also determined through measurements.

Table I

USRP N200 Specifications and Configurations

Component	Specification/Configuration
Motherboard	N200r4
Mac address	00:80:2f:27:21:e4
IP-address	192.168.10.2
Firmware Version	12.4
FPGA Version	11.1
Receivers/Transmitter Frequency range	-50.000 to 50.000 MHz
Daughter board ID	UBX-40 v1
Daughter board Frequency range	10.000 to 6000.000 MHz
Gain range	0.0 to 31.5 step 0.5 dB
FFT points	1024

Figure 2 show the measurement equipment setup that comprised of a laptop, USRP N200 device, Rigol DSA832E spectrum analyzer and an active UHF antenna that was mounted outdoors. The spectrum occupancy measurements were conducted at place in Murang'a county, Kenya, whose coordinates are 0.7957^0 S, 37.1322^0E.

Fig. 2 Equipment setup

IV. RESULTS AND DISCUSSION

Table II show results for the Television channels occupancy measurements using both the proposed USRP based spectrum sensing module as well the commercial spectrum analyzer. From the results, it could be seen that for both the USRP based spectrum sensing module and the Rigol DSA832E spectrum analyzer, the number of channels found occupied and those unoccupied is 12 and 16 respectively. Therefore, for the 28 channels that were scanned, this gave a channel occupancy of 43% which meant 57% of the channels were unoccupied. Figure 3 and Fig. 4 show the distribution of the channels occupancy measured using the USRP based spectrum sensing module and Rigol DSA832E spectrum analyzer respectively. It was noted that both of measurement devices gave similar results in-terms of the percentage of channel occupancy as well as the particular channels that were occupied.

Figure 5 show the TV channels' signal power in dBm for the measurements done using both the proposed USRP based spectrum sensing module as well as the Rigol DSA832E spectrum analyzer. The measurements were done at the channels' center frequencies where signal power is expected to be highest. A different threshold value was set for each measuring device to give the desired $P_d(>90)$ and $P_{fa}(<10)$. The different threshold values could be attributed to the difference in equipment receiver sensitivities. Otherwise, it was observed that the two plots were similar.

Table II

Spectrum occupancy measurement results

Device	Total Channels	Occupied Channels	Un-occupied Channels	% of Occupied Channels	% of Un-Occupied Channels
USRP based detector	28	12	16	43%	57%
Rigol DSA832E spectrum Analyzer	28	12	16	43%	57%

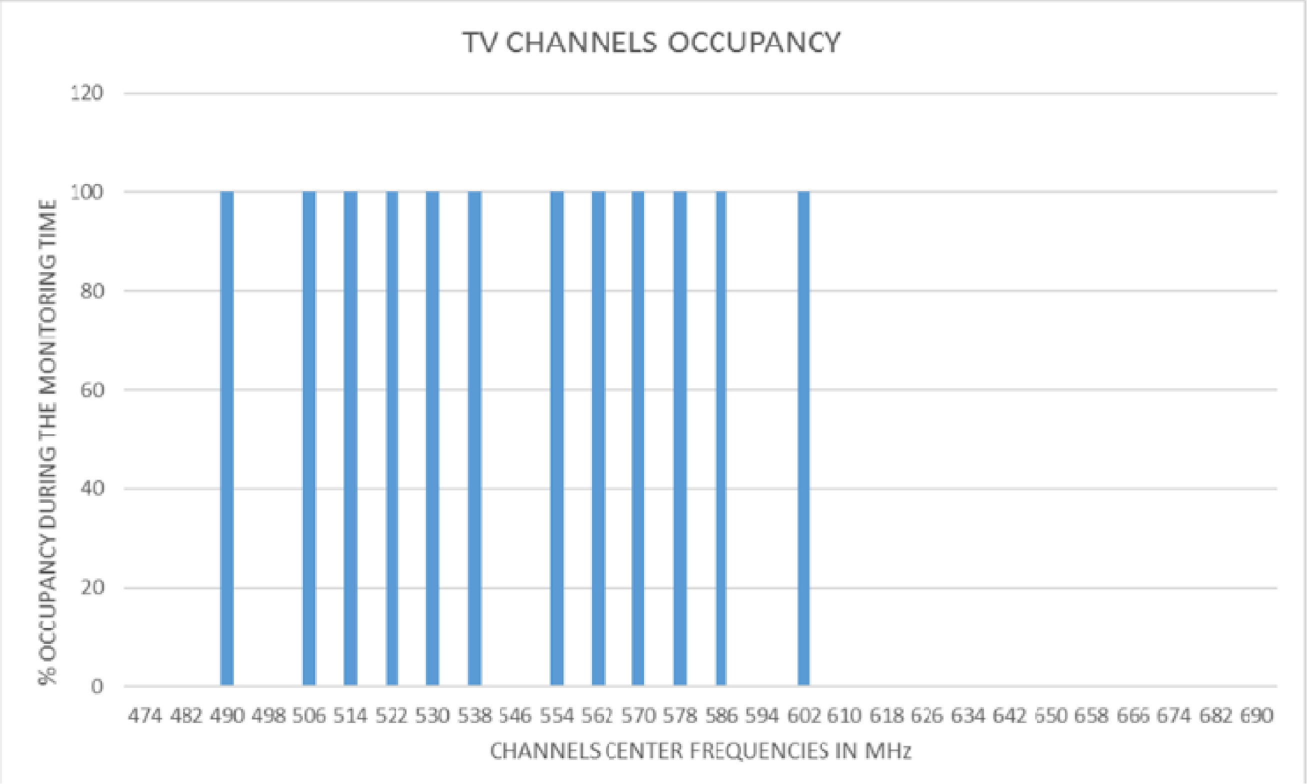

Fig. 3 The TV Channel occupancy based on the proposed USRP based spectrum sensing module measurements

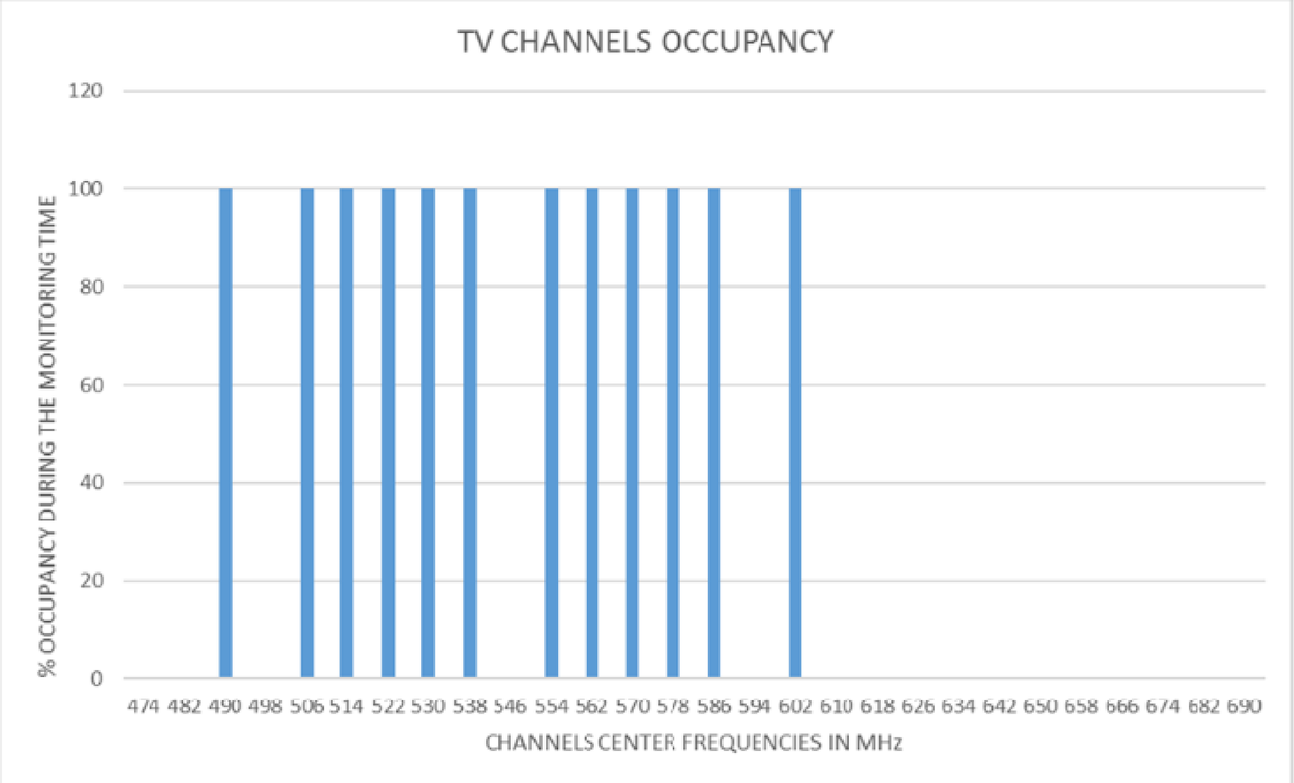

Fig. 4 The TV Channel occupancy based onRigol DSA832E spectrum analyzer measurements

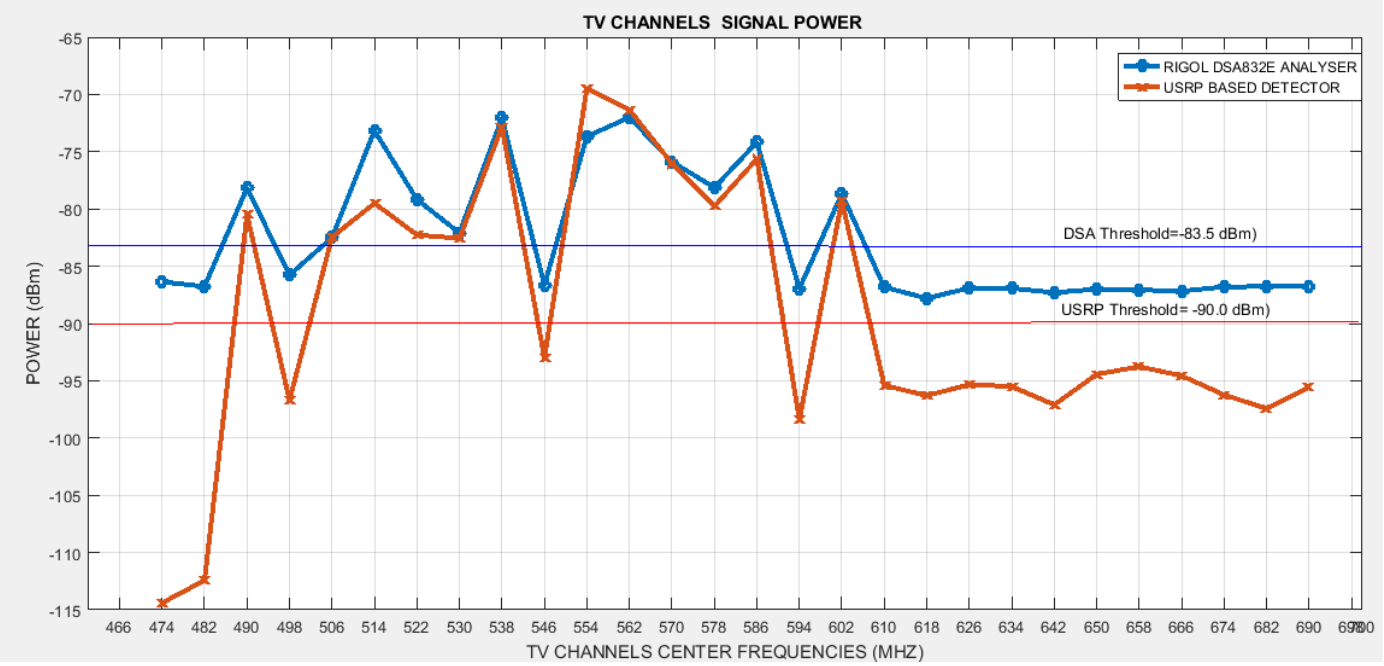

Fig. 5 TV Channels measured signal power

V. CONCLUSION

As seen, the results obtained using the USRP based spectrum sensing module are very similar to those obtained using the commercial Rigol DSA832E spectrum analyzer as far as detecting the PU signals is concerned. We could then conclude that the developed USRP based spectrum sensing module is effective and accurate and could be used for wideband spectrum sensing in the context of cognitive radio. Being a software defined radio based system, it has an advantage over the commercial spectrum analyzers due to its reconfigurability and low cost. The study has thus met its objective of implementing a real-time auto-tunable energy detector for spectrum sensing in the context of cognitive radio.

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