COGNITIVE RADIO SYSTEM FOR DYNAMIC ALLOCATION OF UHF BAND CHANNELS BASED ON 802.11AF AND USING THE ENERGY DETECTION ALGORITHM

DIEGO VELOZ-CHERREZ[1], JORDY BRAVO, CRISTIAN ALVAREZ, JOHANNA DEL POZO[2], JACQUELINE PONCE[1], MARIO PAGUAY[1],
ORCID: https://orcid.org/0000-0002-6084-2213
diego.veloz@espoch.edu.ec
ORCID: https://orcid.org/0009-0001-9580-4487
jorddy_1211@hotmail.com
ORCID: https://orcid.org/0009-0008-7872-0768
jonathancriss72_@hotmail.com
ORCID: https://orcid.org/0009-0005-8680-8741
Johanna.delpozo@unical.it
ORCID: https://orcid.org/0000-0002-3295-3047
jeponce@espoch.edu.ec
ORCID: https://orcid.org/0009-0000-1157-4972
alejandro.paguay@espoch.edu.ec
[1]Escuela Superior Politécnica del Chimborazo (ESPOCH)
Riobamba, Ecuador
[2]Università della Calabria

Abstract— This paper describes the development of a cognitive radio system through a software-defined radio approach, using universal software radio peripheral (USRP) devices and digital television equipment for communication in the UHF band. The algorithm was developed in LabVIEW and is based on energy detection, where the average power of the video carrier of the tv signal is calculated and compared with the established threshold value. As a result of detection, free channels are determined and assigned for the transmission of an Secondary User (SU), which will synchronize with the receiver the same working frequency. For the evaluation of the performance tests, a DTT transmitter and receiver were used, which simulate a Primary User (PU), and when the system detects it, it releases the frequency in use of the SU and assigns another free frequency to it to guarantee continuity of trasmission service. Tests were carried out to determine the efficiency of the system, taking into account the response time of the system and its efficiency to allow coexistence of systems within the same spectrum. System response times were measured, being 1.07 s and 41.47 s the shortest and longest response time respectively, for frequency change in order to avoid interference with the PU. Using sampling techniques, the average system response time was 21.33 s, proving that the system is efficient in environments with high interference for services that are not sensitive to latency.

Keywords— Cognitive Radio, USRP, SDR, WiFi, Coexistence, Interference

I. INTRODUCTION

The continuous technological development has generated an increase in wireless networks and applications a greater use of the radioelectric spectrum. If we add to this an inefficient use of this spectrum, they lead directly to obtaining a saturated communication systems. For this reason, different mechanisms have been developed to optimize the use of frequency channels [2] [17].

With this problem in mind, cognitive radio appears as a solution for radio spectrum congestion, which is characterized by sensing the spectrum and determining the portions of frequencies that are not used by primary users (PU) in order to be used by a secondary user (SU) without causing interference between them. Additionally, theses systems have the ability to release the channel when a PU is going to transmit in the same channel, avoiding spectrum underutilization [19].

On the other hand, control entities such as ITU (International Telecommunications Union) have encouraged the use of software-defined radio (SDR) and cognitive radio (CR) to optimize the spectrum. A cognitive radio system allows detecting when a channel is free to be used.

Despite VHF and UHF frequency bands are assigned to both analog and digital television services, not all frequencies are used. In such way, free channels can be determined and could be assigned for use by other telecommunication services. In this context, different standards have been created for spectrum optimization, such as IEEE 802.22, which bases its operation on cognitive radio and allows to take advantage of television white spaces to be used for third-party transmission, which represents using spectrum more efficient.

Due to the potential of cognitive radio and its characteristic of optimizing spectrum allocation and improving the flexibility of wireless communication systems, this work focuses on research through a bibliographic review on the detection methods that can be implemented in CR systems to determine free channels and allow the coexistence of communication systems, sharing the same spectrum and avoiding interference between them. In order to achieve this objective, software-defined radio (SDR) platforms were used for finding, identifying and using TV white spaces of the UHF frequency band as a solution to spectrum congestion. In addition, performance tests were carried out to fix possible errors in its performance through evaluation of response times, spectrum detection, efficiency of the detection algorithm and consumption of system resources.

II. COGNITIVE RADIO

Joseph Mitola III and Gerald Q. Maguire Jr. pioneered cognitive radio, which term was first introduced in their article in 1999 "Cognitive Radio: Making Software Radios More Personal", where Mitola described how to improve the flexibility of wireless services through a radio and a new language known as Radio Knowledge Representation Language (RKRL). Over the years, various authors have contributed and reformulated the concept of cognitive radio, defining it as an intelligent wireless system that interacts with its environment, which learns and adapts its operating characteristics such as frequency, transmission power, modulation, etc., providing reliable communication through efficient use of the spectrum [21]. On the other hand, Federal Communications Commission (FCC) defines this technology as a radio with the ability to vary its transmitter parameters based on the interaction of the system with the environment in which it operates [17].

In the same way, another concept mentions that CR is a system that detects the spectrum in its environment to determine whether or not to use it and intelligently obtains the necessary information to make decisions about transmission [22].

Based on these concepts, it can be said that cognitive radio is a radio frequency system that interacts with other systems within its spectrum and varies its operating parameters based on the results of spectrum sensing and thus determine the free channels to be used by unlicensed users transmission without causing interference to licensed users.

A. CR Features

A cognitive radio system has three fundamental features [22]:

- Ability to obtain knowledge: obtaining knowledge from different sources, both internal and external to the CR by sensing the spectrum. This knowledge includes: the geographical environment and the orientation of the antennas of the different systems, distribution of users in the coverage area, maximum power levels, distribution of the traffic load, established policies for using the spectrum, preferences of users, spectrum usage patterns, the existence of other radio systems, the assigned frequency and bandwidth, the coverage area and the level of interference present, and high-speed access, or low latencies, or better cost/ performance.
- Ability to modify its operating parameters: Characteristic that does not require user intervention but must be able to autonomously and dynamically adjust its operating parameters and protocols used based on the knowledge obtained through sensing.

  Decision making can be done centrally or distributed, through the collection of information from system nodes and central node (radio base or access point) and thus avoid underutilization of radio resources, using them most effective possible. However, when the number of nodes increases in the network, it becomes difficult to scale. Likewise, when networks include a set of base radio nodes or access points, and a large number of terminals, it is difficult to coordinate decisions centrally, for which reason cognitive radio systems (CRS) will require multiple decision-making teams. decision, in a distributed architecture, which allows a scalable and efficient solution.
- Ability to learn from the results obtained to continue improving their performance: This process aims to improve the performance of the cognitive radio system, using the information obtained from the actions and results stored in the previous stages. To achieve this, algorithms and

models are used to evaluate each action, thus being able to quickly optimize the operating parameters, to improve the quality of the decisions made by the system, as a way to obtain better performance.

.

B. CR Performance

A cognitive radio system must fulfill specific functions, which are shown in Figure 1. The processing functions of radio frequency signals (sensing, cognitive and adaptation) are performed by the physical layer (PHY), while the MAC layer is responsible for collecting sensing information and making operating decisions.

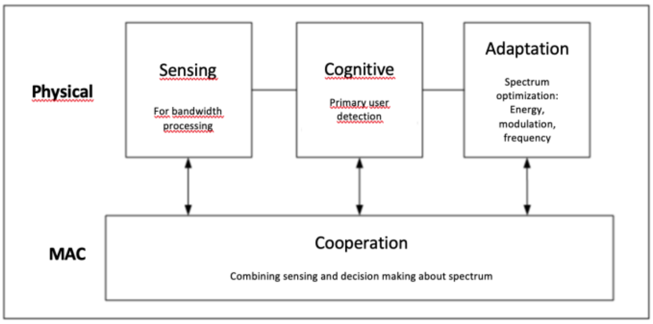

Figure 1. Stages of cognitive *radio operation [19].*

The concept of CR as a dynamic spectrum access technology is described by the cognitive loop. The cognitive system allows dynamic access to the spectrum and initiates the cognitive cycle in a portion of the radio spectrum, and later, with the use of devices with cognitive capabilities, detects the presence or absence of users through spectrum sensing, thus getting knowledge of the white spaces that will facilitate the analysis and allocation of the best available channel according to the characteristics of transmission.

Figure 2 shows the functions that a cognitive radio must fulfill both in transmission and reception, where it is observed receiver needs a mechanism to sample input signal and perform high-frequency processing. speed that allows detecting the presence of a PU [19].

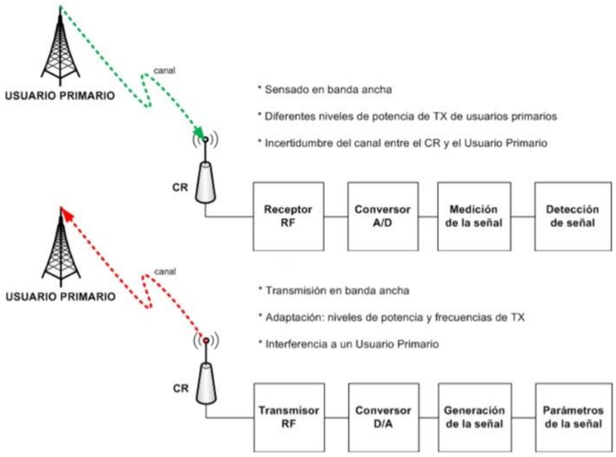

Figure 2. *Structure of cognitive radio transmitter and receiver [19].*

Referring to cognitive cycle, it is necessary to mention the main functions are sensing, managing, analyzing, allocating and sharing the spectrum. This hole cognitive process makes cognitive radio agile as long as it provides the ability to change operational parameters by means of learning and adapting to the environment.

This cycle is made up of 4 phases as shown in Figure 3 and includes analysis and identification of free spectrum channels (Spectrum Monitoring), selection of frequency bands with suitable characteristics for secondary users (Spectrum Administration) , spectrum coordination for primary and secondary users (Spectrum Sharing) and spectrum mobility when licensed users start transmission (Spectrum Mobility) [19].

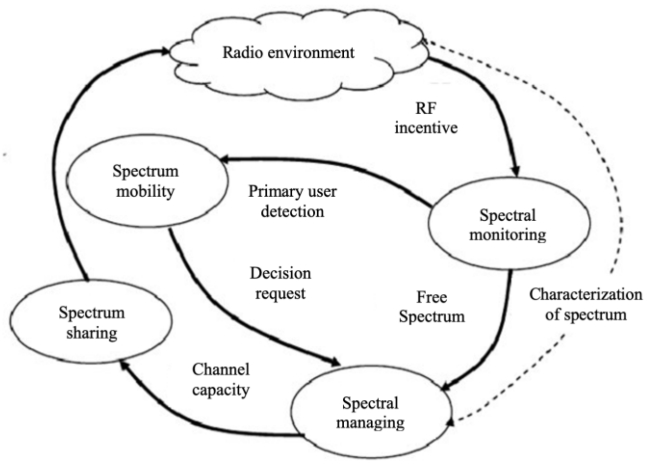

Figure 3. *Cognitive cycle for spectrum access [19].*

Each of the phases of the cognitive cycle, and the functions of each one, are described below.

- Spectrum monitoring

In this phase, SU or cognitive users carry out monitoring activities on the spectrum channels to be used, in order to detect the presence or absence of PU activity and thus determining free channels and allocating them for transmission [37].

- Spectrum management

It consists of selecting the most appropriate channel for communication from among all available channels. It refers to the technique selection to use spectrum more efficient, always keeping in mind PU have priority to use channels and establish communication in their own frequencies [37]. Initially, cognitive networks only focused on allocation and use of frequencies during the time slots were unused by PU, identified by spectrum monitoring. Current selection methods consider different policies and preferences and can be divided into two stages: spectrum analysis and decision making.

In spectrum analysis, a spectrum characterization is performed to determine resources that can be used. It is necessary to explain certain concepts about the transmission channel in order to better understand spectrum sharing techniques. Basically, techniques mentioned above consider the channel as the minimum unit of spectrum necessary for operation and expect all channels to provide the same characteristics, therefore, same capacity [37]. Channel features to be consider are: power, frequency, time, directionality, polarity, coding and modulation. However, in reality it is not possible to consider same capacity for every channel. As a result, it is necessary to take into account, for instance, interference levels, path loss (due to loss of propagation), frequency maintenance time (frequency usage time of an SU) and link layer delay (delay In communication)

On the other hand, when making a spectrum decision, it is necessary to select the pertinent operating parameters for transmission based on channel characteristics and the quality of service (QoS) demanded by the users [37].

- Spectrum sharing

This phase describes the methods to share available spectrum channels among different cognitive users, depending on CR criteria. Spectrum sharing techniques are classified according to two criteria:

- *Classification according to your network architecture:*

Centralized: A centralized entity is defined to be in charge of controlling procedures for the allocation of spectral resources and the method of medium access.

Distributed: Channel assignment is the responsibility of each network node and either local or global policies are used to medium access. This mechanism is more complex to implement because there are cases where several secondary networks compete for channels.

- *Classification according to their behavior:*

Cooperative: Cognitive users share their spectrum monitoring results from each other, in order to obtain more information and select the most suitable allocation algorithms. Centralized ones are generally considered cooperative solutions, although cooperative-distributed may also exist.

Non-cooperative: There is no exchange of information between nodes and therefore each node will take actions based on the information it obtains locally.

- Spectrum Mobility

The last phase of the cognitive cycle is responsible for changing features and transmission parameters when a PU starts using of the spectrum portion that was being used by a SU. This action implies SU migrates to another free frequency band, preserving communication [37].

The main objective is to make these transitions smooth, reducing the impact on the quality of communication, therefore, there must be a fast detection of the presence of the PU and an efficient frequency hopping.

C. Cognitive Radio Architecture

Basic architecture for cognitive radio system is a platform-independent, software-defined algorithm package, called a Cognitive Engine (CE), with a radio interface [4]. In the cognitive engine we find different functional modules designed for each cognitive capacity, among which we have: awareness, reasoning, creating solutions and adaptive control of the radio.
Cognitive radio systems define the form of the software package as a means to provide cognitive radio functionality. In such a way, it can work with radio hardware platforms that allow to reconfigure transmission parameters.

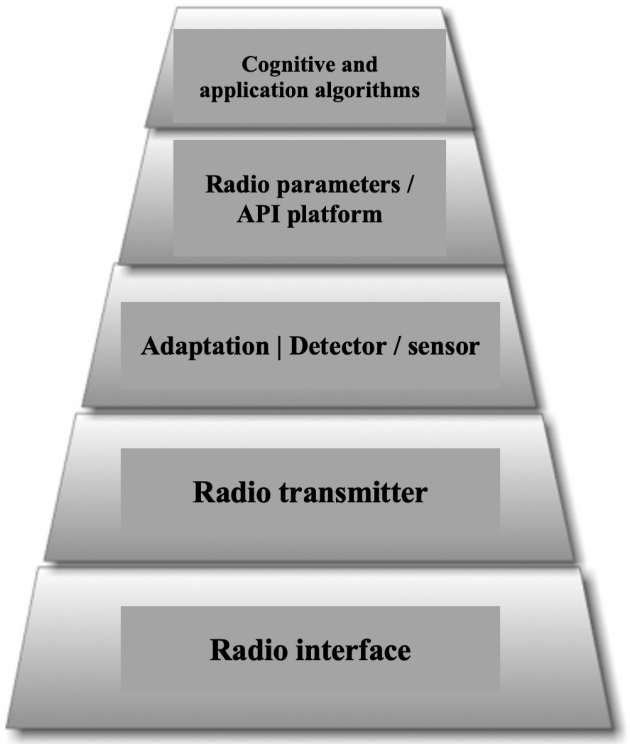

Figure 4. *General model of a cognitive radio system [4].*

Figure 4 shows a general architecture of a cognitive radio system. The cognitive engine or algorithm package manages the resources of the radio to execute cognitive functions by linking the machine learning processes together with the radio operation and adapting its operation features to achieve optimal performance [4].
Currently, there are various types of cognitive radio architectures, many of them developed by government agencies or educational institutions in order to optimize the use of the radio spectrum. Among the most outstanding: CORTEKS, which is a cognitive radio from Virginia Tech University that uses neural networks to detect and share the spectrum; CORVUS, which manages a group of unlicensed users who communicate through an ad hoc network; KNOWS, a system that detects TV spectral gaps through cooperative sensing that dynamically adjusts the frequency, channel time occupancy and bandwidth [24].

Conventional architecture of a cognitive radio network are made up of two networks: primary and secondary.

Primary or Main Network: It is the one used by the primary users. It is made up by:

- Primary User: Primary users (PU) have an exclusive use license for a certain portion of the radio spectrum. The access could be managed by the users' own base station. It should not suffer from interferences in their transmissions caused by unauthorized user operations. PU do not need additional modification or function to coexist in the environment of a CR system [37].
- Primary Base Station (PBS): It is a fixed element within the network infrastructure with a licensed spectrum, whose main function is to provide connectivity to all network devices. It should be noted that the base station does not have cognitive radio capacity or characteristics to share the spectrum [37].

Secondary or Cognitive Network: It is a network with unlicensed users, which make use of a certain portion of the radio spectrum without affecting the normal operation of the established primary network. A secondary network is made up of:

- Secondary or Cognitive User: Also known as unlicensed users. Secondary users (SU) do not have an established or licensed frequency of operation. Therefore, they implement CR functionalities and characteristics that allow them to use the spectrum dynamically without causing interference to PU [37].
- Secondary network base radio: Its function is similar to PBS. However, this base radio has cognitive radio characteristics that allows it to provide connectivity to cognitive radio users without licenses in order to use radio spectrum without produce interference [37].

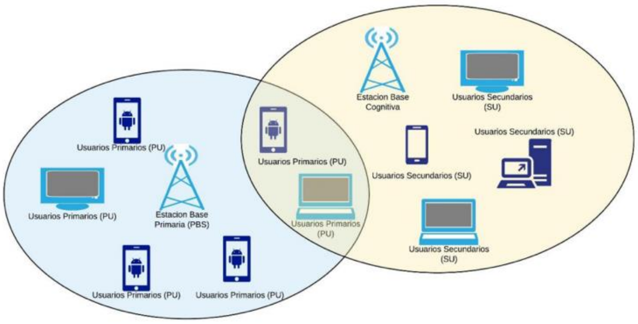

Figure 5. *Primary and secondary network of a cognitive radio network [20].*

D. Cognitive Radio Standarization

There are different proposals for standards defined by the Institute of Electrical and Electronics Engineers (IEEE):

- IEEE 802.22 (WRAN): Its purpose is to allow the deployment of regional area networks to promote wireless broadband services, extending the reach in dispersed geographic areas, such as sparsely populated rural areas that generally do not have adequate access to connectivity. It proposes the use of the television spectrum to unlicensed devices in the so-called television white spaces (TVWS)
- EEE 802.16h (WMAN): 802.16h adds CR functionalities to the IEEE 802.16 standard at the MAC and PHY layers to allow operation in license-free bands below 11 GHz. As a result, mechanisms are added to detect interference, and allow coexistence with other systems present in said bands.
- IEEE 802.11.af. (WLAN): It is a standard that defines a technology to exchange data, or connect to a wireless network access point, thus allowing Internet access [11]. IEEE 802.11af was formed in 2009, which introduces modifications to the physical (PHY) and medium access (MAC) layers of the IEEE 802.11 standard to allow operation in TVWS in the range of 54 MHz to 790 MHz. For this reason, the technology is known as White-Fi, using cognitive radio techniques and geolocation databases.

E. IEEE 802.11af Standard

This is a different version from 802.11 that generally operates in the 2.4 GHz and 5 GHz bands. It operates in the television spectrum from 54 MHz to 790 MHz and its principle is using television white spaces (TVWS). Previously, white spaces had the purpose of avoiding transmission interference between adjacent channels, but multiple investigations ensure that the spectrum spaces could be used to implement communication systems that allow access to broadband internet or other services and also allow working simultaneously with broadcast analog and digital television [15]. It would be a solution for rural areas where they lack internet access infrastructure and need low-cost implementation alternatives.

The 802.11af standard has a physical layer (PHY) that is based on orthogonal frequency division multiplexing (OFDM). Table 1 shows the parameters of the PHY layer of the standard, where it is observed that the propagation loss and attenuation due to materials is much lower compared to the other 2.4 and 5 GHz versions due to the fact that it uses frequencies of the VHF and UHF bands [5].

The main feature of the 802.11af standard is to use 114 subcarriers for the OFDM implementation, it also occupies channels with a bandwidth of 6, 7 and 8 MHz. Up to four channels or two contiguous blocks can be joined. Thus also the MIMO operation reaches up to four streams used for space time block code (STBC) or for multi-user operation (MU-MIMO). The maximum data transfer rate that can be obtained per spatial stream is 26.7 Mbps for 6 and 7 MHz channels and 35.6 Mbps for 8 MHz channels. On the other hand, if four spatial streams are used, could get a maximum transfer rate is 426.7 Mbps for 6 and 7 MHz channels and 568.9 Mbps for 8 MHz channels [18].

TABLE I. PHYSICAL LAYER PARAMETERS

Modulation	OFDM
Digital Modulation	BPSK, QPSK, 16-QAM
Convolutional coding rate	1/2, 3/4
FFT size	128
Channel bandwidth BW (MHz)	6, 7 y 8
Guard time duration (µs)	3, 6
OFDM subcarriers	114
Useful subcarriers	-58 a -2 y 2 a 58 con índice 0 en DC
Pilot index	± 11, ±25 y ± 53

Based on regulatory environments for use of unlicensed devices on available channels, the operation of TVWS is permitted on 6 MHz bandwidth channels in the United States within the frequencies 54 to 698 MHz. On the other hand, for Europe, the operation of 8 MHz channels is allowed within the frequencies of 470 to 790 MHz. In the case of Ecuador, according to Arcotel, the operation of 6 MHz channels is allowed on the frequencies of 54 to 698 MHz [12].

The topology defined by the IEEE 802.11af standard is point-multipoint, where the following elements are identified:

- GDB: Geolocation databases.
- RLSS: Secure server for registered locations.
- STA: Stations. These can be AP-STA (Access Points) or non AP-STA (User Stations).

The stations can be of two types, dependent (dependent) or enabling (enabling) with respect to a GDB. Dependent stations are those that require information to be delivered from the GDB in order to start in the network and maintain themselves. The enabling stations are those that, once the information is received from the GDB on the availability of the radioelectric spectrum, control the other dependent stations belonging to the same GDB.

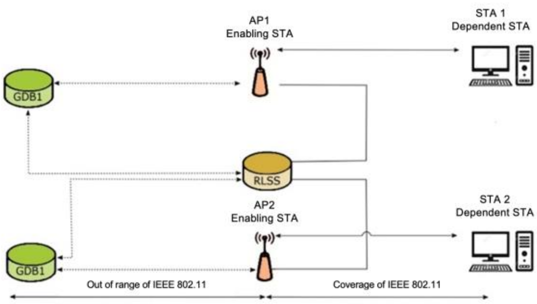

Figure 6. *IEEE 802.11af network topology*.

Geolocation databases (GDB) are responsible for storing, available frequencies by geographic location. The RLSS server uses GDB local database, which contains the geographic location information and the parameters of a number of basic service sets (BSS) of the base station. It is also responsible for distributing the parameters to the APs and STA. Dependent entities operation is controlled by an authorized GDB. The STAs maintain wireless two-way communication with the AP within any TVWS channel [12].

Figure 6 shows that the APs are working as enabling stations while the user terminals are working as dependent or slaves. This means that the APs will get the information about which spectrum to be used from the GDB and then based on that information, it is able to control the user stations to operate on the available portion of the spectrum.

To share the use of the spectrum and the TVWS map, a protocol called Registered Location Query Protocol (RLQP) is used, and the White Space Map (WSM) is used among the enabling stations. In addition, the dependent stations can consult this information both to the enabling stations and to the RLSS [22]. Because of using this information, stations can intelligently use their available spectrum, power and bandwidth resources for establishing communications.

F. Sensing spectral methods

A cognitive radio based system continuously senses the spectrum and allocating frequencies to SU when a PU is not using it. Hence, it is necessary to detect the free transmission channel in time and frequency using a spectral sensing method. That is, a SU has to periodically detect if there is a primary transmission in a certain spectrum band, otherwise, execute its transmission [31].

There are several methods of sensing the spectrum in cognitive radio which allow determining the presence or absence or of PUs in the radio bands. These methods are classified according to the type of detection that can be active or passive. The following figure shows the classification of spectrum sensing methods.

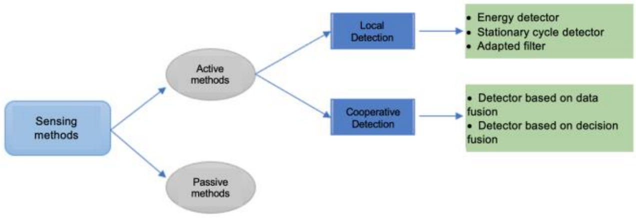

Figure 7. *Sensing spectral methods*

In this research, the energy detection algorithm was adopted to evaluate its effectiveness in avoiding interference and allowing coexistence of systems in the same spectrums.

G. Energy detection algorithm

The energy sensing technique is the most common sensing spectral method to detect channel availability [29]. Basically, the method consists of calculating the average power level of the signal received in a given bandwidth (BW) and comparing it with a threshold value (λ).

One of the advantages of this method is that the primary signal is not necessary to be known. However, it is required to have prior knowledge of the noise floor level in the channel in order to adjust the threshold as accurately as possible.

Due to its generality, the method is simple and easy to implement, as shown in Figure 8. Due to the simplicity of the detector, wrong detections are very common, since only measuring the power of the signal, without determining its origin, does not discriminate if it is an information signal or a signal of noise, interference or other secondary users [7].

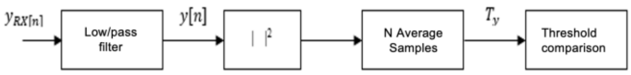

Figure 8. Energy detector block diagram

If signal to be received is considered:

$$y(n) = x(n) + r(n) \quad (1)$$

Where:

$y(n)$: Signal to be received
$x(n)$: target signal
$r(n)$: Gaussian white noise
n: Sampling Number in time or symbol index in frequency.

Assuming that each of the samples of $x(n)$ is independent. For this reason, the correlation between the samples will improve the detection technique. In addition, the channel noise samples $r(n)$ are also independent, which leads to defining that the samples $y(n)$ will also be independent [29].

The problem of sensing the radio spectrum can be expressed through two hypotheses: H_0 and H_1 that they represent the absence and presence of a primary user in the channel respectively.

$$H_0: y(t) = n(t) \tag{2}$$

$$H_1: y(t) = s(t) + n(t) \tag{3}$$

Where:

$y(t)$: Received signal

$s(t)$: Transmitted signal by PU

$n(t)$: Noise signal

Detection is done comparing the method's statistical value (M) with threshold value (λ). There are two types of relevant index in this type of detection: the probability of successful detection (P_D) and the probability of false alarm (P_{FA}).

the probability of successful detection is the probability that refers the exitency of PU in a cannel and this occurs when:

$$P_D = P(M > \lambda)|_{H_1}$$

At the same time, the probability of false alarm suggests a PU is using a cannel when it actually does not exist, causing loss of chances to use free channels. This occurs when:

$$P_{FA} = P(M > \lambda)|_{H_0} \tag{5}$$

In order to get an optimal threshold value and reduce false probabilities, it is neccesary to achieve a balance between P_D y P_{FA}.

Considering both hypothesis and adapting to discret time with an index $i = 1, 2, \dots, N$:

$$H_0: y[i] = n[i] \tag{6}$$

$$H_1: y[i] = s[i] + n[i] \tag{7}$$

The statistical value M for energy detection method is represented by the equation:

$$M = \frac{1}{N}\sum_{n=1}^{N} y[i]^2 \lessgtr \lambda \tag{8}$$

Hence, energy detector would have two scenarios. When $M > \lambda$, it is concluded that there is a PU using the channel. Otherwise, when $M < \lambda$, it is concluded that there is not a PU [7].

Considering variables $s[i]$ and $n[i]$ as random and independent variables and identically distributed with null average and variance ${\sigma_n}^2$, H_1 hypothesis can be defined as:

$$\sigma_y{}^2 = \sigma_s{}^2 + \sigma_n{}^2 \quad (9)$$

One of the weaknesses of this method is that signals are detected by comparing the statistical value or energy detector with a threshold value that depends on the channel noise, making it a real challenge to select a suitable threshold value to optimize detection and reduce the probability of false alarms [29]. In addition, the energy detection technique is not precise, since it does not allow differentiating channel noise from interference produced by other primary users, which limits its performance in low SNR conditions.

- Calculation of the threshold and uncertainty of noise power

As indicated above, the threshold level used in this method depends on the variance of the noise, for this reason, the smallest error in the estimation of the noise power in the channel produces a significant decrease in the performance of the detector. [29]. To reduce the probability of a false alarm and improve accurate detection, the threshold formula is obtained from the equations of P_D and P_{FA}. Considering the Normal distribution statistic for simplification:

$$P_D = P(M > \lambda)|_{H_1} = Q\left(\frac{\lambda - (\sigma_s{}^2 + \sigma_n{}^2)}{(\sigma_s{}^2 + \sigma_n{}^2)\sqrt{\frac{2}{N}}}\right) \quad (10)$$

$$P_{FA} = P(M > \lambda)|_{H_0} = Q\left(\frac{\lambda - \sigma_n{}^2}{\sigma_n{}^2\sqrt{\frac{2}{N}}}\right) \quad (11)$$

Figure 9 shows probabilities described in the previous equations. In addition, the probability of detection failure is observed, which is equivalent to $P_{DF} = 1 - P_D$.

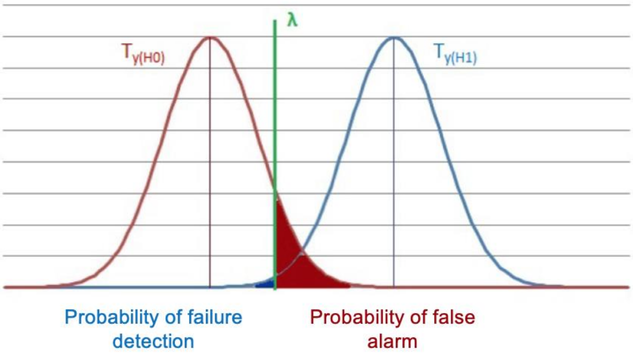

Figure 9. *Graphic representation of* P_{DF} *and* P_{FA} .

Taking into account that the energy detector seeks to increase the probability of detection in noisy environments through a certain probability of false alarm, it is more important to limit interference to a licensed user than to waste opportunities to use the spectrum [7]. For this reason, the threshold is solved in function of P_{FA}

$$\lambda_{FA} = \sigma_n{}^2\left[\frac{Q^{-1}(P_{FA})}{\sqrt{\frac{N}{2}}} + 1\right] \quad (12)$$

Where $Q(x)$ is:

$$Q(x) = \frac{1}{2}\left(\frac{1}{\sqrt{\pi}}\int_{x/\sqrt{2}}^{\infty} e^{-t^2}dt\right) \quad (13)$$

$$Q(x) = \frac{1}{2} - \frac{1}{2}erf\left(\frac{x}{\sqrt{2}}\right) \quad (14)$$

$$Q(x) = \frac{1}{2} erfc\left(\frac{x}{\sqrt{2}}\right) \quad (15)$$

Inverse or $Q(x$ is represented by:

$$Q^{-1}(y) = \sqrt{2} erf^{-1}(1 - 2y) \quad (16)$$

$$Q^{-1}(y) = \sqrt{2} erfc^{-1}(2y) \quad (17)$$

As observed in the equation Q(x), it is necessary to know the level of the noise floor to set the appropriate threshold value to reduce the probability of false alarm.

In order to set a correct threshold level and guarantee a certain detection probability at certain SNR levels, the noise power is considered to vary in the interval $\left[\frac{1}{\tau}\sigma_n{}^2, \tau\sigma_n{}^2\right]$ and fulfills that $\tau \geq 1$. So the noise floor equation is equal to:

$$SNR_{wall} = \frac{\tau^2 - 1}{\tau} \quad (18)$$

Then the noise floor uncertainty is equal to $\tau - 1$, and threshold equations will be:

$$\lambda_{FA} = \tau\sigma_n{}^2 \left[\frac{Q^{-1}(P_{FA})}{\sqrt{\frac{N}{2}}} + 1\right] \quad (19)$$

- *Signal – Noise calculation*

The signal to noise ratio or SNR (Signal Noise Ratio) is the equivalence that exists between the power of the transmitted signal and the noise power in a channel. This value is measured in decibels (dB) and is calculated using the equation:

$$SNR\ (dB) = 10log\left(\frac{Ps - Pn}{Pn}\right) \quad (20)$$

Where:

Ps: Signal power

Pn: Noise power

The SNR is a measure of quality within communication systems. A higher signal-to-noise ratio indicates good transmission and also allows for greater range and distance.

III. METHOD

This section describes the methodology and features of the necessary equipment and tools, as well as the considerations that were taken for the design and implementation of the cognitive radio system. A flow diagram of the programming carried out in the LabVIEW software is presented, focusing on the design of the algorithm for the sensing method for the transmitter and receiver to establish communication, making use of the free channels in the UHF band.

This project was implemented in Riobamba - Ecuador, so the technical legislation and the use of the spectrum that is assigned to this city were considered.

A. System architecture

The cognitive radio system focuses on 4 well-defined functions, which are:

- Monitoring TVWS
- Sensing TVWS
- Storage of sensed channels.
- Use of the appropriate frequency channel for the transmission and reception of the system.

Figure 10 shows the architecture of the cognitive radio system for transmission in the UHF band.

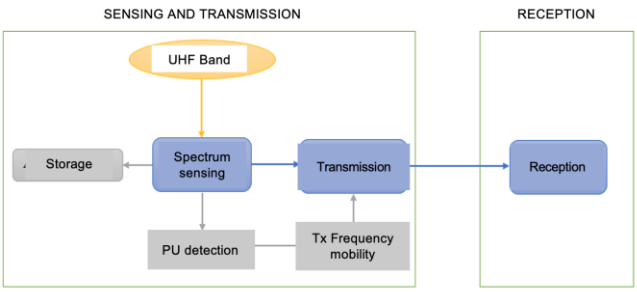

Figure 10. *Radio cognitive system architecture.*

The stages and their function within the system are detailed below:

- Sensing of the spectrum and transmission, this stage is in charge of sensing the TV channels of the UHF band which will be stored for later use.
- Data storage, the frequencies of the channels will be saved with their respective power, after being analyzed by the system.
- Transmission consists of transmitting a tone signal using the appropriate channel among the available UHF channels.
- Detection of the primary user, if the presence of the primary user is detected in the frequency band used, the system will change the frequency to continue its transmission.
- Reception consists of receiving the signal sent by the transmission system.

B. Frequency spectrum considered for sensing

For the automatic sensing of free frequencies, it was considered that the system performs the sensing of all the television channels corresponding to the UHF frequency band of the TV spectrum, it should be remembered that according to the ISDB-Tb standard for digital television, the carrier frequency of the DTT signal must be displaced 1/7 MHz (positively) in relation to its center frequency of the channel, as shown in Figure 11.

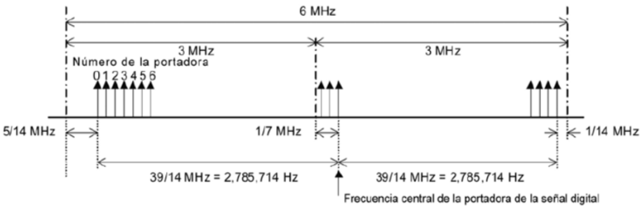

Figure 11. *OFDM carrier arrangement and central frequency of DTT signals.*

Due to the absence of digital channels in the city of Riobamba, according to the database of the Telecommunications Regulation and Control Agency (ARCOTEL), the sensing sweep for analog television channels has been considered. In the Technical Standard for the analogue television service and channel distribution plan, the frequencies of the video and audio carrier, corresponding to each channel, are established. These values are important to consider later in the design of the sensing method to achieve the detection and implementation of the system.

Table 2 shows the UHF channels with the frequency band of each channel, likewise, the frequency values for the video and audio carriers are shown.

TABLE II. UHF CHANNELS

UHF Channels			
Physical channel	**Channel frequency (MHz)**	**Video carrier frequency (MHz)**	**Audio carrier frequency (MHz)**
19	500 - 506	501.25	505.75
20	506 - 512	507.25	511.75
21	512 - 518	513.25	517.75

22	518 – 524	519.25	523.75
23	524 – 530	525.25	529.75
24	530 – 536	531.25	535.75
25	536 – 542	537.25	541.75
26	542 – 548	543.25	547.75
27	548 – 554	549.25	553.75
28	554 – 560	555.25	559.75
29	560 – 566	561.25	565.75
30	566 – 572	567.25	571.75
31	572 – 578	573.25	577.75
32	578 – 584	579.25	583.75
33	584 – 590	585.25	589.75
34	590 – 596	591.25	595.75
35	596 – 602	597.25	601.75
36	602 – 608	603.25	607.75
38	614 – 620	615.25	619.25
39	620 – 626	621.25	625.25
40	626 – 632	627.25	631.25
41	632 – 638	633.25	637.25
42	638 – 744	639.25	643.25
43	744 – 650	645.25	649.25
44	650 – 656	651.25	655.25
45	656 - 662	657.25	671.25
46	662 - 668	663.25	677.25
47	668 - 674	669.25	683.25
48	674 – 680	675.25	679.25
49	680 – 688	681.25	685.25

C. Detection method

Spectrum sensing is one of the main functions of the cognitive radio system. This function allows CR system to know television channels are busy or available, which allows the second stage of the system to be carried out, which is to transmit a tone signal on the free channel. Precisely, the objective of this system is to determine free channels, allocate and the autonomous change from one channel to another according to the media access model, which respects a hierarchy among users.

TABLE III. DETECTION METHODS

Methods / **Features**	**Energy detector**	**Stationary cycle detector**	**Adapted fliter detector**
Signal type to be known	Do not require	Require	Require
Computational processing	High	Very high	Very high
Detection precision	Good	High	High
Implementation complexity	Medium	High	Very high
Efficiency	Analog signals	Digital signals	Digital signals

When carrying out an analysis based on the main characteristics of the detection methods shown in Table III, the energy detector method is chosen due to the certain drawbacks caused by the other method, although it is true that the cycle detector stationary presents a better efficiency in sensing, which increases the complexity in programming and requires more computational processing, but the greatest limitation of using this detector is focused on the requirement of the information of the signal that is to be sensed, it was also considered Since digital television service is currently not available in Riobamba, then the performance of the energy detector is better suited for the implementation of the cognitive radio system, taking into account the presence of 7 licensed television operators in the UHF band, which allows a better demonstration in the verification of the cognitive radio system.

D. Hardware Implementation

The system allows the operation and use of communication channels by PU and SU. The concept of SU was born in cognitive radio in order for this type of users to be able to carry out transmissions in spaces that are not occupied by PUs where the main challenge is to avoid interference. The parameter that the system uses to assign channels to the PU or SU is the signal-to-noise ratio (SNR). To make an estimate of the SNR, the detector calculates the noise power in the channel that is added to a simulated noise signal. For the design of the detector system, a pre-established threshold value was chosen, since there was no presence of digital channels in the chosen study scenario.

Access to the medium of an SU depends on three factors. First, the secondary user must know TVWS or 'free channels' in the radio spectrum, to be able to carry out transmissions in the empty channels. This process is also known as interlacing (interweave). The second involves taking into consideration the transmission power of the SU so that they work properly but mainly avoiding causing interference to the PUs. The third refers to the fact that the SUs must have the capacity to share the same resources as the PUs, considering a simultaneous transmission under considerable transmission levels and through the use of coding and interference management methods, which allows work above the established level [26].

Figure 12. *Proposed Cognitive Radio System.*

Based on the previously detailed design, the system that will be in charge of monitoring the white spaces of the television channels of the UHF band, storing the data in an Excel file and for transmitting a tone signal on said frequency. You will need adequate hardware and software equipment to obtain maximum performance and proper functioning of the system. As described in Figure 12, the HyperLOG 30180 antenna is connected to the RX2 terminal of the USRP (IP:192.168.10.2) using a cable with an impedance equal to 50 ohms through SMA connectors, just like the other antennas. It was decided to use this type of antenna since it has a greater bandwidth and covers the entire UHF band. In the same way, using a category 5E UTP patch cord, we connect this USRP to the Ethernet port of the laptop that performs the system processing through a Labview script. The port speed is 1 Gbps full duplex, meeting the requirement of the radio transceiver. To this USRP we also connect the periodic LOG antenna to the TX1/RX1 terminal, which is in charge of carrying out the transmission stage of the cognitive radio system.

To connect the USRP (IP:192.168.10.3) to the laptop we use the USB 3.0 to Gigabit ethernet adapter, which allows communication to be established at the speed of 1 Gbps through the category 5E UTP patch cord. Finally, we connect the periodic LOG antenna to the RX2 terminal, which is in charge of carrying out the reception stage of the cognitive radio system.

E. Software implementation

The programming algorithm of the cognitive radio system developed in LabVIEW is explained by the flow chart in Figure 13, beginning with the establishment of the connection with the USRP through its IP address. Next, using a for loop, the carrier frequencies of the channel are generated and entered together with the USRP reception parameters such as: IQ rate, gain, active antenna, etc. During this same cycle, the IQ data of the channel are acquired and the spectrum is monitored, generating a frequency graph and calculating the values of energy, power, intensity and signal-to-noise ratio of each of the channels.

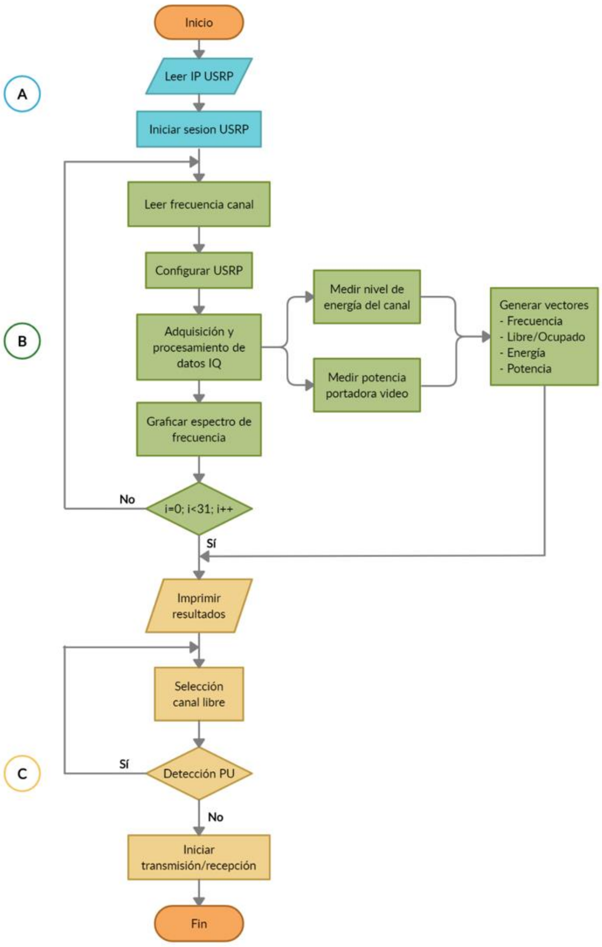

Figure 13. *System diagram flow*

With the data obtained, the channel, frequency, user absence/presence, energy and power vectors are generated, from which they are processed to determine the "freest" channel or channel with the lowest power corresponding to the channel available to generate the transmission. Once the free channel is determined, the transmission of a tone signal is generated simulating the use of the channel for our system.

Subsequently, this process is repeated for the frequencies of the UHF TV band to determine the presence of a primary user on the system's transmission frequency, and if affirmative, the system generates a transmission frequency change, releasing the channel. to avoid interference to the primary service. The sensing process is continuously repeated to detect the presence of a primary user on the used channel.

For the communication between the code developed in LabVIEW and the USRPs of the cognitive radio system, the IP addresses of each USRP are established, which are necessary parameters. Next, in Table IV, the IP addresses of each USRP and their assigned role within the system are shown.

TABLE IV. USRP FUNCTION AND IP ADDRESSING

IP Address for USRP 2932	Assigned function
192.168.10.2	Sensing and transmission
192.168.10.3	Reception

Once the IP addresses are configured, the USRP reception session is opened, through the niUSRP Open Rx Session VI function, returning the session identifier that connects to the niUSRP Set Time VI to establish a timing time for the USRP device. , this allows the program to be executed continuously and marks the time for the start of the new acquisition and giving the device time to "set" the values stored in the buffer avoiding errors in the execution of the program.

In order to automatically generate the thirty frequencies of the UHF band channels detailed in Table II, a sweep of the spectrum was carried out through a for cycle, the same one that for each cycle obtains the carrier frequency, configures the parameters of the USRP starts the data acquisition process and performs the respective measurements in each of the channels to later print the vectors corresponding to channel, frequency, absence or presence of primary user, energy and power.

First the carrier frequency of each channel is generated. The frequencies are stored in a constant vector and by means of the index Array function the frequencies are taken one by one for each execution cycle, this value together with the reception parameters, such as: IQ rate, gain and active antenna. After generating the receiver parameters, the USRP signal is configured to then start the acquisition of the waveform using the niUSRP Initiate.vi function.

Subsequently, using the niUSRP Fetch Rx Data.vi function, it starts processing the received IQ data, providing a signal in the time domain at the output of the USRP.

This signal is processed by decomposing the data into its rectangular components to obtain its IQ graph, and in turn; Using the FFT Power Spectrum and PSD.vi function, the time domain signal obtained is converted into a frequency domain signal to obtain the frequency spectrum graph and calculate the maximum intensity of the channel.

After this, the energy level is calculated for which a simulated noise signal (AWGN) is generated with a noise power of which is added to the signal acquired by the USRP and passes through a low-pass filter (frequency of cut = 3 MHz) to finally obtain the energy level of the channel using the Energy Detector.vi function.

For the energy detection process, enter the filtered signal from which the number of samples, N, is obtained, to then calculate the sum of the square modulus of the N point energies that are finally divided for the N samples, giving as a result the average energy of the signal.

To determine the signal-to-noise ratio, the following equation is used:

$$SNR\ (dB) = 10log\left(\frac{Ps - Pn}{Pn}\right)$$

Where Ps is signal average power obtained by the USRP after being filtered and Pn is total noise power (power noise + simulated power noise).

Finally, the calculation of the channel power is carried out, using the SMT Basic Zoom Power Spectrum.vi function, the spectral power average of the signal obtained by the USRP is calculated and after being filtered, it returns a power spectrum of real value. This real value spectrum is fed into the SMT Power in Band.vi function which calculates the power in the specified band.

For the software, a portion of the channel was chosen, which corresponds to the channel's video carrier frequency to determine the presence or not of primary users. This process is explained in detail later.

Once the energy, SNR and channel power values, have been calculated, they are displayed one by one for each execution cycle of the for loop.

Finally, the measured parameters of each channel are arranged in four vectors: frequency, free/busy (T or F), energy and power; which are printed at the end of the for loop. Once the vectors with the parameters measured in the UHF band channels are obtained, the channel available to send and receive the signal of the cognitive radio system is obtained. To determine the most suitable channel for transmission, the channel with the lowest average power is calculated, in other words; the channel with the lowest noise floor using the Array Max & Min function, and in turn, using the index characteristic of the function, the frequency and channel available are obtained. Meanwhile, the vectors are concatenated with the measured parameters to form a matrix that is stored in an Excel spreadsheet.

In this way, the process of sensing the spectrum of the cognitive radio system is executed. The stages of transmission-reception, detection of the primary user and the change of frequency of the cognitive radio system are detailed later.

The algorithm for the detection of primary transmissions in the UHF band is based on the measurement of the average power in the video carrier frequency, which has higher power compared to the audio and color carriers and is located at 1. 25 MHz of the initial frequency of the channel as shown in Figure 14. This average power value is compared with the predetermined threshold and the presence or not of primary users in the channel is established.

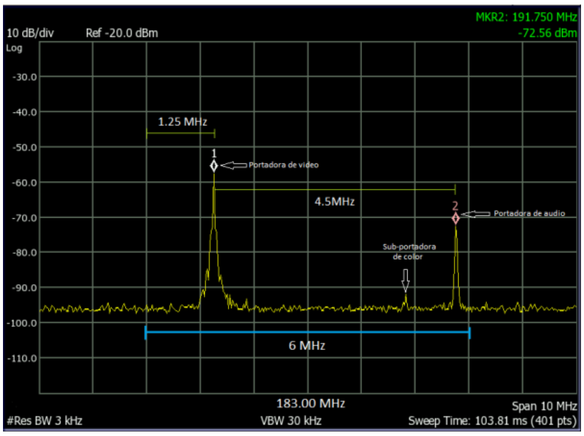

Figure 14. Analog channel frequency spectrum

The calculation of the average power of the channel is carried out by SMT Basic Zoom Power Spectrum.vi and SMT Power in Band.vi which are functions of the Spectrum Measurements Toolkit module of LabVIEW, which allow performing frequency analysis tasks. SMT Basic Zoom Power Spectrum.vi is used to calculate the power spectrum of the input signal in the time domain, around a central frequency and a specific bandwidth, obtaining at the output a power spectrum of real value and the spectral properties. On the other hand, SMT Power in Band.vi allows to measure the total average power in the channel or in a specific frequency band. In the algorithm of our program, the portion of frequencies in which the video carrier of the analyzed channel is located is defined. In addition, this tool applies signal smoothing methods through windowing and, in turn, zero padding.

Once the spectrum sensing process is carried out, the occupied channels are determined and the channel available to be used by the secondary user is calculated from the lowest stored power and its position (index) within the power vector. However, for each sense cycle the available channel changes because the average power is not constant and varies as a function of time, which would cause the secondary user's transmission to change frequency for each sense cycle. To solve this inconvenience, an algorithm was programmed that allows maintaining the free frequency of the first sensing cycle while the channel is not occupied by the primary user.

Once the spectrum sensing process is carried out, the occupied channels are determined and the free channel to be used by the secondary user is calculated from the lowest stored power and its position (index) within the power vector. The position of the free frequency obtained after the first sensing cycle is stored in position 0 of the vector index Array. This free frequency will be called the frequency in use, which is assigned to the transmitter and receiver to establish communication. Then, the same position value is taken to determine the indicator led.

Next, to determine whether or not the presence of the primary user exists, the LED indicator of the frequency in use is compared at the end of each sensing cycle. If the result of the comparison is false, the position value of the new free frequency is stored in position 1 of the vector index Array, otherwise, the value of position 1 of the vector is taken and overwritten in position 0, with what which the frequency change is achieved at the end of the sensing cycle.

This process will continue for as long as the cognitive radio system is running, making it possible to detect the appearance of the primary user on the frequency in use. However, the system should wait for the end of the cycle to change the frequency in use. To anticipate the detection of the primary user and reduce the frequency change time, an algorithm was added inside the for loop and it is based on two case loops that change the transmission channel if and only if the carrier frequency is equal to the frequency in use and the free channel led indicator is off, that is, the channel is busy. For all other cases the transmission frequency is maintained.

The transmission and reception system of the secondary user is synchronized by means of a local variable called Frequency to use, which stores the first free frequency detected by the spectrum sensing stage. As previously explained, the algorithm for the detection of primary users is constantly sensing the spectrum, verifying that the channel used by the cognitive radio system is not occupied, if applicable; the change of frequency is generated and, therefore, the value of the variable Frequency to use. For this reason, both the transmitting and receiving systems must have the ability to reconfigure their frequency parameter while transmitting or receiving. To achieve this, the transmitter and receiver were designed based on the instruction examples offered by the LabVIEW software to test its SDR functions.

The transmitter system shown in Figure 15, which begins with the niUSRP Open Tx Session.vi function in charge of initiating the transmitter session through the USRP IP control (Tx), which contains the IP address of the USRP device, and generates a session ID that connects to the other functions of the transmitter. Then the niUSRP Configure Signal.vi function which sets the transmission parameter values. For this case, the Enable channels input is defined by a constant to define a property node that will allow reconfiguring the transmission parameters on the fly.

Subsequently, a sinusoidal waveform is continuously generated at a frequency defined by the variable “Frecuencia de tono”, which is used to generate the real part of an array of sample data being transmitted. In the same way, a 90 degree out-of-phase sine wave is generated to obtain the imaginary part of the complex array of sample values to be transmitted. These data enter the niUSRP Write Tx Data.vi function that writes the baseband signal to the USRP device, then transmits the signal on the selected channel.

To maintain the transmission continuously, this function is placed inside a while loop that allows the block of baseband signal samples to be sent over and over again until the execution of the program stops or in the event that the system transmitter detects an error. Likewise, it can be observed that through a property node located inside the while loop, the transmission parameters are configured and using a local variable (Frecuencia a usar) the value of the carrier frequency is reconfigured on the niUSRP Write Tx Data function.vi , thus complying with the fundamental characteristic of cognitive radio: ability to modify its operating parameters.

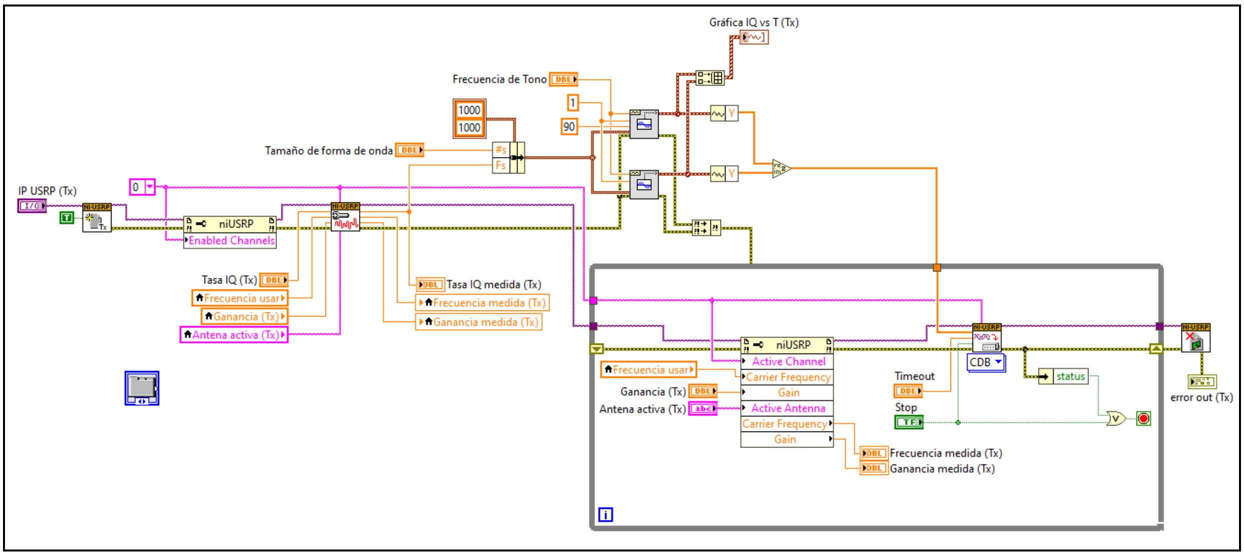

Figure 15. *Transmitter system block diagram*

In the same way, the receiver uses a property node inside the while loop to obtain the characteristic of reconfiguring its carrier frequency during the execution of the system. Figure 16 shows the diagram of the secondary user receiver. In addition, unlike the transmitter, the niUSRP Initiate.vi function is used, which sends the selected reception parameters and initiates data acquisition.

Meanwhile, the niUSRP Fetch Rx Data.vi function retrieves and processes the sent sample blocks in which the data matrix is obtained in the form of a time domain IQ data function. Subsequently, the frequency spectrum with its graph is calculated. At the same time, the real and imaginary part of the received signal is separated to give the IQ vs time graph.

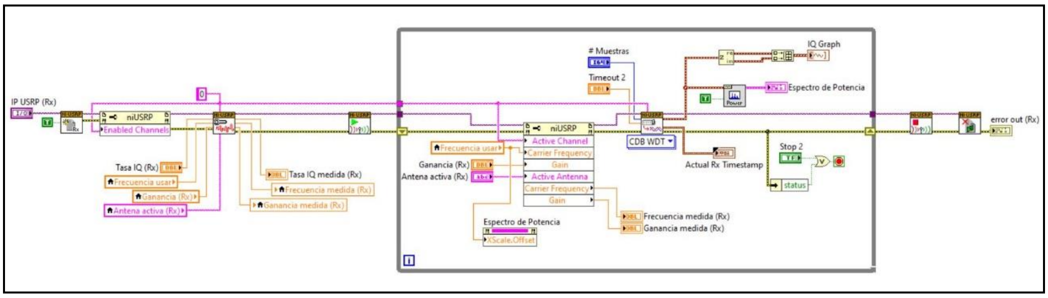

Figure 16. *Receptor system diagram block*

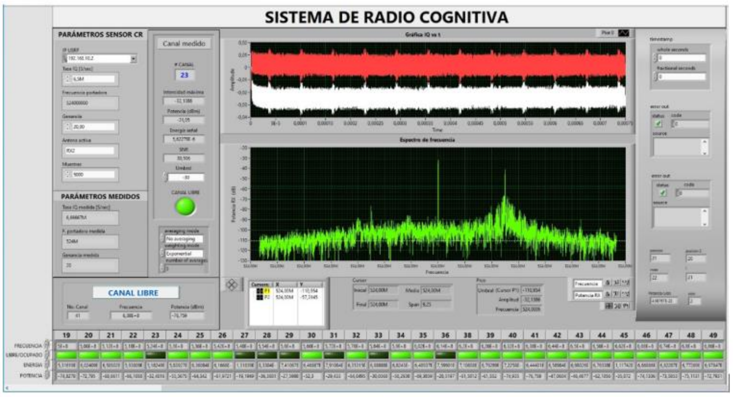

Figure 17. *Front panel of the sensing stage of the cognitive radio system.*

On the other hand, figure 17 shows the graphical interface of the software created to control and process the designed cognitive system. In this you can see the reception parameters of the CR sensor, measured parameters, the characteristics of the measured channel, in the center; we have the graphs obtained from each channel and error clusters on the right side. Finally, at the bottom are located the vectors with the channels, frequencies and parameters obtained by the sensing algorithm.

This part of the algorithm is made up of the transmission and reception parameters that are entered into the USRP, the IQ vs. time and power spectrum graphs where the execution of the transmissions in the free channel determined by the sensing algorithm will be displayed.

IV. Results

To start with the data collection in the USRP it is necessary to establish the parameters of the sensor, the transmitter and the receiver. All the parameters configured in the cognitive radio system are shown in Figure 18.

For the sensor, an IQ sampling rate of 6.5 MHz was considered due to the fact that TV channels have a bandwidth of 6 MHz, therefore a lower IQ rate would cause errors in the execution of the system due to the characteristics of the filter. and in turn; a much higher IQ sampling frequency generates an excess of samples generating more processing to the computer. In addition, a gain of 25 dB was established because robust detection is required to correctly determine the presence and/or absence of primary users.

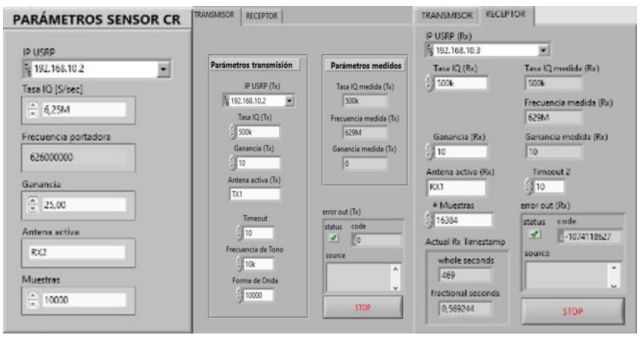

Figure 18. *Parameters configured in the sense, transmitter and receiver.*

In the same way, for the transmitter, an IQ sampling rate of 500 kHz and gain of 5 dB was configured for the secondary user signal so that the signal power does not generate interference to the adjacent channels and only occupies the channel chosen as 'cleaner' by the sensing stage. In turn, for the receiving system, an IQ sampling frequency of 1 MHz was established so that when applying the transform, the spectrum graph can be better visualized and a 20 dB gain to obtain better data reception.

The spectrum graph of the power spectrum is displayed on the front panel of the program. Figure 19 shows the spectrum obtained by the USRP for a channel occupied by a primary user or, in certain cases, with an average power level that is higher than the threshold level. In this case, we have the power spectrum of channel 31 with a bandwidth that goes from 572 MHz to 578 MHz.

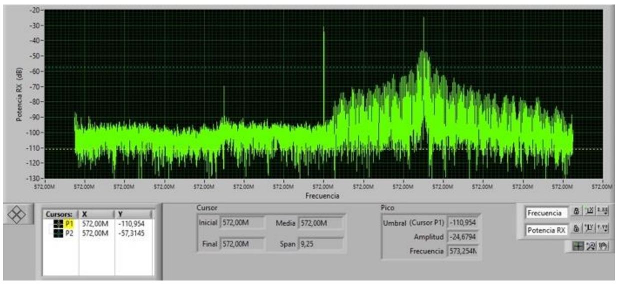

Figure 19. Power spectrum of a busy channel

The spectrum is centered on the 572 MHz frequency and concentrates the greatest amount of energy on the video carrier located 1.25 MHz from the central frequency. The system calculates the average power in a 400 kHz bandwidth around the frequency where the peak is located, in this case at 573.15 MHz, which is the one corresponding to the video carrier.

On the contrary, for a free channel, the power spectrum does not present any peak at 1.25 MHz from the central frequency, showing only the noise present in the channel, as shown in Figure 20. It should be noted that the USRP model used for the implementation it introduces a sharp peak at the central frequency (frequency 0) product of the DC compensation used by the same device and should not be confused with a video carrier.

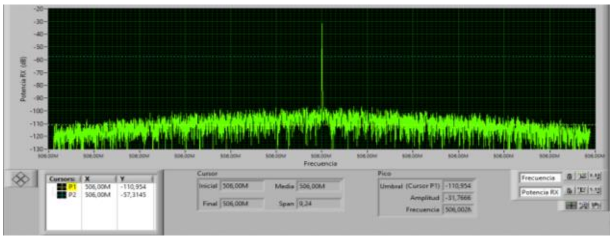

Figure 20. *Power spectrum of a free channel*

The system therefore defines the frequency and mean power of the free channel with the least noise determined by the sensing algorithm. Due to the programming logic, the system prints this value at the end of the sensing of all the channels belonging to the UHF band assigned to the television services and because the noise in the channel is variable, this value can be maintained or changed to the channel of each cycle.

After executing the algorithm, the system determined 9 busy channels and 21 free channels as indicated in Figure 21. Channels 23, 27, 29, 31, 33, 35 and 38 were the most constant, staying busy in most of the executions, while channels 43 and 44 were variable, maintaining time intervals in which no presence of transmissions was detected.

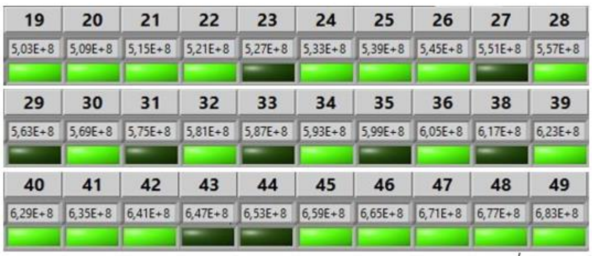

Figure 21. *Free and busy channels determined by the cognitive radio system*

When comparing the results obtained by our algorithm with the list of radio broadcasting stations and open television obtained from the ARCOTEL page, it was determined that the system correctly detected the presence of channels 23, 27, 29, 31, 33, 35 and 38 that belong to the open television stations Canal Uno, TeleAtahualpa (RTU), Ecuavisión, Televicentro (TVC), UCSG Televisión, Oromar and Puruha TV respectively

RADIODIFUSIÓN SONORA Y TELEVISIÓN ABIERTA
Categoria:Infraestructura
Listado completo de estaciones de radiodifusión sonora y televisión abierta a nivel nacional
AGENCIA DE REGULACIÓN Y CONTROL DE LAS TELECOMUNICACIONES

Provincia	Categoría	Nombre Estación	Frecuencia	Canal	Area Servida	Clase	P.E.R.
CHIMBORAZO	TV - Televisión Abierta	ECUAVISION	563	29	CHAMBO-GUAMOTE-PENIPE-RIOBAMBA	Privada	560
CHIMBORAZO	TV - Televisión Abierta	TELEVICENTRO - TVC	575	31	CHAMBO-PENIPE-RIOBAMBA-GUANO	Privada	5370
CHIMBORAZO	TV - Televisión Abierta	PURUHA TV	615,25	38	RIOBAMBA-GUANO-CHAMBO	Comunitario	16035
CHIMBORAZO	TV - Televisión Abierta	TELEATAHUALPA (RTU)	551	27	CHAMBO-GUAMOTE-PENIPE-RIOBAMBA	Privada	7940
CHIMBORAZO	TV - Televisión Abierta	CANAL UNO	527	23	CHAMBO-GUAMOTE-PENIPE-RIOBAMBA	Privada	9817,48
CHIMBORAZO	TV - Televisión Abierta	OROMAR	599	35	COLTA-CHAMBO-GUANO-RIOBAMBA	Privada	5084,1
CHIMBORAZO	TV - Televisión Abierta	UCSG TELEVISION	587	33	CHAMBO-GUANO-RIOBAMBA	Pública	13214

Figure 22. *Licensed TV channels in the UHF band for the city of Riobamba [3].*

On the other hand, the algorithm detected channels 43 and 44 as busy because they exceed the established threshold level. However, the ARCOTEL database indicates that these channels are free and are not in use by any broadcast television station. However, in the tests carried out, it is determined that the power is -16.86 dBm for channel 43 and -17.71 dBm for channel 44, exceeding the threshold level of -25 dB established for this test. In addition, the frequency spectrum obtained in these channels does not define the video and audio carriers present in the frequency spectrum of an analog signal, so it could be some clandestine transmission or interference produced by another communication system.

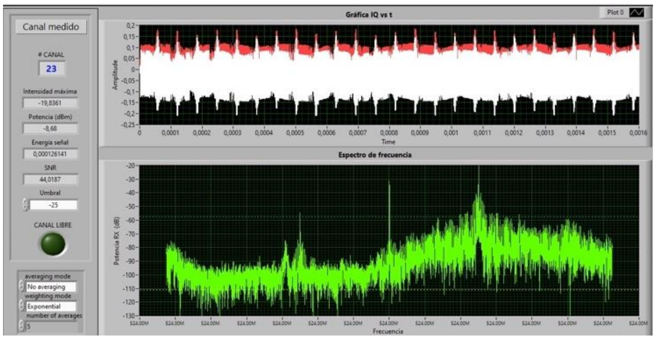

Figure 23. *Frequency spectrum of channel 23 obtained by the CR system*

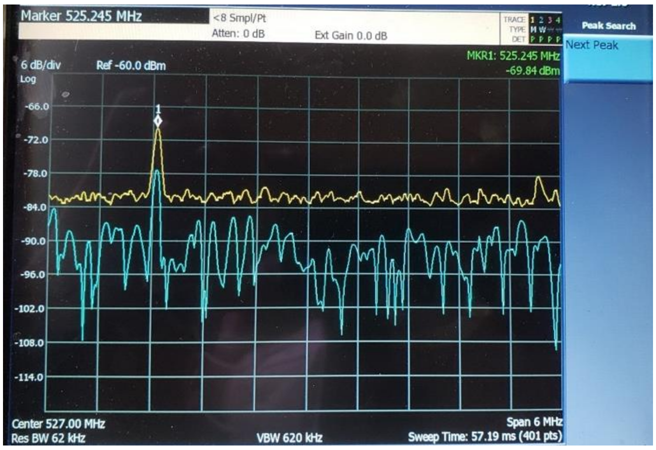

Figure 24. *Frequency spectrum of channel 23 obtained by the spectrum analyzer*

Once the first cycle of the CR sensor is finished, the free and busy channels in the UHF band are determined and the system takes all the empty channels and selects the one with the lowest power as a free channel that is assigned to the transmitter, which in turn is synchronizes with the receiver, establishing communication in the UHF band and simulating the transmission of a secondary user within the Cognitive Radio system. This assigned free channel will be used by the SU until the system detects the presence of a PU. The system is constantly updated at the end of each cycle.

In addition to the free channel assignment, the system also determines a second channel, which is defined as the Available Channel for frequency change, when the presence of a PU is detected on the channel being used by an SU. For the frequency change tests, an EN-206 HD digital modulator and a TV Explorer HD ISDB-T/Tb digital receiver were used, equipment that allowed simulating the presence of a primary user. Once the transmission of the primary user has been carried out, simulated by the DTT equipment, the cognitive radio system detects it, releases the channel in use and reconfigures its parameters to continue the SU transmission. To carry out this process, the system has the available channel, which is updated at the end of each sensing cycle and is the most suitable for SU transmission.

Due to the fact that the power measured in each channel varies constantly in each cycle, execution tests were carried out and to determine the number of tests necessary, the ideal sample size was calculated so that there is a more reliable representation of the results, such as it's shown in the following:

$$n = \frac{{Z_\alpha}^2 \cdot p \cdot q}{i^2}$$

Where:

n: size of sampling
Z:Gauss distribution value
$(Z_{\alpha=0.1} = 1{,}645;\ Z_{\alpha=0.05} = 1{,}96;\ Z_{\alpha=0.01} = 2{,}58)$
p: is the expected prevalence of the parameter to be estimated (If unknown p = 0.5)
q: is equal to 1 - p
i: is the expected error (Generally 10% is used)
To determine the number of response time samples of our system, a confidence level of 95%, an expected prevalence of 70% and a percentage of error to be made of 10% are considered. having then:

$$n = \frac{{Z_\alpha}^2 \cdot p \cdot q}{i^2}$$

$$n = \frac{(1{,}645)^2(0{,}7)(0{,}3)}{(0{,}1)^2}$$

$$n = 56{,}83 \approx 57$$

Therefore, 58 spectrum sensing tests were carried out, obtaining that on 14 occasions the system determined that the most frequent free channel is 19 corresponding to the frequency of 503 MHz and with an average power of -71.64 dBm. . In addition, channels 46 and 48 also appear as free with 11 and 9 occasions respectively.

A. System response time before channel change due to PU detection

To evaluate the efficiency of the cognitive radio system, it is necessary to determine the response time of the system before the sudden use of PU of the channel that an SU is using for communication. The objective is to measure the time it takes for the system to make the change of frequency from the moment the transmission of the primary user is generated until it is detected by the sensing algorithm, therefore, it makes the change of communication channel. It is necessary to mention that the time that the system takes to generate the frequency change will depend on the moment in which the transmission of the primary user is carried out, since the system senses the channels sequentially. Therefore, factors such as: the channel used for communication, the moment in which the PU transmission begins and the channel that the sensing algorithm is measuring at that moment must be considered. Thus we have two cases:

• Favorable case: When the PU transmission starts just before the sensing algorithm analyzes the channel in use, causing an almost instantaneous frequency change and reducing interference to a minimum.

• Critical case: When the PU transmission is generated just after the sensing algorithm analyzed the channel in use, in such a way that the system must sense the following channels and restart the sensing cycle until detecting the PU transmission. . This case evidently causes interference between the PU and the SU until the frequency change is made.

In these two cases there was a clear difference in response time. In the most favorable case, a time of 1.07 s was obtained between the detection of the PU and the change of the frequency of the transmission channel for the SU. In the most critical case, 41.47 s was obtained for the frequency change. These two scenarios are evidenced in the figures below:

Figure 25. *System response time for the favorable case*

Figure 26. *System response time for the critical case*

In order to determine the average response time in the detection of PU and frequency change, the calculated sample size was taken into account to carry out the different measurements shown in the following table:

TABLE V. MEASUREMENT OF VARIABLES

Sampling number	Response time [s]	Sampling number	Response time [s]
1	3,30	**30**	16,95
2	32,21	**31**	9,13
3	12,43	**32**	19,14
4	18,52	**33**	21,41
5	24,19	**34**	6,17
6	40,44	**35**	25,95
7	18,70	**36**	10,62
8	42,55	**37**	17,30
9	13,80	**38**	25,67
10	30,65	**39**	11,70
11	29,19	**40**	13,33

12	23,82	**41**	27,11
13	30,53	**42**	19,27
14	29,19	**43**	35,85
15	8,59	**44**	42,53
16	7,48	**45**	31,88
17	41,22	**46**	15,58
18	8,30	**47**	25,72
19	2,46	**48**	5,63
20	24,75	**49**	39,31
21	38,28	**50**	8,18
22	33,31	**51**	35,57
23	9,11	**52**	12,08
24	17,64	**53**	26,15
25	20,51	**54**	2,03
26	40,49	**55**	24,02
27	7,68	**56**	14,27
28	37,17	**57**	7,89
29	28,28	**58**	11,33

V. DISCUSSION

After analyzing time samples detailed in Table 1-3, it was determined that the average time that takes for the cognitive radio system to detect the appearance of a PU and change the frequency of the channel used is 21.33 seconds.

Considering that TV transmissions are continuous, unlike fixed-mobile systems, and that the application of the system was executed in a simulated environment, the average response time is considerably good, fulfilling the objective of causing interference as little as possible.

The detection time of the system is 1.5 seconds, this is due to the fact that the NI-USRP 2932 equipment needs at least 1 second of sensing time to carry out the acquisition and processing of the data. Despite this, the system complies with the phases of the cognitive cycle of a CR network, which are: sensing, administration, sharing and spectrum mobility, demonstrating that the system design is effective and reduces, to the extent possible, interference to authorized users and the impact on communication through efficient frequency hopping.

For all the above, this system has a certain engineering application value and can be used in systems based on IEEE 802.22, 802.11af and 802.16h standards to provide different services such as: telephone calls, Internet access service to rural areas, positioning services, etc.

Cognitive Radio presents a great benefit for telecommunications thanks to its ability to optimize the use of the radio spectrum, allowing the reuse of blank spaces from television channels and providing the opportunity to be used by other systems.

Although the energy detection method has allowed us to meet the proposed objectives. However, it is recommended to be implemented in environments with high noise, since it can increase the probability of false alarms, being able to detect free channels as busy channels.

REFERENCES

[1] AARONIA. HyperLOG 30180. [On line]. AARONIA AG, Germany. 2019. pp. 1 [Consultation: 2020-10-05]. Available in: https://aaronia-shop.com/productos/breitbandantennen-hyperlog30180

[2] AFONSO, Carlos. Usage of spectrum in LatinAmerica: Case studies of Argentina, Brazil, Colombia, Ecuador, Perú y Venezuela. [On line]. 2011. [consultation: 2020-10-09]. Recover from: https://www.apc.org/sites/default/files/ca_sintesis_final-AF_0.pdf
[3] AGENCIA DE REGULACIÓN Y CONTROL DE LAS TELECOMUNICACIONES. Sound broadcasting and open television. [On line]. 2020. [consulta: 2020-10-09]. Available in: http://www.arcotel.gob.ec/radiodifusion-sonora-y-television-abierta2/
[4] AGUILAR RENTERÍA, J. & NAVARRO CADAVID, A. "Cognitive radio – State of the Art". Sistemas y Telemática [On line], 2011, 9(16), pp. 31-53. ISSN 1692-5238. [Consultation: 2019-11-04]. Available in: https://www.icesi.edu.co/revistas/index.php/sistemas_telematica/article/view/1028/1053.
[5] ÁLCOCER ERAZO, Jonathan David. Performance analysis of the IEEE 802.11AF standard in TVWS through implementation in a software-defined radio platform [On line]. (Undergrade) ESPE, Sangolquí, Ecuador. 2019. pp. 1-100. [Consulta: 2020-03-24]. Available in: http://repositorio.espe.edu.ec/bitstream/21000/15813/1/T-ESPE-040692.pdf.
[6] ALOMOTO, Diego y MARTÍNEZ, Iñigo. Analysis and simulation of algorithms for spectrum detection in cognitive radio [On line]. (Undergrade) EPN, Quito, Ecuador. 2018. pp. 1-116. [Consultation: 2020-03-24]. Available in: https://bibdigital.epn.edu.ec/bitstream/15000/19078/1/CD-8479.pdf.
[7] ARAUJO TORRES, Michelle Estefanía. Implementation of a cognitive radio system for the detection of TVWS frequency bands [On line]. (Undergrade) ESPE, Sangolquí, Ecuador. 2018. pp. 1-123. [Consultation: 2020-03-24]. Available in: http://repositorio.espe.edu.ec/xmlui/bitstream/handle/21000/14849/T-ESPE-040376.pdf?sequence=1&isAllowed=y.
[8] ARTIEDA, Luis & CORONEL, María. Análisis Analysis of the implementation in Ecuador of systems based on the IEEE 802.22 standard, ESPOL, Guayaquil, Ecuador. 2014. pp. 1-133 [Consultation: 2020-03-24]. Available in: https://www.dspace.espol.edu.ec/retrieve/101992/D-84450.pdf.
[9] AWIN, F.A., et al. "Technical Issues on Cognitive Radio-Based Internet of Things Systems: A Survey". IEEE Access [On line], 2019, 7(1), pp. 97887-97908. [Consultation: 2019-12-01]. ISSN 21693536. Available in: https://ieeexplore.ieee.org/abstract/document/8766798.
[10] BAIRD, D. "NASA Explores Artificial Intelligence for Space Communications". Space Communications and Navigation [On line]. 2017, diciembre, 11. [Consultation: 2019-11-06]. ISSN 1090-7807 Available in: https://www.nasa.gov/feature/goddard/2017/nasa-explores-artificial-intelligence-for-space-communications
[11] BARRIONUEVO, Evelin y TAMAYO, Viviana. Analysis of the performance of a network with WiFi technology for long distances in a rural environment of the Sierra region [On line]. ESPE, Sangolquí, Ecuador. 2011. pp. 1-174. [Consultation: 2020-02-14]. Available in: https://repositorio.espe.edu.ec/bitstream/21000/2934/1/T-ESPE-030883.pdf.
[12] BELTRAN, Lianne. Simulation design and analysis of Wi-Fi networks that operate in television white spaces using cognitive radio. [On line]. Madrid Polytechnique, Madrid, España. 2016. pp. 55-65. [Consultation: 2020-02-11]. Available in: http://oa.upm.es/43260/1/PFC_LIANNE_LAMORENA_BELTRAN_2016.pdf
[13] BOLAÑOS, E. Sample and samplig. [On line]. Universidad Autónoma del Estado de Hidalgo, México. 2012. pp.2-8 [Consultation: 2020-11-07]. Available in: https://www.uaeh.edu.mx/docencia/P_Presentaciones/tizayuca/gestion_tecnologica/muestraMuestreo.pdf
[14] CÁCERES TOVAR, Rodrigo Alberto. Techniques for detection and analysis of spectral occupancy in cognitive radio in the northwestern area of the city of Bogotá. Universidad Distrital Francisco José de Caldas, Bogotá, Colombia. 2017. pp. 1-80 [Consultation: 2020-02-14]. Available in: http://repository.udistrital.edu.co/handle/11349/5875.
[15] CASTAÑEDA, Paulo & GUERRERO, Carla. Television White Space. 2015. pp. 1-5. [Consultation: 2020-02-14]. Available in: http://www.academia.edW26348239,"T
[16] EKLUND, C. et al. IEEE standard 802.16: A technical overview of the Wireless MANTM air interface for broadband wireless access. IEEE Communications Magazine, 40(6), june 2012. DOI: 10.1109/MCOM.2002.1007415.
[17] FEDERAL COMMUNICATIONS COMMISSION. "Facilitating opportunities for flexible, efficient, and reliable spectrum use employing cognitive radio technologies". ET Docket No. 03-108. [On line], 2003, pp. 1-53. [Consultation: 2019-10-20]. Available in:

https://www.fcc.gov/document/facilitating-opportunities-flexible-efficient-and-reliable-spectrum.

[18] FLORES, A. et al. IEEE 802.11af: A standard for TV White Space Spectrum Sharing. [On line]. October 2013, IEEE Communications Magazine, 51(10), pp. 92-100, [Consultation: 2020-02-20]. Available in: https://www.researchgate.net/publication/260670622_IEEE_80211af_A_standard_for_TV_white_space_spectrum_sharing

[19] GOMEZ, Santiago et al. COGNINET Cognitive Radios and Sensing of the Radioelectric Spectrum [On line]. Universidad de la República, Montevideo, Uruguay. 2014. pp. 1-143. [Consultation: 2020-02-14]. Available in: https://iie.fing.edu.uy/publicaciones/2014/GMS14/GMS.pdf.

[20] GUAMO MOROCHO, Andrea Katherine. Implementation of a communications link based on principles of cognitive radio systems in the faculty of energy, industries and non-renewable natural resources of the National University of Loja through SDR (Software Defined Radio) [On line]. Universidad Nacional de Loja, Loja, Ecuador. 2019. pp. 1-109. [Consultation: 2020-02-13] Available in: https://dspace.unl.edu.ec/jspui/bitstream/123456789/22050/1/Guamo%20Morocho%2c%20Andrea%20Katherine.pdf

[21] HAYKIN, S. "Cognitive Radio: Brain-Empowered". IEEE Journal on Selected Areas in Communications [On line], 2005, 23(2), pp. 201-220. [Consultation: 2019-11-06]. Available in: https://ieeexplore.ieee.org/document/1391031/versions.

[22] HERNÁNDEZ, Patricia. & CARRO, Gonzalo. Principles, standards and solutions of Cognitive Radio [On line]. Universidad de la República, Montevideo, Uruguay. 2016. pp. 1-39. [Consultation: 2020-02-02] Available in: https://iie.fing.edu.uy/proyectos/esopo/wp-content/uploads/sites/3/2017/01/Doc4_20170118_CognitiveRadio.pdf.

[23] LEE, B.M., et al. "Implementation of a Regional Spectrum Sensing Based Cognitive Radio System for Digital TV White Space". IETE Technical Review (Institution of Electronics and Telecommunication Engineers, India) [On line], 2018, 35(6), pp. 590-598. [Consultation: 2019-11-20]. ISSN 09745971. Available in: https://www.tandfonline.com/doi/abs/10.1080/02564602.2017.1354731.

[24] MÁRQUEZ RAMOS, R. "Cognitive radio architectures: a review". Tecnura Magazine [On line], 2014, 18(39), pp. 181-196. [Consultation: 2019-11-16]. Available in: http://www.scielo.org.co/pdf/tecn/v18n39/v18n39a14.pdf.

[25] MEJÍA CANDO, Julio César. Development of an algorithm in Matlab for optimizing the resolution of a USRP B210 card for SDRADAR applications. Escuela Superior Politécnica de Chimborazo, Riobamba, Ecuador. 2017. [Consultation: 2020-03-24]. Available in: http://dspace.espoch.edu.ec/bitstream/123456789/7523/1/98T00160.pdf

[26] JIMÉNEZ MOPOSITA, Jorge Vinicio. Analysis and evaluation of the radio spectrum in the VHF and UHF bands through an algorithm carried out in USRP radio for potential use of the IEEE 802.11af standard in the urban area of Ambato canton [On line. Escuela Superior Politécnica de Chimborazo ESPOCH, Riobamba, Ecuador. 2017. pp. 36-69. [Consultation: 2020-11-13]. Available in: http://dspace.espoch.edu.ec/handle/123456789/7406

[27] NATIONAL INSTRUMENTS. Radio Definido por Software USRP - National Instruments [On line]. 2017 [Consulta: 12 febrero 2020]. Available in: http://www.ni.com/es-cr/shop/select/usrp-software-defined-radiodevice?modelId=125052>.

[28] NATIONAL INSTRUMENTS. Specifications USRP-2932 [On line]. 2017 [Consultation: 12 february 2020]. Available in: http://www.ni.com/pdf/manuals/375988d.pdf.

[29] PEDRAZA, L. et al. "Spectrum detection for cognitive radio". Chilean magazine ingeniería [On line], 2012, 20(2), pp. 197-210. [Consulta: 2019-11-01]. Available in: https://scielo.conicyt.cl/pdf/ingeniare/v20n2/art07.pdf.

[30] PONCE PINOS, Jaqueline Elizabeth. Evaluation of the occupation of the radio spectrum and feasibility analysis of the use of cognitive radio in the UHF band (450 – 512 MHZ) for its optimization in the city of Riobamba. (Postgrade) Escuela Superior Politécnica de Chimborazo, Riobamba, Ecuador. 2019. pp. 1-70. [Consultation: 2019-10-17]. Available in: http://dspace.espoch.edu.ec/bitstream/123456789/9439/1/20T01133.pdf

[31] RUIZ, L. Spectral Sensing in Cognitive Radio. [On line]. Universidad de Paderborn, Paderborn. 2015. [Consultation: 2020-07-30]. Available in: https://e-archivo.uc3m.es/bitstream/handle/10016/26659/PFC_Lucia_Ruiz_Ruiz_Resumen_Espanol.pdf.

[32] SERRANO FLORES, María Eugenia. Application of resolution optimization algorithm for the detection of moving targets with SDRADAR technology [On line]. Escuela Superior Politécnica

De Chimborazo, Riobamba, Chimborazo. 2019. [Consultation: 2020-02-12]. Available in: http://dspace.espoch.edu.ec/bitstream/123456789/11017/1/98T00240.pdf
[33] SODAGARI, S., et al. “Technologies and Challenges for Cognitive Radio Enabled Medical Wireless Body Area Networks”. IEEE Access [On line], 2018, 6(1), pp. 29567-29586. [Consultation: 2019-11-24]. ISSN 21693536. Available in: https://ieeexplore.ieee.org/abstract/document/8370629.
[34] SOLETO, R., et al. ISDB-T Transmission System. Trabajos de difusión científica. [On line]. 2011. pp. 70-71. [Consultation: 20 septiembre 2020]. Available in: https://www.researchgate.net/publication/277269466_Sistema_de_transmision_ISDB-T
[35] TSCHIMBEN, S., et al. “IEEE 802.11ah SDR Implementation and Range Evaluation”. IEEE Wireless Communications and Networking Conference, WCNC [On line], 2019, vol. 2019-April, pp. 1-6. [Consultation: 2019-11-06]. ISSN 15253511. Available in: https://ieeexplore.ieee.org/document/8885445/metrics.
[36] TUTTLEBEE, W. “Software defined radio: enabling technologies”. Published online: John Wiley & Sons, Inc. 2003. pp. 397. [Consultation: 2019-11-06]. Available in: http://onlinelibrary.wiley.com/book/10.1002/0470846003
[37] VANERIO, Juan Martín. Expert-Based Online Prediction for Cognitive Radio Secondary Markets [On line]. Universidad de la República, Montevideo, Uruguay. 2017. pp. 1-160. [Consultation: 2020-02-14]. Available in: https://iie.fing.edu.uy/publicaciones/2017/Van17/Van17.pdf.
[38] WANG, D., et al. “Intelligent Cognitive Radio in 5G: AI-Based Hierarchical Cognitive Cellular Networks”. IEEE Wireless Communications [On line], 2019, 26(3), pp. 54-61. [Consultation: 2019-11-06]. ISSN 15580687. Available in: https://www.researchgate.net/publication/334155919_Intelligent_Cognitive_Radio_in_5G_AI-Based_Hierarchical_Cognitive_Cellular_Networks.
[39] WIRELESS INNOVATION FORUM. What is Software Defined Radio [On line]. 2008. [consultation: 2020-01-20]. Available in: https://www.wirelessinnovation.org/assets/documents/SoftwareDefinedRadio.pdf