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Opportunistic Communication System for the FM Band.

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***Abstract*—In the last years, cognitive radio (CR) has gained great attention in the scientific community; even though several works has shown novel methods in the CR context there is still a wide open research area due to the lack of precision in the step-by-step implementation process and a clear performance metrics definition. This paper describes in detail a design methodology for a cognitive radio implementation looking for an opportunistic transmission in the FM band and the definition of a performance metrics based on the IEEE 802.22 standard. The CR system was finally implemented on an Ettus B210 software defined radio platform programmed over GNU Radio software. A novel energy spectrum sensing, analysis, decision and transmission algorithm were implemented and tested in order to measure the system performance. Additionally, it is worth to mention this work presents a new approach for defining the average noise floor threshold in the spectrum sensing decision process. The achieved opportunistic transmission parameters are also shown given insights and recommendations for the technology selection and the FM band in the CR environment.**

I. INTRODUCTION

The wireless communications have experienced significant growth in recent years, more and more services that require the use of the radio spectrum (RS) generating a high demand for this resource. This high demand is generating the need to investigate new ways to perform wireless communications making a better use of the RS. One of the fields that is now being studied is the Cognitive Radio (CR), multiple works [1], [2] have defined the CR concept and its operating principles, by tackling the problem of the inefficient use of the radioelectric spectrum (RS), particularly for new generation networks.

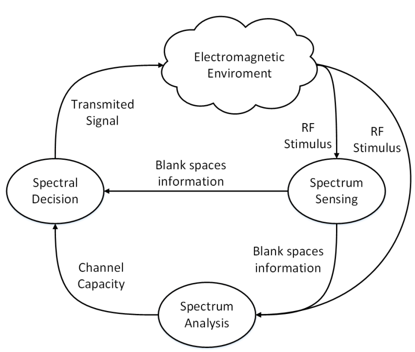


Fig. 1: Cognitive Cycle.

Within the CR concept the process of cognition is included, by being the process from which a radio knows the RS of its environment and, by knowing the transmission parameters required by the user, makes a decision of use of that spectrum. The cognition process is defined by the Cognitive Cycle which is composed of three main functions: sensing, analysis and spectral decision. The sensing of the spectrum is the process that allows the CR to detect the primary users and the free bands that can be shared to the secondary users without generating any type of interference for the primary users. The spectral analysis is the processing of the data taken in the sensing in order to determine the characteristics of the empty channels. Finally, the spectral decision consists of defining the best band according to the needs of the secondary user and the spectral analysis.

Taking into account that one of the most important points of the cognitive process is the sensing part and in special the choice of the threshold, this article uses the energy sensing method with a novel way to define the threshold. This method allows, through a previous analysis of the environment, to obtain a threshold that gave a detection probability of 87.49% and a false alarm probability of 12.51%. For the implementation, 2 Ettus B210 SDR cards, 2 antennas for the frequency modulated band (FM) and the GNU Radio programming interface were used.

II. SYSTEM DESCRIPTION

The designed CR system allows to perform a sensing of the RS, to make an analysis of it and take a decision according to the needs of the secondary user and later realize an opportunistic transmission. To achieve this, the system is divided into two parts described as follows.

In the transmission part, the detection of white spaces is carried out, the definition of whether the white space is suitable or not for transmitting, and liberating the white spaces in case a primary user comes up in the channel. The transmission is in charge of controlling the use of the spectrum to avoid interference with the primary users. The transmission is responsible for the generation of the packets to be transmitted, the synchronization between the systems to be communicated and finally the sending of the data.

A. Sensing Method

This is one of the key points to choose when thinking about the design of a CR system, depending on the needs such as complexity, precision or accuracy, from the work in [3] different methods are compared as shown in Fig. 2.

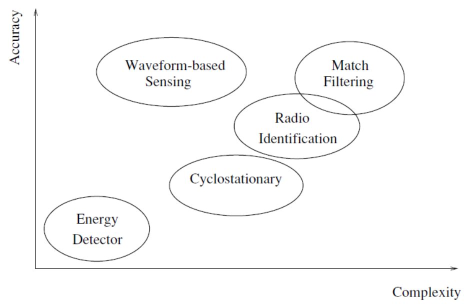


Fig. 2: Sensing method Complexity VS Accuracy

In this article the use of the energy sensing method was chosen due to the simplicity in the implementation and little computational requirement [2]. This method consists in the calculation of the average energy of the received signal to compare it with a threshold and determine the state of occupation of the channel. To determine the presence or absence of a primary user, a hypothesis is defined to model the problem according to [4] and [1] as shown in (1)

$$y(t) = \begin{cases} w(t), & H_0 \\ s(t) + w(t), & H_1 \end{cases} \tag{1}$$

Where $y(t)$ represents the received signal, $s(t)$ the signal to be detected and $w(t)$ additive white Gaussian noise (AWGN). Hypothesis H_0 corresponds to the absence of signal and H_1 the presence of signal. The decision of presence or absence of the signal is made by evaluating a random variable T with a threshold τ. The performance of the detector is evaluated with the false alarm probability and the detection probability given by (2) and (3), respectively. The probability of false alarm is then defined as the probability of choosing H_1 when the real signal is H_0 and probability of detection as the probability of choosing H_1 when the signal received is actually received is H_1.

$$P_F = P(T > \tau | H_0) \tag{2}$$

$$P_D = P(T > \tau | H_1) \tag{3}$$

The block diagram that defines the process of the energy sensing method in the frequency is shown in Fig. 3. As it is observed, the process begins with the signal $y(t)$ being sampled by a analog to digital converter (ADC), obtaining a discrete signal $y[n]$. Then, the Fast Fourier transform (FFT) is performed where the norm of its result is taken and squared. Finally, a sum of the samples is done to have the value of the energy of the channel that is compared with the threshold, if the channel is empty, then a spectral decision process is carried out.

The hypotheses H_0 and H_1 of this method of detection are described mathematically by the equation (4), where $S[n]$ is considered a deterministic signal and $W[n]$ is a complex random Gaussian variable with variance σ^2. T will then have a distribution χ^2 with 2N degrees of freedom under H_1 and a χ^2 distribution not centered with 2N degrees of freedom under H_1.

$$T = \begin{cases} \sum_{n=1}^{N} |W(n)|^2, & H_0 \\ \sum_{n=1}^{N} |S(n) + W(n)|^2, & H_1 \end{cases} \tag{4}$$

According to this new system of equations, the detection threshold must be defined with the probability of false alarm. In [5] they define the threshold according to the equation (5), where $Q^{-1}()$ is the inverse Marcum Q function, P_{FA} is the false alarm probability and P_N is the power of the noise. On the other hand, the detection probability P_D is defined according to (6), where P_S is the signal power at the receiver. With these two equations the result of the threshold can be interpreted depending on the desired false alarm probability, because the threshold will be directly proportional to the value of $Q^{-1}(PFA)$, can be analyzed that as the false alarm probability decreases, the value of $Q^{-1}(P_{FA})$ tends to infinity when P_{FA} approaches to zero. According to this statement, it is interpreted that the threshold will be infinitely higher than the noise floor, that means, in order to avoid false alarms, the threshold is set too high so that the channel will never be occupied. However, setting a threshold that tends to infinity affects the detection probability, since if γ is much greater than $P_S + P_N$, $Q(-\infty)$ will tend to 1, causing P_D is equal to 0. Thus, a direct compromise is seen between the false alarm probability and the detection probability.

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

$$P_D = 1 - Q \left[\frac{\sqrt{N}}{P_S + P_N} (P_S + P_N - \gamma) \right] \tag{6}$$

After clarifying the theory, for the development of the sensing system it was necessary to take into account the implications of the use of an FFT and an ADC. For which additional processing was done to the signal, which were:

1) Gain Adjustment: Due to the ADC it is necessary to make a compensation of the received signal to obtain the value in mV, according to [4],[6] the calculation of the gain is calculated in (7).

$$G_{Voltage} = \frac{V_{IN\,ADC}}{2^{effective\,bits}} \tag{7}$$

2) Choice of the FFT window: Because it can't be done an infinite points FFT, it's necessary to choose a window that fits the needs of the application, since in this case the FM band channels have the maximum concentration of energy in the

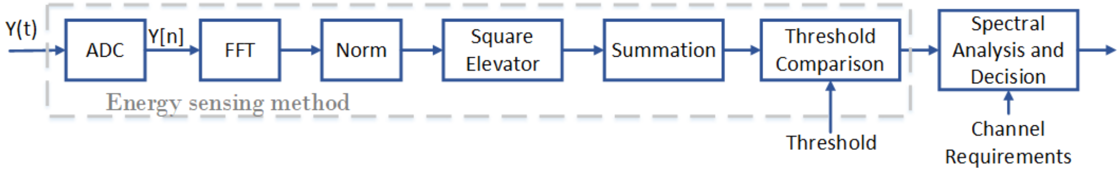


Fig. 3: Sensing method scheme.

center of the channel, therefore, they have a main lobe, the Blackman-Harris window was chosen. It is also important to emphasize the implications between the number of points and the computational cost, more points in the FFT implies better resolution but more computational cost.

3) Windowing compensation: The use of a window function implies a compensation for the FFT, in [6] the equations are defined: (8) and (9) to make this compensation. Where Z_{in} is the input impedance of the system, Wc is the compensation for the window, tap_n is each of the values of the window, S_n is each of the values of the squared norm of each point of the FFT and N is the number of samples of the FFT.

$$P_{channel} = \frac{1}{Z_{in} W_c} \sum_{n=1}^{N} S_n \tag{8}$$

$$W_c = \sum_{n=1}^{N} tap_n^2 \tag{9}$$

4) Threshold Definition: It is done in a special way in this article since the definition of the noise floor presents a complication, given that the noise is a Gaussian distribution it can't be defined an exact value of noise at every moment, due to the nature of the Q function, the small changes that the noise floor value may have generate a drastic change in the final value of the threshold. Thus it is proposed to make a measurement of the environment where the device will be used in order to define an average noise floor of the free channels of the band, this value is the one used as the noise floor to define the threshold.

B. Analysis And Spectral Decision

The importance of the analysis and spectral decision lies in the need to be able to carry out an optimal transmission according to the user's requirements; For the spectral analysis the value of the energy of the channel is used, once the system has determined that that channel is free, the measured energy will represent the noise floor of the channel and, through an approximation of received power determined in [7] with a link budget model defined in (10) the SNR is determined. In (10) P_{Tx} is the transmited power, L_{Tx} y L_{Rx} are the losses due to connectors and losses due the cables in the transmitter and the receiver respectively G_{Tx} y G_{Rx} are the gains of the transmitting and receiving antenna, L_{Path} are the losses due to the wave propagation, F_m is the fading margin and L_{Sh} are the Shadowing losses.

$$P_{Rx} = P_{Tx} - L_{Tx} + G_{Tx} - L_{Path} + G_{Rx} - L_{Rx} - F_m - L_{sh} \tag{10}$$

With this received power value, the SNR is obtained with (11) and the capacity calculation of the Shanon channel is performed with (12). The spectral decision is made by comparing the channel capacity with the transmission rate defined for this article, with a 4-QAM modulation, which has a bit time of 16 μs resulting in a rate of 125 $kbps$.

$$SNR = \frac{P_{Rx}}{P_{Ruido}} \tag{11}$$

$$C = BW \log_2(1 + SNR) \tag{12}$$

If the calculated value of Shannon's capacity with the SNR of the free channel is greater than the transmission rate defined for this article, the transmission will be carried out.

C. Transmission And Handshake

As this is an overlay transmission scheme, it is necessary for it to be able to do burst transmissions for a controlled time making a best effort transmission. In this work, the transmission has a variable time that depends on the sensing time, the time of connection establishment and the maximum time by which it can transmit, chosen according to the IEEE standard 802.22 [5]. Thus, the transmission time will be defined by (13), where T_{tx} is the transmission time, T_s is the sensing time and T_{hs} is the HandShake time, being 2 the maximum time in seconds established by the standard.

$$T_{tx} = 2 - T_s - T_{hs} \tag{13}$$

Regarding the transmission parameters, a 4-QAM modulation without channel coding was chosen, adding a 32-bit cyclic redundancy code for error detection, the frames to be transmitted contain a header with a 3-byte preamble and an access code of 8 bytes, followed by a payload of 192 bytes and ending with the CRC of 4 bytes for a total of 206 bytes.

Due to the need to synchronize the transmitter with the receiver in such a way that the two parties know the channel in which the communication will be done, a TCP/IP connection was proposed for the synchronization between the two computers that will process the data of the SDR's. This creates a client/server system where the receiver acts as a server and the transceiver as user, the connection is established by sending a connection request message, upon receiving the acknowledgment the transceiver sends the channel frequency with which the receiver analyzes the message, moves to the channel and after achieving the movement sends an ACK message to confirm that it is already in the found channel.

III. Implementation And Test Protocol

For the realization of the system, 2 antennas for the FM band were used , 2 computers and 2 SDR ETTUS B210 cards which can be programmed through the GNU Radio interface.

GNU Radio is the core of the system in terms of software, initially developed for Linux and with a programming language based on Python and C ++. In GNU Radio it is possible to create blocks of signal processing that are able to do things such as signal sampling, Fourier transforms or even high complexity signal processing.

A. Test protocol of the sensing method, analysis and spectral decision

Sensing tests consist of measuring the probability of false alarm and the probability of detection, characteristics that define the performance of a sensing in cognitive radio. To obtain these measurements, the physical system of Fig. 4 was implemented and the system of Fig. 5 which receives the signals of the RS, makes the compensation for the use of the ADC, then performs the FFT, calculates the standard squared samples and finally in the block prom-ff created for this work, the summation is done with the respective compensation for the windowing to determine the energy of the channel.

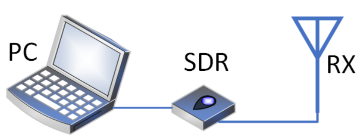


Fig. 4: Sensing Testbed.

Taking into account the sensing process, a program which used a total of 100000 cycles was created, in this program each of the channels of the FM band was reviewed and, it was defined whether the analyzed channel was occupied or not and if It was suitable for a transmission. In the same program there was a database of which channels were actually occupied and which ones were not, this information was obtained previously with a periodic measurement of the spectrum with a spectrum analyzer. With this database it was possible to know if the decision made regarding the occupation of the channel was correct or not and therefore define if the count increased the probability of detection (Probability of deciding that the channel is busy when it really is) or the probability of false alarm (Probability of deciding that the channel is busy when it is not), on the other hand there was a counter that allowed the system to determine how many times the channel was suitable for a transmission with the parameters previously defined. At the end of all the cycles, each of the counts was divided by 100000 to obtain the probabilities.

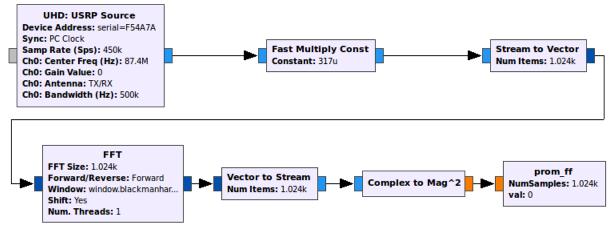


Fig. 5: GNU Radio Sensing program.

B. Transmission test protocol

The objective of this test protocol is to measure some transmission performance parameters, such as the Round trip time (RTT) of the synchronization, the Bit Error Rate (BER), the Frame Error Rate (FER) and the bandwidth, for this it was necessary to use the test bed of the Fig. 6 and the GNU radio programs of Fig. 7 where the basic blocks of the transmission are the source of information, a block created to perform the desired modulation, a multiplier that together to the power squelch have the function of valve to control the data flow and the exit to the USRP; the other blocks are used to obtain the information in different points of the process. On the part of the Block diagram of the reception there was only the need of several points where the information can be taken.

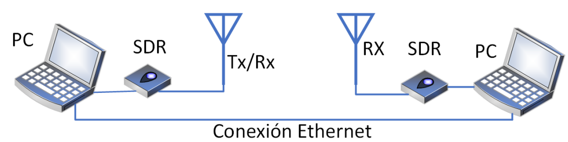
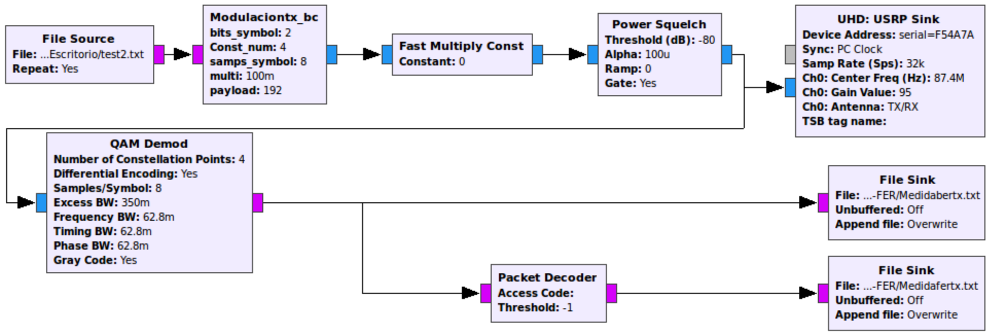


Fig. 6: Transmission Testbed.

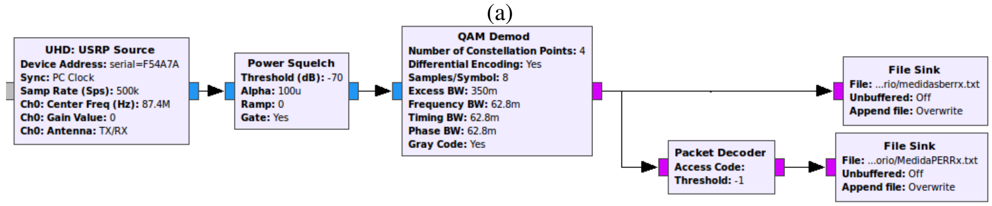
For the measurement of the RTT, a program was designed internally, in the python script generated by GNU Radio, which measures the time that takes the entire establishment of the connection, from the moment the request is sent until the final Acknowledge (ACK) is received. At the moment prior to sending the request, a time counter starts and ends when the final ACK arrives, defining the RTT. To measure the bandwidth, a transmission was made and with the help of the NEX-1 LSA-132 spectrum analyzer, the bandwidth measurement was performed. Finally, for the BER and the FER tests, a program was designed, in which a known data frame is sent. The signal is packaged, modulated, transmitted through the wireless channel, demodulated, unpacked and the frames, as well as the bits received are compared with the transmitted ones to obtain the BER and FER value.

C. Test Protocol of the Cognitive Radio

For the tests of the cognitive radio a protocol was designed to show how the complete system works, that means that it is able to do the sensing, find the free channel, perform the transmission and release the channel in the Handoff time established. In order to carry out this protocol, the testbed used was the one of Fig. 8 and the system implemented in



(a)



(b)

Fig. 7: (a) BER and FER trans-receiver block diagram (b) BER and FER receiver block diagram

GNU Radio that consists of the union of both transmitter and receiver programs, joining the diagrams by means of programming threads in Python.

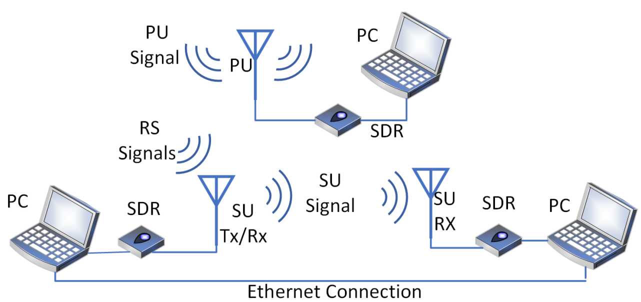
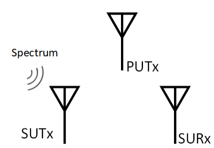
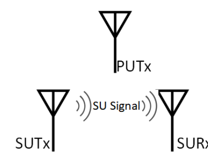


Fig. 8: Cognitive Radio Test bed.

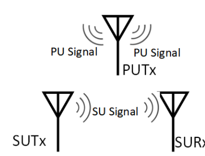
To carry out the performance tests, the following protocol was designed: Considering that the system is sensing the channel and the PU is absent as in Fig. 9a, the system finds a free channel, that channel is verified with the spectrum analyzer to confirm that it is indeed free, then the transmission begins as shown in the Fig.9b and in the spectrum analyzer it is verified that the system occupies the free channel. In the case where the PU occupies the channel during transmission, as shown in Fig. 9c, the two users will interfere during the maximum handoff time. At the end of the transmission of the SU, the system senses the PU as can be seen in the Fig. 9d and releases the band to avoid interference, it must be confirmed with the spectrum analyzer that the system releases the band in the presence of a PU. In this same process, the handoff is measured with a subprocess that starts counting the time the channel lasts to be released, thus the value of the handoff will be the time from when transmission begins until it defines whether the channel is free or not again.



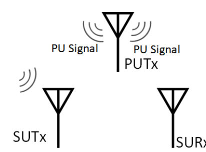
(a) Sensing



(b) Data transmission



(c) PU and SU transmission

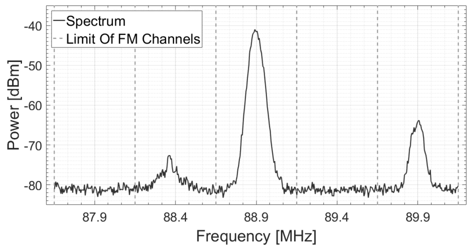


(d) Channel release

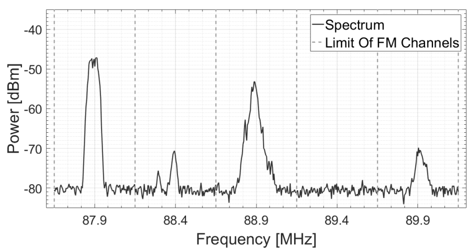
Fig. 9: Possible states in the cognitive radio system

IV. Results

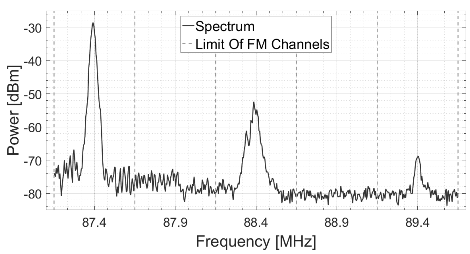
The results of the tests show a probability of false alarm of 12.51%, a value close to the desired one of 10%, on the other hand a detection probability of 87.49% was obtained. When comparing with the standard IEEE 802.22 where a maximum false alarm probability is established for a cognitive radio system of 25.5%, we can not compare directly with the standard as it is for TV band, nevertheless is a metric that allow a comparison for the proper functionality of the system. On the other hand, the average time it takes for the system to sense the channel is 495.8 s. Because the IEEE standard 802.22 does not specify a sensing time, this result is compared with the sensing times in [8] that, under other similar conditions, performs the sensing in 31.59 ms. With respect to the connection establishment, 2500 samples were



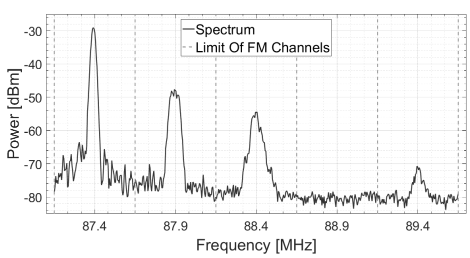
(a) Sensing stage



(b) Data transmission stage



(c) PU and SU transmission



(d) Channel release

Fig. 10: Radio cognitive stages.

taken, which resulted in values between 171 s and 59,577 ms, the majority between 171 s and 541s also the average RTT was 4,476 ms.

With respect to the BER, the comparison of the bits transmitted with the received bits was carried out. Taking into account that the preamble can also be damaged, a processing was performed on the data of the received bits by means of a correlation system that finds the beginning of the frame using the highest correlation point. Thus, a point-to-point comparison of 30 Mbits was delivered, obtaining a BER value of 558.19x10-6. On the other hand, the comparison of the FER files was made to determine how many Frames were lost in the transmission. With a file of 4784201 lines transmitted, 3348495 lines were received and since each Frame was adjusted to be equivalent to a line of text, the value of the FER was 0.3.

Fig. 11 shows the constellation obtained at the transmitter output (Blue) and the received signal (Orange) superimposed. As can be seen, the constellation transmitted has the points with low dispersion, but when they reach the receiver a high dispersion is seen, which supports the values obtained from BER and FER. It is important to emphasize that the transmitted constellation is not perfect due to the modulator block that uses a raised cosine filter (RRC), so what is observed is a result of intersymbol interference (ISI) by the use of the RRC.

Regarding the results of the cognitive system the data of the spectrum analyzer in each part of the process was taken, Fig. 10 shows the 4 states of the cognitive system in the first 5 channels of the FM band; the signals of the third and fifth channels correspond to national radio stations. The system starts with Fig.10a, where it is observed that the spectrum is free, when performing the sensing and fulfilling all the conditions, the transmission starts as shown in Fig. 10b. After this, a transmission emulating a primary user is started, so there is a moment of interference between the two signals while the SU senses the PU signal, this is seen in Fig. 10c. Finally, the SU ends its transmission, it senses again and jumps to a new free channel, in this case at 88.4 MHz as shown in Fig.10d.

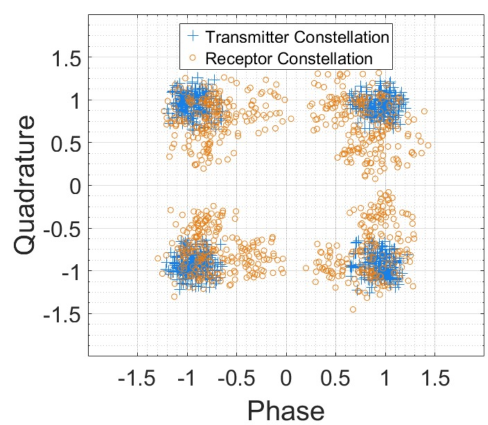


Fig. 11: Constellation sent (Blue) and received (Orange).

V. Conclusions

The low values of BER and FER can be caused because the tests were done indoor with many objects where antennas were not in an appropriate place for radiating without reflection effects, besides having several multipaths that could generate interference. It was found that there are channels with very low power, which are considered as free by the system, however, there is an FM signal that can be demodulated, despite this, it was possible to perform a transmission, allowing to ensure that there are channels with a power sufficiently low to allow a short distance transmission, that does not interfere the SU. Finally, from the results, it is concluded that the energy sensing method is valid for bands that have a high SNR, since according to the measurements made in Appendix C of [4], the occupied channels of this band have an average power above -40 dBm, and the average noise floor of the free channels is approximately -62 dBm, which implies that the choice of the threshold is not critical.

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