

System Level Design for a Cognitive Radio Receiver “Application for IEEE802.22 Standard”

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Abstract — this project aims to design and implement a new Cognitive Radio (CR) receiver targeting the IEEE 802.22 standard as the first world-wide CR standard. In fact, this project starts with a study and a comparison of various CR receivers. This study leads to the presentation of a new approach that was adopted based on sub-band sensing technique for a CR receiver. In addition, we demonstrate a system level design that was applied to this architecture. Then, the overall radio system characteristics, fixed by the IEEE 802.22 Standard specifications, are dispatched through various receiver blocks. Besides, we exhibited the theoretical computation and different techniques of system level design. Each of Radio Frequency (RF) characteristics such as gain, noise figure (NF) and linearity (third order intercept point, (IIP3)) is simulated depending on the analog-to-digital converter (ADC) full scale power requirement. At the end, the system level simulation results justified that the new approach allows to carry out spectrum sensing and communication processing. The receiver presents 51dB as a total gain and an IIP3 of -19.8 dBm for low gain mode. Also, it performs 105dB as gain and a noise figure of 9.9 dB for high gain mode.

Index terms — *Cognitive Radio, IEEE 802.22, Spectrum sensing, Receiver, system level design, budget analysis, linearity, noise, gain.*

I. INTRODUCTION

Although current Wireless networks are characterized by a fixed spectrum assignment policy, different measurements prove that the spectrum occupation ratio varies from 15% to 85% which means that the major part of the accessible spectrum is not well exploited [1]. To alleviate this problem, the Cognitive Radio (CR) appears as a new concept that is seen as a promising solution aiming to use opportunistically the available spectrum by offering the possibility for Secondary Users (SU) to take benefit of spectrum holes whilst Primary Users (PU) are not in phase of communication.. This description reveals one of the significant Cognitive radio characteristics which is Dynamic Spectrum Access (DSA) [2]. To identify these spectrum opportunities, Consumer Premise Equipments (CPEs) shall sense constantly their own environment to notify their related Base Station (BS) about

different vacant spectral segments. This method corresponds to one of the basic aspects of Cognitive Radio which is Spectrum Sensing in addition to awareness, learning, and adaptation capabilities. In our case, a CR receiver shall take into account this functionality and could be able to manage it. For this purpose; we have to consider, as one of the first tasks to achieve, the system level specification as it allows to set different specifications for each receiver block. In order to accomplish this requirement, several standard requirements shall be taken into account such as sensitivity, noise figure (NF) and dynamic range (DR).

In this context, this project aims to design and implement a new Cognitive Radio receiver targeting the IEEE 802.22 standard as the first world-wide CR standard. First, in section II, we will introduce the Cognitive Radio System as a new concept by exhibiting its characteristics, services and especially its ability of spectrum sensing. In addition, the IEEE 802.22 standard will be avowed and its main features will be revealed. In section III, we will study different kinds of receivers that are published recently and related to the Cognitive Radio in general. Based on comparison of these CR receivers, we will introduce our new approach that should comply with IEEE 802.22 requirements and precisely the sensing functionality. In section IV, a methodology for a system level design will be exhibited and applied to our Cognitive Radio receiver and its blocks. In fact, different RF factors such as sensitivity, dynamic range (DR), ADC full scale power (P_{FS}), linearity and noise figure (NF) will be shown. In addition, to fulfil the budget simulation and to meet the challenge between linearity improvement and noise reduction, two gain modes will be detailed in our project. In section V, each block characteristics, such as gain, NF, CP_{1dB} , IIP3 and output power, will be obtained by the RF system budget analysis while making the Budget simulations using ADS tool (Advanced Design System) for these two gain modes. At the end, the distribution of all the IEEE 802.22 requirements will be made among the different receiver blocks. At last, in section VI, a conclusion of our project will be given.

II. IEEE 802.22 COGNITIVE RADIO STATE OF ART

Owing to considerable enhancements in radio technologies (especially on software-defined radios (SDR), power control,

frequency agility, etc.); many spectrum features such as flexibility, reliability and efficiency could be a reality by means of adapting the radio's functional characteristics to its real-time environment conditions. In this context, Cognitive Radio has emerged as a new concept offering the possibility to make the spectrum usage flexible and even to improve its efficiency. Due to the need to alleviate the problem of current low usage of the radio spectrum and taking into account the encouraging propagation features of TV frequency bands, IEEE 802.22 is emerging as a new wireless air interface standard based on Cognitive Radio as a new Wireless Regional Area Network (WRAN) [5]. In effect, the 802.22 network is founded on a Point to Multi Point (P-MP) link. In fact, it is formed of a Base Station (BS) and a number of CPEs. Each of them performs spectrum sensing. However, the BS fixes whilst sensing is acquired, analyses all its feedbacks and then takes the decision of the availability of each sensed TV channel. This type of decision is based not only on spectrum sensing results but also on a variety of auxiliary information that are shared between different BSs. In effect, IEEE 802.22 requirements indicate that there are three various sensing thresholds which are: first, -116 dBm over a channel of 6 MHz to detect DTV Primary Users (PU). Second, a threshold of -94 dBm related to sensing analog TV systems. At last, -107 dBm over a 200 KHz bandwidth to identify Wireless microphones Users. The IEEE 802.22 standard aimed first the commercial deployment of Cognitive Radio over US regions. This objective was reflected on the frequency operational range that is settled from 54MHz to 862 MHz. In fact, this band belongs to the North American regions [5]. In addition, this bandwidth could be extended between 41 MHz and 910 MHz in order to accommodate supplementary international regulatory constraints. Moreover, various international TV channel with bandwidths of 6, 7, and 8 MHz have to be taken into consideration by the IEEE 802.22 standard specifications. The spectral efficiencies could be ranged from 0.5 bit/ (sec/Hz) up to 5 bit/ (sec/Hz) [5].

For example, a spectral efficiency of 3 bits/sec/Hz would allow 18 Mbps as total PHY data rate in a 6 MHz TV channel. In the downstream direction, if we consider that 12 CPEs are simultaneously active, then 1.5 Mbps would be the minimum peak throughput rate per CPE. This peak throughput rate is about 384 kbps in the upstream direction which offers services comparable to DSL ones.

One of the important characteristics of 802.22 WRAN consists on its BS coverage range that could reach 100 Km when power is not a dominant factor. In fact, the favourable coverage range is around 33 Km at 4 Watts CPE EIRP.

In addition, the IEEE 802.22 PHY needs to offer high modulation and coding schemes flexibility. As an example, figure 1 shows different CPEs located at various distances from their associated BS which conduces to several Signal-to-Noise Ratio (SNR) qualities. In this case, the BS shall be able to alter dynamically the bandwidth range, modulation and coding schemes whilst communicating with different CPEs. In effect, OFDMA is a promising way to accomplish these goals as efficient allocation of sub carriers could be possible to convene CPEs constraints. To take into account this technique, the solution is to split sub carriers forming the bandwidth to 48 subchannels. So, modulation schemes are, respectively, QPSK,

16-QAM, 64QAM or even 256 QAM with various convolution coding schemes rates such as 1/2, 3/4 or 2/3. That's why, data rate could be from few Kbps per sub channel to 19 Mbps per TV channel [5]. The different OFDMA specifications for IEEE 802.22 standard are defined for one TV band in [6].

In our case, we will consider only QPSK modulation. Hence, future study will address the impact of other modulation schemes (16-QAM, 64QAM and 256QAM) on our receiver performances. Indeed, adaptive modulation concept could be considered as a promising research area for CRs especially when combined to MIMO systems.

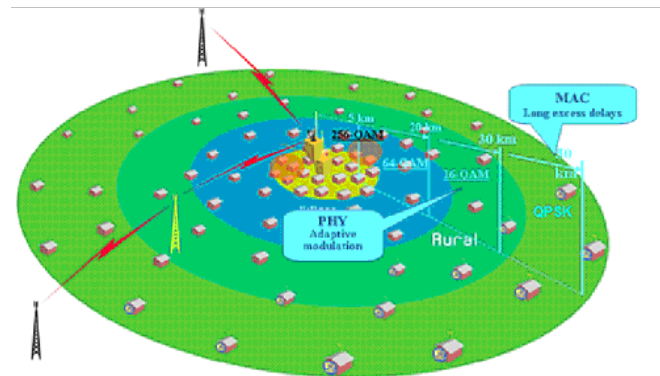


Figure 1. Adaptive Modulation scheme

The various WRAN BS and CPE receiver performances are indicated in the IEEE 802.22 standard Draft. In fact, in the downstream link, Equivalent receiver sensitivity (ERS) is computed as follows [7]:

$$ERS = P_{fl_dens} + 10 * \text{Log}_{10} (OA_{Aper}) + RX_{AGain} + 30 \quad (1)$$

Where:

- P_{fl_dens} : Power-flux-density = -114.8(dBW/m²)
- OA_{Aper} : Omni Antenna Aperture = 0.02(m²)
- RX_{AGain} : RX Antenna Gain = 11(dBi)

After that, the whole CPE Receiver sensitivity could be calculated as shows the next expression:

$$CPE \text{ Receiver sensitivity} = \text{Receiver margin} + ERS \quad (2)$$

Where:

Receiver margin is set to -0.9 dB

Finally, CPE Receiver sensitivity is around -92 dBm as a minimum value [7]. In other hand, the other parameters are assessed such that the operational frequency band is 54-862 MHz using a channel bandwidth of 6 MHz for communication mode and 50 MHz while sensing is performed, a QPSK modulation with rate of 1/2. Moreover, the noise figure is specified to be less than 10 dB with coupling and filter loss of around 2 dB. The required Eb/No is fixed to 6.07 dB which correspond to a BER less than 4.10^{-2} [7]. The maximal input signal, that could be detected and decoded, is also set to -41.8dBm. Parameters that describe the system linearity such

as IIP3 will be evaluated as will be presented in the next sections.

The next table summarizes the various IEEE 802.22 standard specifications that are related to CPE receiver performances [7].

TABLE I- IEEE 802.22 STANDARD SPECIFICATIONS

Modulation	OFDM
constellation	QPSK, Coding rate : $\frac{1}{2}$, Cyclic Prefix: $\frac{1}{8}$
Rate	3.744 Mbps
Bandwidth	5.625 MHz
Eb/No	6.07 dB
BER	$4 \cdot 10^{-2}$
Insertion losses	2 dB
Total Noise Factor	10 dB
Sensitivity	-92 dBm
Input P_{max}	-41.8 dBm
Thermal noise N_{th}	-106.2 dBm
IBO_{max}	12 dB
IBO_{min}	8 dB

III. STUDY AND COMPARISON OF COGNITIVE RADIO RECEIVERS

In this section, we will deal with a concise description of some CR Receivers that are published recently. Indeed, for each CR receiver, we will put the interest only on some criteria that will be used to make the comparison between these receivers. That's why; we will not specify all receivers' details but only some aspects that will be the basis to present our approach for a CR receiver. The criteria are listed below:

- ❖ Targeted Frequency range
- ❖ How spectrum sensing is performed depending on the receiver architecture type
- ❖ Possible Applications
- ❖ Spectrum sensing technique

1- A 100 MHZ – 2.5 GHZ CMOS Transceiver in an experimental Cognitive Radio System

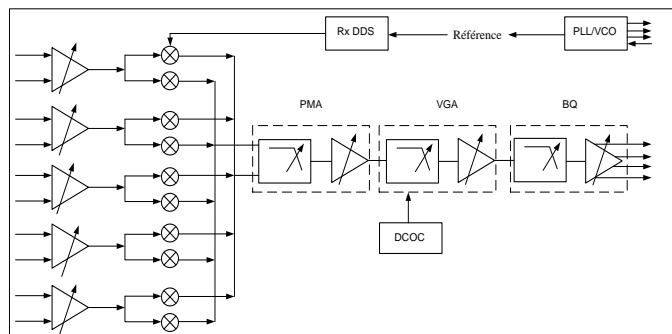


Figure 2. Cognitive Radio receiver architecture for 100 MHz to 2.5 GHz band

Figure (2) represents a direct conversion receiver which is a part of a flexible transceiver used as a CR demonstration [9]. This prototype was based on a Software Defined Radio (SDR) platform that exhibits the CR capabilities such awareness and especially its capability to sense its signal environment and then to determine the spectrum opportunity that would be used for a simple live video application. In addition, this prototype is characterized by a flexible programming that processes signals of several wireless protocols in the range from 100 MHz to 2.5 GHz with channel bandwidths varying from 8 KHz to 20 MHz.

The communication process is based on an OFDM system over arbitrary spectrum spans that are used to perform communication between cognitive radio users and that could be rapidly changed. These spans are also divided into several subcarriers, each modulated with DQPSK. In fact, 96 subcarriers are used comprising 12 spectrum blocks. Every block has a bandwidth of 1.25 MHz and carrying 2.0 Mbps. So a maximum total data rate is 24 Mbps.

❖ Spectrum Sensing Management

The receiver architecture is shared between communication and sensing processing. Indeed, the sensing procedure starts after the analog-to-digital conversion of the acquired samples. The spectrum resolution is settled to 24 bits. After that, the scanned spectrum is divided into small sub-bands of interest and a decision about the occupation state of these sub-bands will be made depending on the analysis of the power spectral density. That's why, for this system, detectors are measuring the energy in each sub-band and the decision is made taking into account adjustable thresholds.

2- Tri-band Cognitive Radio Architecture

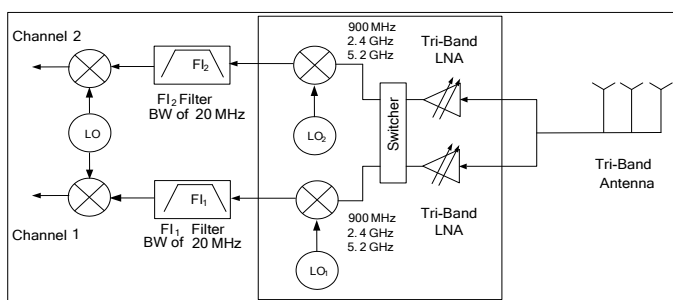
This cognitive radio architecture tends to provide high-performance platform for experimentation with a variety of adaptive wireless network protocols based on an SDR implementation [10]. The architecture of this network-centric cognitive radio platform is based on:

- Fast RF scanning and sensing capability

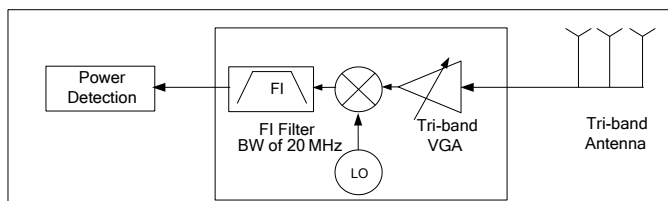
- An agile RF transceiver operating over a range of three ISM frequency bands (900MHz, 2.4 GHz and 5.2 GHz) with a bandwidth of 20MHz.

- A software-defined radio modem that supports a variety of waveforms including OFDM and DSSS/QPSK.

Figure (3-a) represents the RF Front-End part of the tri-band Cognitive Radio direct conversion Receiver that is an element of a full duplex tri-band radio platform. Figure (3-b) shows a tri-band sensing unit which is implemented separately and that would allow to detect opportunities on the ISM frequency bands 900MHz, 2.4GHz and 5.2GHz. The detection method is based on an energy analysis after the analog to digital conversion.



(a)



(b)

Figure 3. RF Front-End part of the tri-band Cognitive Radio (a) direct conversion receiver, (b) Tri-band sensing/monitoring unit

3- UHF-Band CMOS Receiver with Multi-Resolution Spectrum Sensing Functionality for IEEE 802.22 Cognitive Radio Applications

It is a fully integrated CMOS receiver applied to IEEE 802.22 standard. This multi-resolution spectrum sensing (MRSS) receiver is capable to achieve spectrum sensing in the UHF band [11]. This Cognitive Radio functionality is obtained through an analog energy detector technique that is assisted digitally. That's why; the detection decision is accomplished in the digital domain.

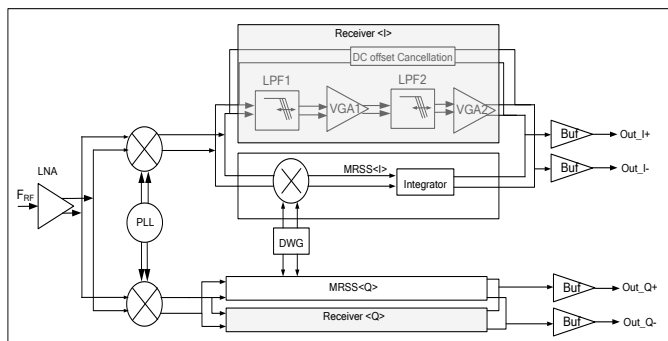


Figure 4. MRSS Cognitive Radio receiver for IEEE 802.22 applications

Figure (4) displays the block diagram of this MRSS receiver.

In effect, it could work as a direct conversion receiver front-end or a spectrum sensing block. Its most important characteristic is that the RF front-end components, such as the low-noise amplifier (LNA) and a mixer, are shared between the receiver mode and MRSS mode that could be switched depending on a serial bus interface control.

In the receiver mode, it is adjusted as a zero-IF receiver. After being amplified and down converted, the RF signal is treated by LPF1, VGA1, LPF2 and VGA2 before being digitized. In this mode, the major part of MRSS blocks is halted to diminish the power consumption.

In the MRSS mode, the receiver works as an energy detector without extra analog filter. Indeed; after being amplified and down converted, the signal is correlated with a flexible window generated from the digital window generator (DWG). So, the output signal is filtered depending on the window of the detection bandwidth which adjusts the sensing threshold and time of detection without having any resort to use a tunable filter. For example, a 100-kHz window allows to have a dynamic range of 32 dB and a detectable sensitivity of 74 dBm.

In this mode, LPF1 and LPF2 are disabled to reduce power consumption.

So, this receiver is compared to a simple spectrum analyzer thanks to the MRSS technique that tends to fasten the sensing mechanism by compromising the sensitivity that could be adapted by the duration and the type of the generated window.

4- A Cognitive Radio Receive Supporting Wide-Band Sensing

The main characteristic of this receiver is that allows to relax ADC's constraints and to simplify the sensing mechanism for the IEEE 802.22 Standard in the range between 41 MHz and 910 MHz [8]. Indeed; considering results of analyzed measurements over expectable spectrum occupation and their impacts on spectrum sensing, it was noticed that many channels in this band do not change while making these measurements. That's why, it is not necessary to achieve a continuous sensing of these statistical spectrum segments which do not present any useful information for an operating Cognitive Radio system. Thus, it is better to leave out these quasi-static frequency segments. Then, it is not necessary to digitize the whole bandwidth at the same time. For that reason,

it could be possible to divide this bandwidth into different sub-bands which leads to the definition of Sub-band Spectrum Sensing technique as a solution to overcome the large bandwidth specified in IEEE 802.22 and the wide dynamic range of signals in this band. In fact, these requirements impose high demands on the receiver's front-end such as ADC's constraints. By applying this technique, the sampling rate of the ADC is decreased since each sub-band is digitized separately. So, these sub-bands are sensed sequentially and the sensing process is repeated periodically.

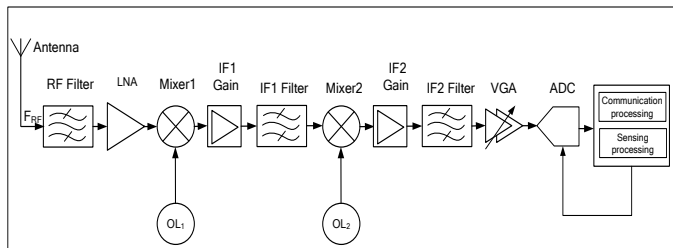


Figure 5. IEEE 802.22 Cognitive Radio receiver supporting sub-band sensing

Figure (5) represents the Cognitive Radio receiver supporting sub-band spectrum sensing. This receiver is based on a superheterodyne architecture that has two Intermediate Frequency (IF) chains for the IEEE 802.22 specifications in the range from 41 to 910MHz. In addition, Its RF Front-end it totally shared between communication mode and sensing mode. To cope with IEEE 802.22 specifications, the bandwidth of each sub-band is fixed to 50 MHz and could be composed either of eight subchannels with a 6 MHz bandwidth or of six sub-channels with a bandwidth of 8MHz. Hence, the sampling rate for this receiver was settled to 100 Msps. The possible digital sensing technique that could be applied is either energy detection or even feature detection algorithm.

❖ Comparison of Receivers characteristics

Table II summarizes various characteristics of the studied receivers where the receiver type column reflects how sensing and communication are implemented (in the same receiver path or with separate receivers). Indeed, we tried in the previous part of this work to put the interest on some specific features for each receiver. In addition, we focused on the way how spectrum sensing is treated and that makes these receivers Cognitive radio systems over various bands and different kind of applications.

TABLE- II RECAPITULATION OF CR RECEIVERS CHARACTERISTICS

Spectral Band	Receiver Type	Application	Sensing Technique
A 100 MHz – 2.5 GHz CMOS Transceiver in an experimental Cognitive Radio System			
100 MHz 2.5 GHz	Direct Conversion Combined	SDR Platform Video application	Digital energy detection

Spectral Band	Receiver Type	Application	Sensing Technique
Tri-band Cognitive Radio Architecture			
900 MHz 2.4 GHz 5.2 GHz	Combined	Platform SDR ISM band	Digital Energy detection
A Fully Integrated UHF-Band CMOS Receiver with Multi-Resolution Spectrum Sensing (MRSS) Functionality for IEEE 802.22 Cognitive Radio Applications			
UHF Band	partially parallel	IEEE 802.22	Digitally assisted analog energy detection
A Cognitive Radio Receive Supporting Wide-Band Sensing			
41MHz → 910 MHz	Combined	IEEE 802.22	Digital energy or feature detection

Based on this comparison, our choice will be made especially depending on the following characteristics:

- Our receiver shall comply with IEEE 802.22 standard requirements. Thus, the first two studied receivers could not be a basis to our receiver design. In fact, the first receiver has a range from 100 MHz to 2.5 GHz and uses an SDR platform. The second receiver is not specified to be an IEEE 802.22 application.

- Second, to meet the challenge of power consumption, our receiver needs to satisfy this criterion. That's why; the Cognitive Radio receiver should treat communication and sensing modes with a maximum exploitation of the RF Front-End part. Indeed; the difference should be located only at the base band part of this receiver where the digital signal is processed separately depending on the processing type. Thus, the spectrum sensing technique should be based on a digital approach that begins with the ADC stage. So, considering our comparison, the MRSS receiver allows only to share the first part of the RF Front-End (only LNA and mixer). Also, this technique is based on digitally assisted analog energy detection. For these reasons, this kind of receiver will not be the basis of our approach. However, if we consider the last studied receiver, we can see clearly that it complies with IEEE 802.22 standard requirements which was our first constraint. Moreover, the entire RF Front-End of this Cognitive Radio receiver is shared between communication and sensing modes. In addition, it uses a digital sensing technique which could be either energy detection or feature detection. Hence, our study will be based on this kind of Cognitive Radio receiver for which the entire band is divided in several sub-bands.

In our study, a Cognitive Radio Receiver supporting sub-bands sensing will be the basis of our study. However, we will exhibit a new approach that complies with the sub-band sensing technique. Indeed, we will present in the next sections a methodology to design this receiver which was not yet applied to any kind of CR receivers. In addition, our approach is based especially on two main points:

❖ As it was mentioned in the IEEE 802.22 specifications, we will consider in our design a spectral band that ranges from 54MHz to 862MHz and not from 41MHz to 910MHz. So, we will adapt the two IF chains of the CR receiver to treat this band by adjusting the frequency range of the first local oscillator LO1 and the bandwidths of the used filters. All details will be given in the next section.

❖ To overcome the trade-off and to relax the ADC requirements for our CR receiver, the sub-band sensing technique will allow us to put a special interest on a new way to treat sensing and communication signals. In fact, we will make the ADC a reconfigurable element and its characteristics will be adjusted depending on the signal's type. These characteristics are bandwidth, sampling frequency and dynamic range.

In the next paragraph, we will exhibit a "Functional description of our CR receiver applied to IEEE 802.22 standard".

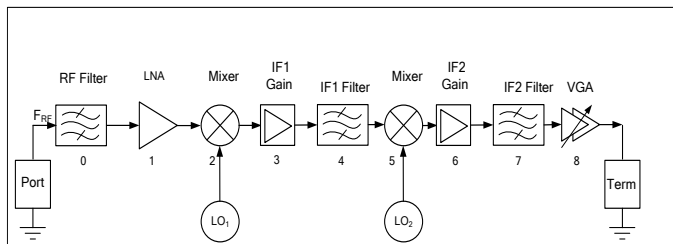


Figure 6. Representation of the simulated CR receiver with ADS tool

Figure 6 presents the architecture of the CR receiver that complies with IEEE 802.22 specifications. We made our simulations on this receiver using ADS tool (Advanced Design System). That's why; we added a port to define the RF input signal that ranges from 54 MHz to 862 MHz. Based on superheterodyne architecture, this receiver has two Intermediate Frequency (IF) stages. After being detected by the antenna, the signal is filtered through the RF filter that limits the needed bandwidth from 54 MHz to 862 MHz. Then, the LNA ameliorates the SNR of the signal which will be up converted up to 1000 MHz through the first Local Oscillator (LO1). Its frequency band ranges from 1054 MHz to 1862 MHz. Thus, the image frequency, which would range from 2054 MHz to 2862 MHz, is not a constraining factor because it will be eliminated by IF1 filter without having resort to use any image frequency rejection filter. Whilst passing through the second transposition stage, the second LO2 down converts

the IF1 signal of 1 GHz with 970 MHz. So the resulted signal is centered at a second IF2 of 30 MHz. Hence, the second image frequency, that is around 940 MHz, will be eliminated by the second IF2 filter. After that, the VGA allows to maintain constant signal strength at the ADC input. As it was mentioned, this receiver supports sub-band sensing technique. That's why; the whole bandwidth of 808 MHz will be divided into several sub-bands of 50 MHz. Each one is composed of eight subchannels with a bandwidth of 6 MHz. Its full scale power is settled to 13 dBm which represents an adequate ADC power level [16]. The overall DR at the receiver input is around 50 dB while processing communication signals which leads to a dynamic range at the ADC input is around 54 dB.

By adjusting the supported bandwidth, it is possible to reduce the effective number of bits N_{eff} through altering the allowed dynamic range either for communication or sensing mode. Thus, this approach will overcome the trade-off that limits ADC performances. For sensing mode, the ADC effective bit number is fixed only to 4 bits with a dynamic range of around 26 dB at the input of the analog to digital converter. This dynamic range is needed in order to detect the primary users in each sub-band. These characteristics are assessed depending on the sensing thresholds defined in the IEEE 802.22 requirements. In addition, the maximum sampling rate is around 100 Msps since the treated bandwidth in this case is about 50 Mhz which represents the fixed sub-band bandwidth. On the other hand, for communication signals processing, the ADC digitizes each sub-channel of the sensed sub-band with a bandwidth of 6MHz. In this case, the ADC sampling rate needed is about 12 Msps with an ADC input dynamic range of 54 dB. So, in this configuration, ADC would require 9 bits as effective resolution and its $\text{SNR}_{\text{in_ADC}}$ is settled to 4.02 dB.

Table III summarizes the different ADC characteristics that are proposed for communication and sensing processing.

TABLE-III SUMMARY OF ADC CHARACTERISTICS

ADC characteristics		
	Communication mode	Sensing mode
N_{eff}	9	4
Bw(MHz)	6	50
DR (dB)	54.22	26.02

IV. METHODOLOGY OF THE SYSTEM LEVEL DESIGN

In this section, we will introduce the methodology that we used to achieve the system level design of the cognitive radio receiver that supports sub-band sensing technique. Indeed, we will detail theoretical computations of the RF characteristics which will be applied depending on IEEE 802.22 specifications [12].

1. Theoretical computations

1.A. Sensitivity and noise figure

One of the significant parameters of a radio frequency receiver is sensitivity. This factor reflects the lowest input signal level in dBm that the receiver can detect and correctly demodulate without deteriorating the Bit Error Rate (BER) [3].

Noise figure allows to describe the system quality. This feature reflects how much the signal to noise ratio (SNR) gets deteriorated while the input signal passes through the receiver. The relationship between NF and sensitivity can be described as [3]:

$$P_{in, min} = -174 \text{ dBm} / \text{Hz} + NF + 10 \log B + SNR_{min} \quad (3)$$

In this expression, B is the channel bandwidth of the receiver evaluated in Hertz, $P_{in, min}$ is the smallest input signal level that gives SNR_{min} and -174dBm/Hz is the thermal noise power for an input resistance of 50 Ohm.

FRIIS formula [4] settles the noise factor of cascaded stages as follows:

$$nf = nf_1 + \frac{nf_2 - 1}{G_1} + \frac{nf_3 - 1}{G_1 \cdot G_2} + \dots + \frac{nf_n - 1}{\prod_{i=1}^{n-1} G_i} + \dots \quad (4)$$

Where nf_i is the noise factor of each block and G_i is its i -th associated power gain. The noise factor is the equivalent in dB of the noise figure as described below:

$$NF|_{dB} = 10 \cdot \text{Log}(nf) \quad (5)$$

1.B. Non linearity and intermodulation issue

Owing to nonlinearities effects, blockers can create third order intermodulation term which is the most dominant product. That's why; Linearity could be characterized by the third order intercept point (IIP3) [3]. The impact of non linearity could devastate the input signal. Next expression describes the whole IIP3 of cascaded stages as a function of each $IIP3, i$ and G_i of the i -th block:

$$\frac{1}{IIP_{3,3}^2} = \frac{1}{IIP_{3,1}^2} + \frac{G_1}{IIP_{3,2}^2} + \dots + \frac{G_1 \dots G_{m-1}}{IIP_{3,m}^2} \quad (6)$$

2. Application of CP_{1dB} AND IIP3 computations to IEEE 802.22 requirements

Owing to instantaneous signal path fluctuations such as shadowing and path loss, the amplitude of transmitted and received signals could expose different ranges of discrepancy. That's why, in order to overcome these problems, RF characteristics have to be specified. In fact, the noise figure performance sets the lowest level of the dynamic range (DR) of any receiver. In addition, the highest signal level is restricted by its linearity performance. To preserve constant signal strength at the input of the ADC, the Voltage Gain Amplifier (VGA) is used to allow an efficient sampling operation. Moreover, along with other RF blocks that may cover large DR, the LNA (Low Noise Amplifier) could be taken as one of the first stages that the signal passes through. Referring to the IEEE 802.22 receiver requirements, the lowest input signal $P_{in, min}$ is assessed to -92dBm and the highest level $P_{in, max}$ is set to -41.8dBm . In order to decrease the large input signal levels, the gain of VGA shall be reduced to prevent the receiver of any saturation effects that could harm the linearity requirements. To carry out this demand, two switched gain modes should be presented to provide the wanted amplification that is related to the signal weakness or strength.

2.A. Low gain mode (LGM)

Due to the signal strength with enough power, in this low gain mode, an important amplification is worthless. Taking into account the fact that IEEE 802.22 standard settles OFDM as the modulation scheme, an input back-off (IBO_{max}) [13] of 12dB is assessed for this mode as the difference between the maximum input signal and the input-1dB-compression point (CP_{1dB}) [15]. In fact, an OFDM signal has an altering envelope that is defined by the Peak-to-Average Power Ratio (PAPR) [2] which is related to the IBO definition.

Considering that the maximum input signal $P_{in, max}$ is -41.8dBm , CP_{1dB} could be calculated as follows:

$$CP_{1dB_min} = P_{in_max} + IBO_{max} = -29.8 \text{ dBm} \quad (7)$$

By virtue of the thumb's rule, the IIP3 is higher than CP_{1dB} by 9~10 dB [15]. Thus, the required IIP3 for IEEE 802.22 receiver in this mode is given to be about -19.8dBm :

$$IIP3_{min} = CP_{1dB_min} + 10 = -19.8 \text{ dBm} \quad (8)$$

2.B. High gain mode (HGM)

Opposing to the low mode, in the high gain mode, a significant amplification is required to surmount the signal weakness that is detected at the input of the RF receiver. In effect, the smallest signal level $P_{in, min}$, that is specified in the IEEE 802.22 standard while communicating, is about -92dBm . Whilst treating these weak signals, the impact of further interferers is more important. To overcome this problem, the minimal back-

off (IBO_{\min}) from the CP_{1dB} is fixed to 8 dB [14]. Thus, the input-1dB-compression point is computed as follows [15]:

$$CP_{1dB_max} = P_{in_max} + IBO_{\min} = -33.8 \text{ dBm} \quad (9)$$

Then, the IIP3 is measured as:

$$IIP3_{\max} = CP_{1dB_max} + 10 = -23.8 \text{ dBm} \quad (10)$$

From these calculations, it is clear that linearity requirements depend on the gain mode and consequently to the signal level detected at the input of the RF receiver. For our case, to be able to treat precisely a signal with maximal power of -41.8 dBm (i.e. in low gain mode), the linearity of the receiver should be at least at -19.8 dBm. Nevertheless, it becomes harder at -23.8 dBm for high gain mode. Thus, we can announce that linearity is the most constraining factor in low gain mode and Noise Figure confines the receiver performances for high gain mode.

V. BUDGET SIMULATIONS

After describing our new approach of Cognitive radio Receiver supporting sub-band sensing, the distribution of IEEE 802.22 specifications could be realised. In fact, by achieving Budget simulations, each block characteristics, such as gain, IIP3, NF, and output power, are obtained through this RF system budget analysis. As we mentioned before, all these parameters are related together as exhibit Friis and IIP3 equations (4), (6). The distribution of the IEEE 802.22 requirements will be made through the receiver blocks that are defined in figure 2. these blocks are listed follows: the first block assigned to 0 is the band pass RF filter, block 1 represents the LNA, block 2 is the first converting stage, blocks 3 and 4 are respectively the IF1 gain amplifier and its associated IF1 band pass filter, the second IF stage includes blocks 5, 6 and 7 which are the second mixer, IF2 gain amplifier and IF2 band pass filter. The block 8 is the VGA as the last block of the analog part of the RF Front-end of our receiver. The different budget simulations will be presented for the two gain modes as follows.

A. Budget simulation for low gain mode

For this mode, linearity is the most constraining factor since strong signals are considered here. That's why, noise figure will be neglected. The budget simulations should expose a total IIP3 around -19.8 dBm. That's why; the VGA gain is settled at its minimum value. The Simulation results of IIP3 and gain evolution are exposed in (figure (7-a)) and (figure (7-b)) respectively. Figure 7 indicates that the linearity requirement is satisfied. In effect, at the input of the receiver, the value of IIP3 (represented by TOI in (figure (7-a))) is -19.77 dBm with a total gain around 51 dB dispatched as

follows: 9.42dB for LNA, 1dB for Mixer1, 20.79dB for the IF1 gain amplifier, 1dB for Mixer2, 20.79dB for the IF2 gain amplifier and 0dB for VGA.

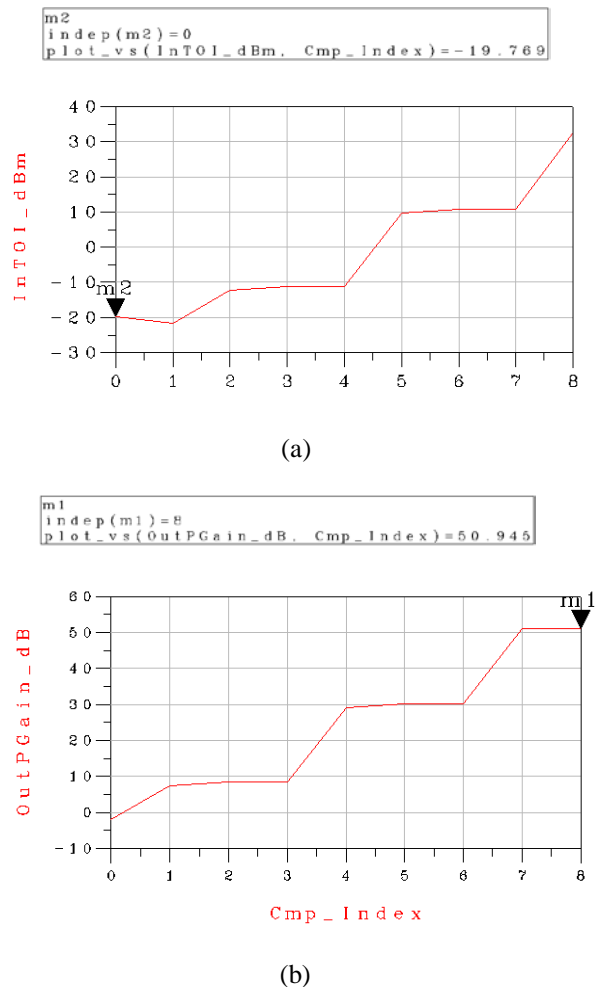


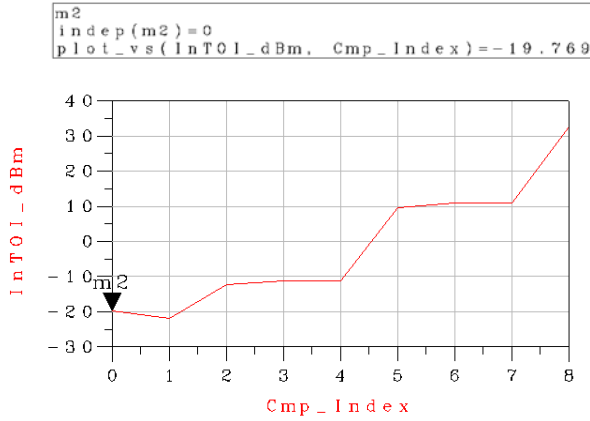
Figure 7. Evolutions of input third order intercept point TOI (a) and gain (b) along with different receiver blocks for low gain mode

B. Budget simulation for high gain mode

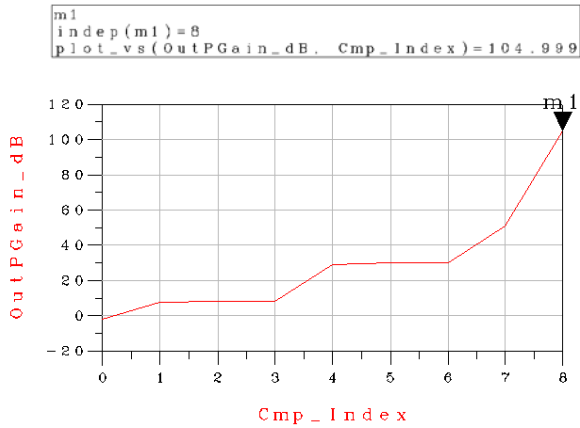
In this case, linearity is not the most constraining matter as the input signal is weak. For that reason, noise could deteriorate the quality of the treated signals. To surmount this fact, only the VGA gain will be amplified to meet the noise requirements without varying the blocks values yet fixed. In addition to IIP3, NF and gain simulations, we will consider the output maximal power (P_{out_max}) obtained at the input of the ADC to convene the full scale power requirement. In fact, figure 8 exposes respectively the evolution of IIP3 (figure (8-a)), Gain (figure (8-b)), NF (figure (8-c)) and P_{out_max} (figure (8-d)). At the input of the receiver, the IIP3 value is about -19.77dB which complies with the specifications as represents figure (8-a). In addition, figure (8-b) demonstrates that the receiver gain has attained 105dB.

Figure (8-c) indicates that the total NF is around 9.6dB dispatched as follows: 1.3dB for LNA, 10dB for Mixer1,

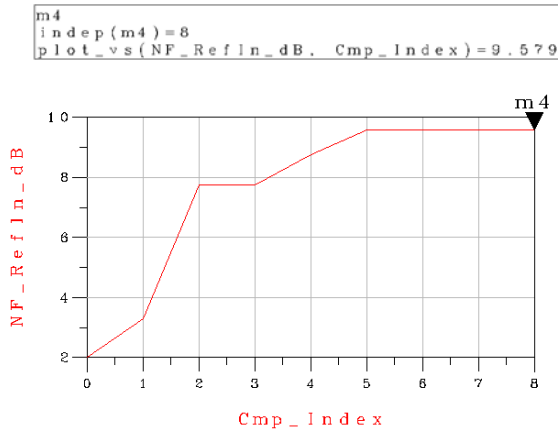
9.5dB for the IF1 gain amplifier, 10dB for Mixer2, 9.5dB for the IF2 gain amplifier and 13dB for VGA. This figure presents also a difference of 2dB at the first bloc which is the RF filter. In fact, it represents the coupling and filter losses, which are fixed by the IEEE 802.22 requirements as a total of 2dB [7]. So, it is obvious that this requirement is taken into account when simulating the ADS receiver model, as the RF filter insertion losses. Moreover, figure (8-d) shows that P_{out_max} is around 13dBm which is equivalent to the full scale power P_{fs} at the ADC input that we fixed previously.



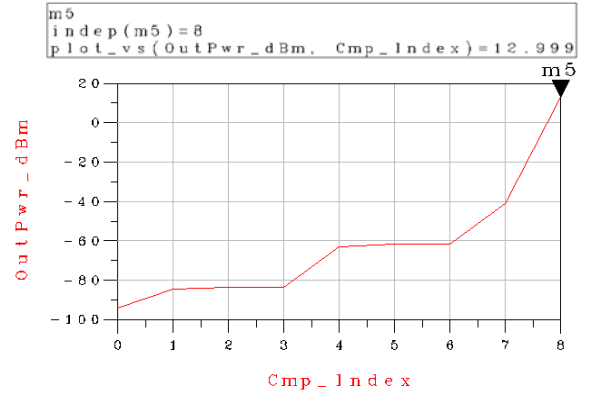
(a)



(b)



(c)



(d)

Figure8. Evolution of input third order intercept point TOI (a), gain (b), noise figure NF (c) and output power P_{out_max} (d) along with different receiver blocks for high gain mode

Characteristics of the studied receiver are summarized in table IV. At the end, the Cognitive radio constraints that are specified at the beginning of this project in terms of IIP3, NF and P_{fs} referring to IEEE 802.22 specifications, are satisfied.

TABLE IV. BLOCKS LEVEL SPECIFICATIONS

Para	LNA	Mix 1	IF1 Gain Amp	Mix 2	IF2 Gain Amp	VGA	
						LGM	HGM
Gain (dB)	9.42	1	20.79	1	20.79	0	54
NF (dB)	1.5	10	8	10	8	11	
IIP3 (dBm)	-5.5	21	18	21	18	32.6	

VI. CONCLUSION

To conclude, we have presented a strategy of a system level design that was applied to a Cognitive Radio receiver that complies with the IEEE 802.22 standard requirements. In fact, we began this project by a concise overview of the CR state of art and we described some basic design techniques that are used to fulfill the budget simulations. We detailed also the IEEE 802.22 specifications. In addition, we made a comparison of different CR receivers that we are based on to present a new approach that takes the interest on the ADC requirements while processing communication or sensing. This receiver supports IEEE 802.22 as the first Cognitive Radio standard that tends to reuse the fallow TV spectrum without harming incumbent users. After that, the distribution of the RF specifications such as linearity, gain and noise are detailed and the correlation that associates them is discussed. At the end, to meet the challenge between noise reduction and linearity enhancement, two gain modes are exhibited. Budget simulations confirm that the receiver offers 51 dB gain and

-19.8 dBm IIP3 in the low gain mode. For the high gain mode, the receiver performs up to 105 dB gain, -19.8 dBm IIP3 and a Noise Figure of 9.9 dB.

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