DESIGN AND IMPLEMENTATION OF ALGORITHMS FOR COOPERATIVE WIRELESS SYSTEMS IN COGNITIVE RADIO NETWORKS

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DECLARATION OF AUTHORSHIP

I declare that the work in this dissertation was carried out in accordance with the requirements of the University's Regulations and Code of Practice for Research Degree Programmes and that it has not been submitted for any other academic award. Except where indicated by specific reference in the text, the work is the candidate's own work. Work done in collaboration with, or with the assistance of, others, is indicated as such. Any views expressed in the dissertation are those of the author.

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ABSTRACT

Recent years with the startling rise of technology, an increasing number of wireless devices, innovative services and mobile users will require more and more spectrum resources. In order to maintain high Quality of Services, we have to introduce new innovative technologies which will satisfy fully publics' demands. The solution to the problem goes by the name of "Cognitive Radio".

Cognitive Radio is a developed technology with the view to exploiting idle spectrum and improve its utilization. The main and most complex way in order to detect unused sub-bands is by sensing effectively the spectrum. However, if the implemented algorithms do not cooperate well with the privileged users who are called Primary Users (PU) and use the distributed bands, then they will interfere each other by using the same Radio Frequency (RF) channels.

Therefore, in this thesis I will present a number of cooperative designs and implementations during experimentations which will try to eliminate the impact from the unexpected interference. Thus, my main goal is to transmit a number of packets in an efficient approach among three pairs of nodes avoiding conflicts in co-channels. The main tools that have been used in order to implement those algorithms: a) Software Define Radios and more specifically USRPs B210 and b) GNU Radio software. Consequently, the two dominant approaches of the development are focused on the process in the Frequency domain and the optimal sensing by Time.

ΠΕΡΙΛΗΨΗ

Τα τελευταία χρόνια με την εντυπωσιακή εξέλιξη της τεχνολογία, ένας αυξανόμενος αριθμός από ασύρματες συσκευές, καινοτόμες υπηρεσίες και χρήστες κινητών τηλεφώνων θα χρειάζονται ολοένα και περισσότερες πηγές ραδιοφάσματος. Προκειμένου να διατηρηθεί η υψηλή ποιότητα των υπηρεσιών, πρέπει να εισαγάγουμε νέες καινοτόμες τεχνολογίες, οι οποίες θα ικανοποιήσουν πλήρως τις απαιτήσεις του κοινού. Η λύση του προβλήματος ονομάζεται «Γνωστικό Δίκτυο».

Το Γνωστικό Δίκτυο είναι μια αναπτυγμένη τεχνολογία με σκοπό την εκμετάλλευση του αδρανούς φάσματος και τη βελτίωση της χρήσης του. Ο κύριος και πιο περίπλοκος τρόπος για να εντοπιστούν αχρησιμοποίητες υπό-ζώνες είναι με την αποτελεσματική ανίχνευση του φάσματος. Παρ' όλα αυτά, αν οι αναπτυγμένοι αλγόριθμοι δεν συνεργάζονται καλά με τους προνομιούχους χρήστες που ονομάζονται πρωτεύοντες και χρησιμοποιούν τις κατανεμημένες ζώνες, τότε θα παρεμβάλλουν μεταξύ τους χρησιμοποιώντας τα ίδια κανάλια.

Ως εκ τούτου, σε αυτή τη διπλωματική εργασία, θα παρουσιάσω τον σχεδιασμό και την υλοποίηση συνεργατικών αλγορίθμων μέσω πειραμάτων, όπου θα προσπαθήσω να εξαλείψω τον αντίκτυπο από την απρόσμενη παρεμβολή. Έτσι, κύριος στόχος μου είναι να μεταδώσω ένα αριθμό πακέτων σε μια αποτελεσματική προσέγγιση μεταξύ τριών ζευγών κόμβων, αποφεύγοντας τις συγκρούσεις στα ίδια κανάλια. Τα κύρια εργαλεία που χρησιμοποιήθηκαν για την υλοποίηση αυτών των αλγορίθμων είναι ένα δίκτυο καθορισμένου λογισμικού που αποτελείται από την δομή δικτύου GNU radio και τις κεραίες USRP μέσω των οποίων έγινε η κατασκευή των επικοινωνιών. Κατά συνέπεια, οι δυο κυρίαρχες προσεγγίσεις της ανάπτυξης επικεντρώνονται στον τομέα της συχνότητας, καθώς και στη βέλτιστη ανίχνευση στον χρόνο.

ACKNOWLEDGMENTS

At this point, I would like to express my sincere gratitude to my supervisor, Professor Korakis Athanasios, who trusted me with the assignment of this specific subject and as well, for our excellent cooperation. Also, I would like to thank my co-advisor, Professor Argyriou Antonios for his contribution.

Furthermore, I feel glad to thank the PhD Candidate Passas Virgilios for his continuous assistance and guidance for the completion of this work.

Finally, I owe a big thank you to my family and especially to Maria, who are always there, helping and supporting me all these years.

To Maria and my family...

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ABBREVIATIONS

SDR	SOFTWARE DEFINED RADIO
CR	COGNITIVE RADIO
GNU	GNU'S NOT UNIX RADIO
PU	PRIMARY USERS
SU	SECONDARY USERS
SNR	SIGNAL-TO-NOISE RATIO
AWGN	ADDITIVE WHITE GAUSSIAN NOISE
ADC	ANALOG TO DIGITAL CONVERTER
A/D	ANALOG TO DIGITAL CONVERTER
DCA	DIGITAL TO ANALOG CONVERTER
D/A	DIGITAL TO ANALOG CONVERTER
LNA	LOW NOISE AMPLIFIER
DSP	DIGITAL SIGNAL PROCESSOR
GUI	GRAPHICAL USER INTERFACE
DDC	DOWN DIGITAL CONVERTER
LPF	LOW PASS FILTER
CIC	CASCADE INTEGRATE COMB FILTER
NCO	NUMERICALLY CONTROLLED OSCILLATOR
GMSK	GAUSSIAN MINIMUM SHIFT KEYING

CHAPTER 1

INTRODUCTION

1.1 Motivation

There is no denying that the startling rise of the technology has brought an explosive development in the wireless communications. An increasing number of users and applications demand more and more spectrum resources in order to maintain their communications. It is extremely obvious that the wireless communications will constitute a significant role for the economic growth of every country in the next few years. However, the current process of prearranged frequency allocation cannot satisfy these demands and the inefficient utilization of the spectrum resources has created great problems. Thus, the continuing researches for the efficient use of the spectrum bandwidth has led in a cognitive radio (CR) and a dynamic spectrum access.

Even though, the researches have done a lot of steps forward, their main field of study is limited on a priority-based model where the users are classified into two main categories called Primary Users and Secondary Users. The former are users with high priority usage or have licensed rights in order to exploit some specific frequencies. The latter are unlicensed users and allowed to use the spectrum by the time it is not in use or they do not cause harmful interference to the primary users. Nevertheless, this approach has some staring drawbacks as when multiple users try to exploit the same frequencies having pre-established priority, then the sharing algorithm would be inefficient due to the fact that a great delayed would be occurred.

Moreover, this thesis is motivated by the DARPA's Spectrum Challenge. The Defense Advanced Research Projects Agency (DARPA) has create a competition called DARPA Spectrum Challenge where the researchers are called to demonstrate a robust communication system in a specific set of frequencies with the presence of other dynamic users and unknown interference. The competition consists of two challenges, the cooperative and the competitive one.

Thus, this thesis focused on a cooperative spectrum challenge, where all users, without previous knowledge of the spectrum, through energy detection will utilize it in a framework of synchronization or they will exploit unused parts of it. For instance, in the first case, the users have to wait for a period of time in case they detect the presence of another user in the same frequencies and in the second case, they scan the spectrum in order to find unused channels and to establish a communication link.

1.2 Thesis Outline

This Thesis is developed by the use of GNU Radio software and the Ettus Universal Software Radio Peripheral (USRP) hardware in order to design and implement the radio protocols. The outline is organized as follows. The Chapter 2 summarizes the background of the current used technologies. There is a description of SDR, GNU Radio tools and the construction of USRPs. Subsequently, the Chapter 3 explains the terminology of Cognitive Radio and some existing methodologies. In Chapter 4, the review of the rules and the strategies which are implemented, is introduced. Also, strategies are analyzed and evaluated in comparison. Finally, in Chapter 5 the Conclusion of the experiments and the Future work are presented.

CHAPTER 2

BACKGROUND

2.1 Software defined radio

As it can be found widely in literature the «**Software-defined radio** (**SDR**) comprise a radio communication system where components are implemented by software on a personal computer or an embedded system instead of implemented with real hardware such as mixers, filters, amplifiers, modulators, demodulators, detectors etc. »[1]

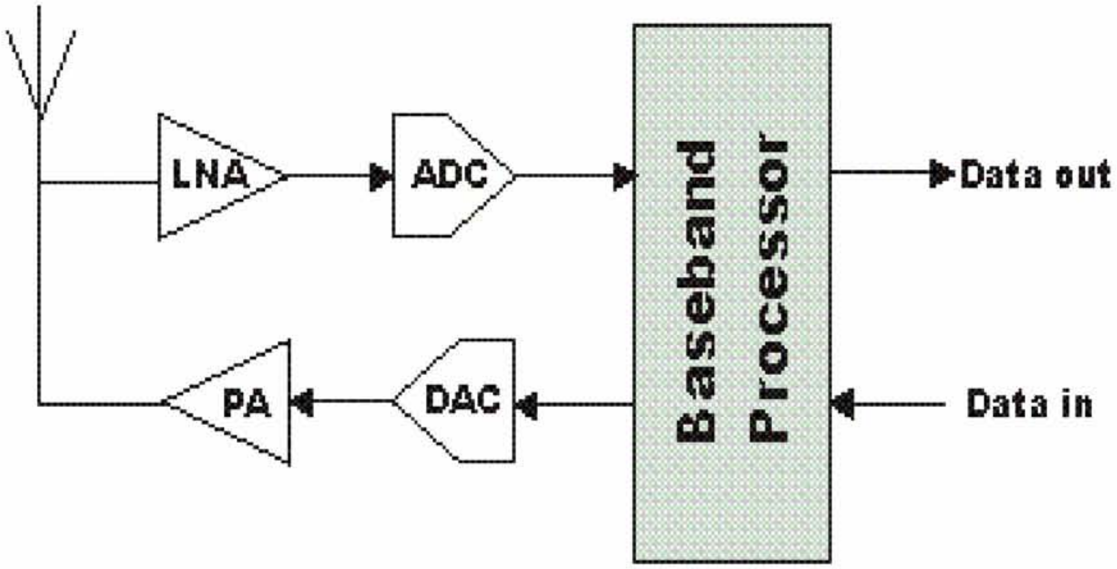

FIGURE 1: IDEAL SDR

[1] *SDR, Wikipedia*

2.1.1 Characteristics of SDR

One of the main operating principle of an ideal SDR is to include an ideal transmitter and an ideal receiver. At the beginning, in the receiver side will be installed an analog-to-digital converter close to an antenna and a digital signal processor would read the converter. Then, the software will transform the stream of data from the converter to the desirable one. With a similar operation in the transmitter side, a digital signal processor would generate a stream of digits which would be sent to a digital-to-analog converter connected to a radio antenna. The baseband processor will handle all the other functions of the radio such as modulation/demodulation, filtering and up/down conversions. A Digital Signal Processor (DSP) or FPGA can perform these functions.

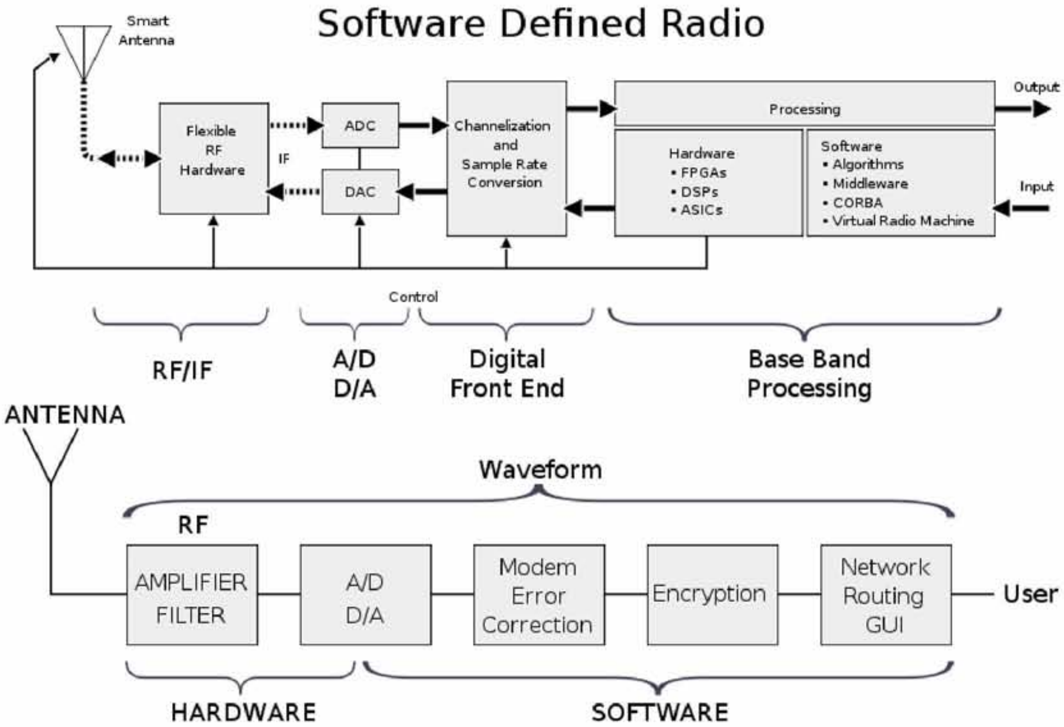

FIGURE 2: SDR BLOCK DIAGRAM

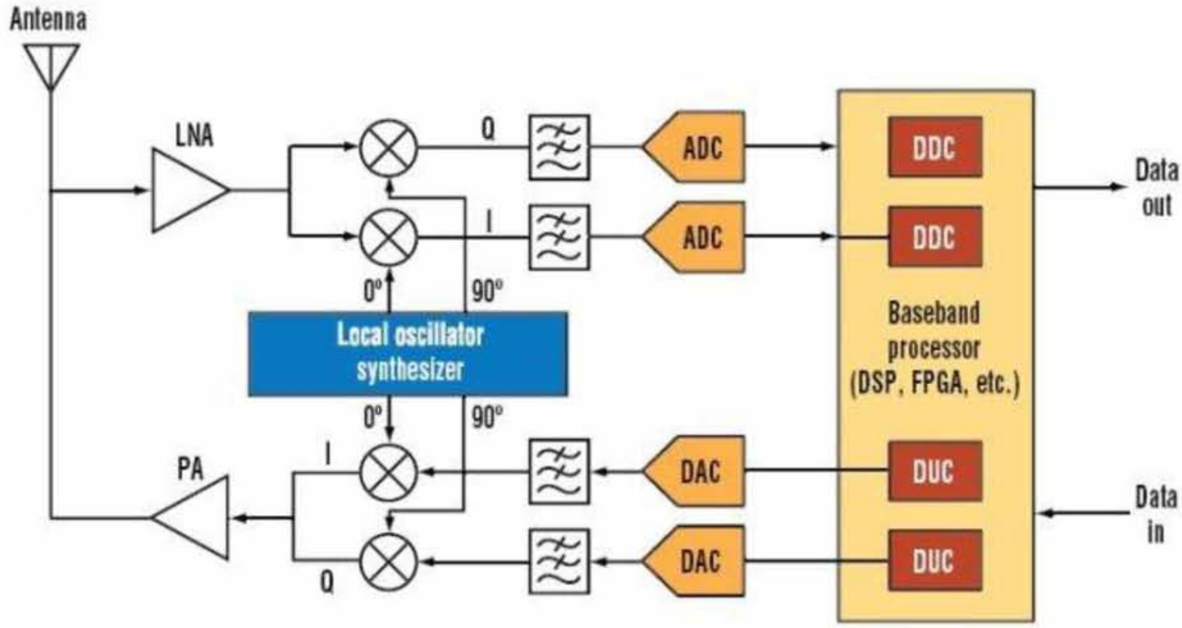

FIGURE 3: REAL SDR STRUCTURE

2.1.2 Advantages and Disadvantages of SDR

It is clear enough that the ability of SDR to operate in multiple function is the most significant advantage. A SDR system can operate flexible enough through the programmable ability of the FPGA. Moreover, it can assure that the hardware is used in order to design various experiments will maintain its reusability. What is of utmost importance is that can replace some current and most complex telecommunications systems with better performance and reliable results.

Some cases where a SDR can be deployed is in mobile networks where the high speed of FPGA can contribute in the high demand for data rates and in satellite communications where the cost of the designed blocks is outrageous. Another important sector where it can contribute to is the military operations. The need for well-established communications which provide security and effective cost concurrently is a high demand for the military.

On the other side, the real problem is that the actual limits of this technology is not completely defined. So, the main issue is the difficulty of conversion between the digital and the analog domains at a high enough rate and a high enough accuracy at the same time. Physical interference and electromagnetic resonance can cause problems in the performance of SDR.

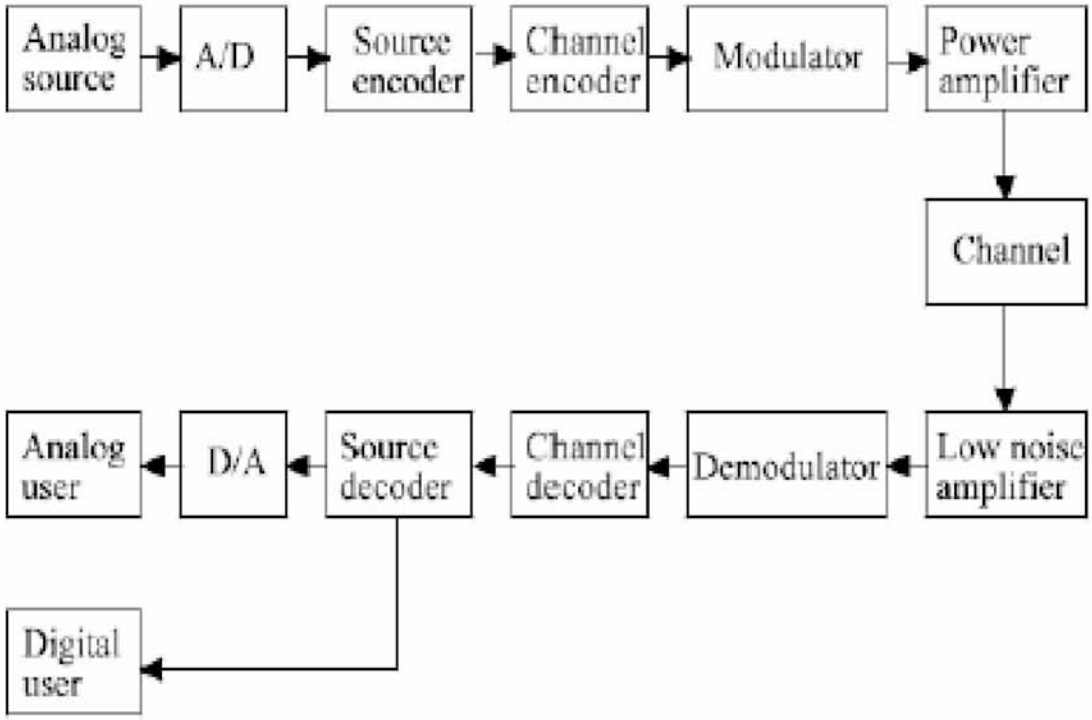

FIGURE 4: BLOCK DIAGRAM OF A TYPICAL COMMUNICATION SYSTEM

2.2 GNU Radio

Our radio is implemented with the CNU radio 3.7.11 software and the USRP B210 and their definitions are presented as they are explained by the developers.
«**GNU Radio** is a free and open-source software development toolkit that provides signal processing blocks to implement software define radios and signal processing systems. It can be used with external RF hardware to create software defined radios, or without hardware in a simulation-like environment. The software provides the framework and the needed tools in order to design the desirable protocol. Its flow graphs are written in either C++ or Python. »[2]

[2] *GNU Radio, Wikipedia*

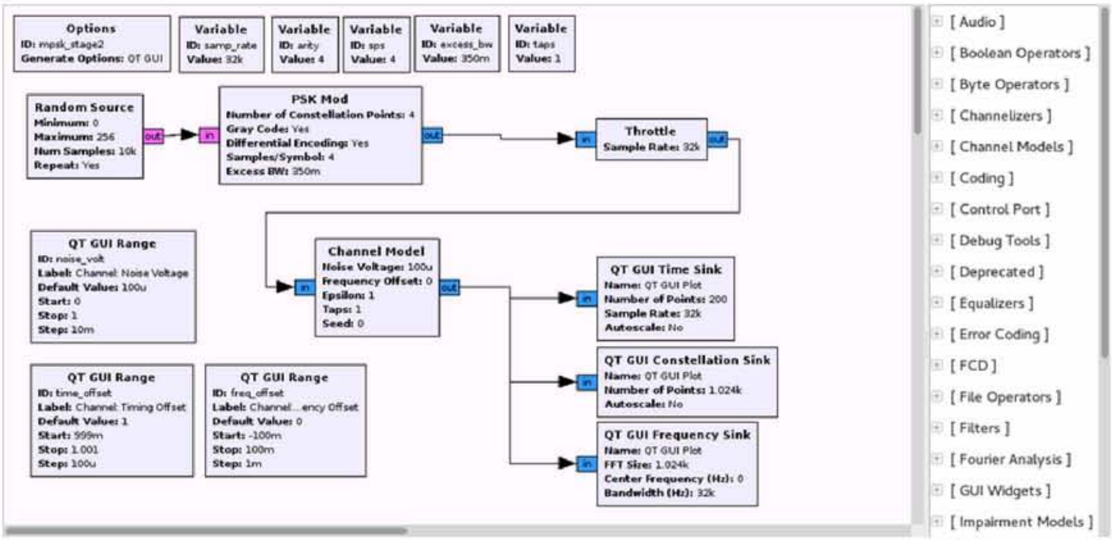

FIGURE 5: EXAMPLE OF IMPLEMENTED BLOCKS IN GNU RADIO COMPANION

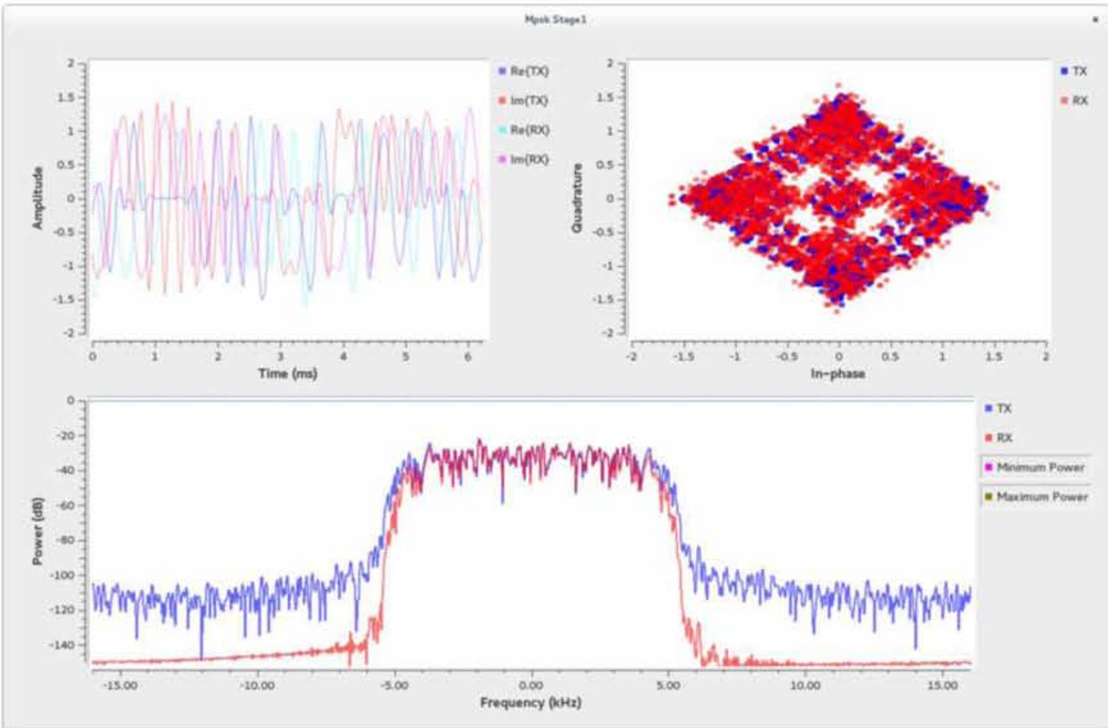

FIGURE 6: INSTANCE OF THE OBSERVING TOOL

2.3 Universal Software Radio Peripheral

«**USRP** is a hardware platform used for implementing a range of software defined radio designs and is sold by Ettus Research and its parent company, National Instruments. The USRP products have mainly the similar architecture.
A motherboard provides the following subsystems: clock generation and synchronization, FPGA, ADCs, DACs, host processor interface and power regulation. Also, a modular front-end component which is called daughter board is responsible for analog conversions, filtering and other signal conditioning. »[3]

[3] *USRP, Wikipedia*

The general architecture of the USRP hardware:

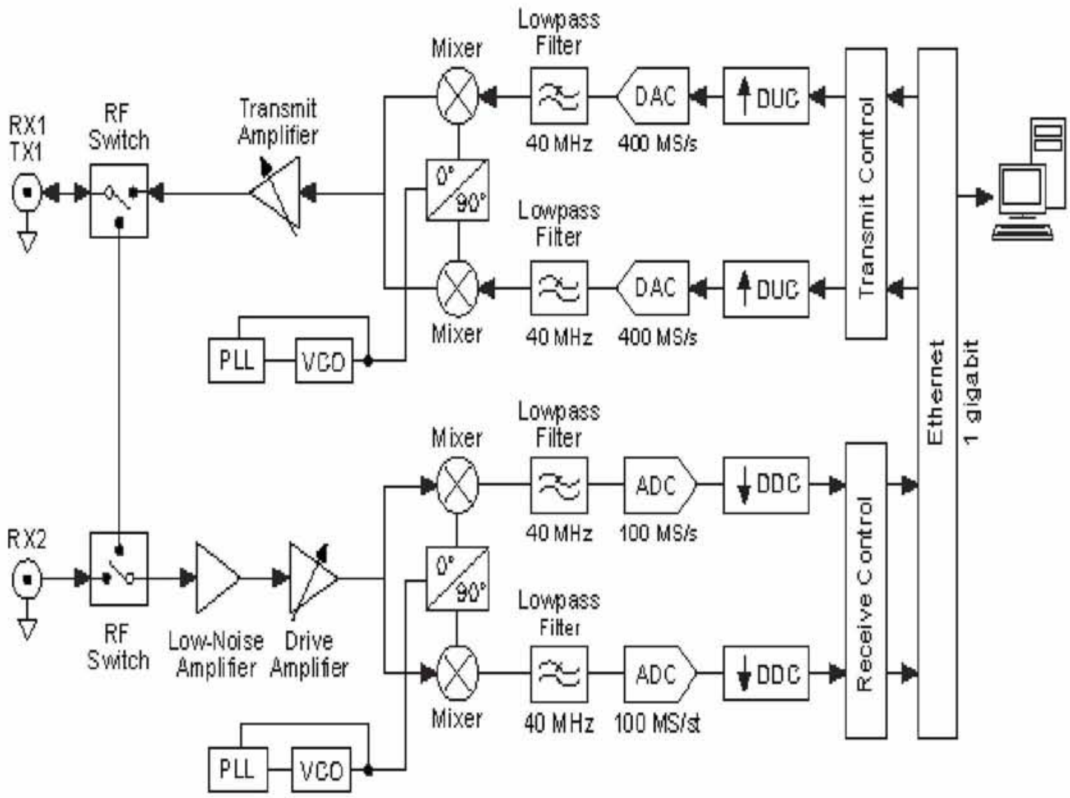

FIGURE 7: GENERAL USRP ARCHITECTURE

The architectural diagram of a USRP B210 hardware components can be observed below.

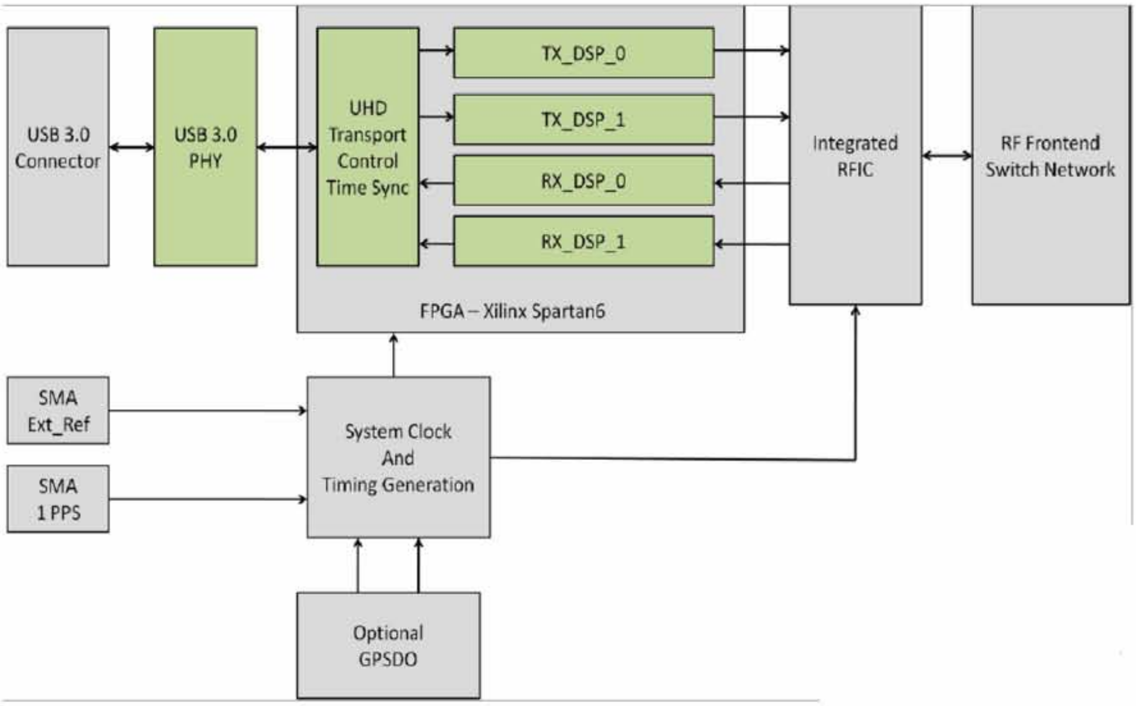

FIGURE 8: USRP B210 ARCHITECTURAL DIAGRAM

FIGURE 9: USRP B210 BOARD ARCHITECTURE

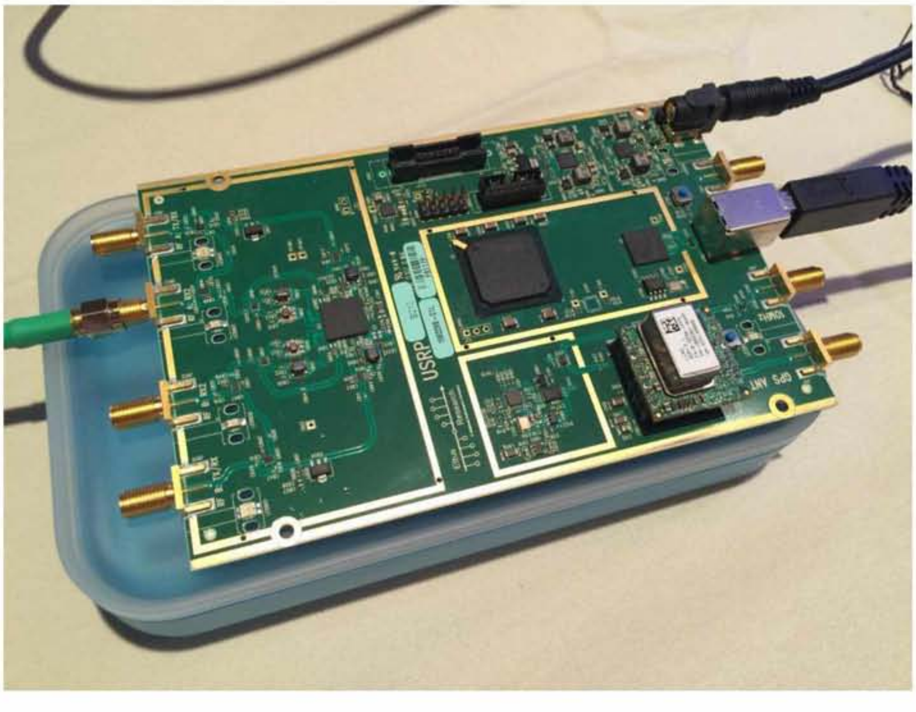

FIGURE 10: USRP B210

2.3.1 FPGA

The main component which performs several digital signal processing is the FPGA. «Field Programmable Gate Away (FPGA) is an integrated circuit designed to be configured by the user in order to control the data rates from reals signals in the analog domain to lower rate, complex, baseband signals in the digital domain which are transferred to a host processor. »[4]

So, FPGA contains a multiplexer that supports the input signals. The input signals from each of the A/D converter is led to the DDC by the multiplexer. The DDC consists of a Numerically Controlled Oscillator (NCO), a Cascade Integrate Comb filter (CIC), a digital mixer and a decimating Low Pass Filter (LPF). The received signal is down converted to baseband frequency range, then is under sampled and transferred to the LPF.

[4] *FPGA, Wikipedia*

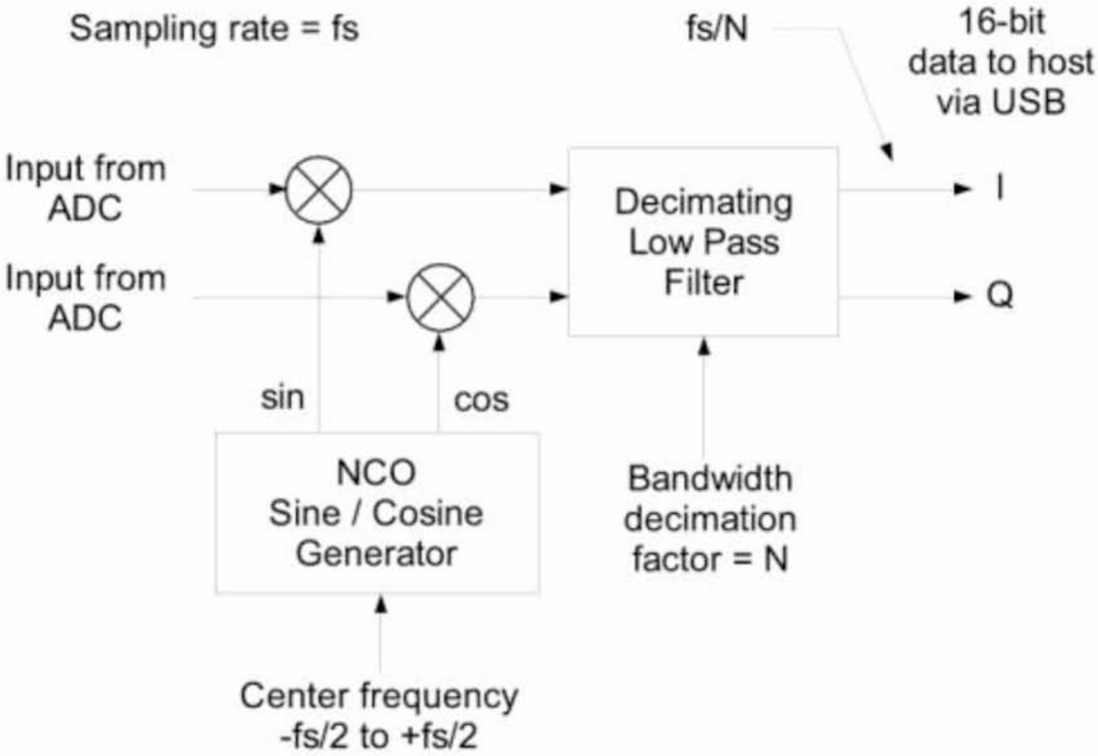

FIGURE 11: BLOCK DIAGRAM OF A DIGITAL DOWN CONVERTER IN FPGA

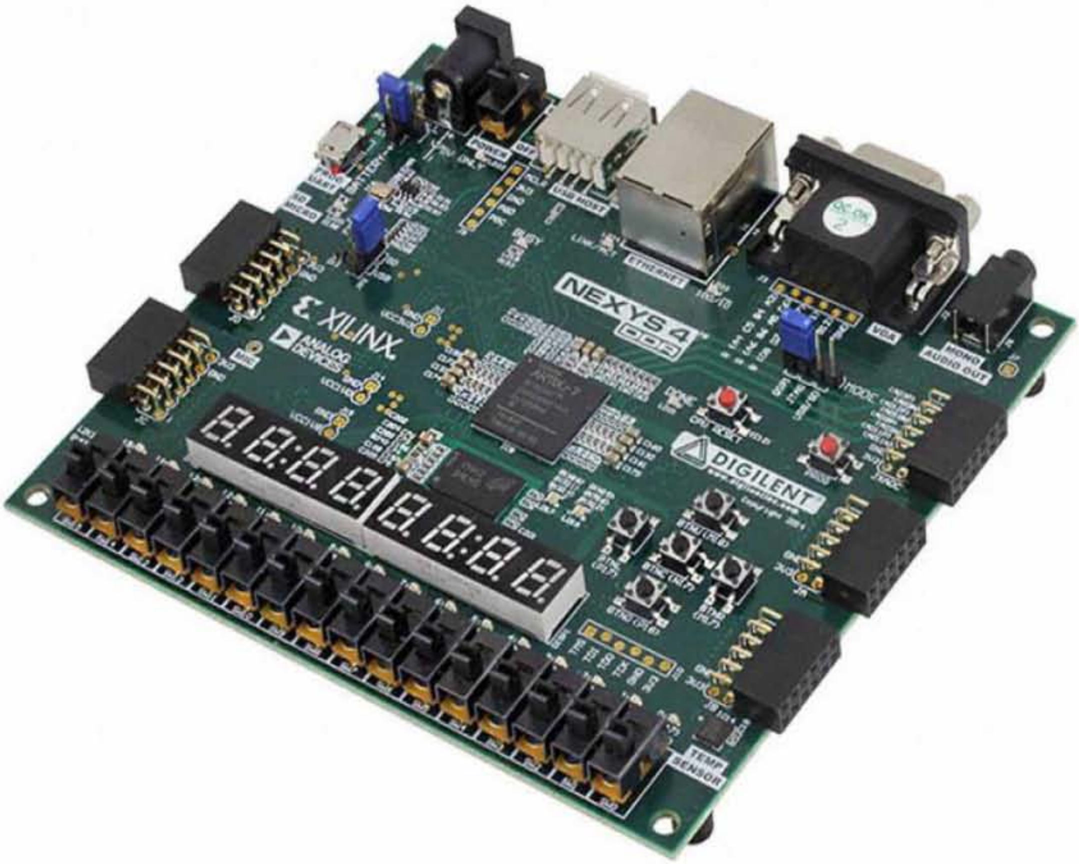

FIGURE 12: FPGA BOARD

2.4 Cognitive Radio

As it is explained widely in literacy, the «**Cognitive Radio (CR)** is an adaptive and intelligent wireless communication system that is aware of its surrounding environment and uses the methodology to learn from the environment and adapt its internal state. »[5] A radio of its kind can detect the presence of interference from other users, automatically change the transmission settings to an available channel in the wireless spectrum and maintain the connection links. A CR is a hybrid technology that involves SDR which is responsible for the application of its intelligence. Therefore, a transceiver is capable to determine its geographic location, identify and authorize its users, encrypt or decrypt signals, compress transferred data, sense neighboring wireless devices in operation and adjust output power and modulation settings [12, 13, 15].

2.4.1 Types of cognitive radio

There are two main type of cognitive radio, the Fully Cognitive Radio and the Spectrum-sensing cognitive radio.

- The Fully Cognitive Radio has the ability to adapt in every transmission parameters to an occurring environment and it is implemented as a SDR.

[5] *Cognitive Radio, Wikipedia, Search Networking*

- Spectrum-sensing cognitive radio can only adapt the carrier frequency and the bandwidth to an occurring environment. Its main use is for the exploitation of spectral white space, commonly the parts of the available spectrum that are not currently in use. Subsequently, this radio is called Dynamic Spectrum Access by its ability to adapt with the existing condition [12, 13, 14].

2.4.2 Spectrum Sensing

«**Spectrum Sensing** is the process of periodically monitoring a specific frequency band with the aim to detect the presence of primary users and to obtain an environmental awareness. This procedure enables the capability for a CR in order to detect vacant spectrum bands. »[6]

The most common feature for performing a spectrum sensing is the Energy Detection upon a baseband of frequencies. At the beginning, during an observation interval, measures of the received energy on a primary band are gathered and the evaluating process begins. Then, a threshold is set in order the measured energy to be compared. Consequently, in case that the measured energy is less than the properly set threshold that declares a white space to operate in. It is clear that the longer the observation interval is, the more accurate results will draw up.

[6] *Spectrum Sensing, Wikipedia*

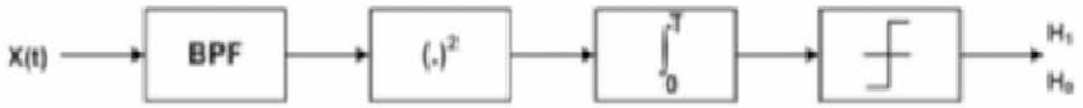

FIGURE 13: SIGNAL PROCESSING

This approach introduces some extremely useful benefits, but on the same time it has also some striking drawbacks.

To mention briefly the benefits:

- It is a simple technique and can be demonstrated easily
- There is no need for previous knowledge of the primary signal structure
- Sensing procedure needs a short period of time

On the other hand, some of the drawbacks are below:

- It can be observed a performance degradation by the time when the Signal-to-Noise ratio (SNR) is low
- There is no distinction between PU and SU signals and there can be faults in the transmission priority.
- It cannot work accurately for wide spread spectrum signals due to the fact that it can be unable to detect correct.

Finally, Spectrum Sensing is distinguished at the local and the network level. The local Sensing is performed at user's device, meanwhile network Sensing involves cooperation between cognitive users [11, 13, 14, 15].

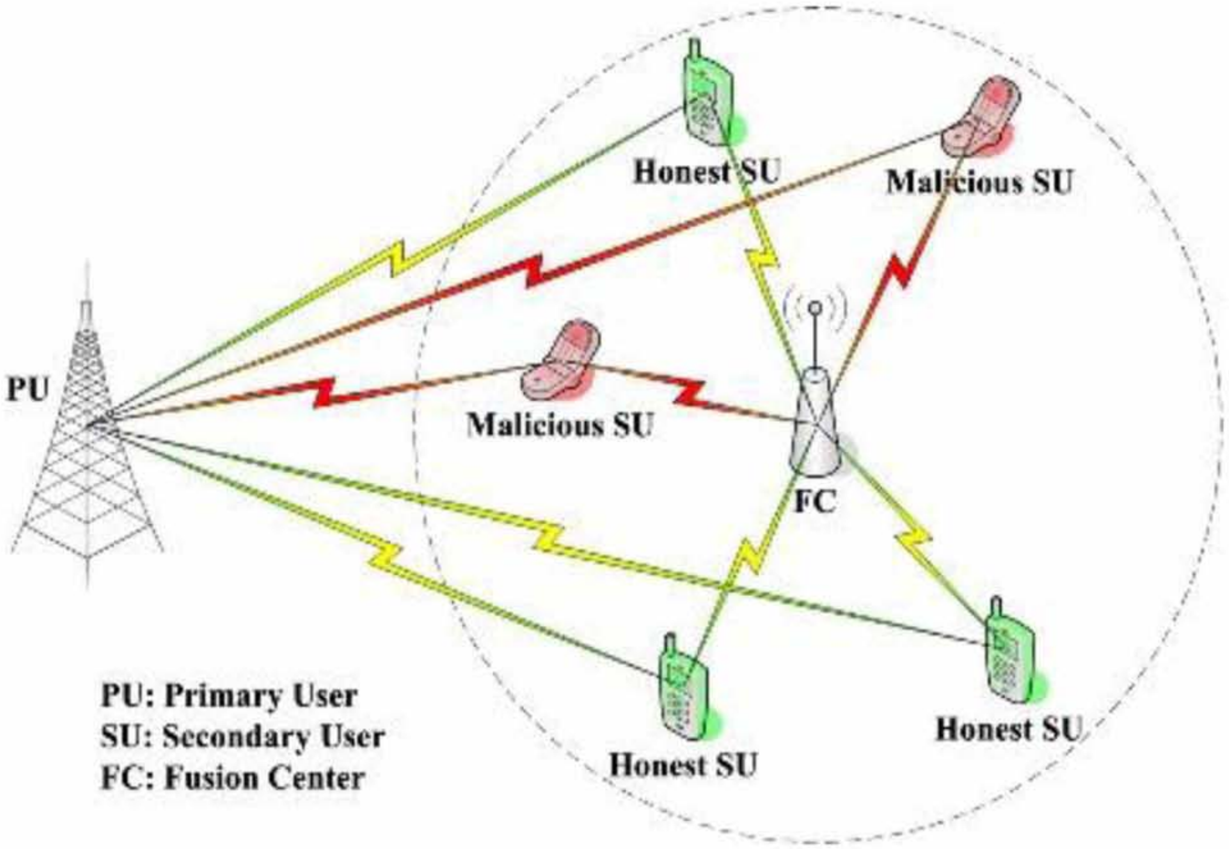

FIGURE 14: CORRELATION BETWEEN DIFFERENT USERS

CHAPTER 3

COOPERATIVE ALGORITHMS

3.1 Rules of Cooperative Challenge

As it has already been mentioned, this thesis is motivated by the DARPA Contest and especially, by the Cooperative Spectrum Challenge. The Cooperative challenge, unlike the Competitive challenge, has not stable and continuous interference among the spectrum. The main goal is to demonstrate a number of well-established protocols that would be used by pair of nodes in order to cooperate appropriate and achieve a successful transmission. So the rules are as follows: First and foremost, the experiment will be carried out by three pairs of nodes. The main target is to design and implement a protocol with the grounds on that every pair of nodes to achieve a successful transmission of 4000 packets in a period of 60 seconds. The communications will operate in a bandwidth of 5 MHz and a center frequency at 1803 MHz. Therefore, a successful implementation will be evaluated by how many will be transmitted without being interfered, even if they have not managed to get through all of them [8, 13, 14].

In order to achieve the best possible implementations, I have to think in two specific directions. The first will be developed considering the frequency domain and the rest will be determined by the time domain.

3.2 Analysis of the main algorithm

According to the above at the first place, a successful implementation will be designed in the Frequency domain with absolute compliance to the rules so that no protocol exceeds them. For convenience, I will name every algorithm with the view on making the experiments more practical.

- ***1st algorithm***

To begin with, the main aspect of thought is to take advantage of the available extended bandwidth. Thereby, the first move is to share the spectrum in 3 predetermined primary channels. Then, the constructed radio system should avoid conflicting with another implementation in the co-channels. However, there is no prior knowledge of the spectrum usage and a radio pair cannot recognize the existence of other users. Therefore, it is essential to sense the spectrum at first and monitor other nodes activity. To achieve a successful sensing, it should be applied on the source side, commonly the receiver should analyze the spectrum. That information from sensing must reach somehow at the transmitter side and to do so I implemented a feedback channel.

Channel	Modulation Scheme	Center Frequency	Offset	Bitrate	Gain
Center channel	GMSK	1803000000	0	2000000	80
Left Channel Center	GMSK	1802281250	718750	1000000	80
Right Channel Center	GMSK	1803718750	718750	1000000	80
Left Feedback Center	GMSK	1800531250	2468750	62500	89.9
Right Feedback Center	GMSK	1805468750	2468750	62500	89.9

TABLE 1: 3 PRIMARY CHANNELS AND 2 FEEDBACK CHANNELS

The settings which are chosen are the following:

- Modulation scheme: GMSK. The fact is that this modulation can lock back easier on to the carrier than others modulations when there will be problem with the link due to interference.
- The gain is set at 80 gain compression
- The amplitude is set 0.9

So, to get into the technical aspect of the algorithm, I will describe the exact process that is followed.

First of all, the implementation in the benchmark_tx.py script will take the 4000 packets from a packet server once and then the server will shut down. So, that I compress the data of the packets and then I save them in an array, in case of retransmission. After that, I predetermine the frequencies where the communication will be established with caution to not exceed the limits. I construct two specific arrays, the first one includes the settings of the primary channels, which are the modulation scheme, the offset from the center frequency, the bitrate and the transmitter gain. The second one includes settings for the feedback channel which are the feedback modulation scheme, the bitrate and the receiver gain. The gain of the feedback channel is set in a high level and specifically in 89.9 in case to avoid any unexpected interference and because of the short duration of operation. As a part of feedback channel creation, I placed the DSP chain of receiving in the transmitter side so that to receive the acknowledgments from the sensing of the receiver. Also, I used the threading process for the feedback channel so I can achieve an independent manipulation of data separately from the main process.

From the receiver side, the benchmark_rx.py was the modified script. Compared with the implementation on the transmitter, there was a need for the DSP chain on the receiver. Seeing that, I need the feedback channel that will forward the acknowledgments to the transmitter, I created the transmitting chain on the receiver side. Also, the feedback channel transmits 10 times per second to avoid unexpected interference. The process is as follows. At first, the received data are decompressed and stored in a list. With the use of a counter, I record only the missing packets in case of retransmission. By the time receiver gets the 4000 packets is closed, otherwise he sends the requested packets through the feedback channel to transmitter and waits until he reaches the packet limit in order to close.

Subsequently, the whole procedure which is controlled by receiver begins with testing each modulation for 1 second and store the compressed received number of bytes. Then the adaptive algorithm will choose between the modulations and use it for the next 10 seconds. After that, a check will occur in order to discover if the modulation scheme is the default one and the received bytes are greater than the Bitrate divided by 2. In the case where the answer is true, everything will remain the same, otherwise the procedure will start over. Finally, the discontinuation ability has been added in order to give time and space where the others nodes can operate their implementations.

3.3 Analysis of the assistive algorithms

For the purpose of this thesis, a number of more simple algorithms than the mentioned one were used in order to accomplish the experimentation procedure. Due to the fact that the main protocol was established on the frequency domain, the rest of the used algorithms are developed with respect on the time domain.

- ***2nd algorithm***

First of all, the most unsophisticated algorithm that was used is the already existent communication protocol given from GNU Radio with the only change to the discontinuation setting in the benchmark_tx.py script. This will achieve an interrupted communication and as a result, a discontinued usage of the spectrum. To make that clearer, the algorithm gets in an idle situation for 2 seconds after has sent 100 packets.

- ***3rd algorithm***

Then, the next algorithm will be modified so that to move in a deterministic pattern between two channels. On the transmitter side, the RX chain is added with the same process as the main algorithm in order to detect the presence of other transmitters and change channels if it is necessary. Due to the fact that the USRP uses the DSP chains independently, I take advantage of that ability to create a pair with spectrum agility. So, in the benchmark_tx.py script I calculate the current magnitude squared and then I compare it with a threshold. That helps to detect the interference and change channels. The receiver on the other, changes channels in case of receiving no packets after some period of time. With the thread process I can record the received packets independently. The packets are transmitted compressed and are decompressed in receiver side.

MODULATION	BITRATE	GAIN	LEFT CENTER FREQUENCY	RIGHT CENTER FREQUENCY	OFFSET
GMSK	200000	60	1801750000	1804250000	1250000

TABLE 2: SETTINGS OF THE 4TH ALGORITHM

❖ *4th algorithm*

This algorithm follows the same design as the previous one, however I try a more sophisticated spectrum sensing approach. The approach is focused on estimating the SNR of the signal compared with statistics from the received sample. The technique has to do the calculation of the SNR over an AWGN channel and tries a more accurate detection. So, I choose the M2M4 SNR technique which uses the second and fourth moment of a signal to estimate the SNR [10].

MODULATION	BITRATE	GAIN	LEFT CENTER FREQUENCY	RIGHT CENTER FREQUENCY	OFFSET
GMSK	200000	60	1801750000	1804250000	1250000

TABLE 3: SETTINGS OF THE 5TH ALGORITHM

3.4 Experimentation of cooperative algorithms

The main goal of this thesis is to point out the results of various algorithms which are loaded on different nodes concurrently. Thus, through a number of different experimentations, I will exclude some results in order to highlight the best possible cooperative combinations. I will find out which algorithm attributes the best in cooperative conditions and what its results are.

3.4.1 Results and Evaluations

Starting from the simpler implementations and as we proceeded to the more complex algorithms, we discovered which algorithms can be used under cooperative conditions. For the purpose of my study, I divided the implementation into experimentation cases.

- ***1st case***

At first, I examined a simple case, where I used concurrently the 1st algorithm on the first pair and the 2nd algorithm on the other two pairs. The point is that I have a fully functional cooperative approach among with a simple and not efficient approach which uses the discontinuation ability of the script.

	MODULATION	BITRATE	GAIN	FREQUENCY
TEAM 1 -> 1ST ALGORITHM	GMSK	200000	80	1803000000
TEAM 2 -> 2ND ALGORITHM	GMSK	200000	60	1801750000
TEAM 3 -> 2ND ALGORITHM	GMSK	200000	60	1804250000

TABLE 4: SETTINGS FOR THE 1ST CASE

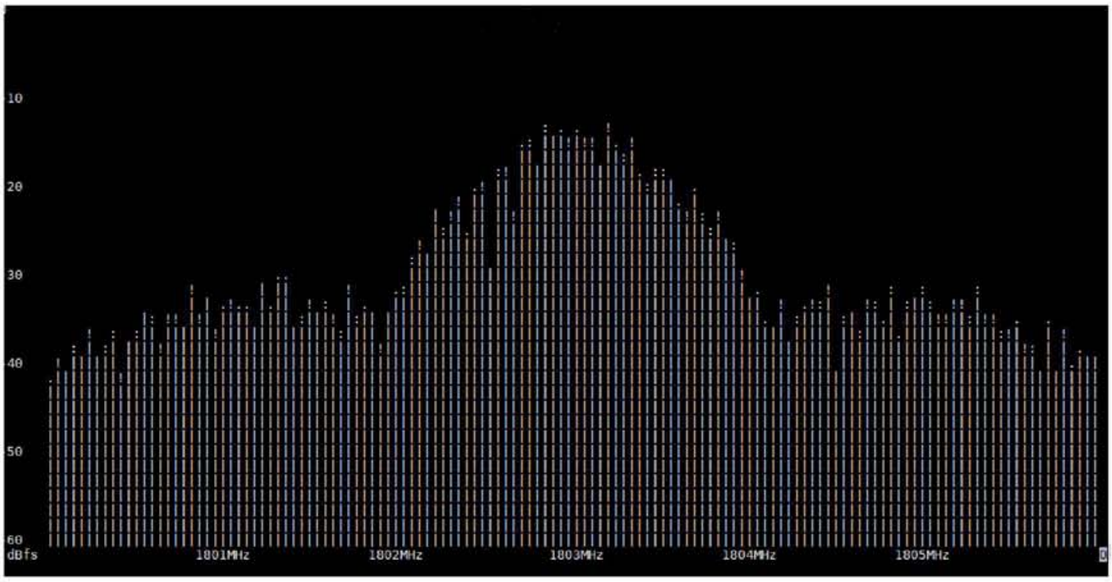

FIGURE 15: TRANSMISSION PROCESS OBSERVED BY ASCII TOOL

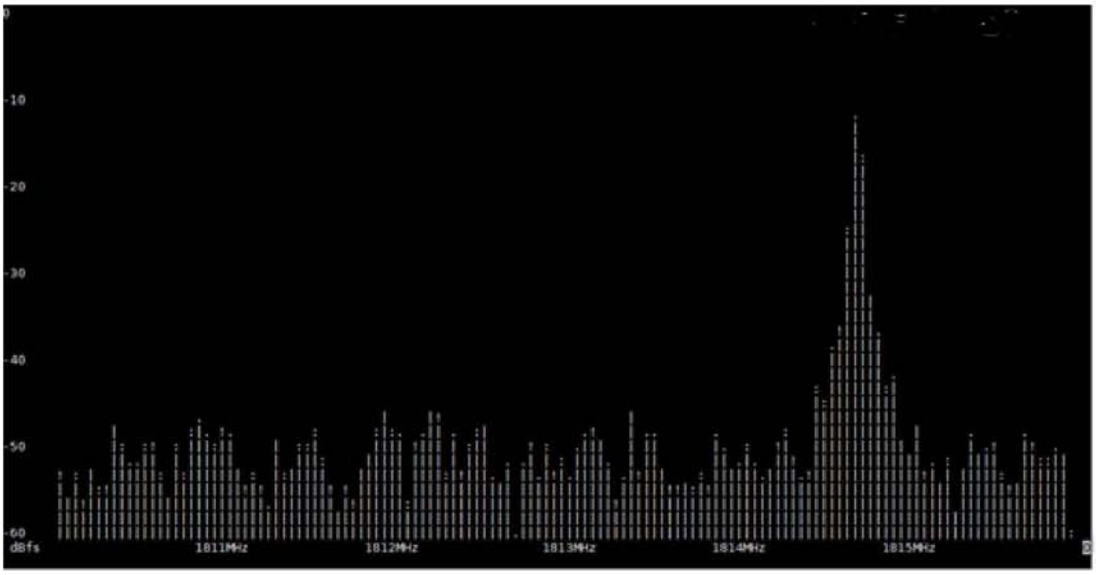

FIGURE 16: FEEDBACK CHANNEL

```
INFO Object: ================================================
INFO Object:
INFO Object:                  Score Report:
INFO Object:
INFO Object:
INFO Object:    Team1  Received 3998 packets correctly
INFO Object:
INFO Object:
INFO Object:    Team2  Received 225 packets correctly
INFO Object:
INFO Object:
INFO Object:    Team3  Received 228 packets correctly
INFO Object:
INFO Object: ================================================
INFO OmfEc::Experiment: Experiment: 2018-07-03T22:11:56.382Z finished
```

FIGURE 17: RESULTS 1ST CASE

Observing the results, it is clear enough that the team1 which uses the 1st algorithm is fully functional and had achieved to transmit almost every packet. However, as it has been already mentioned, the other two teams used an inefficient algorithm which is based on discontinuation. That means, when one of nodes with the discontinuation ability tries to utilize the spectrum, it discovers that the spectrum is being already used by the nodes with 1st algorithm.

Finally, when it succeeds to transmit and reaches a number of packets, it gets on an idle condition which has as a result to lose significant time. Thus, we have two teams with very low transmission rate and one with almost perfect.

- ***2nd case***

In this case, I examined a couple of simple and inefficient algorithms alongside with the 1st algorithm. These algorithms where the 2nd algorithm and the basic communication protocol as it comes from GNU Radio.

	MODULATION	BITRATE	GAIN	FREQUENCY
TEAM 1 -> 1ST ALGORITHM	GMSK	200000	80	1803000000
TEAM 2 -> BASIC	GMSK	200000	60	1801750000
TEAM 3 -> 3RD ALGORITHM	GMSK	200000	60	1804250000

TABLE 5: SETTINGS FOR THE 2ND CASE

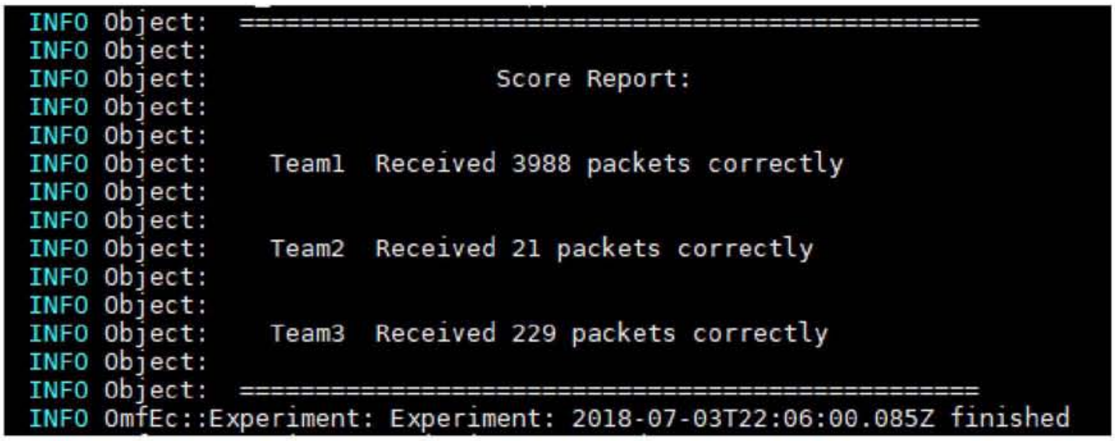

FIGURE 18: RESULTS 2ND CASE

During this case, we experienced a similar situation like the 1st case. We had used again two less intelligent algorithms alongside with more sufficient one. This time, we applied the basic functionality of GNU Radio that can only create a communication link without a sensing ability and it had been proved that it cannot accomplish much. Subsequently, we have over again low scores for two teams.

➢ *3^{rd} case*

For the 3^{rd} case of the evaluation, I considered the simultaneously running of the 1^{st} algorithm on every pair of nodes in order to monitor the way a more efficient algorithm reacts.

	MODULATION	BITRATE	GAIN	FREQUENCY
TEAM 1 -> 1^{ST} ALGORITHM	GMSK	Predefined	80	Predefined
TEAM 2 -> 1^{ST} ALGORITHM	GMSK	Predefined	80	Predefined
TEAM 3 -> 1^{ST} ALGORITHM	GMSK	Predefined	80	Predefined

TABLE 6: SETTINGS OF THE 3^{RD} CASE

```
==================================================

                  Score Report:

  Team1  Received 3787 packets correctly

  Team2  Received 3145 packets correctly

  Team3  Received 1833 packets correctly

==================================================
```

FIGURE 19: RESUTS 3^{RD} CASE

As it can be seen, applied the same intelligent algorithm on every node can bring some high scores. That happens because, this algorithm is implemented to operate in three predefined channels.

Even if he meets somewhere along the spectrum unexpected interference, he can transmit upon the next available channel. Also, it has been enabled the discontinuous option and can act in cooperative manner in order to leave the other pair too transmit simultaneously.

- ***4^th^ case***

For the 4th and the following cases, I examined the behavior of an algorithm which is implemented with predefined channels and at the same time with another one which uses a spectrum sensing technique based on the comparison with a threshold. So, I applied the 1st algorithm on the first pair of nodes and the 3rd on the others.

	MODULATION	BITRATE	GAIN	FREQUENCY
TEAM 1 -> 1ST ALGORITHM	GMSK	Predefined	80	Predefined
TEAM 2 -> 3RD ALGORITHM	GMSK	200000	60	1801750000
TEAM 3 -> 3RD ALGORITHM	GMSK	200000	60	1804250000

TABLE 7: SETTINGS OF THE 4TH CASE

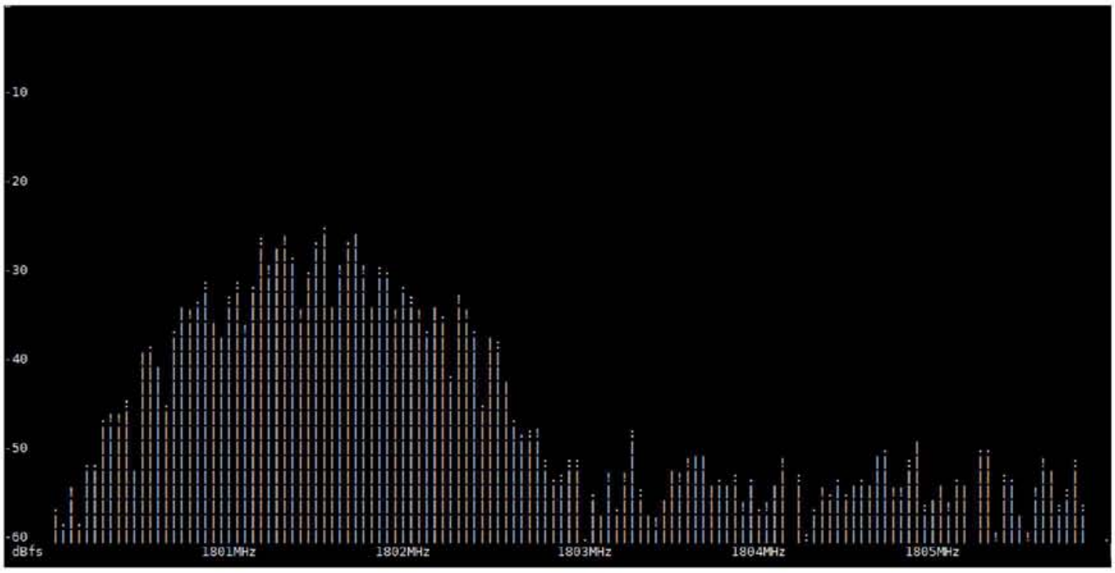

FIGURE 20: TRANSMISSION PROCESS OF 3RD ALGORITHM

```
=================================================

                 Score Report:

   Team1  Received 4000 packets correctly

   Team2  Received 4 packets correctly

   Team3  Received 230 packets correctly
=================================================
```

FIGURE 21: RESULTS 4TH CASE

For the first time, I apply an algorithm which tries dynamically to sense the spectrum. I can surely say that the approach to measure the signal energy and then to compare it with a threshold is a correct choice. However, due to the fact that the 1st algorithm operates continuously in order to find the best modulation, except if it reaches a point and then sleeps for a period of time, it can be recognized as a possible interference. Thus, the dynamic spectrum sensing can avert an attempt of transmission. Also, the period of time in which is utilized does not suffice to transmit as much packets as possible.

➢ *5^{th} case*

For the 5^{th} case, I used the 1^{st} algorithm on the one pair and the 4^{th} algorithm on the others, which uses the more sophisticated SNR estimation.

	MODULATION	BITRATE	GAIN	FREQUENCY
TEAM 1 -> 1^{ST} ALGORITHM	GMSK	200000	80	1803000000
TEAM 2 -> 4^{TH} ALGORITHM	GMSK	200000	60	1801750000
TEAM 3 -> 4^{TH} ALGORITHM	GMSK	200000	60	1804250000

TABLE 8: SETTINGS OF THE 5^{TH} CASE

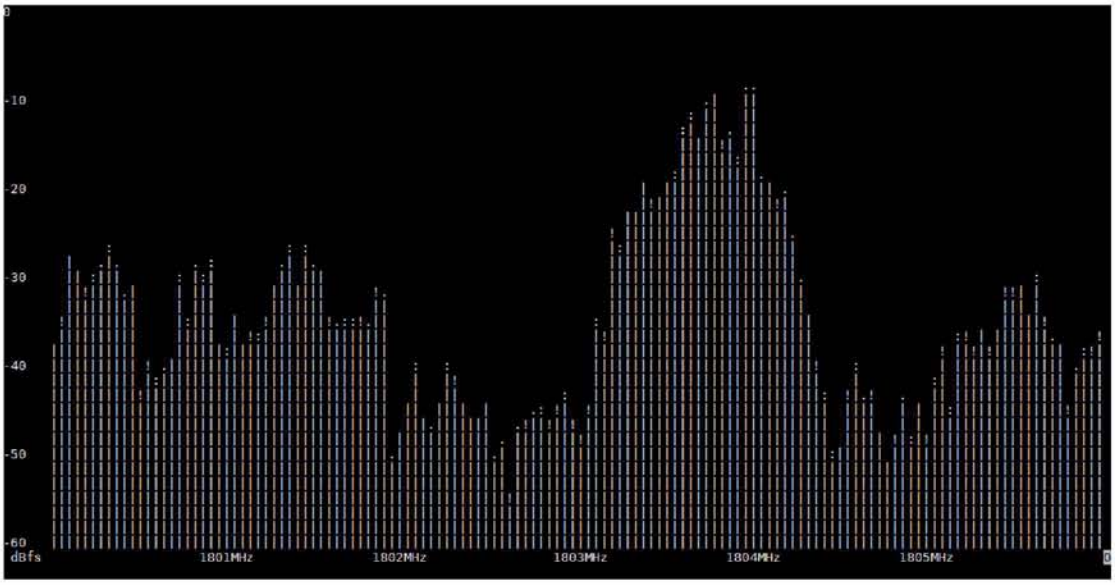

FIGURE 22: TRANSMISSION PROCESS

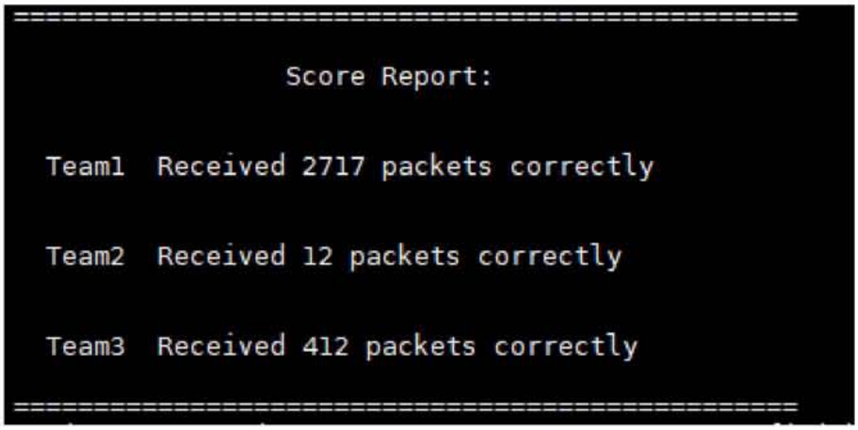

FIGURE 23: RESULTS 5^{TH} CASE

Observing the results of 5^{th} implementation case, I cannot emphasize to the used designs because of the succeeded transmission which is low for the nodes where I applied the SNR estimation. The reason of happening that is due to the fact that those algorithms are implemented to utilize the spectrum by the time they sense the spectrum. However, the first design tries to exploit the whole available bandwidth and gives some period of time for the others. Thereafter, its ability to transmit everywhere is monitored by the SNR estimators as a possible interference and they do not start the transmitting process.

➢ *6^{th} case*

During this case, I experimented with 3 different algorithms, the 1^{st}, the 3^{rd} and the 4^{th}. The 4^{th} algorithm takes advantage of the SNR technique, which calculates the signal power at the second and fourth moment.

	MODULATION	BITRATE	GAIN	FREQUENCY
TEAM 1 -> 1^{ST} ALGORITHM	GMSK	200000	80	1803000000
TEAM 2 -> 3^{RD} ALGORITHM	GMSK	200000	60	1801750000
TEAM 3 -> 4^{TH} ALGORITHM	GMSK	200000	60	1804250000

TABLE 9: SETTINGS OF THE 6^{TH} CASE

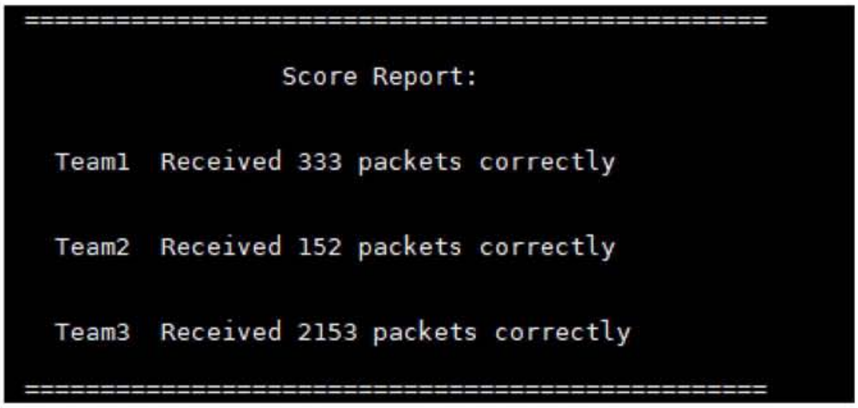

FIGURE 24: RESULTS 6^{TH} CASE

For these results, I can say that what I have mentioned before in the 5^{th} case have also effect here. The fact that I use two different SNR estimators, a sophisticated one and another who compares the average magnitude squared with a threshold, does not change their main philosophy in sensing the spectrum.

➢ *7^{th} case*

In this evaluation, I examined the occasion where every pair of nodes use the 3^{rd} algorithm that uses a spectrum sensing technique.

	MODULATION	BITRATE	GAIN	FREQUENCY
TEAM 1 -> 3^{RD} ALGORITHM	GMSK	200000	80	1803000000
TEAM 2 -> 3^{RD} ALGORITHM	GMSK	200000	60	1801750000
TEAM 3 -> 3^{RD} ALGORITHM	GMSK	200000	60	1804250000

TABLE 10: SETTINGS OF THE 7^{TH} CASE

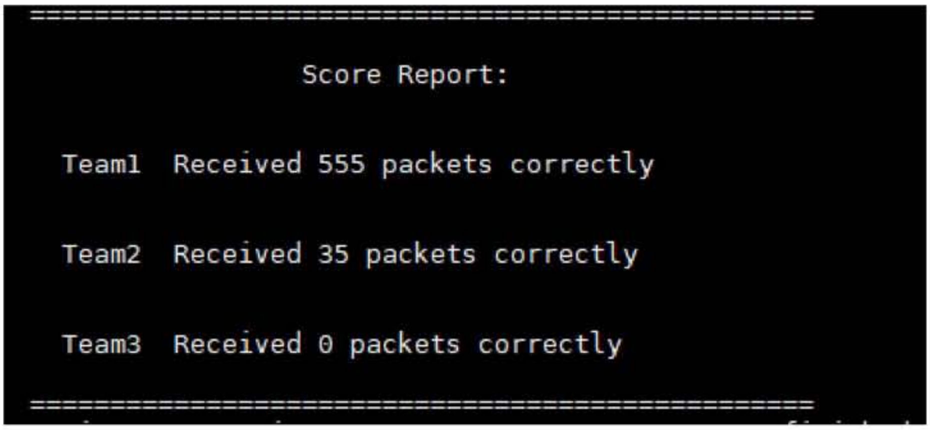

FIGURE 25: RESULTS 7^{TH} CASE

It obvious that using the same sensing algorithm in every node is not efficient due to the fact that these algorithms have implemented in order to have an assistive role and though they have not the appropriate performance to combine them. Nevertheless, they play a significant role in our final evaluation of the 1^{st} algorithm.

3.5 Final performance evaluation

To conclude the evaluations, there is no denying that the most capable algorithm is the first. As part of my implementations, this algorithm combines quite a lot of elements that make him a cooperative approach. At first, I took advantage of the available bandwidth in order to transmit in different set of frequencies by the time it senses interference. Therefore, its implementation follows my first approach as it has mentioned before, to exploit the frequency domain. Afterwards, I have added the ability to wait when he achieves to transmit a number of packets, so that he gives the time to other implementation to transmit as long as he is idle. That state, pursue my second main approach that every implementation should respect the time domain in order to have the chance every implementation to transmit. Finally, that was the main target of this thesis, to design a communication system in which every node has a cooperative behavior and a competitive one. That means, that in an appropriate cooperative system every pair of nodes will have to transfer packets

CHAPTER 4

CONCLUSIONS AND FUTURE WORK

4.1 Conclusions

All things considered, this thesis was focused on the developing of a number of different algorithms, in order to point out the appropriate approach for cooperative communication. My target of thought was concentrated on implementing those cooperative communications in two specific directions. At first, I manage to develop an algorithm which exploited the available bandwidth. I shared the available spectrum to 3 predefined primary channels in order to take advantage of the available set of frequencies. So, I develop this algorithm on the frequency domain and not to expand through the defined limits. Then, the rest of the assistive algorithms which were simpler than those on the frequency domain, were implemented with respect on the time domain. That is to say, that these implementations waited a period of time in order to operate some other protocols in that time. Seeing that, there is no prior knowledge of the spectrum usage and a radio pair cannot recognize the existence of other users, I implemented algorithms with spectrum sensing ability. Thus, my implementation are more efficient and present a better performance. However, along the way I dealt with some unexpected challenges that were created during the experimentations. The main challenge was that when I tried to share the bandwidth in 4 and more channels, I encountered a trouble with the synchronization between the transmitter and the receiver. Finally, the experimentations showed that the pair of nodes who running a more complex algorithm had better results than those with simpler approaches, but sometimes there were caused some great issues from them. The fact that they run a less intelligent algorithm had as a result to block every communication upon the spectrum and no connection could be established.

4.2 Future work

As future work I can declare that the challenges which I had encountered are a matter of thought. That has to do with the unsuccessful synchronization between the transmitter and the receiver when the bandwidth is shared in more than 4 primary channels. So, we should establish a more intelligent way in order to synchronize the two parts more easily and at the same time to maintain their cooperative ability. Also, I want to mention that a more demanding environment could be problematic. Because of the fact that except of the implementations which cooperate well between them, there can be some potential interference which can distract our communications systems. Subsequently, an implemented algorithm with Real-time spectrum sensing should be developed to sense the spectrum all the time, and spectrum occupancy should be adjusted dynamically to avoid spectrum conflicts as the spectrum occupancy of other radios changes. Thus, with such improvements, the current communications will operate better.

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