AALBORG UNIVERSITY
DENMARK

Title: Practical Implementation of Hybrid Accuracy-Time Spectrum Sensing for Cognitive Radio Networks
Semester: 10th
Semester theme: Master Thesis
Project Period: 01/09/2015 – 01/06/2016
ECTS: 55
Supervisor: Albena Mihovska
Project group: ICTE10 – 1095

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Pages: 72
Supplements: 1 CD ROM

ABSTRACT:

Since its conception nearly two decades ago, cognitive radio (CR) has been the topic of numerous research studies in different areas. CR is considered to be a viable and an important part of the wireless networks of the future because it can allow for a more efficient spectrum utilization and an increase in the overall system throughput. CR devices are envisioned to provide new services and even operate within the coverage of different technologies, to cooperate with the users of their networks, since their functional frequency and modulation are programmable

The rise of the cognitive radio systems as a concept for future networks has seen a great amount of scientific effort in the recent years. Appropriately, much attention is given to how the vital function of spectrum sensing should be executed. The cognitive radio device is required to be able to evaluate the spectral environment properly so that it may not create additional interference to the primary users. The task is further complicated by the need of optimization of the speed of the process so that the spectrum holes can be utilized. The sensing accuracy and sensing time are conflicting parameters, therefore, a suitable trade-off is necessary for an optimal efficiency. We propose a dual-approach solution. The decision about the spectrum occupancy is made using the measured signal-to-noise ratio (SNR) and the received signal levels as inputs in a fuzzy logic algorithm. The result is then compared with the one acquired using the statistical method. Finally, an optimal balance between the sensing time and accuracy is obtained for the current environmental conditions using the derived closed form expression. The algorithm has been practically implemented using a software defined radio platform comprising USRP and GNU Radio. Through simulation results, we have shown the efficiency of our proposal in relation to other existing methods. The performance of the practical implementation has also been analyzed.

By signing this document, each member of the group confirms participation on equal terms in the process of writing the project. Thus, each member of the group is responsible for the all contents in the project.

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ACKNOWLEDGEMENTS

In these lines I would like to thank all the people who supported me during the preparation and writing of this thesis. First of all, I would like to express my sincere gratitude to my supervisor, Albena Mihovska, whose vast experience, professional advice and encouragement have been indispensable during the whole process. I am also very grateful to the Nissen family, Erik Schak and Emil Petersen for their friendship which brightened my stay in Aalborg from the very beginning. There is also a host of true friends from the four corners of the world who have encouraged me in my endeavor. Finally, I would like to give my love and gratitude to my family who have always supported me in everything.

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LIST OF ACRONYMS AND ABBREVIATIONS

5G	Fifth Generation of mobile communications
ADC	Analog-to-digital converter
CDF	Cumulative Distribution Function
CR	Cognitive Radio
DAC	Digital-to-analog converter
DSP	Digital signal processor
FFT	Fast Fourier Transform
FL	Fuzzy Logic
GUI	Graphical User Interface
IEEE	Institute of the Electrical and Electronics Engineers
MIMO	Multiple-Input Multiple-Output
OFDM	Orthogonal Frequency Division Multiplexing
PSD	Power Spectrum Density
PU	Primary user
RF	Radio-Frequency
ROC	Receiver Operating Characteristic
SDR	Software Defined Radio
SNR	Signal-to-noise ratio
SU	Secondary user

SWIG	Simplified Wrapper and Interface Generator
Tx	Transmitter
UHD	USRP Hardware Driver
USRP	Universal Serial Radio Peripheral

NOMENCLATURE

P_d	Probability of detection
$\overline{P_d}$	Predefined probability of detection
P_{fa}	Probability of false alarm
$\overline{P_{fa}}$	Predefined probability of false alarm
P_{md}	Probability of miss-detection
τ	Sensing time
N	Number of samples
$y(k)$	Received signal level of the k-th sample
$T(y)$	Received signal level over N samples
λ	Decision threshold of the statistical method
λ'	Decision threshold of the Fuzzy Logic method
H_1	Hypothesis 1
H_0	Hypothesis 0
$s(k)$	Signal component of the k-th sample
$n(k)$	Noise component of the k-th sample
f_s	Sampling frequency
P_n	Noise power
$\overline{P_n}$	Average noise power
P_r	Received signal power

$\overline{P_r}$	Average received signal power
$\overline{SNR}$	Average SNR
σ_s^2	Variance of the signal
σ_n^2	Variance of the noise
γ	Signal-to-noise ratio
$\mu_M(SNR)$	Membership function of the SNR
$\mu_M(P_r)$	Membership function of the P_r
T	Period of the frame of the SU
T_{tr}	Transmission time of the SU
$\zeta(\tau)$	Sensing efficiency
$\phi(P_d, P_{fa})$	Probability of proper detection of the states of the PU
$P(ON)$	Probability of the PU being in active state
$P(OFF)$	Probability of the PU being in passive state
T_{ON}	Period of the active state of the PU
T_{OFF}	Period of the passive state of the PU
T_{RP}	Period of the renewal process of the PU
μ_{ON}^{-1}	Mean of T_{ON}
μ_{OFF}^{-1}	Mean of T_{OFF}
μ_{ON}	Reciprocal of the mean of T_{ON}
μ_{OFF}	Reciprocal of the mean of T_{OFF}
S_n^j	Sum of the n realizations of the j-th variable

S_n^{RP}	Sum of the n realizations of T_{RP}
$f_{RP}(t)$	Probability density function of T_{RP}
P_{nc}	Probability of non-collision
$E(T_{RP})$	Mean of T_{RP}

CHAPTER 1. INTRODUCTION

1.1. FUNDAMENTALS OF SPECTRUM SENSING FOR COGNITIVE RADIO

Software Defined Radios (SDR) have presented a wide range of new possible solutions for the coming generations of telecommunications. Improvement of current services and introduction of new ones require the terminal to be adaptable and operate with different wireless standards [1]. This is made possible by implementing the baseband part of the transceiver using only programmable digital signal processors (DSPs) while the digital-to-analogue/analogue-to-digital converters (DAC/ADC) and RF segment are realized with tunable analogue elements (Fig. 1-1) [2].

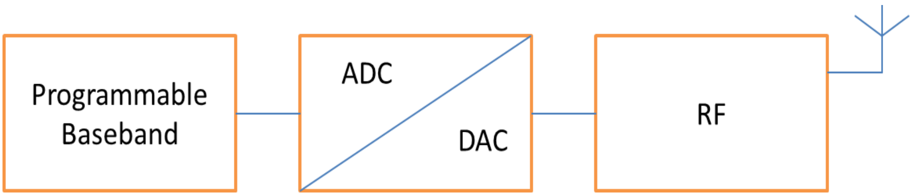

Figure 1-1. Software Defined Radio transceiver.

Therefore SDR is not only a driving force of 5G but has also a great potential for the enhancement of the efficiency of the existing networks. That is because many of today's most used spectrum bands (terrestrial TV, mobile networks and others operating in the range below 6 GHz) are in fact under-utilized [3], [4]. There are short periods, during which portions of this spectrum are unused and are often referred to as "spectrum holes" [5]. This presents the opportunity for these bands to be employed for the needs of other, secondary services. Thus, the challenge arises of how and when this can be done. In other words, SDR is required to implement a process of cognition, in this context the terminal is referred to as a Cognitive Radio (CR) device [5]. It is designed to adapt its transmission parameters in response to the changing characteristics of the environment by the means of logic. This operation has to be performed as fast as possible so that the CR device can identify and utilize the holes in the spectrum. Since the terminals (also called incumbent, or primary users), which usually operate on a specific band may start to use a spectrum hole and thus "fill" it again, the SDR (or a secondary user, SU) is needed to quickly move out of it and scan the spectrum again to locate a new hole. If the CR device fails to do so, it will create unwanted interference to the primary users (PU) and the quality of the services they use will be degraded. These concepts are illustrated in Fig.1-2.

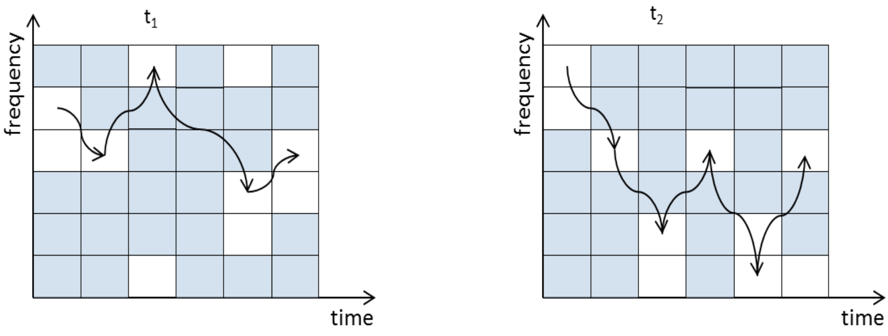

Figure 1-2. Spectrum holes. The SU device moves from one of to the other.

A central function of the CR terminal is the spectrum sensing. It is defined by the ability of the device to scan a range of frequencies and determine (with sufficient probability) whether a primary user transmits in this band. If the spectrum portion in question is free, the secondary user can utilize it, otherwise, it will have to move on to another one. In the case that the CR is using the band and the PU moves into it, the SU must vacate it and look for another one, which is available. In order for these processes to take place, the spectrum sensing procedure needs to be fast (to adapt to the changing environment) and accurate (to be able to differentiate between the presence and the absence of a PU signal, so that it does not create interference). The issue with these two is that they are contradictory since in order for the result of the sensing to be reliable, the algorithm that performs it, needs to capture enough samples to determine whether the spectrum is free or not. At the same time, the dynamics of the radio environment require the quick making of a decision. Therefore, the aim is for a method that complies with both of these requirements to a satisfying degree, to be developed. Thus, are set the boundaries of the speed-accuracy trade-off problem. The specific characteristics that need to be accounted for in the process are the following [6]:

- Probability of detection (P_d) – the probability that the CR device will determine correctly the presence or absence of a PU.

- Probabilities of a false alarm (P_{fa}) and miss-detection (P_{md}) –

the probabilities of the CR device deciding that the PU occupies the band when it does not, and that it is not present when it actually is, respectively.

- Signal-to-Noise ratio regime – there is an SNR level (an “SNR wall” [7]) below which, the CR device is no longer able to detect the PU signal due to uncertainty in the noise variation. Therefore, in order for weak signals to be identified, a more complex and expensive receiver is required. Thus, when a spectrum sensing algorithm is implemented, a reasonable trade-off between price and SNR needs to be achieved.

- Frequency range of operation – depending on the scenario, the specific spectrum which is to be sensed, is also defined. The bandwidth has influence on the sensing method. It may not be possible for the CR terminal to perform sensing on the whole band at the same time.

- Sensing speed – it is required that the algorithm is able to assess the conditions of the radio environment quickly so that the SU may utilize unoccupied spectrum if such is found.

Of course, a number of SDR terminals can constitute a CR network and this way the problem of spectrum sharing comes into view and extends the spectrum sensing function to accommodate for the cooperation between the secondary users (cooperative spectrum sensing). However, this case is outside the scope of this work because it will concentrate on the sensing of the individual SU (also called local sensing).

There are several basic spectrum sensing techniques which the CR can use to assess the occupancy of the spectrum. They will be briefly reviewed in the next section. A complete solution to the trade-off between sensing speed and accuracy problem requires building of its logic on top of one of them.

1.2. TRADITIONAL SPECTRUM SENSING TECHNIQUES

1.2.1. ENERGY DETECTION

This method relies on the energy received by a CR to discriminate between an occupied and unoccupied spectrum band. A threshold is defined, that represents the minimum level of received power at which the SU will decide that a PU signal exists. The device will add together the squares of the energy of the samples taken during the sensing period and average them. After that it will compare them to the threshold. If the result is smaller than the threshold, the CR will conclude that the spectrum is available. The problems of this method are that it cannot differentiate between the PUs and the SUs, and that the threshold is hard to define since the levels of noise and interference are subjects to constant change [2]. Its advantages are the low implementation complexity and high speed. That is the reason why it has been widely used.

1.2.2. MATCHED FILTER

This filter uses information about the characteristics of the PU signals so that the sensing function is able to compare the received samples to its a priori knowledge and thus decide whether the spectrum is available or not. This comparison is performed by convolving the received signals and a time-reversed version of the signal which is taken from the knowledge base and matching the result with a threshold which defines when the CR must decide that a PU is present [2]. The advantages of the method come from speed and accuracy since it needs less samples to make a correct detection and it maximizes the SNR of the received signal. These strengths come at the price of implementation complexity because the CR may need to be able to demodulate PU signals from multiple systems which will require a separate receiver for each one [2], [8].

1.2.3. CYCLOSTATIONARY DETECTION

In this case, a special property of the PU signal is utilized. Most of the standardized radio signals exhibit cyclostationarity (their autocorrelation function is periodic) which characterizes each system and because of that they can be detected and differentiated. This periodicity can be represented mathematically through the cyclic frequency which defines the spectral correlation function that can be used for discrimination between different PU signals even when they have indistinguishable power spectrum densities [8]. Moreover, the cyclostationary detection is more robust than the energy detection since it can also identify the noise which does not have the periodic attributes of the useful signals. Unfortunately, this method requires longer sensing time and is harder to implement.

1.2.4. WAVELET DETECTION

This method relies on applying the Wavelet transformation to the power spectral density measured over the whole frequency band. This way, it is split into sub-bands which can be assessed individually and the existing alterations between them can be used by the detector to make a decision. This solution is more flexible when it comes to wide-band signal detection but it is slower and has limitations for the types of signals that can be processed [2].

1.3. MOTIVATION

Although spectrum sensing has been a subject of extensive research ([9] – [14], [16] – [23]), there are few works which deal with the important question of how the balance between the speed and accuracy of the spectrum sensing method is to be found. This is vital because the algorithm is required to match the alternations of the radio environment which (as stated above) change rapidly and randomly, if it is to provide optimal utilization of the unused resources without creating intolerable interference. Therefore, its logic has to take into account the input from the measurements and adapt the sensing time and the period of transmission (if such is possible). The majority of the proposed methods ([9] – [13], [20] – [23]) attempt to only deal with the need of accurate detection (specifically in low SNR) but the time of their execution is either fixed or not considered at all. There are few works which indeed develop frameworks for adaptive sensing and use similar overall line of reasoning even though they look at the issue from different angles ([14], [16] - [19]). In this project the focus is on finding an appropriate balance between the precision of the process and its speed based on the measured signal power. The performance has been studied for the case of a single SU assessing a spectrum band which is utilized by its incumbent PU. Thus, other characteristics like the capacity of the SU link and the interaction between multiple CR devices are not considered.

Another topic of critical importance is the actual implementation of a spectrum sensing algorithm. It has also been studied in only a handful of works ([20] – [23]). They mostly concentrate on the capabilities of the equipment to detect the presence of the PU signal and rarely go beyond that. The importance of experiments based on practical implementations, lies in the fact that computer simulations do not model the hardware limitations of the SDR device and its performance depending on the design of the spectrum sensing solution.

1.4. PROBLEM DEFINITION

This thesis aims to examine the spectrum decision function of the CR in the following aspects:

- Assessment of the performance of an algorithm based on energy detection which uses two complementing methods to achieve correct decisions.

- Utilizing different techniques to build the logic which will drive the sensing process with the purpose of finding a trade-off between accuracy and speed.

- Implementing the spectrum sensing solution using suitable hardware and software platforms and studying its performance.

- Observation of the implementation particularities, especially when it comes to some of the algorithm's parameters and the limitations of the equipment.

1.5. STATE OF THE ART

When it comes to the speed-accuracy trade-off in spectrum sensing, the majority of research works is devoted to the optimization of either one or the other of these two characteristics. However, there are some, which focus on finding the optimal balance between the speed and the performance of the algorithms. They will be used as building blocks for the trade-off formulation in this project. Others use two techniques to increase the efficiency of the detector. Some develop more sophisticated models of the PU signal and noise for more realistic examination of the algorithm. Even though there are many proposals based on energy detection, most of them are analyzed only using a computer simulation. Those that present practical implementation, for the most part, do not study complex adaptive algorithms and do not examine the performance of the detectors in great detail. In the next sub-sections, a short review of these relevant works will be made.

1.5.1. ENERGY DETECTION-BASED SPECTRUM SENSING

Because of its ease of implementation, speed and low computational complexity, this is the method which has been studied in this thesis. This section summarizes some known algorithms, which are based on it.

- Combination of spectrum sensing techniques [9]. This work proposes the use of energy detection first but since it is unreliable in low SNR, if the detected signal strength is lower than the defined threshold, a second sensing method with greater accuracy will be employed. Noise uncertainty was also accounted for. This study shows that the performance depends mostly on the algorithm, with the slowest one giving most accurate results. Nevertheless, noise uncertainty also plays a part.

- Switching between local and cooperative sensing on the basis of SNR [10]. This method proposes activation of cooperative energy sensing if the SNR is below the predefined threshold level so that a better accuracy may be achieved.

- A novel examination was presented in [11] which studied the performance limits of the CRN when the number of its nodes is very large. The developed system model is mainly concerned with the influence of that number on the sensing time of the individual nodes and on the utilization of the sensed spectrum. The study showed that the possibility of false alarm approaches zero as the number of nodes is increased. However as it can expected (and also seen in other works) when the SNR reaches very low levels (below -20 dB), the performance is significantly degraded. In such cases, lower probability for false alarm can be attained when the sensing time is increased. In favorable SNR conditions this time can be greatly decreased as the number of CR nodes increases. That is because the proposed method establishes the sensing time as dependent on the number of nodes.

- A deeper look at the channel and signal characteristics is found in [12]. It takes into account the multipath fading of the signals during the sensing interval and looks at the decision-making process as based on two states (absence and presence of the PU) which change from one to the other in the aforementioned time-span. The channel is considered as time-varying multipath flat fading and the two states are modeled as the hidden states of a dynamic discrete state model. The noise uncertainty is also considered. The results are obtained by using different static lengths (the number of time slots during which the multipath components have constant amplitudes), types of channels, noise uncertainties and modulations. It is thus shown that the less changing a channel is the more probable it is for detection to be made. In high SNR environments, noise uncertainty does not significantly degrade the performance.

- Fixing the detection threshold using Fuzzy Logic which takes into account the PU signal energy and SNR [13]. The spectrum sensing scheme used is energy detection. Several different threshold levels which form a rule base are defined depending on the energy and SNR, and using them, the method is able to differentiate which portions of the spectrum are available and which are not. Since it does not produce a clear numerical output, its efficiency can be examined only by its logical decisions and not using the standard metrics. Speed is not considered in this algorithm.

These observations serve as examples of the capabilities of the energy detector based spectrum sensing algorithms. Since this project focuses on the practical implementation of local sensing, the theoretical description of the signal and the noise depend on the way, in which the measurement process is executed. In the current case, the knowledge of the received signal structure (Gaussian distribution) gives a justification for making the simplified assumptions in this regard. Thus, the performance of the detector has been assessed using the classical statistic expressions. In addition to that, the Fuzzy Logic method has also been applied as a supplement because it is simpler and has less computational cost. Its efficiency has been examined in comparison to the standard model.

1.5.2. SPEED-ACCURACY TRADE-OFF ALGORITHMS

Special attention was given to proposals which, build upon the standard energy detector using logic that allows for adaptability of the method to be achieved.

- In [14], the authors present a method, in which the optimal sensing and transmission times can be obtained by using the probabilities of miss-detection and of false alarm of the detector. A model of the PU transmission pattern built as a Renewal Process [15] is also a part of the expressions. In this way the opportunity of the SU to access the spectrum has also been calculated. The sensing speed and transmission periods are the main results of the work.

- A similar study [16] develops a framework for finding the trade-off but uses the capacity of the CR network as a performance metric. It divides the sensing time into slots and combines their results to obtain the decision. The multi-user scenario for the CR network and its efficiency is also considered.

- Another method in [17] optimizes the efficiency of the sensing by finding a trade-off between the transmitted power of the SU and its overall capacity over several channels. It uses a similar way of reasoning to the other proposals in these sections.

- [18] presents a framework, which has the same purpose as the others reviewed here but introduces new parameters such as the measures of the interference, which the PU receives from the SU transmissions, of the under-utilization of the white spaces and the sensing time efficiency. This method also includes a model of the PU behavior and considers the case of a CR network (cooperative sensing).

- The authors in [19] propose an adaptive scheme which divides the time periods (frames) of operation of the CR terminal into slots. Based on the SNR, the algorithm determines how many slots are to be used for the sensing process. The utilization of the band which the SU manages to achieve is also obtained.

In this project, a similar line of reasoning as in the above reviewed papers will be followed. The speed-accuracy trade-off expression will be modeled to include the PU transmission pattern and the probability of proper SU operation (SU should transmit only if it has correctly detected the absence of a PU). Some of the proposed methods will be utilized for the modeling of the equation. It will be used to find an optimal sensing time using the result of the detection parameters (probabilities of detection and of false alarm) as an input.

1.5.3. SPECTRUM SENSING PRACTICAL IMPLEMENTATIONS

There are a few works which study the issue beyond the domain of computer simulation. However, they mostly tackle the aspect of accurate detection and the algorithms that they examine are much less complex than those reviewed in the previous sections. All of them look at the scenario where there is one transceiver which acts as a PU transmitter and another, as an SU receiver. The implementations are done using the Ettus Research USRP (Universal Serial Radio Peripheral) hardware platform and the GNU Radio software package.

- In [20], a thorough methodology of how a basic energy detector can be implemented in practice is presented. Its efficiency and speed are not analyzed.

- The authors in [21] analyze the performance of the detector using the classical measures (probability of detection and probability of false alarm) and implement a two-stage (energy detector and edge of the signal pulse detector) method for higher efficiency. The decision threshold is set empirically and the efficiency of the two phases is compared.

- The proposal in [22] follows a similar pattern but only implements a single energy detector. The sensing time is defined analytically by the number of samples required for proper detection under the decision threshold which is also constant and appointed experimentally.

- A deeper look at the specifics of the implementation is made in [23]. It includes more explanations on the limitations of the equipment. The primary purpose of the study is to provide an insight into the abilities of the device to perform measurements by examining its sensitivity.

This thesis presents an implementation of the adaptive algorithm, the concept of which was explained in the previous paragraphs. It uses a measurement setup similar to those in the papers, which were reviewed in this section. However, the practical experiment will provide not only an additional insight into the challenges involved with the process but also will assess the performance and speed of the algorithm.

Some of the contributions of this thesis have been submitted as a journal paper to the Wiley Journal of Networks on May 21, 2016. The paper currently awaits acceptance and publication.

CHAPTER 2. HYBRID ENERGY DETECTION SPECTRUM SENSING

The basic technique, upon which the whole spectrum sensing solution is built, is energy detection because of its speed and ease of the mathematical definition and implementation. This chapter will briefly outline the basic expressions which explain the process and then present its Fuzzy Logic alternative that complements the classical method.

2.1. ENERGY DETECTOR FUNDAMENTALS

This detection mechanism takes the samples of the received signal and compares the samples with a threshold to determine, whether the PU signal is present in the band or not. It is widely used in the literature because of its simplicity. Defined by Urkovitz in 1967 [24], the energy detectors studied today still use variants of his conclusions. In this thesis, the reasoning in [9], [10], [16] – [19], [24] will be followed.

The energy detector senses a specific portion of the spectrum for a period of τ. The square of the gathered N samples of the received signal y(k) are averaged.

$$T(y) = \frac{1}{N}\sum_{k=1}^{N}|y(k)|^2 \tag{2.1}$$

Then the computed level T(y) is compared to a predefined threshold λ. If the signal level is greater, then the hypothesis H_1 (PU is present) will be taken as a decision. Otherwise, the detector will decide in favor of H_0 (PU is absent and the band is available for transmission).

$$y(k) = \begin{cases} H_0, & \text{if } T < \lambda \\ H_1, & \text{if } T \geqslant \lambda \end{cases} \tag{2.2}$$

It is required that the hypothesis H_0 would hold when only noise n(k) is received. While its alternative will be true when both signal s(k) and noise samples are collected during the sensing period.

$$y(k) = \begin{cases} n(k), & H_0 \\ s(k) + n(k), & H_1 \end{cases} \tag{2.3}$$

The expressions which provide us with the decision threshold, the probability of detection P_d and the probability of false alarm P_{fa} are derived using the assumption that the received samples have a probability density function with Chi-square distribution. The classical justification for it is taking N to be sufficiently large number (so the Central Limit Theorem can be applied) [9], [10], [14], [16], [18], [19], [24]. While it is true that N will not be the same in every instance of the detection process, it is fitting to set it to be a constant in the theoretical presentation.

$$N = f_s \tau \tag{2.4}$$

where f_s is the sampling rate. It is also assumed that the signal and the noise are modeled as Gaussian random variables with zero means and variances of σ_s^2 and σ_n^2, respectively. This is true in the case since the OFDM modulated symbols that are used in this project have such distribution. Thus, the probabilities of detection and of false alarm are defined as following [16], [17]:

$$P_d = Q\left(\left(\frac{\lambda}{\sigma_n^2} - \gamma - 1\right)\sqrt{\frac{N}{2\gamma+1}}\right) \tag{2.5}$$

$$P_{fa} = Q\left(\left(\frac{\lambda}{\sigma_n^2} - 1\right)\sqrt{N}\right) \tag{2.6}$$

Then, by setting the desired values of the probability of detection P_d and the probability of false alarm P_{fa} as parameters, we can calculate how many samples we need to properly assess the spectrum using the signal-to-noise ratio $\gamma = \sigma_s^2 / \sigma_n^2$. In this case, P_d and P_{fa} are set to 0.9 and 0.1, respectively because such are the requirements for detection accuracy for the IEEE 802.22 standard [25].

$$N = \frac{1}{\gamma^2}\left(Q^{-1}\left(\overline{P_d}\right) - Q^{-1}\left(\overline{P_{fa}}\right)\sqrt{2\gamma + 1}\right)^2 \tag{2.7}$$

In order to determine the decision threshold of the detector, the usual way of procedure is to set it as a constant using empirical or other means [10], [17], [18], [24]. In this project, it will be calculated for a predetermined value of P_d [16].

$$\lambda = \left(Q^{-1}\left(\overline{P_d}\right)\sqrt{\frac{N}{2\gamma+1}} + \gamma + 1\right)\sigma_n^2 \tag{2.8}$$

A scheme of the energy detector is shown in Fig. 2-1. Since the signal is digitized using Fast Fourier Transform (FFT), it is not necessary to put an analogue pre-filter at the starting point of the receiver. That is due to the more versatile representation of the signal which is provided by the digital representation [2].

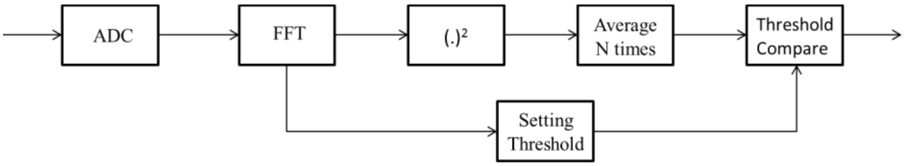

Figure 2-1. Digital implementation of an Energy Detector [2].

2.2. ENERGY DETECTION BASED ON FUZZY LOGIC

The idea of Fuzzy Logic is based on the human ability to process input information and arrange it in different categories, each of which requires a certain course of action [26]. The same principle can be applied in this and many other cases where computers have to take decisions based on environmental characteristics. The algorithm categorizes the specific parameters which are the basis for the resolution-making process, according to their values (fuzzification). This is done using a predefined set of rules which determines the outer limits of every category. Then, a decision which matches the group the parameters were categorized in, is made. After this they are deffuzified so that a value that characterizes the decision may be obtained and used for further processing. The operation of the current FL method is depicted in Fig. 2-2.

The categories, in which the parameters are grouped, can reflect different levels of distinction depending on the specific case. For example, the parameters may be classified not only as “short” and “tall” but also as “very short”, “slightly shorter”, “shorter than”, etc.

This degree of belonging of a parameter in a specific group is described by the membership function.

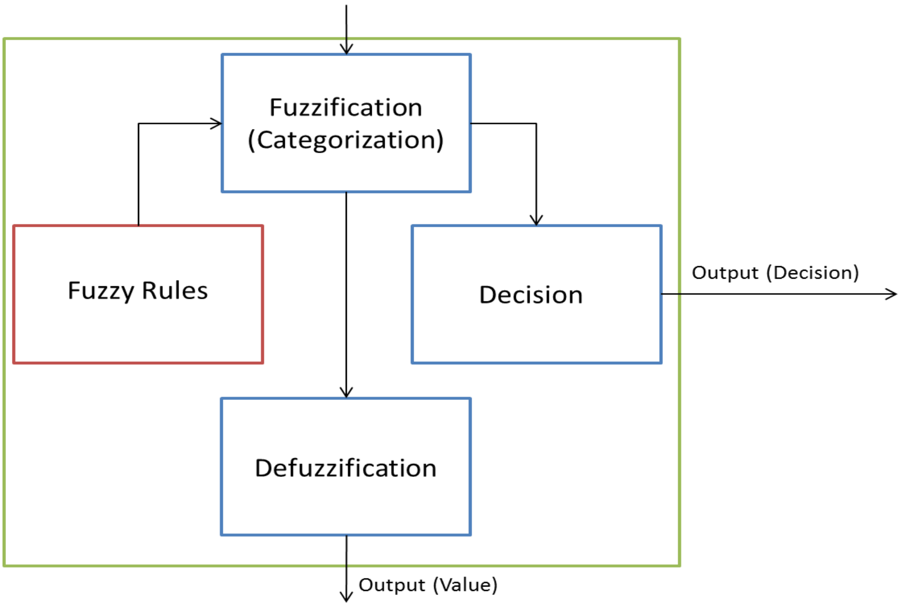

Figure 2-2. Fuzzy Logic scheme.

The parameters which will be categorized in this algorithm are the received signal power P_r and the signal-to-noise ratio (SNR). The categories into which they will be grouped are “Low Level”, “Medium Level” and “High Level”. Table 2-1 shows the limits of the groups. The “Low” category corresponds to “PU is absent” decision, “Medium”, to “Uncertain” and “High” – to “PU is present”. If the SNR and P_r both fall within one of these boundaries, the corresponding decision will be made. Otherwise the algorithm will decide that the environment is “Uncertain”. In this case no action will be taken. Table 2-2 presents the rules by which the decision is made.

To obtain a numerical output which represents the conclusion made by the FL scheme, the categorized inputs have to be defuzzified. This is done using [26]:

$$\lambda' = \frac{\mu_M(SNR)SNR + \mu_M(P_r)P_r}{\mu_M(SNR) + \mu_M(P_r)} \tag{2.9}$$

Here λ' is the decision threshold which is the product of the FL method, $\mu_M(SNR)$ and $\mu_M(P_r)$ are the membership functions of the SNR and P_r, correspondingly. These functions are both equal to 1 because the parameters are unambiguously grouped into one of the three categories. Thus every value belongs only to its specific group.

Inputs	**Low**	**Medium**	**High**
SNR, dB	≤ 1.69	(1.69;6.64)	≥ 6.64
Pr, dB	≤ -110.5	(-110.5;-100.31)	≥ -100.31
Output	λ'		

Table 2-1. Fuzzy Logic numerical inputs and output.

SNR	**Pr**	**Low**	**Medium**	**High**
Low		Low	Uncertain	Uncertain
Medium		Uncertain	Medium	Uncertain
High		Uncertain	Uncertain	High

Table 2-2. Fuzzy Logic rules.

The FL method proposed in this thesis serves as a complement to the statistical expression presented in the previous section, so that a gain in accuracy may be achieved. However, its output will be tested against the decisions which are made by the alternative and if they match, it will be accepted as correct. In the opposite case, the solution of the standard method will be considered. In other words the classic detector model acts as primary and checks the correctness of the FL decision.

2.3. SUMMARY

This chapter presents the theoretical formulations (in the specific context of this project), which are used for the implementation of the statistical and Fuzzy Logic methods. They establish the signal detection process and complement each other to provide accurate assessment of the channel. The statistical method computes a threshold which is compared to the received SNR level, to obtain a decision on the spectrum occupancy. In order to attain such decision, the FL alternative classifies both the SNR and the received signal power in three predefined categories. Thus, it makes the decision. After that, a numerical threshold is calculated from the inputs, which represents the FL decision.

The two methods can be used separately but in this project, the decision taken from the statistical phase is used to check the correctness of the FL decision. This way, the detection is more rigorous.

CHAPTER 3. ADAPTIVE SPECTRUM SENSING AND ALGORITHM DESIGN

3.1. MATHEMATICAL FORMULATION OF THE ACCURACY-TIME TRADE-OFF

Following on the detection methods introduced in the previous chapter, the logic for finding the optimal trade-off between sensing time and accuracy will be presented in this one. The accuracy is given by the probabilities of detection and of false alarm which are the outputs of the detector. They are the basis for the estimation of the sensing period. The accuracy-time trade-off is defined as a closed form expression which gives us the probability that the spectrum portion in question is available and sensed correctly. It is formed by the sensing efficiency (or how much time does the sensing process take), the probability for accurate assessment of the channel and the pattern of the primary user's transmission (when it transmits and does not transmit) [14], [16], [17]. These three components are depicted in the same order in (3.1).

$$\eta(\tau) = \zeta(\tau)\phi(P_d, P_{fa})\psi(PU_{ON}, PU_{OFF}) \tag{3.1}$$

Depending on the purpose of the examination for which the algorithm is developed, the elements in (3.1) can be formulated in different ways. Since this project studies the balance between the speed and correctness of the sensing process, they will be defined as following.

The sensing efficiency $\zeta(\tau)$ is specified in (3.2). It shows the ratio between the time during which the CR device will transmit (transmission period) T_{tr} and the length of one frame period T (it is the frame of operation of the SU). The time during which one spectrum sensing sweep will be done is τ. T is set preliminary and τ is the output parameter which has to be obtained.

$$\zeta(\tau) = \frac{T_{tr}}{T} = \frac{T-\tau}{T} \tag{3.2}$$

For the purpose of this study, it is required for the probability that the states (idle or “OFF”, and active or “OFF”) of the primary user are properly detected. The PU changes its states randomly and quickly in general but in this implementation their probabilities P(ON) and P(OFF) are known [16], [17].

$$\phi(P_d, P_{fa}) = P(OFF)(1 - P_{fa}) + P(ON)(1 - P_d) \tag{3.3}$$

The operation of the PU is described as a renewal process [14], [15]. According to the theory, this process depicts the alternation between two processes which complement each other and form a cycle [15]. The first one, called age process defines the time elapsed since the last change while the other (residual process) is the period until the next one. Together, they form one cycle which is termed a length (renewal) process.

The states of the PU are depicted in Fig. 3-1. They are assumed to be random at length in this theoretical definition and are described as the independent and identically distributed variables T_{ON} (corresponding to active PU state) and T_{OFF} (idle PU state). Since they follow one after the other, they correspond to the age and the residual processes, respectively. The renewal process T_{RP} as consisting of them combined follows the same distribution.

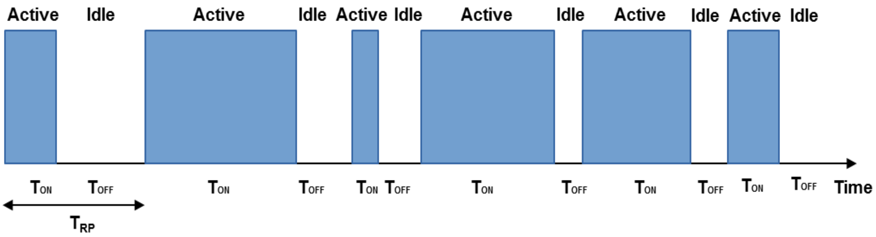

Figure 3-1. Alternation of the states of the primary user.

Thus, the random variables T_{ON}, T_{OFF} and T_{RP} form three sets $\{T_i^{ON}\}_{i=1}^{\infty}$, $\{T_i^{OFF}\}_{i=1}^{\infty}$ and $\{T_i^{RP}\}_{i=1}^{\infty}$ which include all their realizations during the alternations of the states of the PU for the interval [0, t]. T_{ON} and T_{OFF} are defined as:

$$\begin{gathered} S_n^j = \sum_{i=0}^{n} T_i^j, T_0^j = 0; S_{n+1}^j = S_n^j + T_{n+1}^j \\ T^j(t) \equiv \sup\{n \geqslant 0 | S_n^j \leqslant t\} \\ j \in A\{ON; OFF\} \end{gathered} \quad (3.4)$$

Their means are μ_{ON}^{-1} and μ_{OFF}^{-1}, accordingly.

The renewal process as a whole has the same description and sum:

$$\begin{gathered} S_n^{RP} = \sum_{i=0}^{n} T_i^{RP}, T_0^{RP} = 0; S_{n+1}^{RP} = S_n^{RP} + T_{n+1}^{RP} \\ T^{RP}(t) \equiv \sup\{n \geqslant 0 | S_n^{RP} \leqslant t\} \end{gathered} \quad (3.5)$$

It is assumed that T_{ON} and T_{OFF} are distributed in an exponential manner and therefore, the same will be applied for the renewal process. Its probability density function is defined as a convolution of its elements [14], [15].

$$f_{RP}(t) = f_{ON}(t) * f_{OFF}(t) \tag{3.6}$$

$$f_j(t) = \begin{cases} \frac{1}{\mu_j} \exp\left(-\frac{t}{\mu_j}\right), t \geqslant 0 \\ 0 \qquad\qquad\qquad\quad , t < 0 \end{cases} \qquad j \in A\{ON; OFF\} \tag{3.7}$$

$$f_{RP}(t) = \frac{\mu_{OFF}\mu_{ON}}{\mu_{OFF}-\mu_{ON}}\left[\exp\left(-\frac{t}{\mu_{ON}}\right) - \exp\left(-\frac{t}{\mu_{OFF}}\right)\right] \tag{3.8}$$

If the spectrum portion which is sensed is found to be available, the SU will utilize it for the remainder of the frame (the transmission period T_{tr}). However, if at any point during this time, the PU returns to the band in question, the transmissions of the SU will create interference (or “collide” with the data stream of the PU [14]). Not even one “collision” should be tolerated so the aim is to obtain the probability that such will not take place during the transmission period of the CR. It is defined as the probability of the residual life of the residual process. Thus, the probability of non-collision P_{nc} is in fact associated with the purpose of determining the chance that the PU will stay in idle state during the whole T_{tr} period.

$$\begin{aligned} P_{nc}(\tau) &= \frac{\int_{T-\tau}^{\infty} f_{RP}(t)dt}{E(T_{RP})} = \\ &= \frac{\frac{\mu_{OFF}\mu_{ON}}{\mu_{OFF}-\mu_{ON}}\left[\exp\left(-\frac{t}{\mu_{ON}}\right)-\exp\left(-\frac{t}{\mu_{OFF}}\right)\right]}{\mu_{ON}^{-1}+\mu_{OFF}^{-1}} = \\ &= \frac{(\mu_{OFF}\mu_{ON})^3}{\mu_{OFF}^2-\mu_{ON}^2}\left[\exp\left(-\frac{T-\tau}{\mu_{ON}}\right) - \exp\left(-\frac{T-\tau}{\mu_{OFF}}\right)\right] \end{aligned} \tag{3.9}$$

Now the components of the sensing speed and accuracy trade-off expression are defined and put together in (3.10).

$$\begin{gathered}\eta(\tau) = \frac{T-\tau}{T} P_{nc}(\tau)\phi(P_d, P_{fa}) = \\ = \frac{T-\tau}{T} c\left[\exp\left(-\frac{T-\tau}{\mu_{ON}}\right) - \exp\left(-\frac{T-\tau}{\mu_{OFF}}\right)\right] \\ \big(P(OFF)(1 - P_{fa}) + P(ON)(1 - P_d)\big), \\ c = \frac{(\mu_{OFF}\mu_{ON})^3}{\mu_{OFF}^2 - \mu_{ON}^2}\end{gathered} \tag{3.10}$$

In order to find the optimal value of the sensing time τ, the method presented in [14] is applied. Here the period of the CR frame T is constant, as well as the parameters which are derived from the known pattern of the PU transmissions (μ_{ON}, μ_{OFF}, P(ON) and P(OFF)). To obtain the desired value of τ, the first derivative of the expression with respect to τ needs to be calculated. Then, it is equated to zero and solved about τ and from there, the transmission period of the SU can be computed as $T - \tau$. Because of the computational limits of the host computer, the component $\exp\left(-\frac{T-\tau}{\mu_{ON}}\right)$ is ignored during the differentiation and thus it does not affect the final result. During trials it was observed that attempts for solving the derivative of (3.10) if both of the terms are present, would take intolerable amount of processing power and time. The output showed that disregarding the aforementioned term does not lead to a great difference. Such action was also taken in [14].

$$\frac{\partial \eta(\tau)}{\partial \tau} = c(T-\tau)\phi\left(P_d, P_{fa}\right)$$

$$\left[\frac{1}{T}\left(\frac{-exp\left(-\frac{T-\tau}{\mu_{OFF}}\right)}{\mu_{OFF}}\right) - c(T-\tau)\phi\left(P_d, P_{fa}\right)\left(\frac{-exp\left(-\frac{T-\tau}{\mu_{OFF}}\right)}{T}\right)\right] \quad (3.11)$$

3.2. ALGORITHM FORMULATION

In this section the algorithm's operation will be described. It is defined within the time period of one frame so that after its end, it returns to its original state. Fig. 3-2 depicts its operation.

The frame starts with an initial sensing of the spectrum which yields the average SNR for the whole band that is sensed. Based on it, the minimum number of samples needed for proper detection, is calculated using (2.7). Then, N more measurement sweeps are performed and their results for SNR, the received power P_r and the noise P_n are averaged. They are the inputs of the energy detector.

First, the Fuzzy Logic (FL) phase is employed which takes the average SNR and received power P_r. It produces a decision and a numerical value for the threshold λ'. After this, the statistical method gets the measured data and gives the same kind of outputs as the FL. Then the two decisions are compared and if they are the same, the threshold λ' computed by the FL phase will be taken into consideration. Otherwise the algorithm will take the one obtained by the statistical expression (2.8).

Following this, the decision is made by comparing the measured SNR and the resultant threshold. If the average SNR is greater than it, the detector will determine that the spectrum is not available for the secondary user transmissions. Otherwise, the channel will be perceived as free.

The decision threshold will be used for the calculation of the probabilities of detection and of false alarm which characterize the accuracy of the detector. They will be used as inputs for the trade-off expression (3.10) and the sensing time for the next instance of the algorithm will be obtained. The "transmission" period of the SU is the remainder of the frame if the detector has decided that the PU is absent from the band. During this time, the algorithm waits and does not perform any actions, since a transmission by the SU is not implemented. In case the spectrum is found to be occupied, the sensing process will be initiated again and the whole operation is repeated once more, provided there is enough time left in the frame. During measurement trials a minimum limit for execution of the algorithm was found. If the time left in the frame is less than this threshold, the SU will be idle until the frame ends. With the beginning of the next one, the algorithm will start the initial sensing and execute the procedure once again.

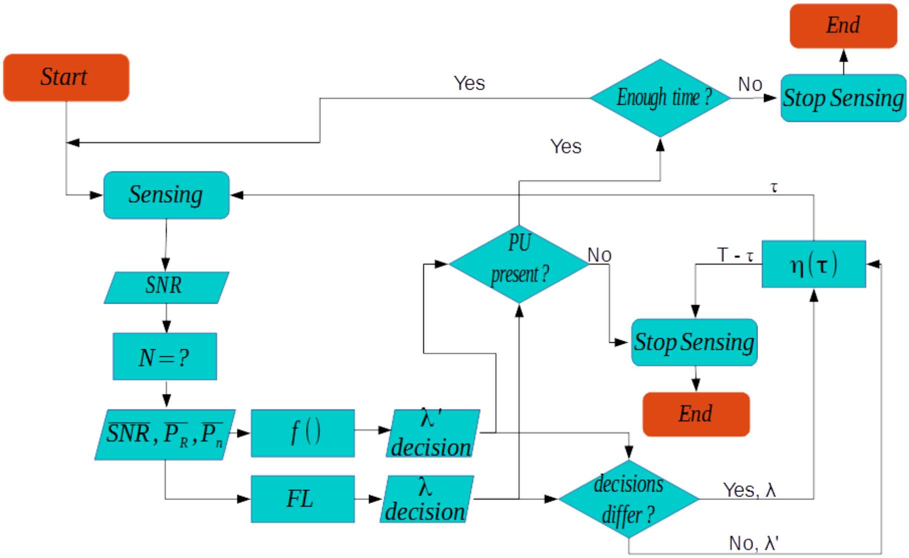

Figure 3-2. Algorithm flow-chart.

3.3. SUMMARY

The theoretical basis for the adaptivity of the detection process was established in this chapter. As a result, an expression which takes into account the behavior of the PU and the output of the detector to determine the sensing time. Thus, it achieves the accuracy-time trade-off in the particular context. After that, the general operation of the complete solution during the time span of one frame of the CR terminal, is explained. First, the way in which the detector makes the overall decision is defined. Then, the logic which uses the decision and the output of the accuracy-time trade-off, to manage the sensing process, is formulated.

CHAPTER 4. PRACTICAL IMPLEMENTATION AND EXPERIMENTAL SETUP

4.1. MEASUREMENT TESTBED

The proposed algorithm is implemented using the well-known hardware platform Universal Serial Radio Peripheral (USRP) by Ettus Reseach [27] and the open-source GNU Radio software package [28]. A brief description of these tools will be presented in this section. They provide a flexible way for performing experimental tests of wireless transceivers in a real-world environment.

The hardware utilized in this project is the USRP2 variant (Fig. 4-1) which has two components – a motherboard and a daughterboard. The motherboard [29] includes programmable digital up- and down-converters, two ADCs with 100 MS/s sampling rate and two 400 MS/s DACs, and can process bandwidths up to 100 MHz. It makes it possible for multiple-input-multiple-output (MIMO) systems to be implemented. Connection with a host computer is established via a Gigabit Ethernet Interface. The model of the daughterboard [30] is XCVR2450 which is a half-duplex dual-band transceiver that can function in the 2.4 GHz and 5 GHz bands. Its output power is 100 mW.

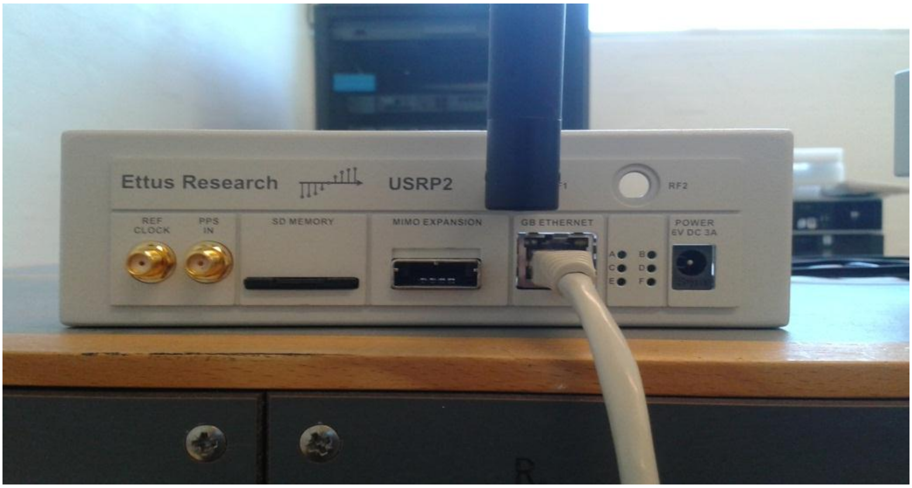

Figure 4-1. USRP2.

The GNU Radio software package allows for easy and flexible programming of the USRP. It provides the necessary drivers and programs (written in C++) which set the commands that are to be executed by the hardware platform. For easier operation, the package connects them with Python scripts (via SWIG – Simplified Wrapper and Interface Generator) which form modules (blocks). These can be put together to build the logic of a transceiver. Since the hardware is also programmable, many kinds of wireless standards can be implemented. The package also includes a graphical user interface (GUI) which provides the ability to assemble the desired device using block diagrams in a Simulink-like environment (Fig. 4-2). Then, the GUI editor automatically translates the diagram into a Python code which is executed. Otherwise, an algorithm can be written directly in Python without using the editor (as is the case in this project).

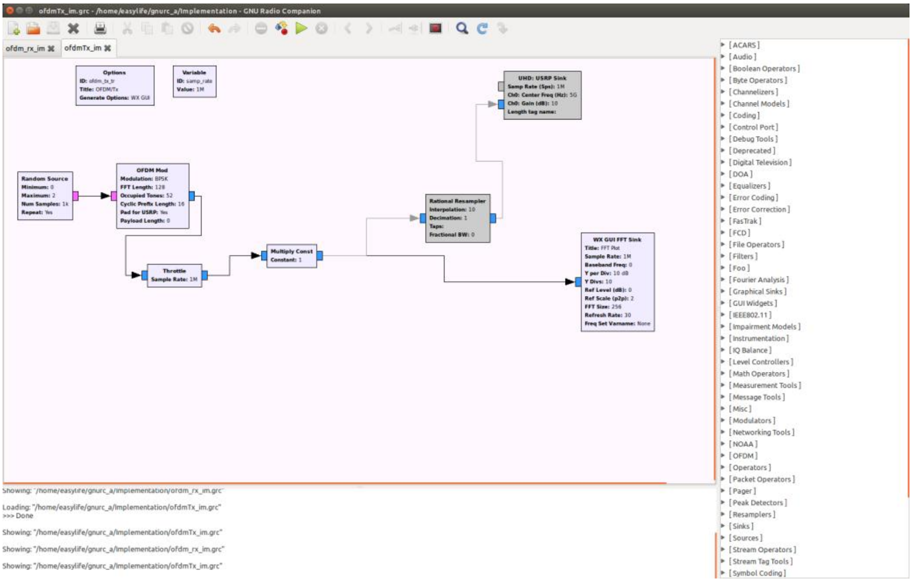

Figure 4-2. Graphical User Interface of GNU Radio.

4.2. MEASUREMENT SETTING AND IMPLEMENTATION

The experimental setup (Fig. 4-3) consists of two USRP units which stand 70 cm away from each other and are each operated by a host computer. The usual scenario also studied by the other implementation-oriented proposals of spectrum sensing solutions, is employed here. One of the USRPs serves as a PU transmitter which broadcasts with short periodical interruptions to emulate a busy traffic case. The other plays the role of the SU device which performs the sensing of the band according to the described algorithm.

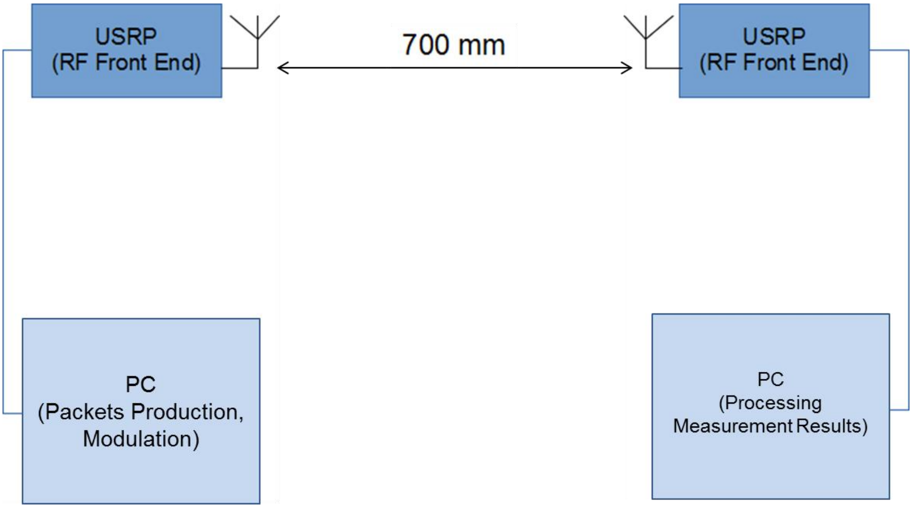

Figure 4-3. Measurements setup.

4.2.1. PRIMARY USER (TRANSMITTER) IMPLEMENTATION

The PU transmitter is implemented using the file *benchmark_tx.py* in the *gr-digital* component of the GNU Radio package. It is a Python script which takes the parameters from the user, creates a packet stream and sends it to the USRP for transmission. The amount of data to be sent, how large every packet will be and whether there will be periodical interruptions in the transmission are the user-defined settings with which the program drives the transmitter's operation. It can also save the packets in a file or read them from such.

There are three other Python scripts which are also used by the script to implement some of its functionality:

- *transmit_path.py* is responsible for setting the transmitter's bandwidth, amplitude and sending the packets to the USRP.

- GNU Radio's OFDM Modulator module – defines the numerical type of the stream (float, complex, integer, etc.), modulation type, FFT size (the frequency resolution of the digital samples), how many OFDM symbols are occupied and the length of the cyclic prefix.

- *uhd_interface.py* tunes the device's address and antenna's port (if there's more than one connected to the USRP), the central frequency, antenna gain.

The parameters used in this setup are presented in Table 4-1. The experiments are conducted by executing the transmitter 10 times, where in each of them the amplitude of the signal is different. It is changed in the following range – between 0.01-0.05 with step of 0.01 and from 0.1 to 0.5 with step of 0.1. The amplitude is one of the settings which can be set before executing the *benchmark_tx.py* file and it is relative (i.e. between 0 and 1) to the capabilities of the USRP. The transmission is completed within about 540 seconds.

Data to be transmitted	20 MB
Mode of transmission	Discontinuous
Transmitter center frequency	5.003 GHz
Bandwidth	1 MHz
Modulation	BPSK
FFT Length	64
Occupied FFT tones	52
Cyclic Prefix length	16 bits
Tx Gain	0 dB
Bytes per packet	400

Table 4-1. Input parameters of the script benchmark_tx.py.

The file *benchmark_tx.py* is slightly modified for the purpose of this examination. The script will pause for 3 seconds after every 1300 packets are transmitted and for 10 seconds every 10000th packet. It also records the times at which every transmission and every pause have occurred in two separate files so that the probabilities of the transmitter being in idle or in active state, can be calculated. The program is available as a supplement to the thesis.

4.2.2. SECONDARY USER (RECEIVER) IMPLEMENTATION

The SU receiver is built upon the *usrp_spectrum_sense.py* file which is a part of the USRP Hardware Driver (UHD) module of GNU Radio. It sets the receiver at a certain center frequency and scans the band defined by a minimal and a maximal frequency, in predefined steps. They define the width of the Fast Fourier Transform (FFT) bins (or sub-bands) in which the whole measured spectrum is divided. Then it gives the measured power on each bin as well as the noise floor power for the whole band (or set of sub-bands). This is done using several of GNU Radio's modules and connecting them as shown in Fig. 4-4.

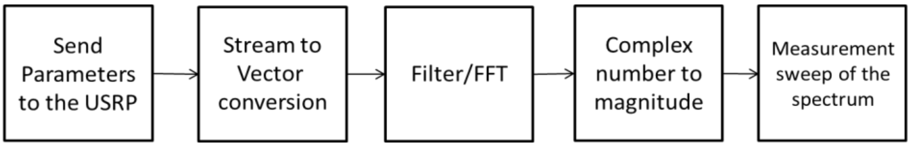

Figure 4-4. Essential blocks of usrp_spectrum_sense.py.

The specific parameters which can be set at the start of the program are the following. The address and the antenna of the USRP (if there are more than one devices connected to the host computer and multiple antennas connected to the USRP), the receiver gain and the sampling rate, the bandwidth of the individual FFT bins (sub-bands) and the size (the number of bins) of the FFT. The last three of these are associated with each other by the dependency in (4.1).

$$\text{FFT size} = \frac{\text{sample rate}}{\text{bandwidth of one sub-band}} \tag{4.1}$$

The last two parameters used for the purpose of this study are the dwell delay and the tune delay. They define the time during which the receiver will measure the band and the time it will wait between the measurements for the central frequency to be set, respectively. They are the most important factors which define the execution time of the whole program and their role will be described in the next section.

The spectrum sensing algorithm uses this script as a basis and the execution time is set to be 540 seconds and it is run at the same time as the transmitter. It measures the whole band on which the PU transmits but the operation of *usrp_spectrum_sense.py* has some differences in comparison to *benchmark_tx.py*. Here, it is the starting and ending frequencies that are defined as an input, instead of the width of the whole band. There are also the sampling rate, the FFT size and width of an individual sub-band (also referred to as channel bandwidth in the “help guide” of the file) which are explained above. Because the width of the whole band is 1 MHz, it is logical that the sampling rate is set to 2 MS/s but then, in order to have sub-bands with the same width as the transmitter (15.625 kHz), the FFT length should be 128. This is done because during measurements the script removes 12.5% of the samples both in the beginning and the end of the spectrum. Thus, only the 64 FFT bins which represent a complete scan of the band are given as output in the end.

The receiver gain is set to default (half of the maximum possible, in this case – 16.65 dB).

Table 4-2 shows the values of these parameters.

Starting frequency	5.0025 GHz
Ending frequency	5.0035 GHz
Sampling rate	2 MS/s
FFT length	128
Channel Bandwidth	15.625 kHz

Table 4-2. Input parameters of the script usrp_spectrum_sense.py

The logic of the proposed algorithm is split into two parts. The detector is implemented as an extension to the file itself (*modified_usrp_spectrum_sense.py*) and a separate script (*execute.py*) which calculates the sensing time using the results of the detection and controls the execution of the sensing. This division is depicted in Fig. 4-5. The two files are available as supplements to the thesis.

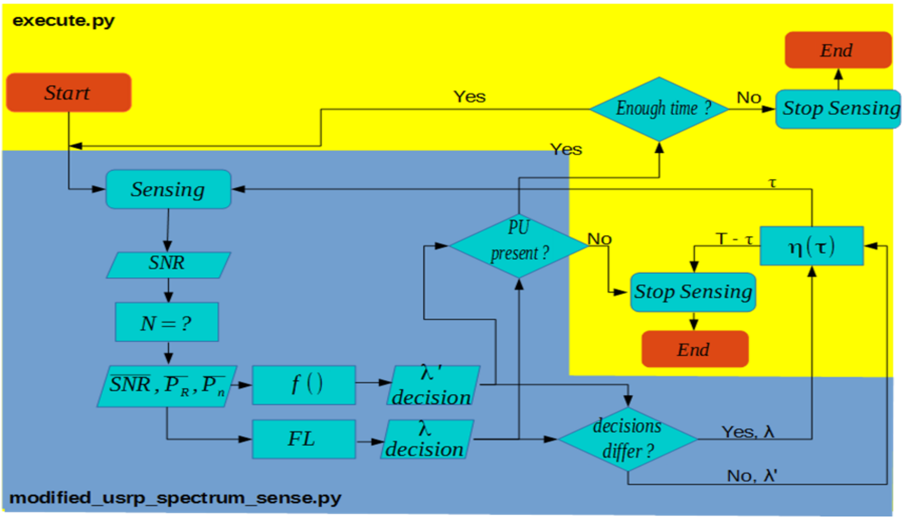

Figure 4-5. Segmentation of the structure of the algorithm.

The operation of the detector (*modified_usrp_spectrum_sense.py*) is outlined here. After the input parameters are sent to the USRP, the result of the sweep of the spectrum band is formed using FFT and the power spectrum density (PSD) of each bin is computed. During the first execution a single sweep of the band is made in order for the algorithm to determine how many measurement samples are needed for proper assessment of the channel. For that purpose the average SNR over all the sub-bands is obtained and (2.7) is applied to calculate N. Then, N more measurements of the band are performed. The SNR and received signal power (P_r) values for each sub-band of all of the measurements are averaged. Then the FL method is employed and produces decisions and thresholds for the individual sub-bands. Similar course of action is taken for the statistical method but it also includes the test of the FL decisions. If they are the same, the threshold computed by the FL phase will be taken into consideration. Otherwise, the one obtained by the statistical method will be adopted as an overall for the sub-band in question. Finally, the probabilities of detection P_d and of false alarm P_{fa} are calculated from the thresholds. Their means for the whole band are taken over all the sub-bands. The decision for the occupancy of the band is made by comparing the sum of the available (vacant) and of the non-available (non-vacant) sub-bands. If the former is greater, then the band will be perceived as free from PU transmissions. Algorithm 1 lists the described procedures.

Algorithm 1. *Energy Detector (modified_usrp_spectrum_sense.py)*

```
Get input parameters from the console
Set the USRP to the parameters
Perform FFT on the signal
for every FFT bin do
   PSD = Amplitude^2
end for
if first run then
   for every FFT bin do
      P_r = 10 * log10(PSD/Sampling Rate)
      P_n = 10 * log10(min(PSD)/Sampling Rate)
      SNR = P_r - P_n
   end for
   Calculate mean(SNR) over all FFT bins
else
   Perform N measurements
   for each measurement do
      for each sub-band do
         Calculate average SNR and P_r
      end for
   end for
   Average SNR and P_r over N
   for each sub-band do
      Apply FL method
      Produce FL_decision and FL_threshold
      Apply statistical method
      Compute statistical_threshold and define statistical_decision
   end for
   if FL_decision is the same as statistical_decision then
      threshold = FL_threshold
   else
      threshold = statistical_threshold
   Calculate P_d and P_fa
   if non_vacant_subbands > vacant_subbands then
      overall_decision -> non_vacant
   else
      overall_decision -> vacant
   Save P_d, P_fa, overall_decision
```

The algorithm is flexible and applying only one of the two phases to test the difference in the performance is easy. That is because each of them is implemented in a separate method which can be removed without affecting the other components of the program. This way the efficiency is examined in two cases – with both of the methods or just the statistical one.

The time-accuracy trade-off is established in the file *execute.py* which also drives the operation of the detector. It organizes the operation of the program in frames. Each frame starts with an initial run of *modified_usrp_spectrum_sense.py* with a predefined value of the dwell delay time. During the rest of the frame, the new dwell delay period is obtained by solving the trade-off expressions, and an action is taken depending on the decision made by the detector. For computational ease, the equation (3.11) was derived preliminary and is used in its final form from which the solution for τ is found (using the methods of Sympy, a Python library for symbolic mathematics). If the band is vacant, the "transmission" period of the SU begins, and it lasts until the end of the frame. During this time the script does nothing and returns to the initial stage when the frame expires. In the case of occupied band, subsequent spectrum sensing is performed only if there is enough time left in the frame (this is defined empirically as trials have shown that *modified_usrp_spectrum_sense.py* would need at least 3 seconds to execute). This cycle will continue until the frame period expires. In case there are less than 3 seconds until the end of the frame and the spectrum is not available, the results will be saved and the algorithm will return to its initial stage. The same will happen if the band is vacant but there is too little time (less than 1 second) left in the frame. Algorithm 2 shows the pseudo-code of *execute.py*.

Algorithm 2. Algorithm execution logic (*execute.py*)

while current_time < execution_time
    start_of_the_frame
    Initial Spectrum Sensing
    initial_sensing_time = current_time - start_of_the_frame
    rest_of_frame = frame_length - initial_sensing_time
    while current_time < rest_of_frame
        Get P_d, P_{fa}, decision
        Solve $\eta(\tau)$ for P_d and P_{fa}
        dwell_delay = τ
        if decision is 'available' and (rest_of_frame - current_time) < 1 **then**
            Save data
            break
        if decision is 'not available' and (rest_of_frame - current_time) < 3 **then**
            Save data
            break
        if decision is 'available' **then**
            Wait until end of the frame
            Save data
            break
        if decision is 'not available' and (rest_of_frame - current_time) > 3 **then**
            Sequential Spectrum Sensing
            Save data
        else
            break
    end while
end while

The parameters which define the transmission pattern of the PU were empirically calculated and listed in Table 4-3.

P(OFF)	0.322
P(ON)	0.688
$\boldsymbol{\mu_{OFF}^{-1}}$	140.37
$\boldsymbol{\mu_{ON}^{-1}}$	66.67

Table 4-3. Parameters of the PU.

4.3. IMPLEMENTATION DETAILS

Realizing an adaptive spectrum sensing solution via a real-world testbed introduces new challenges which are not present when computer simulation is employed. They result from the inherent limitations and characteristics of the equipment and mostly concern the definition of the interval within which the input parameters change and the determination of the constants. This section contains the thorough description of the obstacles faced during the implementation of the algorithm using the USRP and GNU Radio.

One specific peculiarity of USRP2 is the measurement error which is exhibited around the center frequency. These samples were found to have much higher values than all the others, in each state of the channel. For this reason they are discarded. Thus, instead of 64 sub-bands, the whole 1 MHz band is viewed as represented by only 60 during the operation of the algorithm. This abnormality has also been noted in the study in [23]. In addition to this, measurements showed that even when the band is unoccupied, the received signal is much stronger than the noise floor, and so it was normalized so that it may be around the level of the noise. After multiple measurements, an average difference between the signal and noise levels was found and defined as the normalization constant. It is equal to 7.022 dB.

The numerical output (the decision threshold λ') produced by the FL method differs from the threshold λ obtained via the statistical phase. In low SNR this difference proved to be substantial which results in drastically distant values of P_d and P_{fa} in comparison to those acquired from the alternative. In the case when the FL decision on the channel occupancy is correct, the threshold should be in the order of magnitude of the statistical one. Otherwise the results will not accurately represent the performance of the detector. Measurement trials showed that when λ' has a differing magnitude (it is less than 2 times smaller) from λ, it should be multiplied by 3 in order to achieve good precision in computing P_d and P_{fa} in circumstances where its value is very small (between 0 and 1).

In a similar fashion, when λ is calculated in the statistical phase, there have been some occurrences of it being a negative number. This happens in the case when the algorithm detects high SNR during the initial measurement (resulting in N being estimated to be small) but during the consequent sweep which senses the occupancy of the band, the signal level drops. Thus if $N = 1$, the threshold $\lambda < 0$ which is inaccurate. In such case it is multiplied by -1 to be turned into a positive number. This did not affect the decision accuracy of the detector because the SNR is still lower than the threshold.

The dwell delay time determines how accurate the values of the measured signal power and noise will be and for this reason it was defined in the interval between 1 and 250 ms. Thirty measurements were conducted for several values in this interval, namely 1, 2, 5, 10, 15, 20, 50, 70, 100, 120, 200 and 250 ms. The average noise floor and signal power for each considered dwell delay period are compared to the most accurate values (obtained for 250 ms) and depicted in Fig. 4-6. Because the differences in measurement efficiency were less than 1 dB for dwell delays larger than 70 ms, it was chosen as an upper limit. Therefore in order to determine the boundaries of the FL groups (Table 2-1), the measurements were performed only for the dwell delay periods between 1 and 70 ms. To define the “Low Level” category, the band was measured when the PU transmitter is absent. The measurements for the “Medium Level” group were with discontinuous transmission from the PU and for the “High Level”, the band was occupied during the whole time. The SNR and P_r were averaged over all measurements in each of the three cases and thus the limits of the categories were defined.

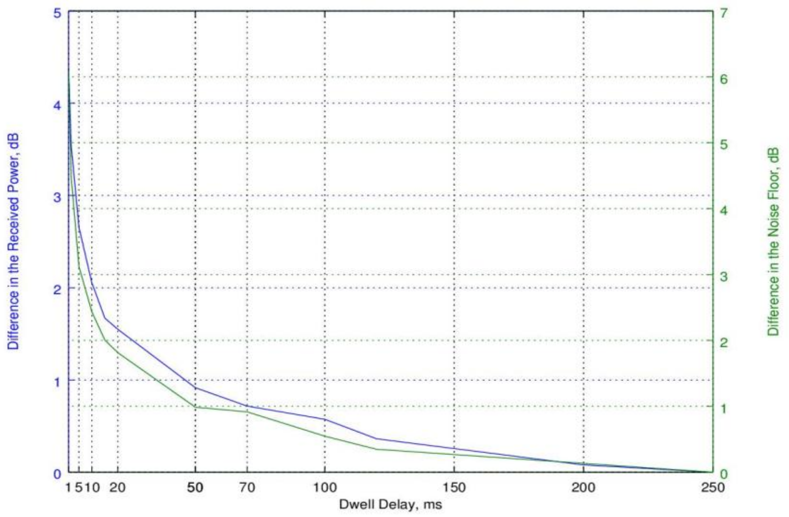

Figure 4-6. Differences in the measurement accuracy for different dwell delay periods.

The tune delay period was set as a constant at 70 ms because the receiver and the program need to have enough time to fix the center frequency. Otherwise, the tuning will at times take place during the measurement sweep. Thus, in the algorithm the dwell delay is taken as the sensing time τ which will be adaptively changed. It is the period during which one measurement of the whole bandwidth is conducted.

The execution time of one instance of the algorithm as described in chapter 3, includes one initial measurement and N sequential ones, with each preceded by a tuning of the frequency. The band is viewed as a single chunk even though it consists of 60 sub-bands. That is because performing a measurement on just a portion of it is not supported. Therefore the results for the individual sub-bands cannot be considered on their own but only as forming the whole band. The average values of SNR and P_r of all sub-bands over the N measurements are inputs for the statistical and FL methods. They produce a threshold, a decision and the resultant values of P_d and P_{fa} for each sub-band. However, because of the reason stated above only their means over the whole band are taken as inputs in the trade-off expressions. The whole 1 MHz spectrum is considered as a single chunk and a decision for its occupancy is made in the way described in the previous section. These facts are used for the determination of the length of the frame because it has to cover the time period for the execution of at least one instance of the algorithm. Therefore it was set to be constant at 10 seconds. However the value of T in the implementation of (3.2), (3.9), (3.10) and (3.11) is not equal to the actual frame length because it must be relative to the average time for which the algorithm is executed (5 seconds). Thus T = 5 and it is divided by 60 in order to be normalized. This is done because the band is represented as consisting of 60 sub-bands and the time during which each of them is measured contributes to the overall spectrum sensing period.

An important aspect in the implementation process is the computational boundaries for the execution of the algorithm, or in this case, in what interval will the input measured parameters (SNR) vary so that the operations which are a part of it can be performed for a feasible time period. This is a necessary consideration because the SNR level is not manually defined as when the detector is built as a computer simulation. Moreover, the number of the measurements N depends on it and if it is too large, the execution time becomes unacceptably long. Fig. 4-7 shows how N changes as SNR declines. It is seen that for levels lower than -15 dB, N grows exponentially. By empirical examination it was shown that performing more than a few hundred measurements presents a great computational strain for the host computer and thus, the minimum acceptable SNR is set to -9 dB. If the initial sensing measures a level lower than this, the measurement will be ignored and the algorithm will start a new one.

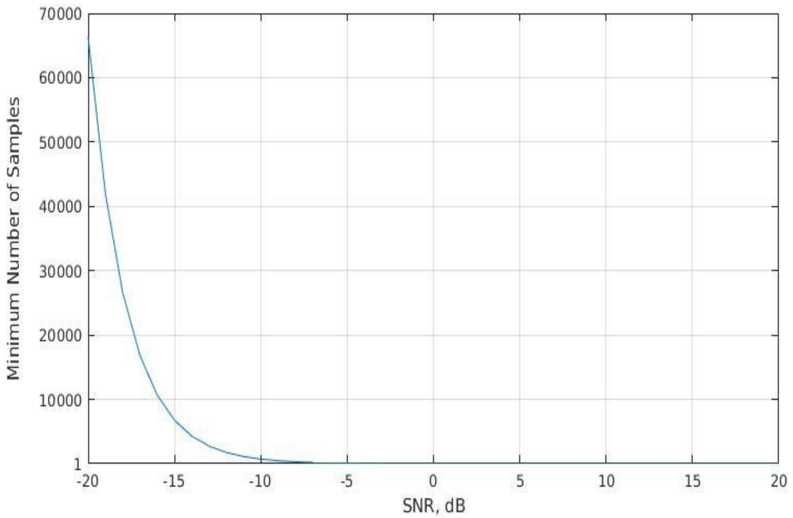

Figure 4-7. Minimum number of samples required for accurate spectrum sensing for different SNR levels.

4.4. SUMMARY

The implementation procedure is described thoroughly in this chapter. The measurement equipment and software, USRP2 and GNU Radio, are presented in the first place. Then, the realizations of the PU transmitter and SU receiver, as well as the specifics of their operation, are explained. Finally, the characteristic details of the implementation process are analyzed.

CHAPTER 5. EXPERIMENTAL RESULTS

This chapter presents assessment of the performance of the detector and the speed-accuracy trade-off solution. The primary parameter, to which most of the results are related, is the measured average SNR for the whole band. A comparison of the efficiency of the algorithm in two different cases will be made. First it will be evaluated for the instance when the detector uses only the classic statistical expressions to obtain a decision (single case spectrum sensing). Then the same will be done for the dual detection approach when both the statistical and Fuzzy Logic methods are employed (hybrid case spectrum sensing).

5.1. SPEED-ACCURACY TRADE-OFF FOR THE SINGLE CASE SPECTRUM SENSING

The implementation of the single case detector is realized by removing the FL functionality from the spectrum sensing program (see Section 4.2.2). In the first place, the detection performance is presented in Fig. 5-1, Fig. 5-2 and Fig. 5-3, which show the distribution of the probability of false alarm, the probability of detection and the complementary receiver operating characteristic (ROC), respectively. The probability of false alarm remains relatively stable until the SNR falls below 0 dB when it rises rapidly. This is because very weak signals are hard to be properly distinguished. The probability of detection is set as a constant but there is however, a minor decline which can be accredited to different rounding of the parameters in (2.5) and (2.8). The complementary ROC shows the probability of miss-detection in relation to the probability of false alarm, which are the two possible detection errors. It supports the fact that the small variation in the detection performance is not drastically affected by the rare increases in the probability of false alarm. Thus the efficiency of the detector does not change much during the measurements in this case.

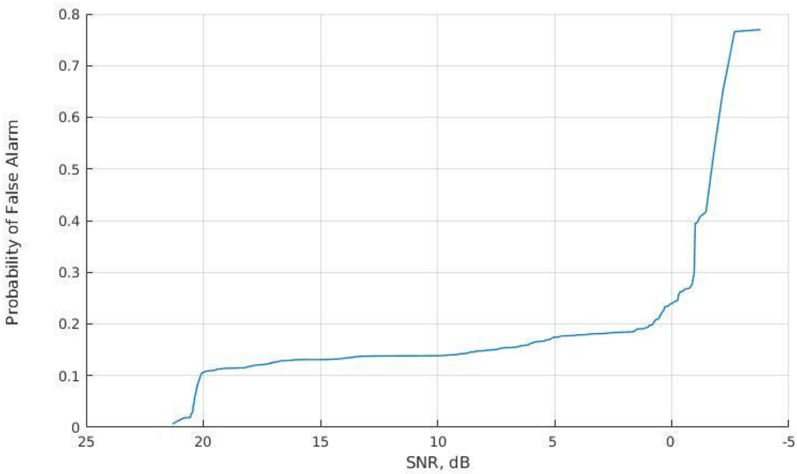

Figure 5-1. Probability of false alarm versus SNR when only the statistical method is employed.

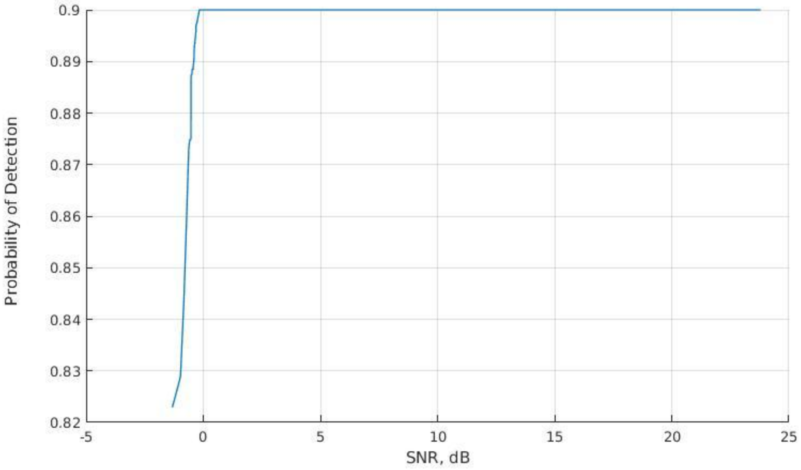

Figure 5-2. Probability of detection versus SNR when only the statistical method is employed.

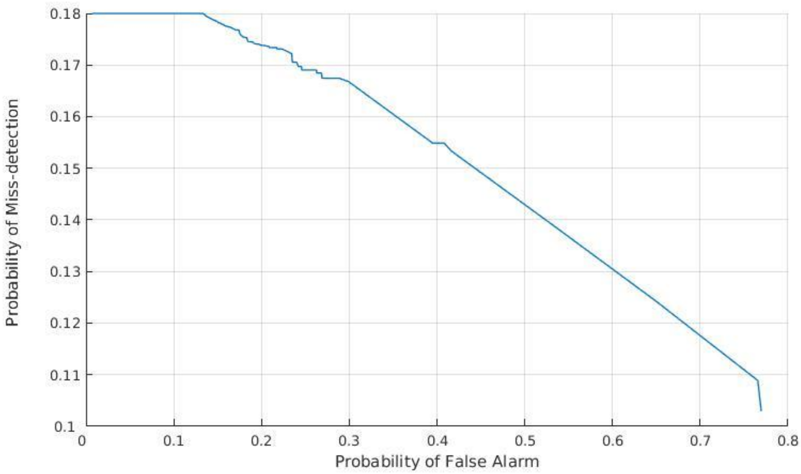

Figure 5-3. Complementary Receiver Operating Characteristic versus SNR when only the statistical method is employed.

The distribution of the probability of false alarm with respect to the number of samples (Fig. 5-4) shows that, it rises significantly in the cases when more than 14 samples were obtained. This happens in low

SNR conditions and a closer examination of the characteristic in Fig. 5-5 reveals that at about -0.2 dB there is an “SNR wall”. With regard to this, the noise uncertainty present in this scenario can be found using formula (6) from [7] and it is 2 dB. Thus when the SNR is below this value, increasing the number of samples does not improve the detection performance. This is the reason for its decline in the results for P_d, P_{fa} and the complementary ROC for SNR less than 2 dB. The effect of the SNR wall is the same for the hybrid case because N is not affected by the threshold calculation.

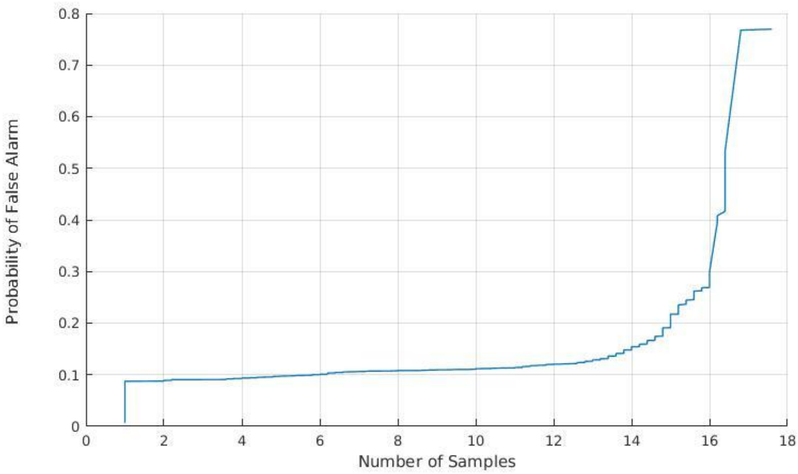

Figure 5-4. Probability of false alarm versus the obtained number of samples.

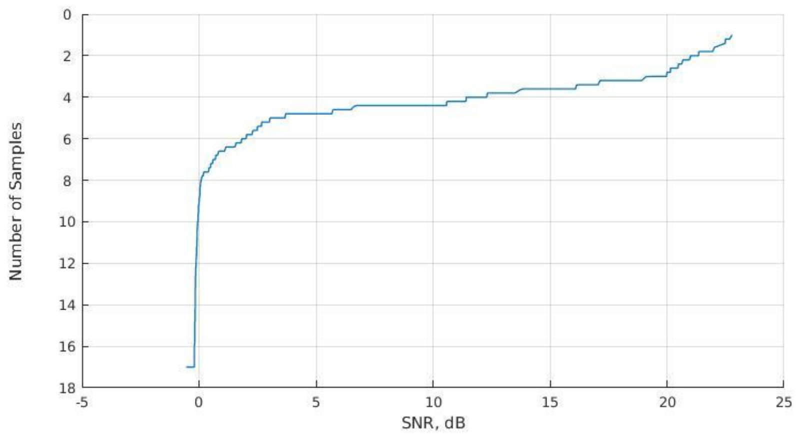

Figure 5-5. The obtained number of samples versus SNR.

There are three metrics to examine the speed of the algorithm – the dwell delay periods, the execution time of the algorithm and the intervals of SU “transmission”. Fig. 5-6 shows the result for the cumulative distribution function (CDF) of the dwell delays. It is evident that the variation in their values computed for each subsequent measurement instance is negligible. This is because in the design of the algorithm, the parameters which have the primary influence in the calculation of the trade-off (equations (3.10) and (3.11)), are the constants which are defined by the PU behavior. Because of this, the results for the dwell delays are identical for the hybrid case and that is why they are only presented in this Section. As pointed out in Section 4.2.2 the initial measurement at the beginning of each frame has a fixed dwell delay, which is 70 ms. The subsequent measurement would have the calculated value which is approximately 68.33 ms.

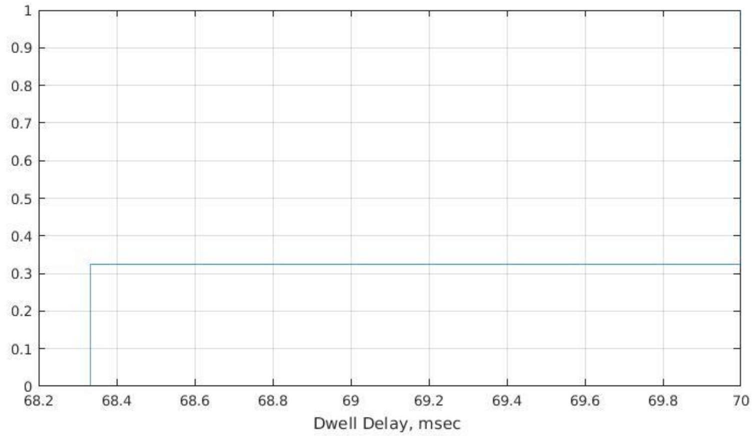

Figure 5-6. Cumulative distribution function of the dwell delay periods.

The variation in the overall execution time of the algorithm is portrayed in Fig. 5-7, which shows that it decreases with the rise in the SNR level. The reason for this result is that in higher SNR conditions, there is a need for fewer measurements in order for the decision on the spectrum occupancy to be made. There is a sharper decline in the execution time for SNR greater than 15 dB because at that point the number of samples is subject to a negligible change but due to N being small its effect on the time is more prominently noticed. When it comes to the transmission time interval (Fig. 5-8), its tendency is to be mostly under 4 seconds, even though there are many instances when it is between 4 and 5 seconds long. Very few of them are over that length.

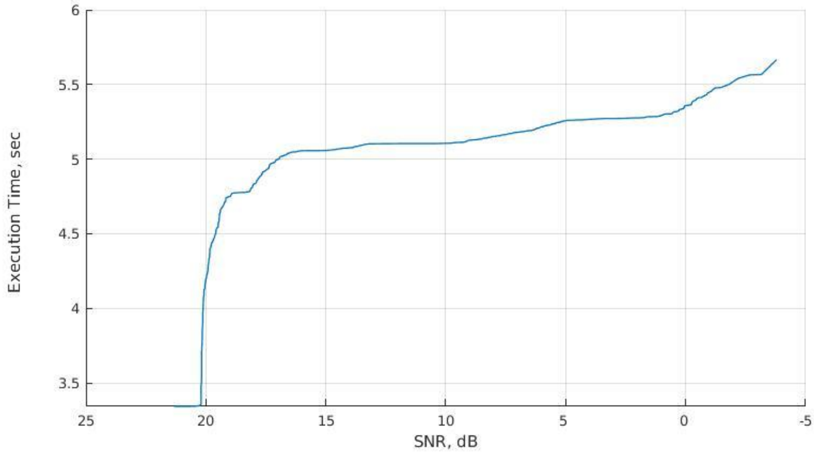

Figure 5-7. Algorithm execution time versus SNR.

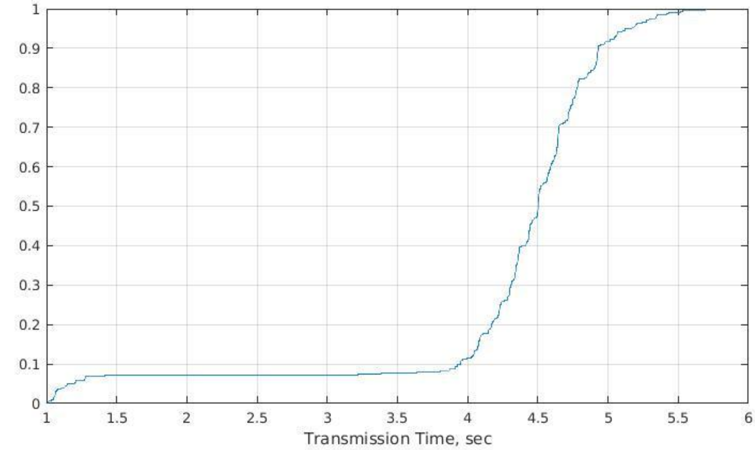

Figure 5-8. Cumulative distribution function of the transmission time periods.

5.2. SPEED-ACCURACY TRADE-OFF FOR THE HYBRID CASE SPECTRUM SENSING

This Section provides a review of the results for the case in which the FL method is active together with the statistical one. The analysis follows the same pattern.

Just like in the single case, the P_{fa}, P_d and complementary ROC are the performance metrics of the detector. They are depicted in Fig. 5-9, Fig. 5-10 and Fig. 5-11, respectively. The probability of false alarm displays the same tendency as in the alternative case but there is a slight improvement in the performance. The inclusion of the FL method has led to a much more notable enhancement in the probability of detection. This effect is also evident from the complementary ROC which reveals a significant decline in the probability of miss-detection. It is also a subject of a lot less variation than its alternative.

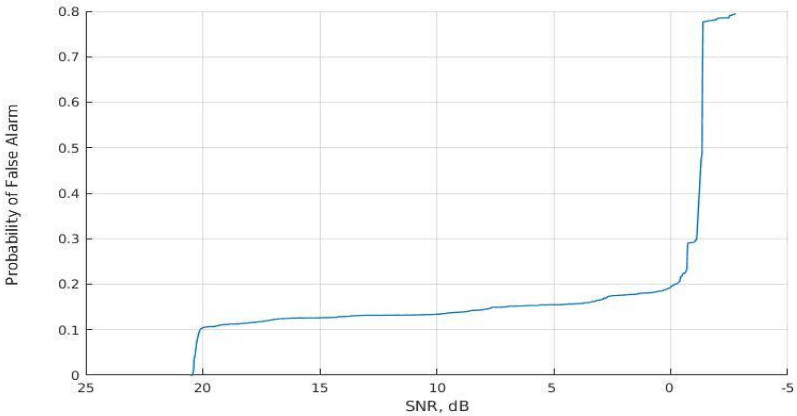

Figure 5-9. Probability of false alarm versus SNR when both the statistical and Fuzzy Logic methods are employed.

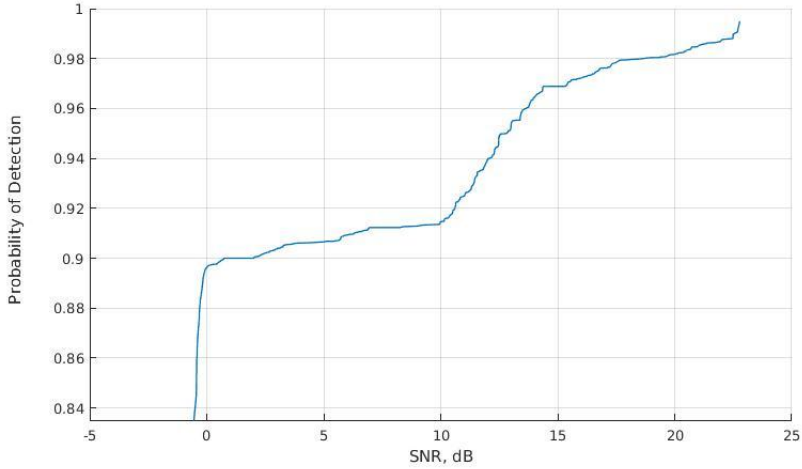

Figure 5-10. Probability of detection versus SNR when both the statistical and Fuzzy Logic methods are employed.

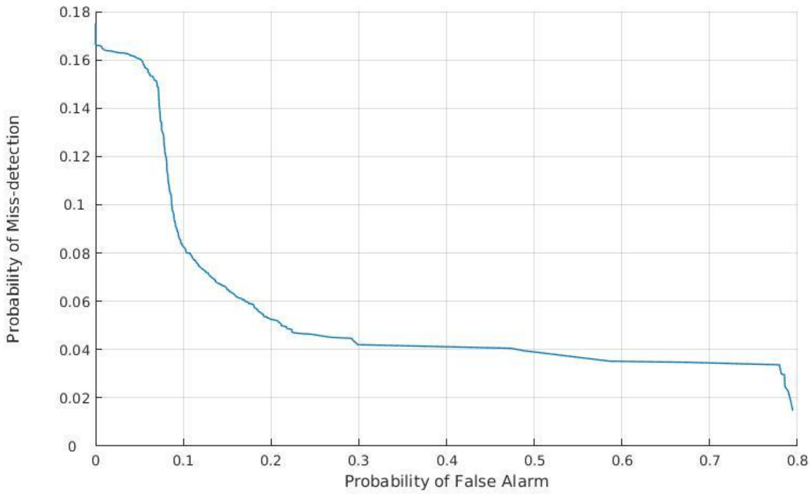

Figure 5-11. Complementary Receiver Operating Characteristic when both the statistical and Fuzzy Logic methods are employed.

The parameters which describe the efficiency in terms of speed are not affected by the addition of the complementing FL method in any evident way. The results for the dwell delay are completely identical because of the reason explained in the previous Section. Because the change in the dwell delays is very small, its impact on the execution time and the transmission time, is negligible. Therefore they only depend on the number of samples N which is driven by the average SNR. Since the transmitter settings were the same in both of the cases, the SNR is very similar and thus the results and the interpretation for the two metrics is the same. That is why it would be redundant to present them in this Section once again.

Finally for this case, the efficiency of the FL method is assessed against its alternative. The decisions taken by the FL phase are compared to those made by the statistical one. This is because the latter has been chosen as primary and thus the correctness of the outcome is provided (as described in Chapter 3). The percentage of correct FL decisions is shown in Fig. 5-12. It is evident that a substantial percentage is often achievable but complete accuracy for all sub-bands is very rarely attained. The cause can be found in the strictness of the definition of the FL rules which are intended to provide precise decision-making.

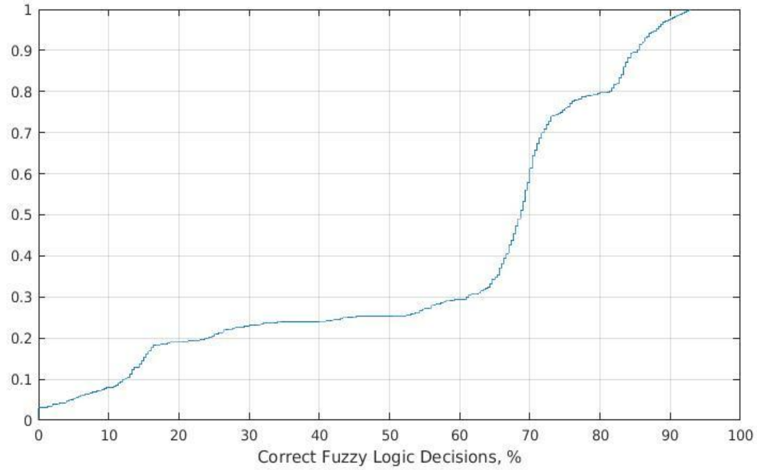

Figure 5-12. Cumulative distribution function of the percentage of correct Fuzzy Logic decisions.

5.3. SUMMARY

This chapter presents the results of the experiments. The performance of the solution is examined for two cases. The first one includes just the statistical method in the detection stage, while the second incorporates both of the methods. Their results are compared and analyzed. Thus, the performances of the detection process, of the time-accuracy expression and of the FL method, are assessed.

CHAPTER 6. CONCLUSIONS AND FUTURE WORK

The goal of this thesis is to propose and study a dual-approach method of spectrum sensing based on energy detection and to describe the process of its practical implementation. The mathematical formulation of the solution is outlined and the way it is applied in Python is specified in Section 4.2. Rather than a computer simulation the operation of the algorithm is studied as implemented in a real-world testbed with a USRP transmitter and receiver scenario. Thus, the experiment provides realistic results, and such have not been assessed extensively in the literature. Moreover, the method combines already known techniques for energy detection and adaptability of the sensing time and accuracy which have mostly been studied via simulations up to now. It shows an example of the performance of such a solution when implemented with the use of real-world transceivers.

The detector functionality includes two phases – a classic statistical and Fuzzy Logic methods. The latter complements the former in the sense that it provides greater performance but the decisions it produces are kept in check by the statistical model. This way the efficiency of the FL method for spectrum occupancy decision-making is examined. From the results it is evident that a significant portion of its decisions are indeed correct which makes its gains (up to 10%) in terms of performance achievable. There is, however, just about 50% chance that less than one third of the FL decisions will be erroneous or unreliable ("Uncertain" decision). This is still a notable percentage and therefore, an optimization of the FL rules is desirable, in order for the process of resolution to become more precise. Such result can be achieved by reconsidering the importance of each of the FL input parameters and changing some of the rules in Table 2-2. Another course of action is to perform the experiment in different conditions and redefine the limits of the FL categories in Table 2-1.

The main disadvantage of the FL scheme is that it requires preliminary knowledge of these limits. Thus, initial measurements are necessary to determine them. This may not be always practical in scenarios where the expected received signal strength cannot be identified. On the other side, the statistical method needs one of its metrics (decision threshold, probability of detection, probability of false alarm) to be set as a parameter and used to calculate the other two. Usually empirical data is used to define the threshold but in this thesis, the probability of detection is set as a constant (in the statistical method) and the other two are derived from it.

The output (probabilities of false alarm and of detection) of the two-fold operation of the detector is used to represent the conditions of the environment so that the sensing time may be adaptively changed in every instance. It is obvious from the results, that the current formulation of the algorithm does not lead to any significant gain in the sensing time (dwell delay) but adaptability is attained by using (2.7) to calculate the required number of measurements which takes the average SNR as input. This characteristic has a substantial influence on the overall execution time of the program.

Implementing the algorithm via USRP and GNU Radio presents the challenge with regard to defining the parameters which are constants in the mathematical model. It is described in *Implementation Details* (Section 4.3). The way in which the measurements are conducted is an important consideration because it determines how the algorithm operates. In this thesis, the examined bandwidth is represented as a composition of sub-bands which are measured and the results give the decision for the occupancy of the whole band because the solution is built on top of the *usrp_spectrum_sense.py* script. The operation of the solution includes the execution time of the script as well as the measurement periods (each of which is comprised of the tune delay and the dwell delay). This makes the time for sensing the spectrum hardly comparable to that of a great majority of the computer-simulated methods proposed in the literature. That is because their operation is within the range of milliseconds but speed of such proportions is unattainable considering the current formulation of the algorithm and the fact that it is implemented on a real hardware platform.

An alternative way of realizing an energy detector in practice is to construct a simple receiver in the standard GUI of GNU Radio. However, the problems that are encountered in this solution are how to determine the number of samples and how to define the noise power in order to estimate the SNR. GNU Radio has a built-in SNR

Estimation block but trials showed that it is difficult to define whether its output is correct and how to interpret it. It supports preliminary defined options which if tuned, might offer a more accurate estimation. The block is also supposed to be used in more favorable SNR conditions (SNR > 0 dB) [31].

Another aspect which requires attention is the restrictions of the USRP2. During initial trials it was observed that there is a minimum sampling rate at which the device can operate. It constitutes that it is not possible for it to process an individual chunk of spectrum on its own if it is narrower than 192.312 kHz. Thus, if a spectrum sensing is to be implemented for a very narrow-band signal, a different hardware platform is required.

In this thesis the influence of the noise uncertainty is observed but it needs to be studied in greater depth in the case of implementations with real-world transceivers. The challenge lies with the fact that it may not be attainable by means other than experimental measurements because it will probably vary significantly from one practical setup to the other.

An interesting direction for further study is the multiple-CRs scenario which includes a deployment of several SUs. This case will allow an even more realistic study of the performance of the algorithm because it will introduce the challenge of the cooperation between the SU devices in the CR network. The reason for this is the fact that the CR terminals are not likely to make the same decision on the spectrum occupancy because they will have different perceptions of the channel. They will combine their decisions to form an overall decision for the whole CR network. Thus the detection process will probably be slower which will make the speed-accuracy trade-off harder to achieve. The SU devices also need to be able to utilize the spectrum, once it has been found to be unoccupied. They will also need a kind of multiple access scheme in order to do that. Thus, it will be possible to study the throughput and the quality of service of the CR network.

The algorithm can be further extended by employing a more complex analytical design of the channel and the received signals, so that its influence on the performance can be studied. Applying a different spectrum sensing technique (like matched filter and cyclostationary detector) may lead to a deeper examination of the problem. For example, implementing detection of the characteristics of the signal (like modulation type) in order to determine its origin.

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