

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

**DYNAMIC SPECTRUM MANAGEMENT USING COGNITIVE RADIO
TECHNOLOGY**



M.Sc. THESIS

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Department of Electronic and Communication Engineering

Telecommunication Engineering Programme

JULY 2021

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To my family,



FOREWORD

This thesis work includes of investigating the Cognitive Radio Technology and proposal of a new method to improve conventional and reference methods.

I would like to pay my special regards to Prof. Dr. Ahmet Hamdi KAYRAN to take me as a student for my thesis project.

Nothing can be possible without support of my family.

June 2021

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TABLE OF CONTENTS

	Page
FOREWORD.....	ix
TABLE OF CONTENTS.....	xi
ABBREVIATIONS.....	xiii
SYMBOLS.....	xv
LIST OF TABLES.....	xvii
LIST OF FIGURES.....	xix
SUMMARY.....	xxi
ÖZET.....	xxv
1. INTRODUCTION.....	1
2. FROM SOFTWARE DEFINED RADIO TO COGNITIVE RADIO.....	5
3. DYNAMIC SPECTRUM ACCESS AND REGULATIONS.....	13
3.1 Dynamic Spectrum Management.....	16
3.1.1 Opportunistic spectrum access(OSA).....	16
3.1.2 Concurrent spectrum access.....	18
3.2 Dynamic Spectrum Management with Different Technologies.....	19
3.2.1 Cognitive radio for dynamic spectrum management.....	19
3.2.2 Blockchain for dynamic spectrum management.....	21
3.2.3 Artificial intelligence for dynamic spectrum management.....	24
4. SPECTRUM SENSING.....	25
4.1 Spectrum Sensing Techniques.....	27
4.1.1 Energy detection.....	28
4.1.2 Pilot detection.....	28
4.1.3 Cyclostationary detection.....	29
4.1.4 Beyond classical detection theory.....	30
4.2 Conventional Detection Methods Considering Impairments.....	32
4.2.1 Energy detection impairments.....	32
4.2.1.1 Energy detection under noise uncertainty.....	32
4.2.1.2 Modeling noise uncertainty.....	34
4.2.1.3 Compensating the uncertainty.....	37
4.2.2 Pilot detection impairments.....	39
4.2.3 Cyclostationary detection impairments.....	40
4.2.3.1 Cyclostationary detection under imperfect synchronization.....	40
4.2.3.2 Modeling and compensating cyclic frequency offsets.....	41
5. COOPERATIVE SPECTRUM SENSING.....	45
5.1 Introduction to the CSS.....	45
5.2 User Cooperation in Cognitive Radio Networks.....	48
5.2.1 Cooperation between cognitive users and primary users.....	48
5.2.2 Active cooperation between primary and secondary users.....	49
5.2.3 Cooperation among cognitive users.....	51

6. SOME SPESIFIC DESIGN PERSPECTIVES AND CHALLANGES.....	55
6.1 Tradeoffs.....	55
6.1.1 Cooperation-processing trade-off.....	55
6.1.2 Reactive vs proactive sensing.....	56
6.1.3 Rate-reliability trade-Off.....	57
6.2 SNR wall.....	57
7. CR REGULATIONS AND STANDARDIZATIONS.....	59
7.1 Introduction to the Regulations and Standardizations.....	59
7.2 History of Regimes.....	60
7.3 Standards and International Activity.....	62
7.3.1 The work of the SCC-4.....	62
7.3.2 The IEEE 802.22.....	63
8. PLATFORMS AND TESTBEDS.....	65
8.1 Introduction to the Platforms and Testbeds.....	65
8.2 Digital Hardware.....	66
8.2.1 Basic digital hardware options.....	67
8.2.2 Making choices.....	68
8.3 Analog Hardware.....	69
8.4 Testbed.....	71
9. SECURITY.....	73
9.1 General Overview of Security.....	73
9.2 Cognitive Radio Related Security.....	76
9.2.1 Physical fakes.....	77
9.2.2 Physical degrading of performance to stop sensing.....	78
9.2.3 Physical tampering with data.....	78
9.2.4 The double sided coin of collaboration.....	78
9.2.5 Physically tampering with CR.....	79
9.2.6 The single points of failure.....	79
9.3 Physical Layer Security.....	79
9.3.1 Eavesdropping.....	80
9.3.2 Jamming.....	81
9.3.3 PUE attack(the primary user emulation).....	82
9.4 Link Layer Security.....	83
9.5 Conclusion of Security.....	83
10. PROPOSED ALGORITHM AND RELATED EXPRESSIONS.....	85
10.1 Introduction to the Algorithm.....	85
10.2 Energy Detection based Spectrum Sensing.....	85
10.3 Cooperative Spectrum Sensing.....	88
10.3.1 Hard decision.....	88
10.3.2 Proposed algorithm and performance results.....	91
11. CONCLUSION.....	105
REFERENCES.....	107
APPENDICES.....	115
CURRICULUM VITAE.....	121

ABBREVIATIONS

CR	: Cognitive Radio
CRN	: Cognitive Radio Network
App	: Application
SS	: Spectrum Sensing
CSS	: Cooperative Spectrum Sensing
SNR	: Signal to noise ratio
FA	: False Alarm
PD	: Probability of Detection
AI	: Artificial Intelligence
ML	: Machine Learning
DSM	: Dynamic Spectrum Management
ED	: Energy Detection
PHY	: Physical layer



SYMBOLS

y	: Received signal
x	: Primary signal
w	: Noise signal
H	: Binary Hypothesis
$\wedge$	: Test Statistic
N	: Number of Samples
m	: Number of cognitive users
σ^2	: Variance
λ	: Threshold
P_d, P_f, P_m	: Probability of detection, false alarm and misdetection
p	: Noise uncertainty parameter
Q_f, Q_d, Q_m	: Global Probability of false alarm, detection and misdetection



LIST OF TABLES

	<u>Page</u>
Table 3.1: Comparison of Access Techniques.....	19
Table 4.1: Comparison of Traditional Detection Schemes	31
Table 9.1: List of Security issues in the CRN.....	84





LIST OF FIGURES

	<u>Page</u>
Figure 2.1: Cognitive Cycle.....	7
Figure 2.2: Spectrum Mobility Techniques.....	10
Figure 2.3: Spectrum Sharing in Cognitive Networks.....	11
Figure 3.1: Inefficient usage of Radio Spectrum.....	15
Figure 3.2: Spectrum Holes in the Licensed Bands.....	16
Figure 3.3: Another perspective to the cognitive cycle.....	20
Figure 4.1: SNR wall phenemenon.....	33
Figure 4.2: Noise power fluxcations.....	34
Figure 4.3: Two staged Sensing Model.....	38
Figure 4.4: Proposed improved Cyclostationary Detector.....	43
Figure 7.1: Interference management setup with guard bands.....	60
Figure 8.1 : Comparison of different hardwares.....	68
Figure 8.2: Generic transceiver architecture from Jeffrey reeds books.....	69
Figure 10.1: Periods of two staged sensing schemes.....	93
Figure 10.2: Double Threshold Scheme.....	94
Figure 10.3: Algorithm of Double threshold scheme.....	95
Figure 10.4: General Algorithm used in the Fusion Center.....	97
Figure 10.5: Effects of the number of samples.....	100
Figure 10.6: Effects of the noise uncertainty level.....	100
Figure 10.7: Empty model with different SNR conditions.....	101
Figure 10.8: Effects of the noise uncertainty parameter to the every model.....	102
Figure 10.9: Bigger noise uncertainty level with different SNR conditions.....	103
Figure 10.10: Deterioting effects of path loss.....	104



DYNAMIC SPECTRUM MANAGEMENT USING COGNITIVE RADIO TECHNOLOGY

SUMMARY

Radio frequency spectrum is one of the most important factors of Wireless Communication. We are making communications over radio frequency spectrum and transmitting data over radio frequency spectrum using electromagnetic waves. However, since the radio frequency spectrum is a physical resource, it can be said that under certain conditions, scarcity of the spectrum can be occurred. These certain conditions are the incread demand on radio spectrum due to the logarithmic technological developments and the inefficient usage of the radio spectrum due to strict and out-dated management regimes.

Most of the radio spectrum, today, is pre-allocated or pre-sold the some licensed users. Outside of the authorized users, noone can reach to these channels. However, the licensed users either dont use the allocated spectrum continuously or dont use it completely. This is simply caused by evasive management regimes. So, the scarcity is inevitable unless we develop more dynamic and adaptive management regimes. For instance, when the licensed user becomes inactive in the allocated frequency channel, unlicensed users can use this oppurtunity to make their own communication. Of course, there should be good working arrangements and standarts. As soon as licensed user is active again, the unlicensed users have to immediatly leave the frequency channel.

There are four main technologies to enable dynamic spectrum management as Cognitive Radio Technology, Blockchain technology, AI- based Methods and the Internet itself. They all have different models, features, functions and performance results. So, we can make use of the either one considering the application and the environment. Since dynamic spectrum management theme, is relatively new concept, there is not only one recognized solution can bu used in every environment. Cognitive Radios with strong observation mechanisms can adapt their behaviours according the past datas collected and reasoning with ongoing decide-act results. It is defined from the software based radios. So, it also simply is software based radio. Mitola who makes this definition, put a goal for designing cognitive radio which does not need any human intervention to adapt its behaviours after deployment. In order to achieve that, cognitive radios should carry various strong signal processing algorithms addition to that high cost hardwares. However, instead of thinking cognitive radio as a single device, if we can consider it as a part of bigger networks, the reality of such goal becomes so much clear.

Coming back to the dynamic spectrum management, the spectrum sensing function of the cognitive radio is the main reason why cognitive radios get so much attention and then recognized as a key technology for DSM. The strong observation mechanisms serve to this spectrum sensing function. There are already standardization in use which are accepted by the IEEE to use cognitive radio technology for DSM. The most important one is the IEEE 802.22 standart where cognivite radios are looking for

spectrum opportunities in the analog TV channels. These TV channels are especially very convenient in the rural areas since they are generally used inefficiently according to the data over years.

Spectrum sensing depends on the detection algorithms which are looking for white spaces in the channel of interest which is allocated to the licensed users in order to find spectrum opportunities. There are three main detection algorithms as Energy Detection, Cyclostationary Detection and Pilot-tone Detection. Even though Cyclostationary Detection schemes give better performance results, they require higher sensing times and prior knowledge about the primary signal. So, it can not be used in every application easily. Especially in the networks where we don't have any knowledge about the primary signal, we are using more simplistic detection algorithm which is Energy Detection. Due to this simplistic nature, even though we have some knowledge about the primary signal, we can instead use Energy Detection in the good SNR conditions.

There are also cooperative networks where more than one cognitive users share their sensing information in order to get better detection results and reliable networks by arranging the interference levels. The common detector used in the local part generally is the Energy Detection. Individual cognitive users, after employing energy detector, send either their whole information about signal or their one bit local decisions to the fusion center where they will be processed to get global decision. These two methods are defined as soft and hard decision fusion schemes in the literature.

The biggest issue accepted in account of the Energy Detection, is the SNR wall phenomenon. Due to noise uncertainties, under a certain SNR condition, the detection of the primary signal becomes impossible. So, most of the works in the literature simply discarded the noise uncertainty to investigate other perspectives. In 2011, it has been proved that the noise wall phenomenon doesn't arise from the level of the noise uncertainty. Instead, it arises when even with the increased sensing time, in the degraded performance results of the noise variance estimation.

Energy Detector simply depends on the classical Bayesian theory. The energy of the received signal is defined as test statistic. Then, it will be compared to the related threshold levels. If the test statistic is bigger than the threshold, the model detects the primary signal. If the test statistic is lower than the threshold, the model detects noise only samples. The most important performance merits of this model are false alarm rate and the probability of detection rate. When we are designing a such model, we generally determine an acceptable false alarm rate, and then we aim to maximizing the probability of the detection rate. To get the best performance results with the Energy Detector algorithms, we need to make the noise variance estimation as precise as possible. The general and also recognized way to employ such model is to use two staged sensing algorithm which is also used in IEEE 802.22. In the fine sensing stage, with the usage of the feature based detection, we can make sure we get noise only samples when the test statistic is lower than the determined threshold. Then, we can estimate the noise variance using maximum likelihood ratio test on the noise only samples. This variance then will be used in the threshold calculation of fast sensing stage which is the other stage of the two staged sensing algorithm.

In 2015, an algorithm is proposed which assumes the usage of two staged sensing algorithm in order to make an ideal estimation of noise variance using maximum likelihood ratio test. However, instead of using conventional single threshold energy detection algorithm, they have proposed a double threshold based energy detection algorithm which calculates the thresholds considering the noise uncertainty

parameter. So, another assumption is made here having the perfect knowledge of the noise uncertainty. According to results of the energy detector, individual cognitive radios either send their local decisions to the Fusion Center or the calculated energy of received signals to the Fusion Center to be processed to get a global decision. In the Fusion Center, the traditional 'OR' scheme is employed to get a global decision. They have showed that the proposed algorithm gives compatible performance results besides the increased reliability of the network. There is some loss of informations come from the confusion region which kinda makes the network more reliable. As in many other theoretical studies, the Path Loss effect has been ignored in this proposed work too.

When I examined this algorithm and the traditional algorithm, I observed that both algorithms suffered a great loss of performance due to the increased noise uncertainty and Path Loss effect. In my work, I proposed a new algorithm in which the information transmitted to the Fusion Center is processed by assigning Weight values in order to minimize this performance loss and achieve better successful detection rates. By assigning Weights in proportion to the magnitude of the signal energy they measure information about individual unlicensed users, I have ensured that users who are less affected by a kind of noise uncertainty and Path Loss effect have a higher impact on the overall decision.

In good SNR conditions with lower noise uncertainty levels, my proposed algorithm gave compatible performance results. However, under the effects of the path loss and bigger noise uncertainty levels, my proposed algorithm did not degrade its' performance as much as conventional method and the previously proposed algorithm in bad SNR conditions. It gave so much better performance results compared to them. So, in case of using two stage sensing like in IEEE 802.22 with better estimation of noise variance or the noise uncertainty levels, my algorithm can be used instead of conventional methods in practical designs.

In the first parts of my thesis, I organized informations about the general topics of Cognitive Radio. In the last part, I completed my work by giving the model I used, my algorithm and the results.



BİLİŞSEL RADYO TEKNOLOJİSİ İLE DİNAMİK SPEKTRUM YÖNETİMİ

ÖZET

Radyo frekans spektrumu, telsiz haberleşmenin vazgeçilmez bir unsurudur. Radio frekans spektrumunu kullanarak elektromanyetik dalgalar vasıtasıyla haberleşme ve veri aktarımı gibi çok önemli fonksiyonlar gerçekleştiririz. Ne yazık ki, radyo frekans spektrumu fiziksel bir kaynak olduğundan, belli koşullar altında kıtlığına yol açılabileceğini söyleyebiliriz. Bu koşullardan en önde geleni, günümüzde üstel olarak ilerleyen teknolojik gelişmeler sebebiyle radyo frekans spektrumuna artan ilgi ve taleptir. Tabii ki, kıtlığa asıl sebep olan şey artan talepten ziyade, geçmişten günümüze gelen radyo spektrum bölme ve atama yöntemlerinin katı ve statik bir şekilde gerçekleşmesinden ötürü ortaya çıkan radyo spektrumunun verimsiz bir şekilde yönetilmesidir.

Çoğu radyo frekans kanalı belli bir zümreye lisanslanarak onların dışındaki kullanıma kapatılır. Bu lisanslı kullanıcılar genelde kendilerine atanan ve ya satın aldıkları kanalı ya sürekli kullanmazlar ya da atanan kısmın küçük bir kısmını kullanırlar. Artan talep ile birlikte bu durum göz önüne alınırsa radyo frekans spektrum kıtlığı çekmemiz kaçınılmaz hale gelir. O yüzden radyo spektrum atama ve yönetimi üzerine daha dinamik modellere ihtiyacımız olduğu gerçeği kendini gösterir. Örneğin lisanslı kullanıcılar atanan kanalda pasif durumdayken lisanssız kullanıcılar geçici olarak kanala erişim sağlayabilirler. Tabii ki bunun için gerekli düzenleme ve standart oluşumlar gerekliliğini akıldan çıkarmamak gerekir. Lisanslı kullanıcı tekrar aktif olduğu anda lisanssız kullanıcı kanalı terk etmelidir.

Radyo spektrumunun dinamik yönetilmesinde kullanılması önerilen dört büyük teknoloji var. Bunlar Bilişsel Radyo Teknolojisi, Blokzincir teknolojisi, Yapay Zeka Destekli Yöntemler ve İnternet'tir. Hepsinin birbirinden farklı işlev, gerçeklik ve performans sonuçları bulunan bu yöntemleri kullanım alanına ve uygulama alanına göre değerlendirip hepsinden faydalanabiliriz. Radyo frekans spektrumunun dinamik yönetimi nazaran yeni bir ilgi alanı olduğundan tek bir yöntem standartlaşmış durumda değil. Bilişsel Radyolar, güçlü gözlem yetenekleriyle donatılmış, gerek geçmiş verileri kullanarak, gerek nedenlemelerle tahminlerde bulunarak kendini uyarlayabilen ve performansını idealize edebilen yazılım destekli radyolar olarak tanımlanır. Bilişsel Radyola'nın tanımını yapan Mitola, hedef olarak hiç bir şekilde insan müdahalesine gerek duymadan çalışabilen ve kendini adapte edebilen radyolar geliştirmeyi seçmiştir. Bunun için Bilişsel Radyoların çok yönlü ve güçlü sinyal işleme algoritmalarına ve yüksek bedelli donanıma sahip olmaları gerekliliği bu hedefi biraz uzak bir noktaya taşımaktadır. Ne var ki, Bilişsel Radyoları ayrı bir cihaz olarak düşünmektense, büyük bir sistemin bir parçası olarak eklediğimiz modelleri düşünürsek bu hedefin gerçekleşme ihtimali artmaktadır. Dinamik radyo spektrum yönetimine dönecek olursak, Bilişsel Radyo'nun en büyük fonksiyonu olan ve güçlü gözlemlene yetenekleriyle desteklenen Spektrum Algılama fonksiyonu, Bilişsel Radyo'nun ilgi çekmesine ve devam eden yıllarda tanınan ve farkına varılan bir teknoloji haline gelmesini sağlamıştır. IEEE tarafından kullanıma sokulan ve

sokulmaya hazırlanan birden fazla Bilişsel Radyo destekli dinamik spektrum yönetim ağı standartları bulunmaktadır. Bunlardan en önemlisi olan IEEE 802.22, analog TV kanallarına atanmış radyo frekans aralıklarında, özellikle kırsal alanlarda daha verimsiz kullanıldığından, Bilişsel Radyolar kullanarak lisanssız kullanıcılara frekans spektrum olanakları sağlama üzerine kullanıma sokulmuş bir standarttır.

Dinamik spektrum yönetiminden bahsettikten sonra, Bilişsel Radyo'nun Spektrum Algılama fonksiyonuna geçmek istiyorum. Spektrum Algılama fonksiyonu lisanslı kullanıcılara ayrılmış frekans kanalları üzerine algılama ve tespit etme algoritmaları uygulayarak lisanssız kullanıcılara kendi transmisyonlarını yapabilecekleri beyaz boşluk adı verilen spektrum olanakları bulmaktır. Belli başı üç geleneksel yöntemlerden biri olan ve en başarılı performans sonuçları veren Özellik Detektörü algoritmaları olmasına rağmen, lisanslı kullanıcılara ait bazı bilgilerin önceden bilinmesi gerekliliği ve daha uzun gözlem sürelerine ihtiyaç duyması nedeniyle her uygulama için en uygun detektör olarak kullanılamamaktadır. Özellik Detektörü'nün kullanılmasının mümkün olmadığı, tespit edilecek sinyalin tamamen bilinmez olduğu ve daha çok tek antenli alıcılı modellerde bir diğer geleneksel yöntem olan Enerji Detektörü algoritmaları kullanılır. Bunun yanı sıra, bu detektörler çok daha basit yapılı ve daha kolay görevlendirilebilir algoritmalarlardır. Yani, bazı uygulamalarda, sinyal tamamen bilinmez olmasa da, SNR koşulları uygunsa Enerji Detektörü kullanılabilir. Birden fazla lisanssız kullanıcının bir araya gelerek ve gözlemlediği bilgileri paylaşarak tespit etme performansını artırıp, ağın güvenilirliğini girişim seviyelerini düşük seviyede tutarak sağladığı kooperatif ağ modellerinde de en yaygın olarak kullanılan detektör Enerji Detektörü'dür. Lisanssız kullanıcılar bireysel olarak Enerji Detektörü algoritmaları uygulayarak, ya elde ettiği bilgileri direk Füzyon Merkezine işlenmesi üzerine gönderir, ya da bireysel ve lokal bir karar verdikten sonra, bir bitlik sadece karar bilgisini Füzyon Merkezine gönderebilir. Bu iki farklı uygulama Sert Karar Füzyonu ve Yumuşak Karar Füzyonu olarak adlandırılan geleneksel Kooperatif Ağ Füzyon metodlarıdır.

Enerji Detektörü ile ilgili literatürdeki en büyük problem gürültünün belirsizliği sebebiyle belli SNR seviyelerinin altında lisanslı kullanıcının sinyalinin tespitinin imkansız hale gelmesidir. Dolayısıyla çoğu teorik çalışma gürültünün belirsizliğini ihmal ederek yapılmıştır. 2011 yılında, SNR Duvar'ı olarak adlandırılan bu problemin gürültünün belirsizliğinin değerinden ziyade, artan gözlem sürelerinde gürültü varyansının tahminin performansının düşmesine bağlı olarak ortaya çıktığı ispatlanmıştır.

Enerji Detektörü algoritmaları klasik Bayesian modellerine dayanır. Hesaplanan enerji seviyeleri test istatistiği olarak tanımlandıktan sonra belli bir eşik değeriyle kıyaslanır. Test istatistiği eşik değerinden büyükse sinyal tespit edilmiş, test istatistiği eşik değerinden küçükse sadece gürültü tespit edilmiş demektir. Bu sistemi ölçen en önemli performans ölçütleri yanlış alarm oranı ve ya başarılı tespit etme oranlarıdır. Modeller oluşturulurken genelde belirli bir yanlış alarm oranının kabul edilebilirliği belirlenir ve başarılı tespit etme oranı maksimize edilmeye çalışılır. Bu modelde en iyi performansı almak için sadece gürültü tespit ettiğimizden emin olabildiğimiz şemalar dizayn etmeliyiz. Bunun en genel ve kabul edilmiş yöntemi, IEEE 802.22 Standard'ında da kullanılan iki aşamalı tespit etme algoritmaları kullanmaktır.

2015 yılında gürültü sinyalinin örneklerinin iki aşamalı tespit etme algoritması ile elde edilip en büyük olabilirlikli kestirim ile hesaplandığı ve gürültü belirsizliği parametresinin bilindiği varsayımı altında, ağın güvenilirliğini arttırmaya yönelik iki eşik değerli bir enerji detektörü kullanarak elde edilen bilgilerin Füzyon Merkezinde geleneksel 'Ve-ya' yöntemiyle işlendiği bir algoritma önerilmiş ve uyumlu-geçerli

performans sonuçları simülasyonlarla ispatlanmış. Bilgi kaybı sebebiyle sonuç etkilense de, kaybolan bilgi konfüzyon bölgesinden geldiği için sistemin güvenilirliğinin arttığı gösterilmiş. Bir çok diğer teorik çalışma da olduğu gibi Yol Kaybı etkisi göz ardı edilmiş.

Bu algoritmayı ve geleneksel algoritmayı incelediğimde, artan gürültü belirsizliği ve Yol Kaybı etkisi sebebiyle, iki algoritmanında büyük oranda performans kaybına uğradığını gözlemledim. Çalışmamda bu performans kaybını en aza indirmek ve daha iyi başarılı tespit etme oranları elde edebilmek için Füzyon Merkez'ine iletilen bilgilerin Ağırlık değerleri atanarak işlendiği yeni bir algoritma önerdim. Bireysel lisanssız kullanıcılara ait bilgiler ölçtükleri sinyal enerjisinin büyüklüğü oranında Ağırlıklar atanarak, bir nevi gürültü belirsizliği ve Yol Kaybı etkisinden daha az etkilenen kullanıcıların genel karara etkisinin daha yüksek olmasını sağladım.

Düşük gürültü belirsizliği seviyelerine sahip iyi SNR koşullarında, önerilen algoritmam uyumlu performans sonuçları verdi. Bununla birlikte, yol kaybının ve daha büyük gürültü belirsizliği seviyelerinin etkisi altında, önerilen algoritmam, kötü SNR koşullarında geleneksel yöntem ve daha önce önerilen algoritma kadar performansını düşürmedi. Onlara kıyasla çok daha iyi performans sonuçları verdi. Bu nedenle, IEEE 802.22'deki gibi gürültü varyansının veya gürültü belirsizlik seviyelerinin daha iyi tahmininin iki aşamalı algılama algoritma kullanılarak sağlanması durumunda, pratik tasarımlarda geleneksel yöntemler yerine önerilen algoritmam kullanılabilir.

Tez yazımın ilk kısımlarında Bilişsel Radyo'ya ait genel konulara dair bilgiler düzenledim. Son kısımda ise kullandığım modeli, algoritmamı ve sonuçları vererek çalışmamı tamamladım.



1. INTRODUCTION

Radio frequency spectrum is one of the most important factors of Wireless Communication. We are making communications over radio frequency spectrum and transmitting data over radio frequency spectrum using electromagnetic waves. However, since the radio frequency spectrum is a physical resource, it can be said that under certain conditions, scarcity of the spectrum can be occurred. These certain conditions are the incread demand on radio spectrum due to the logarithmic technological developments and the inefficient usage of the radio spectrum due to strict and out-dated management regimes. Most of the radio spectrum, today, is pre-allocated or pre-sold the some licensed users. Outside of the authorized users, no one can reach to these channels. However, the licensed users either dont use the allocated spectrum continuously or dont use it completely. This is simply caused by evasive management regimes. So, the scarcity is inevitable unless we develop more dynamic and adaptive management regimes. For instance, when the licensed user becomes inactive in the allocated frequency channel, unlicensed users can use this oppurtunity to make their own communication. Of course, there should be good working arrangements and standarts. As soon as licensed user is active again, the unlicensed users have to immidiately leave the frequency channel.

There are four main technologies to enable dynamic spectrum management as Cognitive Radio Technology, Blockchain technology, AI- based Methods and the Internet itself. They all have different models, features, functions and performance results. So, we can make use of the either one considering the application and the environment. Since dynamic spectrum management theme, is relatively new concept, there is not only one recognized solution can bu used in every environment.

Cognitive Radios with strong observation mechanisms can adapt their behaviours according the past datas collected and reasoning with ongoing decide-act results. It is defined from the software based radios. So, it also simply is software based radio. Mitola who makes this definition, put a goal for designing cognitive radio which does not need any human intervation to adapt its behaviours after deployment. In order to

achieve that, cognitive radios should carry various strong signal processing algorithms addition to that high cost hardwares. However, instead of thinking cognitive radio as a single device, if we can consider it as a part of bigger networks, the reliability of such goal becomes so much clear.

Coming back to the dynamic spectrum management, the spectrum sensing function of the cognitive radio is the main reason why cognitive radios get so much attention and then recognized as a key technology for DSM. The strong observation mechanisms serve to this spectrum sensing function. There are already standardization in use which are accepted by the IEEE to use cognitive radio technology for DSM. The most important one is the IEEE 802.22 standard where cognitive radios are looking for spectrum opportunities in the analog TV channels. These TV channels are especially very convenient in the rural areas since they are generally used inefficiently according to the data over years.

Spectrum sensing depends on the detection algorithms which are looking for white spaces in the channel of interest which is allocated to the licensed users in order to find spectrum opportunities. There are three main detection algorithms as Energy Detection, Cyclostationary Detection and Pilot-tone Detection. Even though Cyclostationary Detection schemes give better performance results, they require higher sensing times and prior knowledge about the primary signal. So, it can not be used in every application easily. Especially in the networks where we don't have any knowledge about the primary signal, we are using more simplistic detection algorithm which is Energy Detection. Due to this simplistic nature, even though we have some knowledge about the primary signal, we can instead use Energy Detection in the good SNR conditions.

There is also cooperative networks where more than one cognitive users share their sensing informations in order to get better detection results and reliable networks by arranging the interference levels. The common detector is used in the local part generally is the Energy Detection. Individual cognitive users, after employing energy detector, send either their whole informations about signal or their one bit local decisions to the fusion center where they will be processed to get global decision. These two methods are defined as soft and hard decision fusion schemes in the literature.

The biggest issue accepted in account of the Energy Detection, is the SNR wall phenomenon. Due to noise uncertainties, under a certain SNR condition, the detection of the primary signal become impossible. So, most of the works in the literature simply discarded the noise uncertainty to investigate other perspectives. In 2011[1], they have proved that the noise wall phenomenon doesn't arise from the level of the noise uncertainty. Instead, it arises when even with the increased sensing time, in the degraded performance results of the noise variance estimation.

Energy Detector simply depends on the classical Bayesian theory. The energy of the received signal is defined as test statistic. Then, it will be compared to the related threshold levels. If the test statistic is bigger than the threshold, the model detects the primary signal. If the test statistic is lower than the threshold, the model detects noise only samples. The most important performance merits of this model are false alarm rate and the probability of detection rate. When we are designing a such model, we generally determine an acceptable false alarm rate, and then we aim to maximizing the probability of the detection rate. To get the best performance results with the Energy Detector algorithms, we need to make the noise variance estimation as precise as possible. The general and also recognized way to employ such model is to use two staged sensing algorithm which is also used in IEEE 802.22. In the fine sensing stage, with the usage of the feature based detection, we can make sure we get noise only samples when the test statistic is lower than the determined threshold. Then, we can estimate the noise variance using maximum likelihood ratio test on the noise only samples. This variance then will be used in the threshold calculation of fast sensing stage which is the other stage of the two staged sensing algorithm.

In 2015,[2],they proposed an algorithm which assumes the usage of two staged sensing algorithm in order to make an ideal estimation of noise variance using maximum likelihood ratio test. However, instead of using conventional single threshold energy detection algorithm, they have proposed an double threshold based energy detection algorithm which calculates the thresholds considering the noise uncertainty parameter. So, another assumption is made here having the perfect knowledge of the noise uncertainty. According to results of the energy detector, individual cognitive radios either send their local decisions to the Fusion Center or the calculated energy of received signals to the Fusion Center to be processed to get a global decision. In the Fusion Center, the traditional 'OR' scheme is employed to get a global decision. They

have showed that the proposed algorithm gives compatible performance results besides the increased reliability of the network. There is some loss of informations come from the confusion region which kinda makes the network more reliable. As in many other theoretical studies, the Path Loss effect has been ignored in this proposed work too. When I examined this algorithm and the traditional algorithm, I observed that both algorithms suffered a great loss of performance due to the increased noise uncertainty and Path Loss effect. In my work, I proposed a new algorithm in which the information transmitted to the Fusion Center is processed by assigning Weight values in order to minimize this performance loss and achieve better successful detection rates. By assigning Weights in proportion to the magnitude of the signal energy they measure information about individual unlicensed users, I have ensured that users who are less affected by a kind of noise uncertainty and Path Loss effect have a higher impact on the overall decision. In the first parts of my thesis, I organized information about the general topics of Cognitive Radio. In the last part, I completed my work by giving the model I used, my algorithm and the results.

2. FROM SOFTWARE DEFINED RADIO TO COGNITIVE RADIO

SDR is a radio where the RF parameters and characteristics can be changed, i.e reconfigured according to the situation it has faced, by the help of signal processing techniques or in general by a software. Cognitive radio is basically adding cognitive capabilities to the software defined radios. While software defined radios has prebuilt algorithms and processing techniques, in addition to that features CR can make uses of the emerging machine learning and artificial intelligence studies at the last decades. It can adapt its behaviour and functions according to either past experiences possibly recorded to a database or processing the oncoming data from observations with different representation and reasoning models. So, it can optimize its actions through a time table, you can visualize this as Monte carlo simulations, where they are helping to answer to the probability questions with repeated random sampling to obtain numerical results.

As you can see from above explanation, CR is tightly involved with several serious other studies and one of them is 'Probability and Statistics'. Communication researches and models generally depend on the probability functions as anyone in this area know because we are simulating a possible models with different statistics. Eventhough, in practice, especially when noise and distortion is on the table, randomness outweighs the stable statistics(various mean and variance), statistics gives us the oppurtunity the generate different models. In addition to the processing of statistic features, with the cognitive learning capabilites, CR is a great technogy and is a possible key to the future developments in the communication technologies. We are building smart devices, smart cars, smart cities etc. with AI and IoT. CR is the smart radio which can help to the development and deployment of every other smart emerging technologies.

Radio technology, while practicing a communication, has to operate lots of complex signal processing algorithms in order to arrange its communication characteristics. There are many bad effects in the environment such as multipath fading, shadowing

etc. Radio needs to evaluate such effects continuously. So, it has a big processing capacity. However, not every environment has the similar effects. For instance, in the some areas there would be very little shadowing or fading. The radios work in such environment waste their processing capacity. Instead monotone radios, if we can have radios with cognitive capabilities which adapts its actions and algorithms according to the observations on the environment, we can save a big cost and potentially wasted processing capacity. Including this to the above introduction phase, I can conclude this paragraph saying that, the main approach or goal of Mitola when he defines Cognitive radio was reducing the unnecessary processing capacity. Another insight of Mitola, even it requires some time, we might adopt cognitive radios dont need any human interpretation and touch at all. [3] Realizing this insight, in addition to the cognitive capabilities involves with making observations and taking actions, cognitive radio networks have to develop their own protocols according to the needs of that specific network. However, I can say we are too early to imagine such networks before we have steady and beneficial exemplary networks. The first aim is not to develop cognitive radios with that much capabilities, instead to standardize the cognitive radios with cognitive capabilities our first aim. Even it requires significant memory, computational resources for cognitive radio. Furthermore, we need a very comprehensive theoric researches to model the cognitive radio networks. Good thing to mentioned here, it has been over a decade since Mitola first defined the cognitive radio, so we have some IEEE standardization and very basic literature right now. Yet, it is not sufficient at this phase. The literature is expanding through adopting cognitive radios with 5G and beyond technologies and the results look very promising. Before leaving this paragraph I want to give some of the definitions of cognitive radio. The first one comes from the Mitola[3] “A radio that employs model-based resulting to obtain a specified competence level in radio-related domains.” After this simple definition, Mitola created a basic cognition cycle which explains how cognitive radio should work. The main parts of the cycle are observation part, action part, deciding part and learning part as you can see from the next figure.

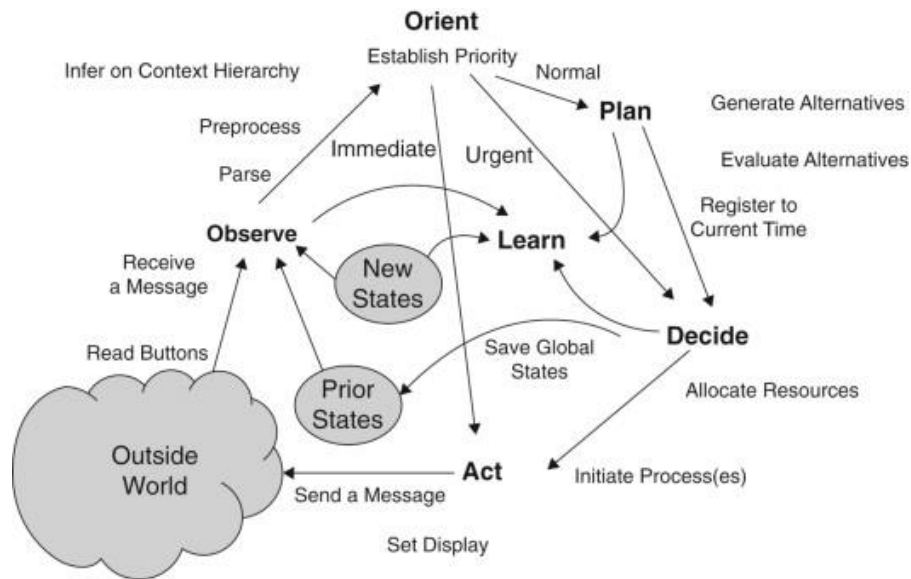


Figure 2.1: Cognitive Cycle.

The second definition I want to give, comes from another well known researcher in the communication area who is Simon S. Haykin. He basically interpreted the above cognition cycle into a very good definition where he explained the cognitive radio through perception-action cycle. Furthermore, he is more concerned about the intelligence and learning capabilities of cognitive radio. He published some survey papers and a book about cognitive devices which are cognitive radios and cognitive radars.

The third definition, I think it sums it up very well [4]: “ A cognitive radio is a device which has four broad inputs;

- an understanding of the environment in which it operates,
- an understanding of the communication requirements of the users,
- an understanding of a regulatory policies which apply to it,
- an understanding of its own capabilities.”

The last one is the definition in the wikipedia which is widely used website. So, whoever become curios about the cognitive radio who works outside of the relevant areas probably is going to see this definition[5]:” A cognitive radio (CR) is a radio that can be programmed and configured dynamically to use the best wireless channels in its vicinity to avoid user interference and congestion. Such a radio automatically detects available channels in wireless spectrum, then accordingly changes its

transmission or reception parameters to allow more concurrent wireless communications in a given spectrum band at one location.”

In addition to that comprehensive cognitive radio definitions, Cognitive Radio technology is widely investigated to solve frequency spectrum scarcity which comes from inefficient usage of the radio frequency spectrum. The old and strict regulatory policies and lavish usage of the radio spectrum are the main reasons of the inefficient usage of the spectrum. The old and strict policies use very strict and static spectrum access models where the channel of interest is assigned to a licensed user and no other users can use that channel. However, licensed users don't use the assigned spectrum continuously. With the exponential growth of the technological developments, the demand for radio spectrum is increasing rapidly. Since the radio spectrum is actually a physical resource, with the strict and static access policies, we can not handle with this demand. So, we need new regulatory policies and dynamic spectrum management methods where unlicensed users can use the channel of interest while licensed users not. So, with the strong observation mechanisms and cognitive capabilities, cognitive radio technology is recognized as a key technology to improve spectrum utilization with dynamic spectrum management. The strong observation mechanism I am mentioning is called spectrum sensing where observations be made over the channel whether licensed user is present or not. So, spectrum sensing is very important feature of the cognitive radio. If we can build good performing spectrum sensing algorithms, we can provide reliable dynamic spectrum management methods in order to use the spectrum efficiently and hopefully we can solve the frequency spectrum scarcity problem. So, while giving common sight of the cognitive radio, I will focus on the parts of cognitive radio technology concerning dynamic spectrum access, so spectrum sensing. There are four main parts of the cognitive radio operation on behalf of the spectrum management as follows:

i) Spectrum Sensing: In this part, users observe the environment they operates, makes useful informations and realizations over the observations. So, spectrum sensing is the function where the cognitive users also so called unlicensed users observe the radio spectrum in their range of transmission and find a vacate channel or available channel to use without interfere the licensed users' transmission.

ii) Spectrum Monitoring: This can be defined as a special case of spectrum sensing. Cognitive radio sensed the spectrum and found itself a spectrum hole where a licensed user is vacated. However, it can be back on channel any time. In order to avoid to disrupt licensed user's transmission, cognitive user needs to leave from the channel as soon as licensed user is present again. So, instead of looking for spectrum opportunities, cognitive radio has to monitor/sense the spectrum in order to catch licensed user's activity immediately to leave the channel.

iii) Spectrum Mobility: We know that cognitive radio should immediately leave the channel as soon as licensed user is back. However, it naturally wants to continue its transmission. So, it needs a new appropriate radio channel to switch its transmission. This event is called spectrum mobility. We can divide mobility into two processes as spectrum handoff and connection management. As the name suggests, in the spectrum handoff process, the main goal is to transfer the communication data from the channel should be left to new channel can be used. It is basically a data handoff. However, it puts additional latency and cost to cognitive user's communication and decreases the performance. Another example case for need a spectrum handoff is where the channel degraded and decreases the performance of the cognitive user's transmission. It can be caused by natural effects such as shadowing or other cognitive-unlicensed users' interruptions. In order to deal with additional latency and cost issue, connection management process is created to mitigate the effects. The main goal of this process is to adjust the new protocols according to the new transmission features and parameters robustly. There are three main handoff techniques I can list as:

- Reactive handoff: After the interruption to its' communication, cognitive user will employ sensing process in order to find a new channel to use.

- Proactive handoff: Even though cognitive user found itself a channel and using it, it will periodically sense the radio spectrum in order to prepare possible new channel if its' transmission will be disrupted. It can list a possible channels available.

- Hybrid techniques: Cognitive radio takes advantage of both reactive handoff and proactive handoff according to the network's conditions. Easily seen that, proactive handoff method decreases the handoff latency and superior to the reactive handoff in terms of performance results. However, it requires more computational power and

cost. So, in order to have low latency and good performance with less computational cost, hybrid techniques can be employed with proper strategies.

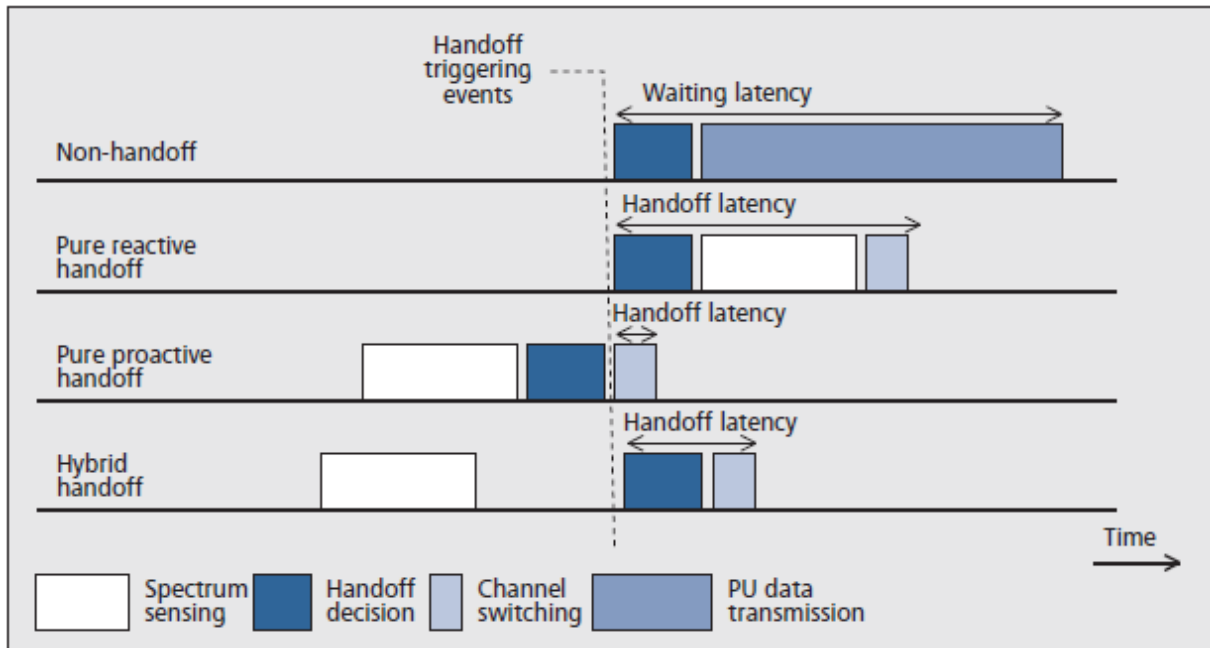


Figure 2.2: Spectrum Mobility Techniques [5].

iv) Spectrum Sharing: I already stated that the dynamic spectrum management is the process of allocation of the spectrum to the licensed and unlicensed users. This is just one way of spectrum sharing. We can generalize the cognitive radio networks in the name of the spectrum sharing like in the next figure. Every terms in the figure either has already explained or will be explained in the next chapters.

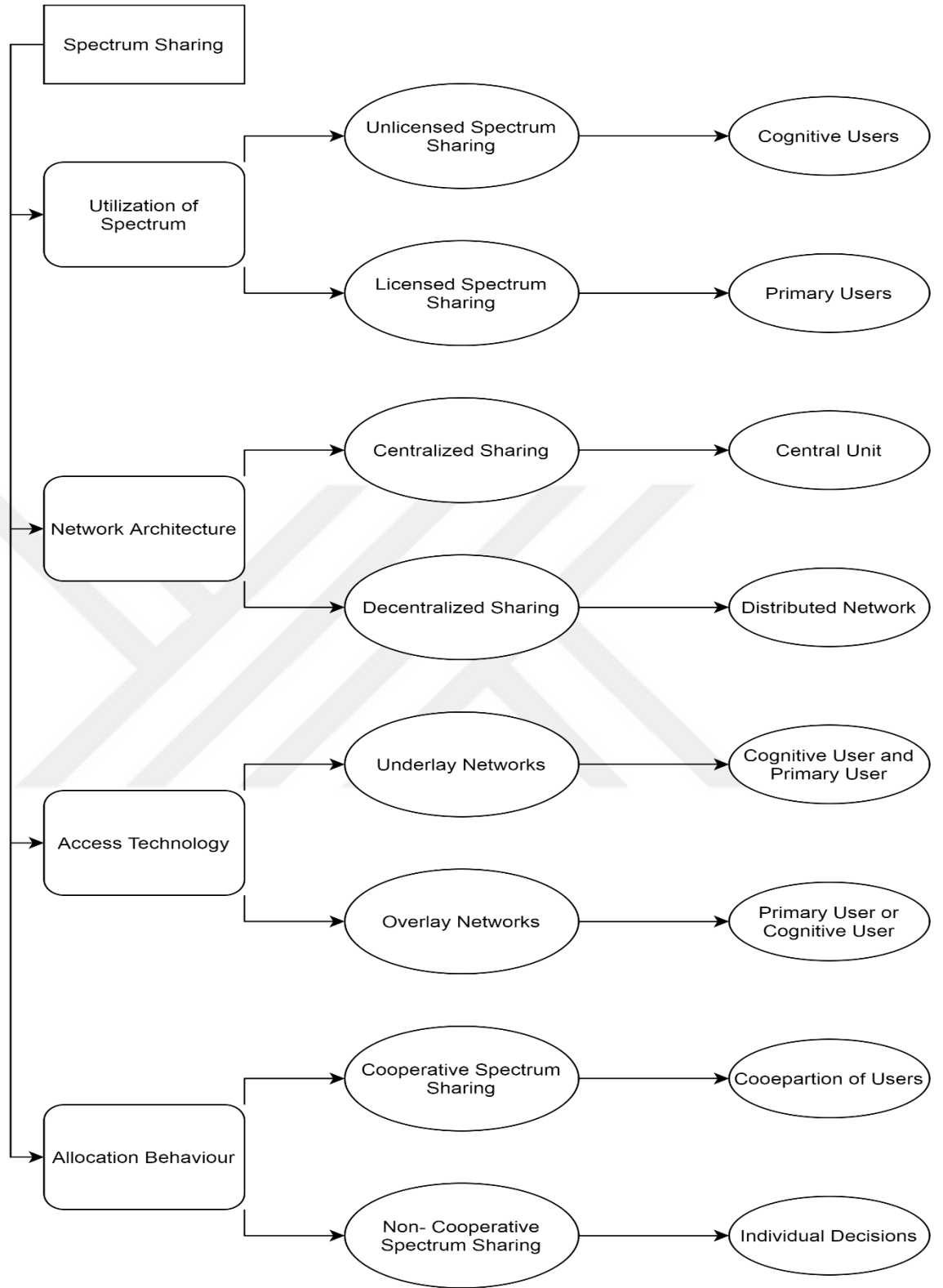


Figure 2.3: Spectrum Sharing in Cognitive Networks.



3. DYNAMIC SPECTRUM ACCESS AND REGULATIONS

I have been mentioning from the start that inefficient usage of the frequency spectrum had been started a huge problem with demanding increase on the spectrum usage owing to latest technological developments. These technological developments bring massive internet and frequency spectrum traffic with sending and sharing huge data sets by video sharing, live streams etc. Another technology which will be add huge amount of traffic and usage to the radio spectrum is emerging Internet of Things technology. With the massive deployment of IoT at the following years, radio spectrum scarcity could be much more problematic issue if we wont manage to find effient ways use the spectrum and prepare for exponential increase of the spectrum usage. Since, we have to look at the frequency spectrum as physical resource which can be exhausted, we have to use the spectrum more efficiently. Yet another issue is the ensure the quality of service of users. So, if we want to deal with this situation and use the spectrum more efficiently, we also have to consider to meet the users interests like quality of service, continuity of service, agility of service etc. One of the main reason why software defined radio evolves to the cognitive radio with adaptive spectrum sensing techniques is to manage this scarcity of the frequency spectrum and use it much more efficiently since we are building cognitive radios with strong observation capabilities. Even though my main intereset was on the spectrum sensing on cognitive radio networks, I should mention dynamic spectrum access history, old and emerging techniques and regulatory process of dynamic spectrum access in order to prepare a infrastructure for understanding the spectrum sensing. I would like to draw your attention that cognitive radio is not the solely solution to the efficient dynamic spectrum access. So, I will briefly mention about the artificial intelligence related and blockchain related dynamic spectrum acess solutions as well.

Eventhough frequency spectrum is a open medium on the air if we define it basically, it is under certain and strict regulations by government services like Federal Communications Commission (FCC) in the United States, the Office of Communications(Ofcom) in the United Kingdom etc. These regulatory authorities govern the rules for how to use the spectrum, sharing the certain bandwidths with different services. These services we already defined as licensed users are the only ones making use of the radio spectrum although they are not always using it every portion assigned to them every time. So, this strict and static usage of the radio spectrum is wasting the resources and prevent more efficient usage. On the bright side there is an ISM(Industrial, Scientific and Medical) radio band which can be used for industrial, scientific and medical purposes through relatively easiser process. However, this band is also under severely overloaded recently. Basically we have to asses the features of radio spectrum robuslty, and give a chance the unlicensed users to use the radio spectrum whenever licensed primary users not on the channel or at the same with managed interference under certain thresholds to not distrub the licensed users' transmission with being sure of their own transmission quality not suffer. Since generally, unlicensed users need less bandwidth on smaller time period, this type of dynamic spectrum management which is cognitive radio based on is a very convient way to deal with scarcity of radio spectrum.

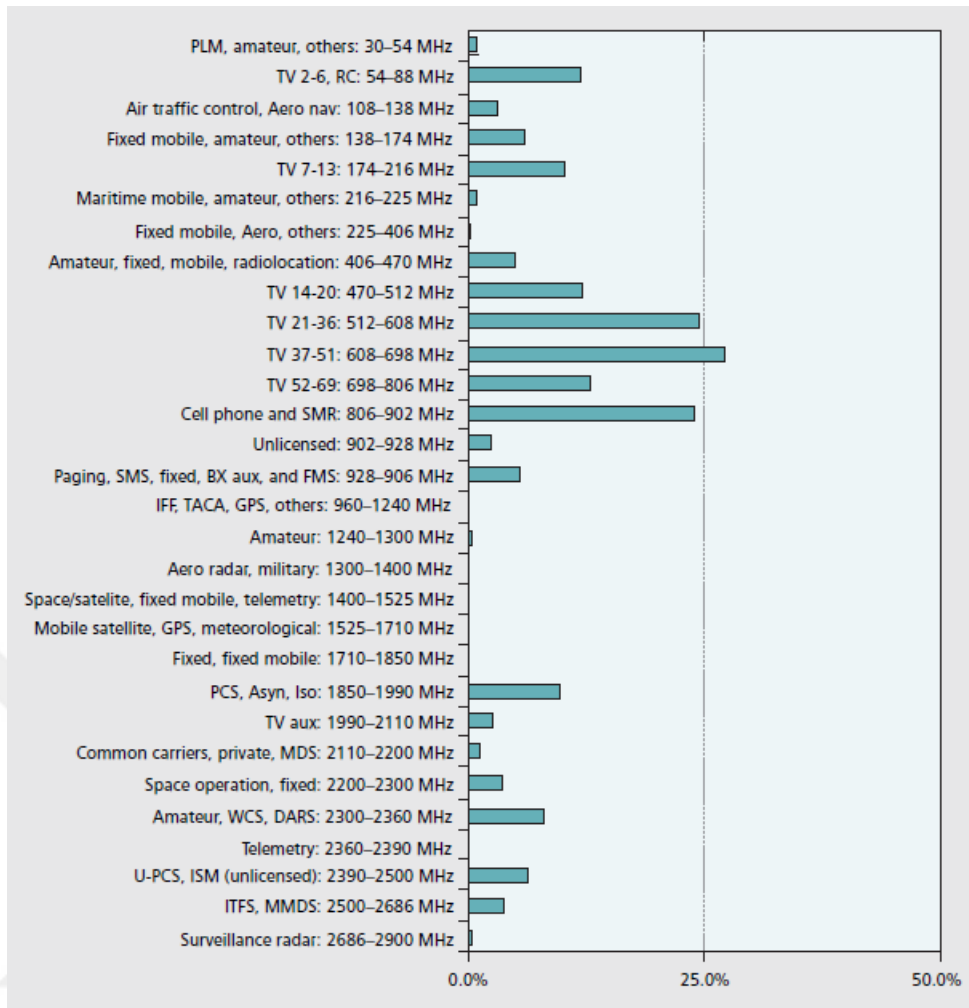


Figure 3.1: Inefficient usage of Radio Spectrum[6].

This figure shows us to inefficient usage of the radio spectrum very well. As you can see from the figure specific radio spectrum ranges licensed to the specific users. That means, with static spectrum management, unlicensed users can not use that range. However, most of the spectrum is not in use by licensed users most of the time. Figure shows the ratio in use, so the efficiency. Just I told you above that, cognitive users need less bandwidth for smaller time periods. So, we can perform dynamic spectrum management where cognitive users can use the radio spectrum when licensed users are vacate. This management will increase the radio spectrum usage efficiency big time.

3.1 Dynamic Spectrum Management

Dynamic spectrum management which is basis of the cognitive radio technology was proposed and quickly recognized as the main way of dealing this physical radio spectrum scarctiy. It has been anticipated that with the use of the Dynamic Spectrum Management, we can reduce the possible frequency traffic by four times which will be added by the massive deployment of Internet of Things(IoT) [8]

As I already explained, the basic idea behind this method is dynamically make use of the radio spectrum by seconday unlicensed users without dedicating spectrum to them. This can be done with several ways. Two main method is either use the radio spectrum whenever licensed users is not on the channel or use the radio spectrum with licensed users if this usage gives sufficient quality of service for unlicensed users' transmission without harm licensed users' transmission by adjusting the interference level.

Next, we can seperate Dynamic Spectrum Access techniques to two basic models related the above explanitaon and investigate them:

- 1) Oppurtunistic spectrum access(OSA)
- 2) Concurrent spectrum access(CSA)

3.1.1 Oppurtunistic spectrum access(OSA)

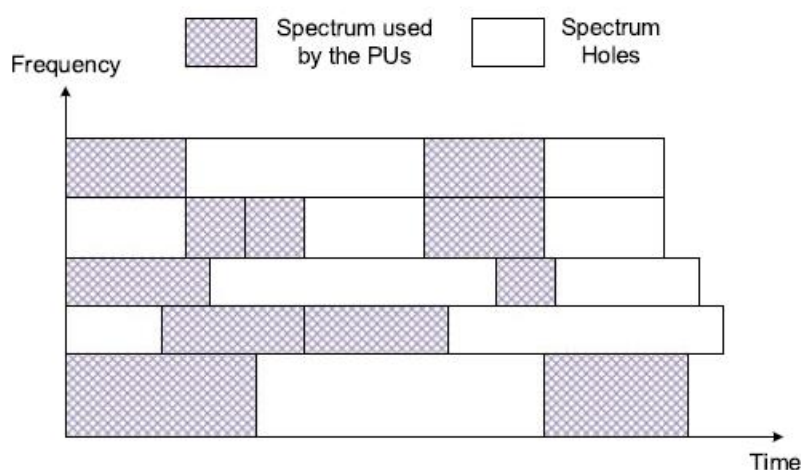


Figure 3.2: Spectrum Holes in the Licensed Bands[3].

Opportunistic spectrum access method refers where unlicensed users are taking advantage of the vacant radio spectrum channel. So, they should observe the possible radio spectrum range they can use for their transmission, and after making sure of that licensed users are not on that channel, they can start their transmission on that channel by adjusting their transmission characteristics such as bandwidth, modulation type etc. These channels where unlicensed users find them vacate by licensed users is called as spectrum holes. As you can see from the figure that there is a range of radio spectrum over a specific time period where unlicensed users' transmission features allow them to use the spectrum. As I pointed out that first problem was finding spectrum holes through this spectrum. So, to decide whether licensed users are active or not is first and very crucial problem. If unlicensed users start their transmission before licensed users vacate the specific channel or start their transmission without properly observing the spectrum and making sure of the vacateness, they will interfere the licensed users' transmission and decrease and possibly disrupt their communication. When this interference occurs, not only communication of the primary users' affected but also it will damage the reliability of such dynamic spectrum access. Moreover, regulatory parties and government services should possible block the dynamic spectrum access without further notice.

The second problem is uncertainty of whenever the licensed users start their transmission back again where the spectrum hole unlicensed users start their transmission. This is also very important problem to be handle if we want to manage healthy dynamic spectrum access. These two functions of the dynamic spectrum access, is defined as spectrum sensing and spectrum monitoring. Spectrum sensing is the function where the cognitive users for in our case, also so called unlicensed users observe the radio spectrum in their range of transmission and find a vacate channel or available channel to use without interfere the licensed users' transmission. The second function, spectrum monitoring can be done through many methods. To clarify what spectrum monitoring is I will explain it with using only one of the method. This method where cognitive radio keeps monitoring the spectrum it used, so it can vacate the channel as soon as it senses any licensed users' activity. So, monitoring is an another form of spectrum sensing by simplistic definition. I will talk about the spectrum sensing in the next chapter but we can say it is a very crucial tool for dynamic spectrum

access for next developments. Yet, there are other methods to manage dynamic spectrum access.

One of them is using geolocation database where primary users' locations and activities are saved. Unlicensed users can use these informations saved in database in order to start and stop their transmission. Easily seen that, it looks a more primitive way. However, there are some use case of this method where licensed users' presence are highly predictable. So, without using any further and possibly complex signal processing techniques to sense the spectrum to find vacate channel, dynamic spectrum access can be done robustly. Yet, with increasing demand on the radio spectrum and massively increasing of the radio spectrum users in addition to the large data sizes they want to transmit, this method can only address very small amount of applications of dynamic spectrum management. Opportunistic spectrum access is called as interweave[9] approach or overlay[10] approach in some other papers. I will categorize this approaches later as well to complete my research.

3.1.2 Concurrent spectrum access

The second access method which is concurrent spectrum access based on usage of the same spectrum by both licensed users and unlicensed users. The biggest issue for unlicensed users is to adjust their interference level to the primary users while providing themselves a sufficient quality of service as well. In practice, so called licensed users are already designed to tolerate some amount of interference can be caused by the environmental changes or interruptions can be made by neighbouring electromagnetic devices. There are also basic problems in wireless communications such as shadowing and multipath loss. These also should be considered while designing any radio transceiver. It is important to note here that these shadowing and multipath effects are also important issues in the cognitive radio networks. Since cognitive radio depends on the information coming through sensing the neighbouring environment, both information signals and transmission data can be affected by these phenomena. These tolerance level of primary users is generally defined as interference temperature. We can define a threshold level where the interference temperature should be under these level in order to not disrupt licensed users' transmission. Determining a certain threshold level and ensure the continuity of the healthy network is the main issue here. Unlicensed users can start their transmission if

they are certain about their interference temperature is under this threshold. Another important thing I should be note here is that this interference level doesnt need to be precise and exact number. It can vary through multiple features of the network or primary users. In some areas or applications, adaptive threshold levels have to be used in order to manage the dynamic spectrum access. However, it can easily be understood that it would increase the complexity of algorithms and devices in the network and make it harder for unlicensed users to adapt their designs or behaviours according to. The researches and proposed algorithms are all focused on solving both appearing and possible problems which can be occurred in the practical networks. I will be detailing my explanation in the Spectrum Sensing chapter since it is my focus over cognitive radios for my algorithm.

Table 3.1: Comparison of Access Techniques.

	Oppurtunistic Spectrum Access	Concurrent Spectrum Access
SU can use the channel when	Licensed user is vacate	Licensed user is vacate or not
Observation Type	Spectrum Sensing, Geolocation Database	Channel Estimation, Interference Prediction
Hard condition for usage	Need to make sure of vacateness of licensed users	Interference level shouldnt be higher than agreed level
Performance Merit	Detection Probability/ False Alarm Rate	Interference temperature, Performance Loss Margin

3.2 Dynamic Spectrum Management with Different Technologies

In this part, I will briefly explain three different technologies to enable dynamic spectrum management.

3.2.1 Cognitive radio for dynamic spectrum management

Cognitive Radio technology has been attracted attention for a while now for enabling the dynamic spectrum management. With the increase of the reseaches and developments, it also widely recognized as a key technology to manage radio spectrum management much more efficiently[11].As I already defined to cognitive radio as a smart radio, which can adapt its' behaviors and characteristics' according to the information gathered from environment and the its own network where it has built.

This characteristic basically means that cognitive radios are inherently dynamic devices. So, they are very suitable for the job at hand without complex thinking. Moreover, this characteristic is built on cognitive radios beforehand, so we don't need to make any hardware changes. If necessary, we can update its software, better it can update its software or behaviour by the help of machine learning and artificial intelligence technology. Cognitive cycle in the next figure shows how a cognitive device can handle dynamic changes.

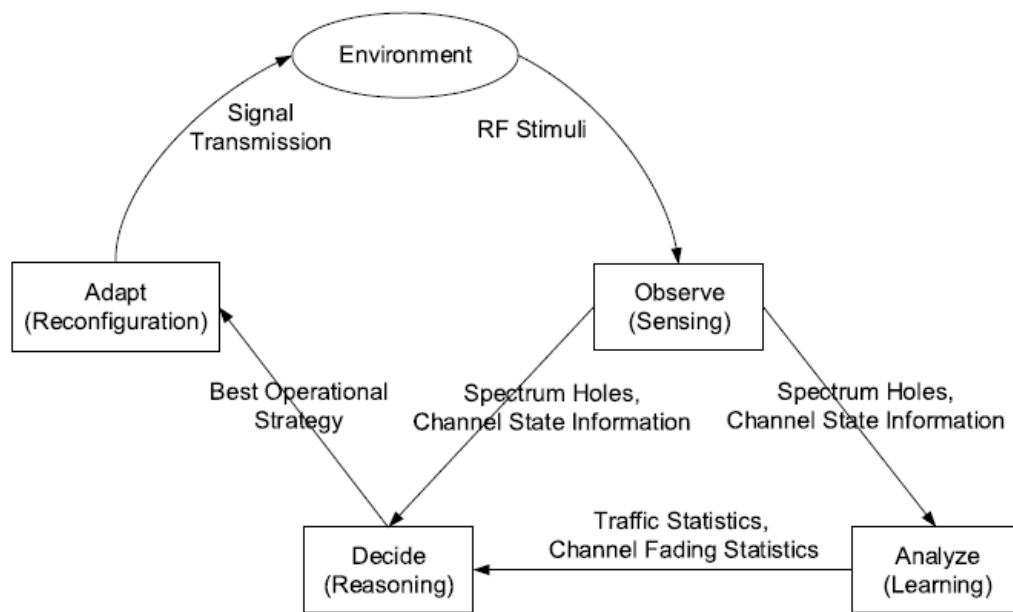


Figure 3.3: Another perspective to the cognitive cycle.

From above explanation, I clarified how we can use cognitive radio for dynamic spectrum access. As I already told, yet I want to remind it here that using cognitive radio for dynamic spectrum access is tightly involved with several other disciplines.[12] So, it is a complex issue. However, another big issue is the regulatory policies. If the regulatory commissions I mentioned earlier does not allow unlicensed users to use the radio spectrum, dynamic spectrum access idea could have gone waste. So, we need to build a reliable network where unlicensed users does not disrupt to licensed users and regulatory policies. That's been said regulatory policies are also unlogically strict and outdated. They should be aware of this fact and start to change and improve the policies. However, good thing here, since cognitive radio is already recognized to a certain degree, there are already in use standardization and upcoming standardization in order to take advantage of the dynamic spectrum management and deal with the scarcity of radio spectrum. One of the main need for this standardization

is that even without unlicensed users' demand, the radio spectrum is started to become scarce for licensed spectrum users with increasing demand on bandwidth etc. While we are working on dynamic spectrum management, other protocols and researches also continue on other topics such as new modulation techniques to reduce bandwidth need for a single transmission.

Under the light of this standardizations, FCC and others already proposed the change this strict spectrum regulatory policies and recognized the need of improving spectrum utilization.

To sum up, using cognitive radio technology to enable improved spectrum utilization is recognized and promising method. Now, I will talk about some other methods which can be used to enable improved spectrum utilization except cognitive radio like blockchain technology and artificial intelligence.

3.2.2 Blockchain for dynamic spectrum management

With increased interest on it over years in last decade, bitcoin which is a cryptocurrency also can be defined as digital currency, has reached over \$1000 Billion market cap already. This cryptocurrency is the first and the most successful applications of blockchain. Blockchain is simply open and distributed notebook which every transaction or data flow is recorded in chain of blocks. Whenever a new node starts using one of the blocks, it also possesses the whole notebook as well. So, it is nearly impossible to hack this blocks right now. There are several methods to select or operate the nodes according to specific blockchain. This decentralized recording mechanism makes blockchain network robust against single points of failures.[11] So far, this definition is applied for public blockchain network. There are also private blockchain networks which are far more decentralized than public blockchain networks. In this private blockchains, every new node can not access the whole notebook. Instead only permissioned and authorized nodes can access every blocks even though they have possessed the notebook as well. After bitcoin gained lots of attention, so many new players enter the market. Nowadays there are over a thousand of different blockchain. Since, the biggest portion of the chains are open sourced github projects, one can say it is easy to build a new chain. The important thing is the reliability, security and functionality of the chain. There are also several methods for securing the network or built smart contracts on the chain for different applications. Although it is still

developing and infant technology, possibility of what it can bring to the future is promising. I will briefly talk about blockchain and how we might use it as tool for dynamic spectrum management. This notebook can be used for different tasks to built on such as data oracles, financial services, internet of things applications and so on. It has attracted the interest of large technological companies, and proved itself as useful in many applications. Even, Facebook is announced that they are building their own blockchain network which will be activated in the next years in 2019. That's how it did reach this market cap. Nowadays, many people around the world is using cryptocurrencies as a tool of investment. There is still big improvement range for blockchain technology, we are still basically at its' infancy.

Other than financial perspective, another big interest on blockchain is using it for IoT applications. With the decentralized notebook construction of the technology, we can secure the massive data produced and shared by IoT devices. From this perspective, there are already several up and running applications of blockchain in some sectors. Examples of these applications are records of food supply, records in healthcare system etc. [13]

That's been said, returning to our topic, there are promising researches on blockchain to use it as a tool to improve the efficiency of usage of the radio spectrum and reduce the cost in the dynamic spectrum management. These researches are started with the idea of improving the quality of services such as telephone number management and spectrum management in cellular networks. Ofcom, the regulatory body in The United Kingdom started a project to investigate the blockchain to manage telephonenumber.[14] The clear approach here is to use the decentralized data notebook functionality of the blockchain. Whenever a person, make a change in his/her service provider, there are lots of issues which the customer has to handle. In addition to this issues, with the developing big data technologies, it became easier to access others' information such as phone numbers as in our example. This situations leads to frauds and scams even with the best care. To summary, this project aims to discard such data related problems and improve customer experience.

According to statement of one of the commissioner of FCC, we might use blockchain technology to monitor and manage radio spectrum. Blockchain can help to reduce cost of system and gives more speed and agility to radio spectrum auctions and trades.

As I just explained at the above paragraph, as every node can possesses the records on blocks, we can say this structure is very transparent for users. If every radio spectrum user could record its interest and demand on spectrum and usage history, in addition to the accessibility for everyone, it is clear that the efficiency of spectrum management can be improved by dynamic spectrum allocation according to the data flow on blockchain.

There are ongoing researches on this topic, I will talk about briefly about some of the exemplary research to give a hint about how can we use blockchain as dynamic spectrum management tool. As I dwell on the topic, cognitive radio technology are enabling the users for more efficient radio spectrum usage through its' decentralized and opportunistic structure. By the time, the networks which cognitive radios deployed are started to become larger with the increased application areas of software defined smart radios. This leads to new approaches for networks such one I want to mention is collaborative sharing methods where users are either sharing basic information like if they sense the licensed user on the channel or not, or complex information like more of the observations on the environment. For instance, in some collaborative networks, there is a central entity which collects these complex information data from every users in the network and process the data to decide if the licensed user is active or vacate on the subject channel. Then, share the final information to the users in the network, so they can act accordingly. Such networks also lead new database related approach as well. As of blockchain focuses on data recording and security, we can see the transition of the approach and possibly usecase of blockchain for dynamic spectrum management.[15]In this paper[15], they focus on this transition and show the benefits and possible downsides of blockchain technology as a tool for dynamic spectrum management.

To sum up, there are two fundamental reasoning how blockchain can be beneficial. First one is blockchain network as a secure and transparent database. Second one is a self organized spectrum market where there is not a centralized regulatory body to restrict and slow down the management and trading process. Instead, blockchain brings every useful function of the traditional regulatory policies using smart contracts,

cryptocurrencies and data oracles. However, if we meant to design and start using such mechanism, there would be tons of problems. Still lots of reserches and standardizations are needed before a deployment of such mechanism. One of the biggest problem for deployment of the network is, blockchains are computationally intensive and it brings huge demanding power consumption and battery cost. There are several different consensus algorithm for different blockchain networks to keep them up and running and manage the computational complexity, however the ideal system is not builted yet.

3.2.3 Artificial intelligence for dynamic spectrum management

Since we are living in an information age, getting informations, then processing them in order to take advantage of the results becomes very crucial. So, data gathering, data sharing, data processing is the main topics involved. These topics are also involved with cognitive radios as you can easily infer from the outlook of my research. Big part of data managing is done with machine learning and artificial intelligence technology nowadays, since they can evolve themselves with simply processing the data and combine results cumulatively. So, more data to process gives better results and performance. Instead of the traditional model based networks, we can create data-driven networks in order to make use of these emerging technologies. Ofcom is already stated that 5G and 6G adoption with the help of these techniques can bring ultra reliable low-latency communication setups. However, deployment of such artificial intellegience techniques increase the computational complexity, so the cost even though it can increase the agility and performance of the network. Another issue here is that, every network can have different data types, so it would further increase the cost and complexity to adopt AI for every data types. So, we are also in the early stage of the artificial intelligence based dynamic spectrum management. Big adoption either requires more research and development or it depends on the trade-off between computationan complexity and benefits over a specisif application networks.

4. SPECTRUM SENSING

Spectrum sensing is a name of the process, as a fundamental function of the cognitive radio which is the main interest of my thesis, which the radio transceiver devices are looking for available radio spectrum for their transmission. With spectrum sensing, CR can see whats happening at the environment where it operates. So, the main feature which CR is looking for is spectrum oppurtunity. Under spectrum sensing, cognitive radio is observing the environment in order the get useful informations such as whether licensed users are vacate or present at the channel of interest, or whether characteristics of the channel of interest is appropriate for their transmission, or if they are going to use the channel at the same time with licensed users how should it set its' transmission characteristics so that it wont exceed the interference threshold, or whether there is another channel oppurtunities in the its' transmission range etc. If they dont use the channel at the same time, cognitive users need to predict the arrival of the licensed users on the channel using complex algorithms. [16]

The answer to the question of how cognitive radios get their informations mostly, is using spectrum sensors which simply scan the radio spectrum. There are different sensor types for different tasks. For instance, while some of the sensors scan for single band or narrowband, some of the sensors can scan for multiple bands or widebands. Logically, single band scanning is the fundamental function for many cognitive devices. However, wideband scanning brings a lot more oppurtunities to the dynamic spectrum management. Rather than scan a single band, a cognitive device can scan multiple bands, then process the informations and it can find possible multiple vacate channels for its' transmission. This way it can choose the better option from the pool of vacate channels. In addition to that, even if the channel it has decided to use becomes unavailable due to the presence of licensed users, available vacate channels' pool give cognitive users a flexibility and chance of switching the channel more agile way. So, wideband scanning is actually much more desirable in terms of more efficient dynamic spectrum management. However, I should be noted here that, it can put more complexity to the device and it can increase power consumption and cost. The

important challenge here to prevent that designing to the device considering what kind environment it will be deployed and what kind of tasks, applications and algorithms it should have. There will be always tradeoffs between the different performance merits. So, when one of the performance merits become worse, i.e. increased power consumption, it does not necessarily mean that the system is failed. Managing the tradeoffs is the most important challenge for every network. Both to sum up the idea of tradeoff and demonstrate the construction of the content in this chapter, I can divide the design procedure to five main stages as follows:

- i) Modelling the procedure,
- ii) Listing the possible sensing impairments through either using cumulative theoretical models or more practical modeling,
- iii) Determine how these impairments can affect the performance,
- iv) Determine the performance under these impairments either separately or some combination of them according to possible usecases,
- v) Develop tradeoff or compensation algorithms and techniques that either mitigates the performance decreaseses given by impairments or improve the overall performance by increasing the desired spesific performance merit.

The researches so far considered wideband sensing as multiple narrowband sensing. However, the process of dividing the wideband into narrowbands is ideal process which generally is not appropriate for practical applications. It might be solved by using adaptive channelization(dividing) techniques which hopelly can be developed in the next years, unfortunately so far, this techniques put so much complexity to the system and generally can not be done robustly. One advantage of the cognitive radio is however, the ability of learning. So, with the development of the machine learning and artificial intelligence techniques, it can possible and much more easy for several application areas. Another problem is that when a channel is in use by licensed user, the adjacent channels suffer from greater interference and they can give wrong or incomplete results because of non-ideal filter mask in practice. Even if they are vacate, these results make it look like channel is in use as well. This make the technique very inefficient. The non-ideal filter mask problem is considered as a brick wall in theory.

4.1 Spectrum Sensing Techniques

I already said that spectrum sensing is about whether licensed user is present or absent or the radio spectrum band of interest. So, what are we actually sensing? Spectrum sensing commonly rely on the information about signal energy. However, there are so many other signal features a cognitive radio can sense, yet not every one of them is appropriate for every application or environment.

From start to today, the basis of spectrum sensing depends on classical binary hypothesis test. What I mean by depending is, spectrum sensing acts like the binary hypothesis test. There are two test results as we know, one is when the signal is present, so the sum of signal and noise are received. , other is when the noise only signals are received. I will give more mathematical details later. There is a test statistic which is used to process N numbers of samples and estimate a desired parameter. Then, we move to the next stage which compare this parameter to the either predetermined threshold or in somecases changing or adaptive threshold. This actually depends on the signal processesing and optimization algorithms in use. This information is outside of the classical binary test, yet it is cognitive radio related. Back to classical test, if the parameter is higher than threshold, we decide licensed user is present, and we received its' signal plus noise signal. In contrary, if the parameter is lower than the threshold, we decide licensed user is absent, and the received signal is all noise. There are two important performance merit of hypothesis test in use, which will be detailed later about their cognitive related behaviour. These are false alarm rate and miss detection rate. Generally the threshold would be determined according to the accaptable false alarm rate or missdetection rate. Since it is very simple one, choosing the parameter as energy is the most common method. However, when we choose it as an energy and perform energy detection, it is not suited for many applications and generally not robust for larger networks. There are lots of paramater options and detection mechanism for spectrum sensing. However, for practical cases, there are three fundamental sensing techniques which are energy detection, pilot detector and cyclostationary detector. I will talk about them first and might probably mention about proposed techniques excluding these techniques. Of course, there will be always complicated and collaborative techniques which use the combination of these

techniques in specific construction. For example, in the literature, there is one specific categorization of sensing cycle as fast sensing and fine sensing. Fast sensing uses the energy detection technique and gives a prior knowledge about the radio spectrum and system starts preparations according to this information. If there is not another sensing method, system will continue its' operation. However, since energy detection is generally more basic and not robust for complex networks, there would be a need for another technique. For example, if there is certain feature of primary signals which can be processed by cognitive radio. We can use cyclostationary detector to get more precise information about whether the licensed user is present or absent. Fine sensing includes both energy detection and cyclostationary sensing. If the results match, then system continue to its' operation. So, there would be some gains such as time and agility. If not, it would be adjust its' transmission parameters through the information gathered by cyclostationary detector.

4.1.1 Energy detection

In the previous part, I mentioned about how cyclostationary sensing works when there is a certain feature of primary signals is known and can be processed. So, it needs prior knowledge about the primary signals. However, the energy detection as known as the simplest form of detection does not require any prior knowledge. Instead the mechanism depends on processing the energy computation of the received signal. I have proposed an energy detection based sensing algorithm. The mathematical expressions and modelling can be found later in the Algorithm chapter.

4.1.2 Pilot detection

Even though changing performance of the energy detection, it can be used in every network since it does not require any prior knowledge. However, there are some systems where some of the primary signal features are willingly planted to the signal. It can be either for necessity of synchronization or to facilitate the signal decoding algorithms. For example, in digital television network, sinewave pilot tones are transmitted for data frame synch.[17]Pilot detection decides whether primary user is present or absent by utilizing prior knowledge like in the example. We also can use changed version of hypothesis test for pilot detection by setting test statistic. In this [17] study, they have showed that ROC performance(detection rate) of this statistic in AWGN channel depends on the power allocated to the pilot tone.

4.1.3 Cyclostationary detection

In the pilot detection, I mentioned that some features are willingly planted to the signal. However, even though it is not the case, the signal can carry some inherent features which exhibit periodic behaviours. Actually, it has been proved that many of the modulated signals are second order cyclostationary, in other words their mean and autocorrelation functions are periodic. The period depends on the both symbol period and the carrier frequency of the signal. [11]

Cognitive radios can sense cyclostationary features by the help of spectral correlation function which is a two-dimensional complex transform. As we already know from the basic signal processing techniques, this transform is strongly related with the power spectral density function. It has been defined as generalization of the power spectral density function in the literature. This generalization brings some important benefits as such:

- The information about phase and frequency is not lost after modulation. It will be held in some features of modulation.

- Since there are more than one spectral feature, it has been observed that some of the features overlapping each other at the power spectrum, does not overlap in the spectral correlation spectrum. When features are overlapping, it is too tough to detect them separately, so we can't obtain much useful information. Spectral correlation techniques make the detection so much easier and so beneficial in terms of reliable information.

- In the Analog and Digital Modulation theories, when we investigate the power spectral densities of different modulation techniques such as QPSK, BPSK, we have proved that some of their power spectral density functions are identical. However, when we convert these functions to the spectral correlation domain, they have highly distinctive spectral correlation functions.

- In wireless systems, one of the fundamental issues we are dealing with is the noise. In the shed of light of decades of work, it has been proven that noise samples do not carry any cyclic features due to their uncorrelated natures. While this nature of theirs is a problem for many other tasks, it brings a very key advantage here. When the noise is very dominant, so we are in very low SNR regime, we can use cyclostationary detection robustly.

Next, we can detect these cyclic features with the help of the cyclic autocorrelation function. In this function, we correlate the received signal with its' frequency shifted version. Then, estimation of the cyclic autocorrelation function should be performed. In basis of the cyclostationary detection, we also use a hypothesis test. So the next step is to perform the test statistic which is strongly related to the computation of the cyclic autocorrelation function.

4.1.4 Beyond classical detection theory

So far, the three main detection theory I mentioned about rely on the classical binary hypothesis problem. However, with the development of the wireless technologies, so many new techniques are proposed and some of them are accepted as convenient methods. Also, there are some disadvantages of classical detection theory because of the assumptions we made. It makes it unreliable for so many practical applications. However, we can use the changed or improved versions of it. The main disadvantages are:

- The noise samples in the network assumed to be generated from a white gaussian wide stationary process. That is far from the practical encounters.
- Second one is also related to the first one: We assume we know the exact variance of the noise. However, not just we can not know the exact variance of the noise, it is not the same through a time period as well due to the nature of noise samples.

It would be better if I first explain how these disadvantages affect the network. For instance, if our sensing method is energy detection, with these assumptions we can calculate exact energy and power of the noises. So, the threshold which will be used for hypothesis test can be exactly arranged to ensure any desired performance merits such as detection rate or false alarm rate. Another example, if our sensing method is pilot tone detection, we are assuming there is a exact synchronization between the receiver of the cognitive radio and transmitter of the licensed users. In practice, we can easily saw that, these are far from the whats happening. However, under good SNR conditions, where noise figure is much less than the signal transmitting by the virtue of good environment conditions, the results in practice nearly convergence to the results in these theoretical binary testing. However, in real world, most of the time, we have to deal with bad SNR conditions and results suffer from either high noise figure

or SNR wall. So, to sum up we need such spectrum sensing techniques that work robustly even at negative SNR regimes or in bad SNR conditions.

As I already mentioned the previous chapter, cognitive radios should be observe through wider radio spectrum for transmission opportunities. So, it canalizes the need of wideband sensing techniques. So far, in researches, the wideband sensing is like multiple narrowband sensing as I already pointed out that. In this method, we can say there will be a spesific hypothesis test for every channel. The implementation of this methods ignores many practical design challanges:

- Strong interferers in some channels, and badly affected adjacent channels,
- Spectral leakages caused by nonideal filters,
- Nonlinearities in the receiver front-end.

Table 4.1: Comparison of Traditional Detection Schemes.

Spectrum Sensing Methods	Advantages	Disadvantages
Energy Detection	Simple scheme with low computational cost and complexity	Longer sensing times, Bad performance results under low SNR regimes
Pilot Tone Detection	Requires less sensing time, Better detection performance	Requires prior knowledge of Primary User and synchronozation, Higher Complexity
Cyclostationary Detection	Better detection performance than E.D, Most resilient one to the variation in noise levels.	Requires prior knowledge of Primary User transmission, Higher complexity compared to E.D

So, we need to look back to the spectrum sensing methods by taking these challanges into consideration. Then, determine how they can affect the sensing performance in the practice. So, we can propose enhance sensing methods by arranging tradeoffs between many different challanges or impairments.

Now, I will investigate the three main detection method considering some impairments.

4.2 Conventional Detection Methods Considering Impairments

In this chapter, I will briefly give the practical schemes of three traditional sensing scheme where the impairments should be considered.

4.2.1 Energy detection impairments

The sensing scheme I have used in my algorithm in the local decision part is the energy detection. So, I will give a general view over how to model the practical scheme. First, the most common noise uncertainty impairment will be explained, then I will explain how to model the noise uncertainty and how to compensate it.

4.2.1.1 Energy detection under noise uncertainty

Even though there can be noise fluctuations over a period of time, when we use energy detection spectrum sensing over a vacate channel, we would get only noise samples. Therefore, we can nearly estimate the average noise variance and can sketch a moderate power spectral density of noise samples. This helps us to optimize the threshold for later when we have to decide whether received signals are noise only samples or sum of the noise and primary signals. As I already stated that we can achieve any desired performance results, either detection rate or false alarm rate, by optimizing the threshold.

One of the benefit of knowing the noise variance is to help us to arrange sensing time to achieve any desired performance results. The theoretical analysis shows us that, in the negative SNR regimes, sensing time, also equivalent of number of samples, asymptotically scales as $1/\text{SNR}^2$. Later, I will discuss about how we can test our theoretical analysis on the real world cognitive radio testbeds where the environment we employ our algorithms are very close to the real world environment even though this still be considered as simulations. There is a such experimental study to test this hypothesis on a real world cognitive radio testbed. [18] The objective in this study, is to sense a QPSK signal under different SNR values with using three aforementioned basic sensing methods.(energy detection, pilot tone, cyclostationary) For our hypothesis, it can be shown from the figure that asymptotical scaling is reliable for SNR values above -20 dB. Contrarily, in the case of the SNR range under -20 dB, detection becomes harder and converges to the impossible as the signal becomes

weaker. The point where detection becomes impossible, even with large sensing times (to clarify that it is independent from the number of samples from this point), around -23 dB, is where the so called SNR wall phenomenon occurs.[19] I will be detailed this phenomenon in the next chapters. This experiment shows us that using energy detector in real world networks where we can face with negative SNR regimes oftenly, is not robust enough. So, we either need some other methods or we need to revise our energy detection method considering the SNR wall phenomenon.

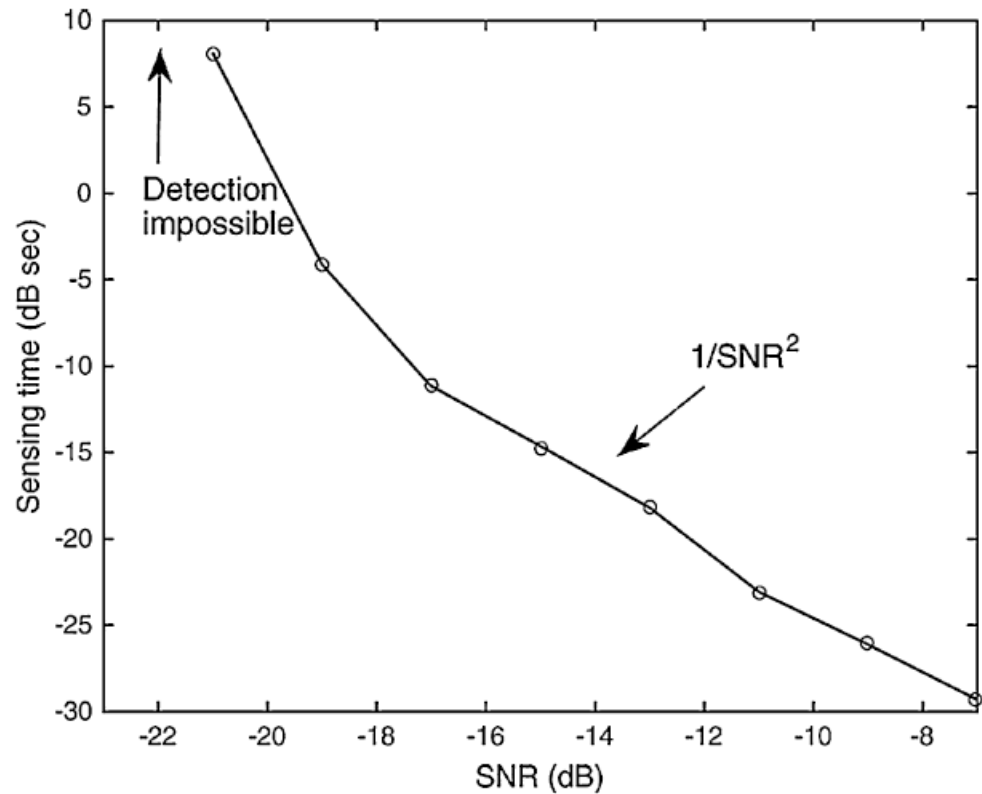


Figure 4.1: SNR wall phenomenon.

There are two main reason why the results predicted by the theoretical referrals and the results calculated in the real world testbed is different.

- First one is the, generally like in this example, we are assuming that the noise is additive white gaussian wide sense stationary process with known variance. However, in practice, noise is a sum of various sources. There are external noise sources can add to our sum like atmospheric interference. In addition, there are internal noise sources can add to our sum which refers to noises generated within the wireless network and its' own RF front-end. These examples and the list of noise sources can be extended easily. This is enough for me to explain my point.

- Second one, as I already mentioned that assuming we know the variance of the noise, we are determining our hypothesis threshold ideally. However, in the real world, since the noise could change over a time period owing to environmental changes, filtering, electromagnetic compability and added new external noise sources. This make it so hard to determine a useful threshold, not to mention about a ideal one. I took the next figure from this literature. We can see the fluctuations of noise over time. There is a noise variance level where the statistics of the received signal wont be affected much to prevent us to discriminate noise samples and primary signals. However, especially under negative SNR regimes, where the signal strength is not enough to discriminate noise samples and primary signals, we can see the impact of these fluctuations on the detection process clearly. It will highly disrupt the process. So, when we design a cognitive radio, we need to make sure to add a part to the sensing process about how we can also observe these fluctuations or the changes of sum of the noise, and eliminate them from our calculations effectively, especially when the receiver operates in negative SNR regimes.

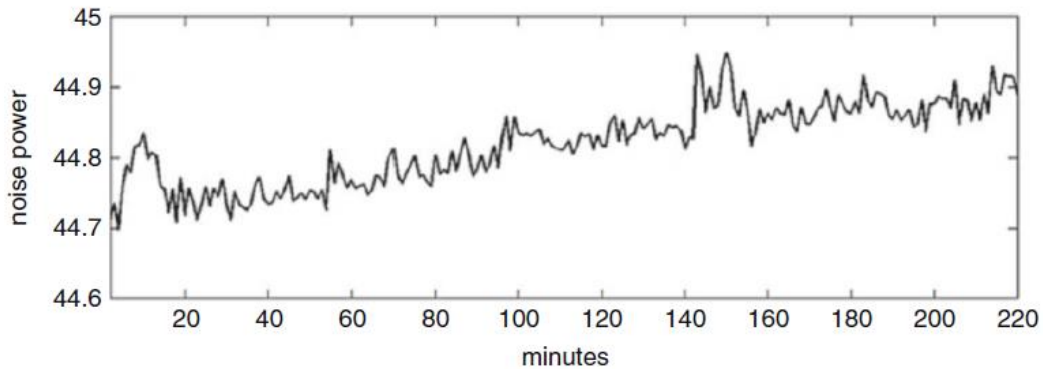


Figure 4.2: Noise power fluxcations.

4.2.1.2 Modeling noise uncertainty

In theoretical studies about sensing model, we generally model the distribution of the noise samples as a gaussian random variable with zero-mean and precisely known variance. As I explanied in the above part, this distrubition never happens in real life and if we were to design the real life cognitive network with this model, there would be so much annoying issues. The performance of our network simply would be in agony. So, we need to model the noise samples with added noise uncertainty parameter considering the noise fluctuations. As we know there is no way to ensure the

get perfect noise samples model with basic computations. However, modelling the system this way, then with recording the data of fluctuations over a period of time, gives a opportunity to get more accurate results. The performance of our network then would be in the acceptable range. In addition to that, since cognitive radios are smart radios using machine learning and processing of historical results by the help of the databases, with the accelerating rate of developments of these technologies, we can optimize our models, and with the enough time it would convergence to the idealistic model where we get the perfect results.

After using a pretentious sentence like that, I need to point out that there is no perfect results in practice. One of the not mentioned reason of why there is no perfect results in practice in this paragraph, there are various different performance merits conflicting with each other. So, to sum up, not just we can not get perfect noise samples model, we also have to make tradeoffs between different performance merits. Therefore, we can not get perfect results, however, we can manage our expectations over different performance merits and we can focus on them according to the their importances which we determine by deciding what do we need or want.

We can simply model the noise uncertainty. Like I pointed out that we generally model the noise samples as zero mean gaussian random variables.

$$w(n) \sim N(0, \sigma_w^2) \quad (4.2.1.a)$$

Instead of using this variance, we can generate noise samples with a variance which considers the noise uncertainty as follows[56], [18]:

$$\tilde{w}(n) \sim N(0, \tilde{\sigma}_w^2) \quad (4.2.1.b)$$

$$\tilde{\sigma}_w^2 \in \left[\frac{1}{p} \sigma_w^2, p \sigma_w^2 \right] \quad (4.2.1.c)$$

where $p \geq 1$ is a noise uncertainty parameter. So, when we have a noise uncertainty paramater equals to the one, we can have perfect knowledge about noise variance. So, our model becomes ideal model.

The ROC performance(probability of detection) under noise uncertainty model is derived in these papers as well:

$$P_d = Q\left(\frac{pQ^{-1}(P_f) - \sqrt{N}(SNR + \frac{1}{p})}{SNR + 1/p}\right) \quad (4.2.1.d)$$

where P_d is the probability of detection, P_f is the probability of false alarm and N is the number of samples. Then they evaluated the SNR wall under noise uncertainty:

$$SNR_{wall} = \frac{p^2 - 1}{p} \text{ where } p_{dB} = 10 \log(p) \quad (4.2.1.e)$$

Simulation of these formulas show us that, even under small noise uncertainty, the performance of the energy detector deteriorates badly in the low SNR regimes.

The next thing to consider is that this uncertainty leads a well known phenomena, which I gave an expression for it just now, in the literatures about cognitive radio networks, which is called as SNR wall. SNR wall phenomena simply tells us we can not detect a meaningful signal under some SNR values. We can get a gasp of understanding by using boundaries of the noise uncertainty parameter. To explain above equations, the parameter of noise uncertainty is greater than one and if it equals to one, here is our nonrealistic ideal point. So, in the upper bound where the parameter growing from one to infinity, the model starts the underestimate the true variance of the noise samples. In contrarily, in the lower bound, where the parameter is falling from one to zero if the model converges to the infinity, the model starts the overestimate the true variance of the noise samples. The underestimation of the true variance leads to the increased false alarm rate. In upper bound, it equals the highest false alarm rate. Unlikely, the overestimation of the true variance leads to the decreased probability of detection rate. To explain these two situations, increased false alarm rate means that results convince the cognitive radio with the increased probability that channel is in use by licensed users even if they are not present. To other end, the decreased probability of detection rate means that results convince the cognitive radio with the increased probability that channel is not in use by licensed users even if they are not vacate.

Using these scenarios, Tandra R. and Sahai A, in the one of the key published papers in the literature of cognitive radio[19,20], they arranged the equations of performance merits and presented the SNR wall by giving the ROC of energy detector like this and then derived the sensing time estimation correlated to.

From the execution of these equations, it is clearly seen that when the sensing time or in other words the number of samples goes to infinity, the detection process clearly hits a SNR wall which makes it impossible the detection. Over the value of this SNR wall level, the detection process can be done. The derivation of the equations show us that we can evaluate the SNR wall level according to the noise uncertainty parameter.

4.2.1.3 Compensating the uncertainty

As we see from the above explanations, changes on noise uncertainty affect the sensing and detection process badly. We need to handle with this issue. One of the easily imaniged way is the continuously monitor the noise uncertainty changes and optimize the process according to. To do this, firstly, we need to know how these changes affect the process and derive improved equations. However, this method has some issues to handle as well. This method depends on the variance estimation of the noise or in other words power estimation of the noise. In the literature, the most used method for the estimation is a very well known method which is using a maximum likelihood estimator. This estimator simply averages the noise variance over various number of noise samples. To estimate the noise variance frequently, we need to make sure of the getting noise only samples. However, weak samples of the primary signals also can be captured. We need to distinguish between the noise samples and primary signal samples. There are no admitted methods for this in every environment yet. One of the proposed method to solve this issue is using a fine sensing cycle which I defined in the previous chapter. It deemed suitable for me to show the structure of this cycle here.

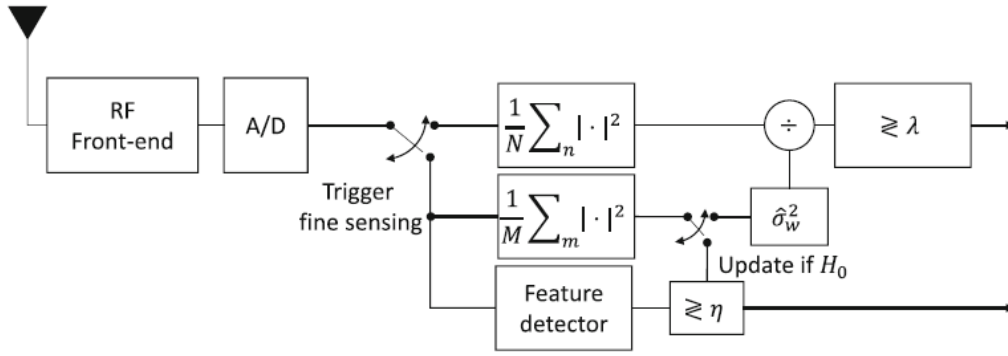


Figure 4.3: Two staged Sensing Model.

First part of the cycle which is fast sensing is where we deploy energy detection to process the samples of received signals. The second part of the cycle is where we deploy a feature detector. With the fast energy detection, we aim two important thing.

- First one is, to sense whether there is a primary signal or not with a predetermined false alarm rate. However, cognitive radio won't start its' transmission until feature detection part confirms there is not a primary user in the channel. The advantage mentioned here is that, we can prepare the characteristics of the transmission according to this detection with sufficiently high accuracy. Not every feature based sensing process is applicable for every network. However, primary signals, contrarily to the noise signals, have various features that their statistics are periodic and we can recognize them if we use appropriate filters. Design of network should also consider to choose better filters for that environment.

- The second one is, which is more relevant with the noise uncertainty, to manage the noise variance estimation. If the feature based sensing, after the triggered fine sensing stage, tells to the cognitive radio, it gets only noise samples not a primary signals sample for that execution, we can acknowledge that the collected samples are noise samples with high accuracy. Having said that, if we know the samples are from noise, we can estimate the new noise variance and arrange the new sensing process according to. The cognitive radio infrequently can use this cycle to arrange the noise variance time to time if there is noise fluctuations that change the power of the noise in the network.

In the paper, they derived the detection rate, false alarm rate and the sensing time of the energy detector and their relations as follows:

$$P_d = Q\left(\frac{1}{1+SNR}\left[Q^{-1}(P_f) - \sqrt{\frac{N.M}{N+M}} \cdot SNR\right]\right) \quad (4.2.1.3.a)$$

They have found that if the time of the fine sensing equals to the square root of the time of the fast sensing, the performance becomes ideal in the negative SNR regime.

As we can see from the equations there is a 1.5 dB SNR value difference from the ideal energy detector. Lastly they derived the SNR levels that avoid from the SNR Wall, so detection can be possible with related to above ROC performance merits and the sensing time of the energy detector.

Lastly, from the results of simulations as expected, we can see the the larger sensing time of the energy detector improves the performance. As I pointed out times and times already that tradeoffs between different performance demands are important. If we keep increase the sensing time, the possibility that we hit the SNR wall would also increased drastically. To handle with this tradeoff, we need to scale the noise power estimation time with the time of the fast sensing.

4.2.2 Pilot detection impairments

Comparison with energy detection, pilot detection offers much higher performance results in the relatively small SNR regimes and in the negative SNR regimes. Then, the answer to the why we are using energy detection comes from two different angles:

- First one, energy detection is much simpler process and easier to deploy.
- Second one is that pilot detection requires some prior knowledge of the primary signals which is not possible for every network. However, if it is possible, it brings major performance benefits to the table. So, it is much more suitable in the negative SNR regimes where the received signals are very weak.

Having said that we need to have some prior knowledge about primary signals, in addition, cognitive radio receiver has to have ideal synchronization with the pilot tone in the received signal. However, in practice, like how power and variance of the noise samples change, there are frequency offsets that break the synchronization. Moreover, in the real world the parts of the networks are not ideal devices as well. So, even

without any other causes for frequency offsets, perfect synchronization between pilot tone and receiver of the cognitive radio is nearly impossible. Nonetheless, as long as we have a strong pilot tone, we can resist against frequency offsets because their likelihood of happenings would be very low and the ideal synchronization would be much like to happen. To achieve that there is such mechanism that estimates the synchronization and correct the frequency offsets easily. However, as power of pilot tone decreases, the aforementioned important SNR wall phenomenon becomes more likely to happen. This also means that the noise is so much strong that prevents the robust estimations of the synchronization. In the end, the frequency offsets reduce the performance of the detection so much that the purpose of why we use pilot tone detectors becomes meaningless. So, we need to monitor the system over time and model the frequency offsets, so we can optimize our sensing algorithms to handle them more robustly.

4.2.3 Cyclostationary detection impairments

In this part, first I will defined the most common impairment in the cyclostationary scheme, then I will briefly give the compensation model.

4.2.3.1 Cyclostationary detection under imperfect synchronization

As I pointed out earlier that cyclostationary detection makes use of the some inherit features of the signal which carries periodic behaviours. In the same way with the pilot tone detector, cyclostationary detector also needs to have prior knowledge about the primary signal. Furthermore, it gives so much better performance results than the energy detector as well in the negative SNR regimes like pilot tone detector if we can somehow possess these prior knowledges. How I said that the perfect synchronization in the pilot tone detector is not possible or to get the precise value of the variance of the noise samples is not possible in the energy detector, expecting perfect knowledge about primary signal in the cyclostationary detectors in real world networks is also impossible. We modelled the imperfections on the other detectors, and then tried to compensate their disadvantages with some methods. This is also what we are going to do here. We need to somehow model to cyclostationary frequency offsets with a sufficiently high accuracy. As cognitive radios are smart devices, we can always improve the prebuilt models to increase the accuracy with the more realizations and

more data. So, we need a basic model which covers every fundamental details as a start.

We know that from the mathematical equations of cyclostationary process, when the cyclic frequency equals to the zero, our detector simply estimates the energy of the signal like energy detector. We can take it forward to simplify our explanation, cyclostationary detector estimates the energy of the signal which have a certain cyclic frequency. With that simplification, theoretically, when the number of samples as known as the sensing time converges to the infinity, the effects of the noise would be eliminated as the detector averages a stationary noise process. This means that, even in the negative SNR regimes, we can get great performance results with sufficiently big pile of the samples.

So, as long as we can have a precise knowledge of the cyclic frequency, we can avoid SNR walls. Therefore, the robustness of the practical cyclostationary detectors come from the success of close estimations of the cyclic frequency values of relevant cyclic features. The next things I am going to tell are what are the common reasons why we cant have precise values of the cyclic frequency, how can we model these imperfections and how can we compensate them with better estimations.

Some of the practical reasons that change the cyclic frequencies over time as follow:

- Doppler shifts,
- Imperfect filters and estimators,
- Usage of incorrect modulation types,
- Imperfect local oscillator etc.

4.2.3.2 Modeling and compensating cyclic frequency offsets

Modeling cyclic frequency offsets are not a big deal theoretically. We can just assume the cyclic frequency with a margin of deviation. Then, we can use learning techniques using previous datas. As the data set expands, we can get better results. In the literature[21], there is another method of modeling the cyclic frequency. They, then, proposed an enhanced cyclostationary detector as you can see from the next figure. They derived the equations of the new detector like test statistics and performance merits. They have proved that when there are cyclic frequency offsets, as number of samples grow, the detection of the cyclic feature becomes harder because its' effects

fade. Unfortunately, we also know that as number of samples grow, the overall performance of the detector increases due to the better estimation of the noise. Then, the tradeoffs should be considered back again. The usage of the enhanced detector gives sufficiently close results to the theoretical results as their simulation results prove. These detector uses the same approach which is using a sensing, as the method used in the pilot tone detector since they both suffer from frequency offsets. Their way of thinking was that if the increase of the sample size affects bad the cyclic frequency and affects well the noise averaging, cant we divide the set of samples into blocks. The hypothesis here is that since blocks have their own sample sizes which are smaller than the total sample size, we can keep the strong cyclic feature traces in the blocks and, also we can average the noise using the results of every block. However, noise averaging of the blocks also matter. So, we need to have a sufficient size of blocks in order to get good results. So, to sum up, the hypothesis is that with arranging the block size and the total number of samples, they can get good results with tradeoff between noise averaging and affects of cyclic feature. Then, they built an framework that optimizes this tradeoff. Even though the framework gives good results.

Another problem is reached to be handle which is neglected during first phase of the framework, is the effect of phase offsets between different blocks also called sampling clock offsets. Under the influence of the sampling clock offsets, integration of the the different blocks can be damaged badly, so the performance of the proposed detector decreases to a great extent. So, lastly, in the second phase of the framework they modelled these imperfections and evaluated their performance affects. They have showed that another approach to the tradeoff is needed and updated their detector according to. In the last status, considering the both imperfections, the optimization of the block sizes and total number of samples gives robust performance results in the negative SNR regimes.

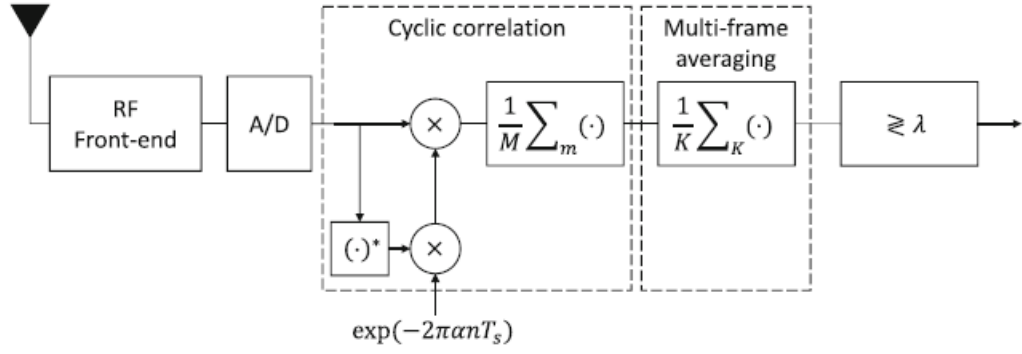


Figure 4.4: Proposed improved Cyclostationary Detector.

In the next chapter, I am going to mention about Cooperative spectrum sensing where multiple users make cooperation in order to deal with some network problems and to increase the reliability of the network. I used cooperative spectrum in my algorithm, so it is fairly important. However, I will give the most of the equations and formulas related to the cooperative sensing later in the algorithm chapter since I have used many of them in my algorithm.



5. COOPERATIVE SPECTRUM SENSING

5.1 Introduction to the CSS

Cooperative spectrum sensing is a technique where multiple cognitive radios in the same network share their informations about local observations in order to get better sensing about the network. So with this technique, we start approaching to the cognitive radios as a one collaborative unit instead of taking them into account individually. There are certain limitations that lead to creation of the cooperative spectrum sensing such as shadowing or a hidden node problem in the wireless networks. Cognitive radios make their local observations in order to determine whether primary user is present or vacate on the specific channel. In this individual process, the detection process would be done with the traditional sensing methods mentioned methods such as energy detection, pilot tone detection etc. However, with the above limitations, the results can suffer, and poor decisions can be taken. I will explain in this chapter how these limitations affect the local decisions and how cooperative spectrum sensing can improve the total performance of cognitive radios in addition to the reduction of extended interferences to the licensed users.

There are two main applications of the cognitive spectrum sensing as centralized CSS and distributed CSS. As the name suggests, in the centralized CSS there is a central unit which collects the informations from all the cognitive radios. Generally, then with the processing of the collected informations, the central unit comes to a decision whether the channel of interest is vacate or not by the licensed users. Then, the processed decision would be sent back to the cognitive users in the collaboration in the network. Contrarily, in the distributed CSS, there is not a central unit. Instead either some neighbouring users or all users in the network share their informations with each other, yet there is not a global decision which must be followed. Every cognitive users come to a decision by itself with the help of the informations shared with them. In addition to the these two main applications, there is an another method to employ cooperative spectrum sensing which is relay based CSS. In the relay based approach,

we have a central node which gives the last decision like in the centralized based approach. However, not every cognitive users send their informations directly to the this node. When they are in bad conditions that affects the local decision badly, they simply dont send their informations for that turn of sensing. Yet, this is not the main touch in this approach. When some cognitive users have bad control channels which are the channel between cognitive users and the cetnral unit, some of the other cognitive users who have good control channels simply relay the informations of the the former ones as well. So, we can say the sharing of informations in the relay based approach is similar to the disributed approach.

Before continuing with the next part, I should point out that there are other sub-methods in the name of centralized CSS and disritubed CSS and the proposed methods which are only applicable for spesific application networks. I will mention about some of them later in this chapter.

To answer how CSS can be beneficial for cognitive networks are as follows:

- To handle with the hidden node problem,
- The SNR conditions in the networks are different region by region. So, some of the cognitive radios would be at disadvantage to avoid noise floor and SNR wall to sense the spectrum robustly. With the colloboration, this disadvantage can be removed.
- To increase the agility of the network. To sense whether the channel of interest is vacate or not the is the first function of the cognitive radio. However, one important function is to sense when the licensed user is back at that channel. As soon as licensed users start their transmission, cognitive users must vacate immidiately. From multiply perspective provided by various cognitive radios in collaboration can easily increase the agility with sensing faster the licensed users activities.
- Since the collaboration can increase agility and total performance of the sensing process, the hardware and software requirements for a individual cognitive radio would be diminished. So, the cost and complexity of device reduces.

Since, I mentioned how CSS can be beneficial, the next question is what are the requirements of deployment of such network to enjoy the benefits.

Even though I said that the cost and complexity for a individual cognitive radio reduces, there are additional hardware and software requirements to create a such network. Plus, even though it doesn't require additional complexity, the individual nodes should bear the burden of some extra works. In addition to their own communications, they also should communicate with the other users to share informations. So, tradeoffs are everywhere. Most of the reseraches have been done towards CSS, are done by handling least additional cost possible so far. [4] I want to talk about which additional resources should be supplied next.

The first of one is the need of a control channel. Cognitive radios have to share their informations through radio spectrum as well. So, without disrupt the integrity of the radio spectrum in the network and without reducing the overall performance of both licensed and unlicensed users, there can be a seperated control channel. However, to have robust control channel still is a formidable problem. As an another approach, we can build a control channel mechanism where the frequencies of the control channel does not have to be fixed. Unfortunately, it is another complex and formidable problem to handle. More researches are required toward to solve the issue of control channel.

The second one is the possible need of synchronization between cognitive users. Since they are located different places and after local sensing, the processes like sharing informations can causes time delays. To provide sufficient performance merits, sometimes, local sensing processes can last longer than the others as well. These time difference could cause big problems without synchronization. There are some recognize methods for sync., however, it will increase the cost and complexity of the newtork. Tradeoffs matter. Another issue that, in the disributed networks, it is hard to have such synchronizations. So, instead asynchronous solutions have to developed for them looks more convenient.

The last one I want to mention is the central node which collects the informations from all CRs and process them. We need proper and reliable information processing algorithms to reach a robust decisions for the sensing process. There are two main fusion method towards processing the informations, compiles them and to reach a

single decision as hard and soft fusion. I am going to talk about them and other proposed mechanisms later in this chapter

5.2 User cooperation in cognitive radio networks

Since my algorithm is about cooperation of the cognitive users to detect primary users, I wrote the introduction part considering this. However, there are other types of cooperations in the cognitive radio networks. Firstly, as I already defined that in the overlay type of CRN, both cognitive user and licensed user use the same channel with controlled interference levels. Since also our main consideration is the dynamic spectrum management, I only mentioned the CRN as a opportunistic networks which can be used by cognitive users for their transmission. However, in practical designs, in some cases, licensed users also expect some gains since they allow the cognitive users to use their preassigned channels. In the context of gain, licensed users expect from cognitive users to offer them such services that improves their either reliability of the transmission or agility of the transmission. Interference matter aside, with the such provided services, licensed users can happily allow cognitive users to use the radio channel. This is an example of cooperation between primary and cognitive users. In this way, the mutual benefit would be achieved that satisfy both parties. Before returning to my main topic, first I want to mention about the cooperation between primary and secondary users. Then, I am going to mention about the cooperation among cognitive users and fusion techniques in the cooperative spectrum sensing.

5.2.1 Cooperation between cognitive users and primary users

For cognitive users, the biggest challenge is the spectrum sensing. They have to perform complex spectrum sensing algorithms to find an available radio spectrum channel for their transmissions. Even after starting their transmission, they must keep monitoring the spectrum channel to notice as soon as possible when the primary user is back at the channel. After noticing the presence of the primary user, they immediately have to stop their transmission. This is such a grueling process for cognitive users. So, one of the methods to handle such issue is to make a cooperation with primary users.

There are two common cooperation methods between cognitive users and primary users. The first one is the aforementioned cooperation in the overlay networks where cognitive users have to provide some services to the primary users, so they can take advantage of the primary users' channel for their transmission without interfering them.

The second cooperation method is where cognitive users lease the temporarily unused spectrum[22]. Instead of services, here, primary users are looking for monetary rewards by renting their licensed channel when they are inactive. The benefit here, the primary users declare to the cognitive users when they are inactive. Hence, cognitive users escape from the burden of spectrum sensing continuously. Primary users can come to an agreement with specific users or they can rent out their channel on the spectrum markets or auctions. The fair pricing policies should be deployed so, primary users don't declare their monopoly and abuse their licenses.

5.2.2 Active cooperation between primary and secondary users

The gain spectrum opportunities, cognitive radios might have to provide some services to primary users. One of the common usage of this cooperation is where cognitive radios work as a relay to some of the transmission's of the licensed users. For instance, this way, they can provide multihop relay service or additional transmission path. The provided services bring diversity gains and performance gains to the communication of the licensed users. One of the example of performance gain can be given as improved reception of licensed users by appropriately combining of the both direct signals and the signals which be relayed from cognitive users. As it can understand from the above explanation, relaying is a service that receives the signal of interest and transmit it to the essential place. Relaying can be done in two recognized ways. First one is amplify and forward(AF). The received signal at the relay will be forwarded without any processing, just simply amplifying its power. The second one is decode and forward(DF). The received signal will be processed first, more specifically it will be decoded. Then, the decoded signal will be forwarded from the relay. The most important thing to consider here is that the communication channels between licensed user and cognitive user should be in a good conditions. So, the relayed signals can be beneficial to the licensed users. So, we can say the performance of the relaying depends on the channel conditions between the licensed user and cognitive user. In a cognitive

network, there are more than one cognitive users. So, every cognitive users have different channels between a licensed user of interest. In addition, every channel will have different conditions. So, every cognitive user can improve the communication of the licensed user at different levels. Hence, the licensed user can choose which cognitive user or users from the list of the candidates, it is going to cooperate with in order to improve its communication.

So, in this perspective, we can say if a cognitive user want to use the radio spectrum assigned to the licensed user, it should improve the conditions of the channel between itself and the licensed user if it is possible. However, it should be mentioned that the improving the conditions of the channel brings extra cost to the cognitive user. The cognitive user need to evaluate whether the gains/opprtunies worth to the cost. In an other perspective, we can say a cognitive user also can choose a licensed user from a list of holders of available channels in its' transmission range considering the gain/cost ratio. However, it should not be forgotten that mostly, licensed users dont have to provide gains to the every cognitive users. So, the choice of cognitive user should be approved by the licensed user. Nonetheless, this cooperation offers multiple possible oppurtunies to the cognitive user as well. There are different cooperation methods between primary users and cognitive users eier using this relaying scheme or using different schemes. I want to give some of examples and direct the readers to the papers addressing them if they are interested. [23,24]

- Three-phase time division multiple access based cooperation,
- Two-phase frequency division multiple access based cooperation,
- Two-phase space division multiple access based cooperation etc.

The last thing I want to mention is the challenging issues in the networks where there are cooperation between licensed users and cognitive users. Then, I am going to finish this part and I will move on the next part where I will investigate the cooperation among cognitive users. The challenging issues can be listed as:

- Motivation for cooperation,
- Physical-layer issues,
- Mac-layer issues,
- Co-channel interference issues etc.

5.2.3 Cooperation among cognitive users

In this part of the chapter, I am briefly going to talk about cooperative diversity which improve the performance of the cooperation among cognitive users. The researches didn't give enough attention to the cooperative gain so far. So, the definition of the fundamental cooperative gain and derivation of its' mathematics is incomplete that we might have missing a great opportunity. We can overcome the problems like multipath fading, shadowing and receiver uncertainty by exploiting spectral diversity and cooperative gain. I will refer a book here to who want to further investigate the mathematics and details of the cooperative diversity. [11]

There are two main goals towards cooperation by cooperative diversity as a throughput optimization and an interference management setup. Most of the models take these goals, and arrange their setups to get convenient performance results according to.

A throughput optimization: The aim here is that minimizing the probability of the false alarm in subject to the probability of detection constraint which represents the interference of cognitive radio to the primary user. So, if we can have lower false alarm rates, we can have higher throughput.

An interference management setup: The aim here is that maximizing the probability of the detection in subject to the false alarm rate constraint. So, if we can have higher detection rates, we can have lower interference levels that primary users continue their transmission comfortably.

In the literature, there are two common ways to define methods of fusion for cooperation among cognitive users as soft decision and hard decision. With this simplification, hard decision is where cognitive users make local decisions and send the results of this decisions (0/1). On the other hand, soft decision is where cognitive users send the informations about primary signal they get without making local decision. In terms of energy and bandwidth efficiency, hard fusion techniques are better than the soft fusion techniques since the reporting channels require so much less complexity and bandwidth. However, soft fusion techniques give better overall performance results. Even though soft fusion techniques give better overall performance results, the hard fusion techniques can give compatible performance results for most of the cases in practice.

So, the important thing what do we what most in our network, tradeoffs matter. For instance, if we want to use energy efficiency algorithms, it is completely fine to use hard fusion techniques over soft fusion techniques thanks to the compatible performance results.

Having said that, the simplification is actually refer to the results of the fusion center instead of the process of the fusion. Hence, there is another way of defining them considering the fusion process as data fusion and decision fusion.

In the data fusion, cognitive users send the pseudosensed signal of primary users directly to the fusion center, without making local decisions. The main advantage of this method is that, cognitive radios dont have to have complex and powerful local sensing algorithms. However, the reporting channel concept becomes so much more important. There are various techniques in order to combine the psedosensed signals and to create the primary signal. Some of them are selection combining(SC), square law selection(SLS), maximal ratio combining(MRC) and square-law combinin(SLC). The basic idea used in these combining techniques is that drawing the primary signal according the channel state informations. Some of tecniques require only channel state informations between licensed users and cognitive users. Some others also require the channel state informations between cognitive users. Hence, their performance results differ. The analytical derivation of the techniques suffers in the literature so far. There are some proposed techniques as well. One straightforward framework for the analytical derivation of the techniques can be found in[25].

I can simply define them by the help of the definitions in[25] and anyone interested to the mathematical equations of the ROC performance of these methods can look into:

- Selection Combining: Simple selection over SNR values at the different cognitive radios in the fusion center is the main approach is used here.
- Square Law Selection: Instead of fusion center, cognitive radios will select the antennas with higher received power among the neighbours who share informations in that sensing period.(you can imagine in it like disributed manner)
- Square Law Combining: Instead of selection of SNR of only one cognitive radio, the received powers(simply SNR values) at the every cognitive radios will be sent to the fusion center and the sum of this power would be compared to a threshold value in order to decide whether licensed user is present or not.

- Maximum Ratio Combining: The summation of the received power and the comparison it to the threshold is again the main approach here. However, different cognitive radios will effect the decision process with different weights. One simple example is where the weights are calculated according to the SNR values at the cognitio radios. So, the biggest SNR means bigger weights and so bigger affect on the decision.

In the decision fusion, contrarily to the data fusion, every cognitive user makes local decision about whether licensed user is present or not. Considering classical binary hypothesis, these decisions generally are shown as 1 (licensed user is present) and 0 (licensed user is not present). Then these decision will be sent to the fusion center through reporting channels. Even though the conditions of the reporting channels still has little signitificance, it is not that important any more since cognitive radios dont send complex datas to be decoded. So, in the literature, the assumption of the having good-error-free reporting channels has been made. In addition to that, the assumption of knowing the SNR statistics of the licensed users also has been made in order not to bother with noise estimation. However, it must be known that these assumptions are not practical. On the other hand, contrarily to the data fusion, in this type of networks, cognitive users need strong and complex sensing algorithms in order to make accurate local decisions. If we come to the fusion center, the processing of the decisions are generally done either 'AND' process or 'OR' process or majority rule which can be generalized as k-out-of-n rule. As we know from the digital curcits, the 'AND' operation means that if the every decision equals to the one, then the output of the operation would equal to the one, otherwise it would be zero. In the same way, the 'OR' operation means that even if only one decision equals to the one, then the output of the operation would equal to the one. So, that means that even if only one cognitive radio says it has detected the licensed user, the all cognitive radios have to act accordingly and dont initiate their transmission on the channel of interest.

I can finish this chapter by listing the research challenges:

- Channel uncertainty: shadowing, multipath fading,
- Cooperation overhead: extra usage of the resources of the cooperation. Sensing time, performance degradation,
- Interference Temperature Measurement,
- Coalition Formation: With the changing number of the users who participate to the cooperation, the results of the deployed algorithms can be changed drastically. So, estimation of the possible number of the users which will participate to the cooperation is a challenge to be handled. If we can estimate the approximate numbers, we can improve the algorithms according to. Another approach to solve this issue can be designing adaptive algorithms. However, it will bring more complexity to the network. So, as a last word, the successful tradeoffs between different demands are the most important thing when we are dealing with multiple performance merits affect the overall performance,
- Error-prone reporting channel: As I explained above, some of the reporting channels can become weak and useless because of the effects such as shadowing and multipath fading. The weakness come from the increased possibility of the errors in the data at the end. So, we need to develop error-prone reporting channels. The development of the control channels and good-conditioned reporting channels are still lacking in the literature,
- Mobility: In the some networks, both primary users and cognitive users are located at a precise locations. Hence, they are defined as immobile devices. However, most of the networks in the practice possess both mobile licensed users and mobile cognitive users. The design of these two different network are very different from each other. The design of the mobile networks are much more complex than the others. That's why the deployment of a successful cooperative networks in a mobile networks is a big-open challenge which is waiting to be solved.

6. SOME SPECIFIC DESIGN PERSPECTIVES AND CHALLENGES

6.1 Tradeoffs

In this chapter, I want to list some of the design tradeoffs which should be considering during designing a spectrum sensing algorithm. One basic trade-off which does not require any specific title is the trade-off between primary user's capacity and the secondary user's sensing robustness. I pointed out that many times that, cognitive radios need to control their interference levels, so they won't disrupt the communication of the primary users. Controlling of the interference levels, can be achieved with higher probability of detections which refers to the secondary user's sensing robustness. On the other hand, with lower interference levels, primary user's signals keep their integrity and power, which refers to primary user's capacity.

6.1.1 Cooperation-processing trade-off

As I explained at the cooperative spectrum sensing chapter, in the soft decision based networks, the cognitive radios don't need to have sensing algorithms since they are relaying the whole received signal to the fusion center without local decisions. However, we need proper sensing algorithms in the fusion center. We can generalize this example for the every network (centralized, distributed, soft, hard etc-generally for cooperative networks) such that: Increase of the local processing overhead relaxes the cooperation overhead. So, we have a trade-off between local processing overhead and cooperation overhead. Relaxed sensitivity requirements mean that we can achieve good performance results with shorter sensing time and less local processing. So, another thing to consider here is that both of the parts of the tradeoff actually change the total sensing time differently. If we want to achieve less total sensing overhead which occurs due to the increasing sensing time, we need to optimize this trade-off. We know that the main contribution of the CSS is that it solves the fading issues in the network. So, as we have less severe fading environment, with the decreased need of the cooperation, we can focus on the local processing overhead.

Since we know from the CSS, with the increase of the number of cognitive radios participate to the cooperation, we can achieve better performance results since we have more data to process in order to sense the licensed user. On the other hand, if we can a better cooperative protocols or fusion techniques which have better ROC performances, with lesser amount of cognitive radios we can achieve the same performance results. However, better techniques often mean that more complex techniques. It means that if we can have higher cooperation levels with the cost of increased protocol complexity. So, we have a trade-off between the cooperation level, also defines as protocol-technique complexity, and the number of cognitive radios.

Also we can define another trade-off between diversity gain which is gained by the cooperation and additional communication overhead which is due to the increased data sharing through reporting channels. I didnt mention this at the CSS chapter. So, I wanted to briefly define it as a trade-off here.

6.1.2 Reactive vs proactive sensing

There is another categorization of the sensing algorithms which I didnt mention in the spectrum sensing chapter as reactive sensing and proactive sensing. As the name suggests, in the reactive sensing, the sensing process will be activated on demand. Like primary users, cognitive users dont communicate constantly. As soon as cognitive radio want to transmit some datas, the reactive sensing algorithm starts looking for spectrum oppurtunities in the radio spectrum. Also, as it can be understood from the name, proactive means taking measures beforehand. The equivalent of this in the network is that, spectrum oppurtunities which can be used later will be listed through periodic sensing at the spectrum. Whenever the need of transmission occurs, the white spaces in the list can be used immidiately. However, it can be easily seen that it increases the periodic sensing overhead while decreases the on demand sensing overhead. So, there is a trade-off between periodic sensing overhead and the on demand sensing overhead. Some applications like public security applications are delay sensitive applications. They generally prefer proactive sensing algorithms. The ones who prefer reactive sensing algorithms are more delay tolerative applications. Also, if their first concern is energy efficiency, it is better to have proactive sensing algorithms.

6.1.3 Rate-reliability trade-off

In the literature, cognitive networks are known as inherently unreliable networks since cognitive radios need to vacate the channel directly when the primary user is back at the channel. This affects badly the quality of the services of cognitive radios' transmission. Cognitive radios can divide their transmission over multiple white spaces in order to have more reliable communications. Even some of the channels became occupied again by the primary users, the others can continue the transmission. So, we can hold the quality of service measure above from very bad conditions, theoretically. OFDM(orthogonal frequency-division multiplexing) is using this dividing method. Subcarrier signals carry the data in parallel. Then, they can be grouped together to form a more reliable cognitive radio link. However there is a drawback of using multiple licensed bands:

- Regulatory constraints: Should be applied on every band separately. This decreases the effective data rate of cognitive radio. Since the resources can be used for the transmission has been spent on the spectral/regulatory processes. (normally one spectral/regulatory process, x number of bands mean x number of spectral/regulatory processes)

So, we can define a trade-off between the appropriate number of independent licensed bands for data transmission and effective data rate and reliability of the cognitive radio link.

In practice, this trade-off should be arranged to optimize the end user's QoS.

6.2 SNR wall

In this part, I want to talk about the biggest issue in the cognitive networks which is the SNR wall phenomenon. This phenomenon especially occurs in the low SNR networks. However, most of the real world networks suffer from low SNR regimes time to time because of the hidden node problems and deep fadings. This either completely prevent cognitive users to find spectrum opportunities, or it would be cause to the disruption of the transmission of licensed users' due to the blind transmission of cognitive users. In the IEEE 802.22 standart, cognitive users have to sense TV transmissions as low as -22 dB to become a part of the network for spectral opportunities. We know that in the real life networks, we have unavoidable noise

uncertainties. So, we need to model these uncertainties in order to get better performance results. In the [19,20], they defined this performance merit which originates from the dealing with noise uncertainties correlated to the SNR wall phenomenon and gave mathematical derivations for the ROC performances as well. SNR wall value is theoretical value is that under this value the detection of primary signal is impossible. That simply means, the effects of the noise and noise uncertainties simply surpass the primary user's signal strength that it became undetectable with any visual feature. At the conclusion part, they said the modeling of noise uncertainties in cooperative networks are open problem. Anyone who want to investigate mathematical derivations and theorems of SNR wall can look into this paper [19,20].



7. CR REGULATIONS AND STANDARDIZATIONS

7.1 Introduction to the Regulations and Standardizations

Cognitive radio networks where unlicensed users are taking advantage of the unoccupied channels assigned to the licensed users without disrupt their transmission. In addition, I mentioned about the security issues which should be considered. If we can have decent regulatory polices which control both the spectrum management part and the security part, it would relieve the burden of the network greatly. However, since we still have static spectrum management policies in use mostly, it can be said that these stric and outdated policies should be changed immidiately, then they can be updated regularly. Hopefully, there are some standarts in use and more upcoming standardizations are under investigation whether they can be used as well. So, this chapter will start from the why we need regulations, how was the first look at the beginning of the cognitive radio technology and then lastly where are we now in terms of standardizations?

First, we need to give our attention to the spectrum management regimes. The main function of the cognitive radio which is dynamic spectrum management is the first regime of interest. The second one is the market-driven spectrum management. I gave the one example of this regime in the cooperative spectrum sensing where cognitive users looking for to lease the channels of licensed users to make their transmission. So, in this regime, whoever buys the channel from market or the auction will get priority access and can get exclusive usage rights to the spectrum. However, in the example, cognitive radios have to careful not the interfere primary users' transmission, espically in the overlay networks. The last one is the regimes based on an advanced commons model. In this regime, there is no licensed users. So, to sum up, the regulations about spectrum management are considering these three regimes. I am going to briefly mention about it, and then I am going to mention about standarts.

7.2 History of Regimes

The approach used in spectrum management before concerns about the scarcity of the radio spectrum come up, there was strict and prescriptive spectrum managers decide which range of frequency bands will be used, who is going to use the radio channels, which services can be used etc. This approach is called administrative approach which is also known as Command and Control approach. As I already mentioned that there are both national level and international level of spectrum managers and regulators like ITU and FCC. One of the biggest reason this strict approach was intriguing to the regulators was controllability and manageability of the interference.

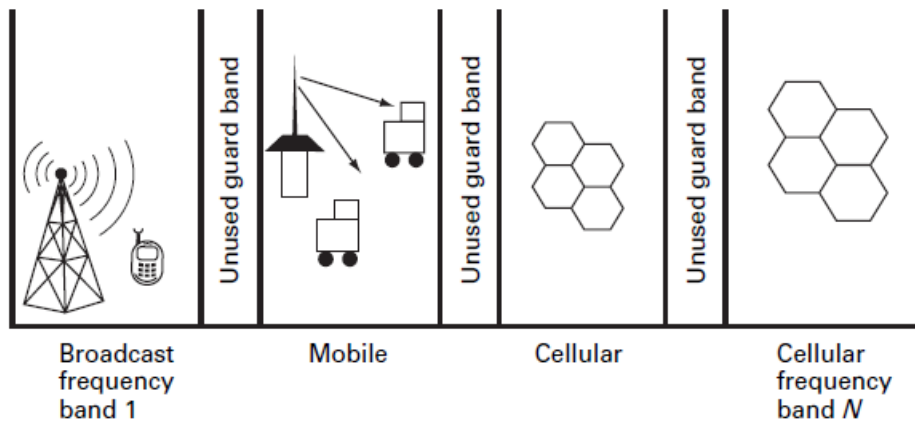


Figure 7.1: Interference management setup with guard bands.

As you can see from the figure, one method is used in this approach to manage to interference is that put unused guard bands between different radio spectrum ranges or services. Another thing can be seen here, spesific range of frequencies are allocating to the certain services and applications. The next step after the allocations is assignment. While most of the allocations is done in international level, the assignment process happens at the national level. Assignment is where spectrum managers determine which networks/users actually use the allocated radio spectrum.

However, with the increased demand on the radio spectrum and inefficient usage owing to the command and control approach, the need for new regimes are arising. One approach to new regimes is to use dynamic spectrum access regimes which can be managed by the development and massive deployment of the cognitive radio technology. This basically involves everything I mentioned through all the chapters.

In common regimes, there are no licensed users who have privileges for using a specific radio spectrum. The biggest example for using such regime is ISM bands. So, basically whoever wants to transmit its data over ISM bands, has to accept any interferences caused by other users. So, the interference levels can easily increase to a level that it makes impossible to communicate robustly. However, one condition in ISM bands is to hold the transmit power under from a certain level, so this is helping with handling the interference issue to some degrees. Yet, it does not solve it entirely. So, when we are saying to create new common regimes, we are taking the ISM bands concepts to a new level. Firstly, we are aiming to create various bands where there are no privileged licensed users. Secondly, we can put more flexible and handful conditions rather than just arranging transmit power levels. ISM bands are known as innovation zones where the most of the proposed techniques in the advancement of both wireless technologies and general technologies founded from. So, having flexible and robust common regimes even besides the dynamic spectrum access regimes are very important for future developments and technological improvements in addition to the non-creative demands for radio spectrum.

Every regime can be beneficial for specific environment or applications, however, there are so many challenges to solve before completely employing a spectrum regime starting with political issues. For example, in the dynamic spectrum access regimes, the regulatory bodies stipulate the cognitive users that they can't disturb the primary users' transmission whatsoever. There can be either mutual network both primary users and cognitive users agree upon or a network where cognitive users can only use without disturbing the primary users. So, the spectrum sensing and monitoring so important and great performance results include probability of detection and total error rate are needed to employ such regimes under the circumstances of world and humanity. That's why IEEE starts one of its' first standardization works for analog TV channels in rural areas which can be easily not disturbed by careful employment of

networks because they have repetitive patterns and that radio channels are mostly unused since the adoption of the digital TV channels.

7.3 Standards and International Activity

Since cognitive radio technology started to be recognized a key technology for the dynamic spectrum management for the future, the works through putting standards are increased. There are already some advanced standardizations like IEEE 802.22 and also there are activities-works which are in early states. IEEE has started annual conferences on Dynamic Spectrum Access Networks(DySPAN) in the 2005. [26] This leads to the creation of the workgroups under the SCC-41 as well.

7.3.1 The work of the SCC-41

The SCC-41 (the IEEE Standarts Coordinating Committee 41) is mainly focused on the dynamic spectrum access topic back in 2000's. After Mitola defined the cognitive radio from the software-defined radio, it has attracted big attention in short amount of time. Since the first and foremost function of the cognitive radio is finding spectral oppurtunities which supports dynamic spectrum management, it also has attracted the attention of the SCC-41. The SCC-41 serves a bridge for different developers and provides them information exchange and coordination in the Dynamic Spectrum Access Networks. So, it supports the activities related to the dynamic spectrum management. However, its' main task of operation is putting standards by the help of the researches and developments for emerging technologies like cognitive radio. There are different workgroups of the SCC-41 which are focusing in the different areas. IEEE working group 1900.1 is the group which focuses on the spectrum management and cognitive radio. The main task is the to put technical precise definitions and explanations in these areas. I want to mentioned here that even though IEEE working group 1900.1 is the main working group for the DSA and CR, some of the other groups also have relations with small parts of the DSA and CR.

7.3.2 The IEEE 802.22

The allocation of the radio spectrum for analog TV channels was so ineffective. The biggest advanced standard for specific use of the cognitive radio which is recognized and in use is the IEEE 802.22. The main purpose of this standard (working group before standardization) to improve the efficiency of the usage of the radio spectrum allocated to the TV channels using cognitive radios. From another perspective, the work on the standard serves to cognitive wireless regional area networks (WRANs). There are continuously large number of white spaces in these range of frequencies which can be used by the unlicensed users especially in the rural areas. So, one of the biggest consideration is that TV channels can be beneficial for spectrum efficiency with geographically unused spectrum allocated to them. However, the most important thing to keep in mind that, cognitive users must not disrupt the TV channels with unacceptable interferences. The following are the advantages of the TV channels for developments of cognitive networks:

- Relatively low levels of industrial noise and ionospheric reflections,
- Reasonable antenna sizes which are related to the bandwidths,
- Relatively good line of sight propagation characteristics,

The followings are some of the concerns of the IEEE 802.22 working group:

- PHY and MAC layer issues (most of the sensing happens at the MAC layer),
- Spectrum sensing,
- Geolocation/database issues,
- Security issues.

As I said from the beginning that, the spectrum sensing process is the main spectrum awareness method for cognitive radios. Hence, the IEEE 802.22, spectrum sensing is also used. However, there is another approach used here in terms of spectrum awareness due to the geographically unused radio spectrum allocated to the TV channels (broadcast bands) which is geo-location database method. I already mentioned how we can use databases in the cognitive radio networks. So, I don't want to put more details here. The technical details of the IEEE 802.22 can be found in [26].



8. PLATFORMS AND TESTBEDS

8.1 Introduction to the Platforms and Testbeds

When I defined the Cognitive Radio, I had been pointed out that it is consisting of two main parts as hardware part and software part. In this section, I compiled the information about hardware part I have been gathering during my research. The parts come to mind of all of us are antennas, RF circuitry, filters, amplifiers, Analog-to-Digital Converters and Digital-to-Analog Converters. Assuming there would be only one antenna or other parts is quite wrong. There could be multiple antennas when we are dealing with MIMO systems or there could be multiple RF frontends are assigned to different task etc. As I continuingly telling that Cognitive Radios are application specific produced devices, so too many other hardware equipped can be added to the list other than fundamental components. I looked through typical wireless systems and listed down some components. Secondly, we can list the Cognitive Radio specialized hardware equipments accommodating that traditional wireless components such as the cognitive engine that use various optimization, decision making and machine learning algorithms, or the policy engine that control the reasoning and realization process as well as database jobs, or security layer that control the security tasks involving decryption-encryption and authentication. To sum up with this paragraph, when we meant to design a Cognitive Radio, it is crucial to have clear design map, involving which sort of components we need fundamentally or application specific way and the relations between the components to have a good working system.

8.2 Digital Hardware

As telecommunication technology and also Cognitive Radio technology advance, too many digital platforms and hardware equipments have been developed dealing with different design maps. So, key question when we meant to design a Cognitive Radio is which platform is better for our intended device. Other than choosing specific platform, there are multiple suited platform for one application specific device. So, answer to how we choose from them is simply lies in three main features. First and foremost feature is system performance. Cognitive radios have complex signal processing algorithms and optimization algorithms that consumes too much time to complete their cycle. We need exceptionally high speeds for execution of these algorithms in order to have better performance. Second feature is power consumption rate. Power consumption is very important issue in handheld devices. Also, power consumption relates to the waste which damage the environment, so it is important the level the power consumption in terms of sustainability, and make sure we do not damage the environment unnecessarily. Last feature is flexibility. It is also important, because as I keep saying that Cognitive Radios are adaptive devices that change their behaviour and functions according to information they gather through observations I defined in previous chapters. So, they need to be flexible to change their characteristics. Of course, different levels of flexibility satisfy different Cognitive Radios. Lastly, we should remember that these three features can contradict with each other. For example, when we increase the speed to get better performance, the power consumption may also increase. So, to set rational tradeoffs between features is very crucial topic for designer.

8.2.1 Basic digital hardware options

In this part, I will be listing some of the most known hardware options and briefly explain them.

ASIC(Application Specific Integrated Circuit)

As we can see from the name itself it is application specific integrated circuit. So, basically ASICs are designed for a application specific tasks. It gives very good performance for task since. Unfortunately, for other tasks, it might not be the best choice as it cannot be reconfigured. Advantages of ASIC are high performance and low power consumption. General place of uses is mobile phones.

FPGA(Field Programmable Gate Array)

As name suggest tasks are defined by the users rather than device designers. The software can be loaded or updated by users. It is a semiconductor device based on basic logic blocks such as OR and XOR. By the time, more complex logic functions are implemented on the new FPGAs. It also has a configuration layer unlike ASICs, where we programme the logic blocks according to algorithm at hand. One of the biggest advantage of FPGA is high degree of parallelism. It means logic blocks execute their assignments at the same time. They dont wait each other and execute sequentially. With this advantage, FPGAs bring computationally high performance to the network. Also as we can update the software any time we need and with partial reconfiguration ability came from the reconfiguration layer ,which means while we are updating or changing one of the parts of the FPGA, the other parts still executes their tasks, we can say one of the other great benefits of FPGA is its flexible functionality. The downside of this flexible functionality is higher power consumption compared to ASICs. General places of uses are basestaions and new proposed systems.

ASIP(Application Spesific Instruction-set Processors)

General design idea is adding a some sort of reconfigurability to the ASICs. Likewise ASICs, they are application spesific devices, so they give good performance for task at hand, yet they have limited amount of reconfigurability provided by a software programmable processor added to the general application spesific hardware component. This brings flexibility from utility perspective, while it also adds more power consumption need from sacrifice-disadvantage perspective compared to the ASICs.

DSP(Digital Signal Processor)

Digital signal processor is a microprocessor where the discrete samples of signals are be subject to processing in order to make use of them as name suggests. They are also programmable devices and have their spesific machine codes. Ability of programmability is crucial for complex cognitive radio networks. Also, lots of digital signal processing algorithms and optimizations are involved with cognitive radio networks. From this perspective, we can say Digital Signal Processors are attractive devices for Cognitive radio networks. As programmability and reconfigurability brings more need of power consumptions, digital signal processors also consume more power than FPGAs. General places of uses are mobile phones and tablets.

We can define and demonstrate more devices possiblty related to the Cognitive Radio Networks, yet these three are more commonly used devices so far at the field. Next part, I will explain how should we choose from different devices and which tradeoffs we can face.

8.2.2 Making choices

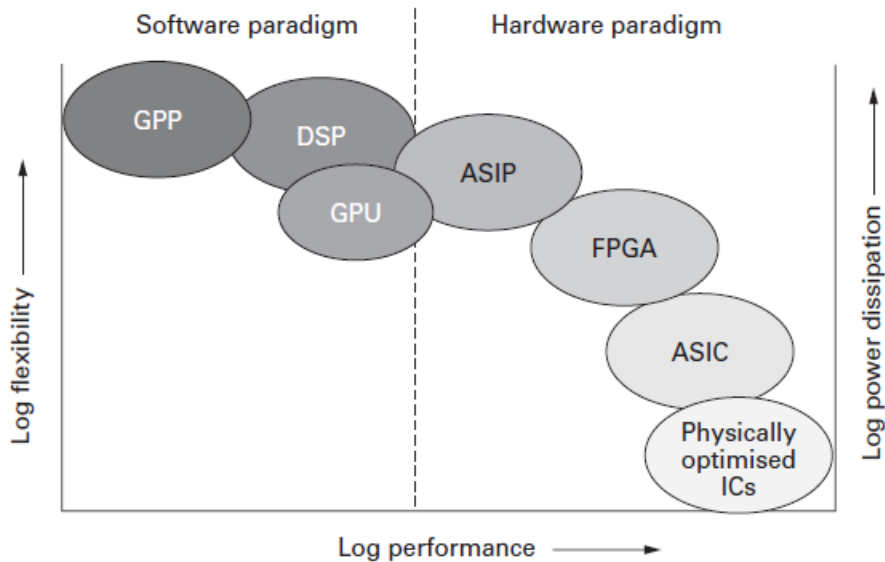


Figure 8.1 : Comparison of different hardwares[11].

As I already mentioned that the three feature are very important to make choice between devices, which are system performance, power consumption rate and flexibility. Different devices with different features and advantages, it can only be logical that we should use a combination of necessary devices since we are working

on a multi-node, multi-sensor complex systems with multiple input multiple output sources. So, choosing one device over another for a execution of a function is a one issue, while the more important issue is using different devices assigned with different tasks together in a system robustly.

8.3 Analog Hardware

So far, I talked about digital hardware options for cognitive radio networks. In this section, I will talk about the analog hardware options with same manner used previous section. It is crucial to remind that Cognitive radios are related with various large and complex fields. So, basically I am trying to highlight more cognitive radio network related parts of the fields to catch a sense of basic characteristics when I deal with different fields. I described three main features for digital hardwares earlier. Now I will talk about the features of analog hardware in order to rate general radio transceiver performance. I also want to remind that these features are important to map the system for designer, while they gave a possibility cluster for users to how they can make use of the system efficiently.

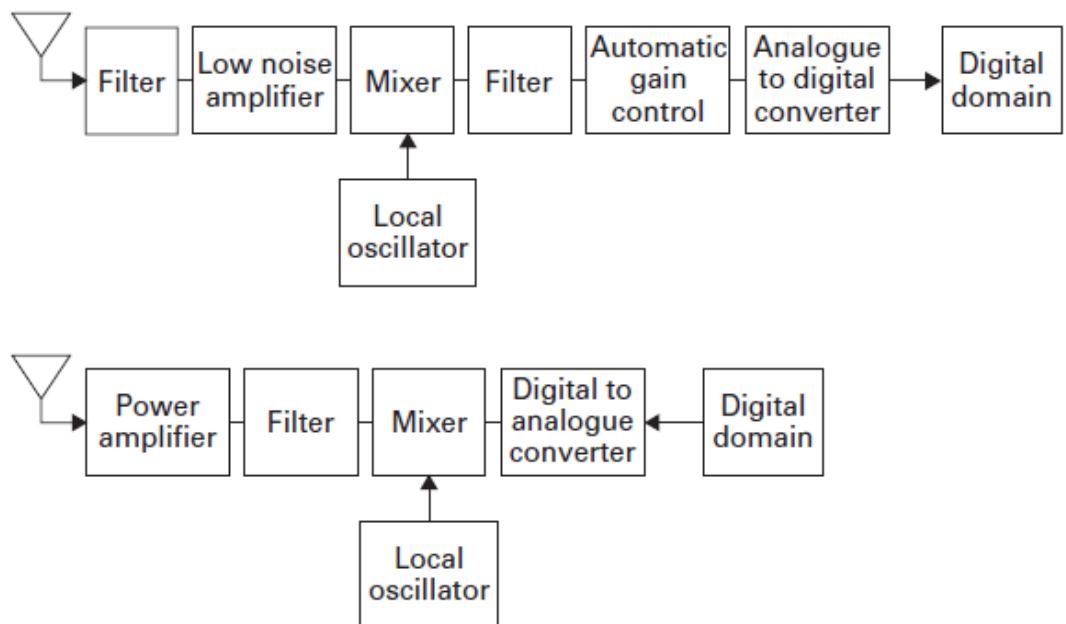


Figure 8.2: Generic transceiver architecture from Jeffrey reeds book[11].

As we can see from the generic transceiver architecture, it consists of various different hardware devices such as antennas, filters, oscillators, low noise amplifiers, converters etc. It shows a single transceiver scheme. Today, we generally are dealing with MIMO systems, so multiple antennas connected multiple RF frontends are more possible case for our up-to-date architectures.

First and foremost feature for analog part is ability to deal with noise and interference since every single one of the devices connected in RF frontend is noise sensitive devices. Also, every single one of them are adding noises to the system. So, we need to deal with the noise both at the element level and general chain level. Yet, noise performance of the first element of the architecture is the most important one in the system since it keeps multiplying along the chain. In wireless system, noises are generally considered in the system by signal-to-noise ratio. The traditional way of define this feature of ability to deal with noise is using dynamic range. Dynamic range is the signal range where the devices are keep working in a healthy manner. Otherwise, outside of the dynamic range, at the high end when devices are overloaded, generally devices are getting into the nonlinear regime. So, the boundary of the low end is where a radio can detect a weakest signal, defined as sensitivity. In addition, at the high end devices can be overloaded which is also a negative situation affects badly the performance with unwanted intermodulated frequency products. We can define one more characteristics for dynamic range in addition to the sensitivity and overloading which is selectivity. Selectivity as the name suggests ability of the select the noiseless signal from the mix of signal of original signal and unwanted signals of device. Selectivity is generally provided by filters to filter out the unwanted intermodulated frequency products. So, how filter performances determine how we quantify the selectivity. Also, the noise floor term, which I already used in previous chapters, means the sum of the all noises coming from unwanted resources and the all noises generated within the chain.

Instead of general transceivers for common communication systems, we need transceivers can deal with cognitive radio network requirements. And if we meant to built an application specific cognitive radio, transceiver should also meet the application requirements.

8.4 Testbed

After Cognitive Radio Technology get lots of attention, there has been numerous theoretical researches and proposals. Yet, we know that to make use of this studies and new proposed algorithms, we need to make sure of they are useful in practical implementations. Generally, studies neglect some of the worth considering practical implementations for the sake of the simplified research and spesific results. One of the approach to this issue is using testbeds where experiments and algorithms can be implemented on more realistic environment to put to the test if they are convenient for practical cases. As comes from the definition of testbeds, they are not also real implementations, instead they are also simulations yet with more realistic difficulties. So, this makes them flexibility and and various reconfiguration chances withouth charging extra costs. In addition, we can always update the software the testbeds use or improve the hardware related simulations. In testbeds, large set of experiments can be realized and enormous statistical data can be acquired. With the acquired data, we can support our proposals more studly or we can decide if our study is reliable or not and we can catch sight of which statistics or features we need to fix or improve.

In wireless communication system research, testbeds are essenially used for decades to analyze some important features such as signal-to-noise ratio, throughput and capacity of the channel, bit error rate under different hardware settings and different wireless propagation environments and mediums. Cognitive radio networks are very similar to that wireless communication system fundamentally, yet we know cognitive radios have various distinctive features only valid for itself. So, we need new and improved testbeds compatible with cognitive radio networks.

Set of requirements a CR testbed should satisfy:

- Since spectrum sensing is the first and foremost featuer of the CR, real time signal processing and agile transmission with sufficiently high throughput and low delay-latency is required.
- Secondly, Implementation of control channel where the transmission informations and required additional information is shared with other network components is required. Improvement of control channel study is very important for Cognitive radio

technology yet there is still relatively small amount of researches has been completed. Because it is still very complex and hard to improve issue.

- Since cognitive radio networks should protect and support both primary users and secondary users, the testbed has to emulate from perspective of either one.
- Last example of requirements is ability of having multiply environments with different shadowing and multipath effects to perform the network.



9. SECURITY

9.1 General Overview of Security

Even though it has been over a decade since Mitola defines cognitive radio using by software defined radio, the technology is still its' early stages. It has been recognized as one of the key technologies we will deploy and facilitate from it on different tasks in the 5G and 6G networks. The practical usage and standardization is not spread enough to complete the researches from every perspective. That's why the researches and works on security issues are published considerably limited. However, whenever we start widely deploy the technology, the security is one of the most important issues. So, the attention it gets becoming hot every other day. So, in this chapter, I will talk about security on cognitive radios and I will answer to the following questions.

- why security is important?
- how can we secure the network?
- what are the main security flaws that can be used by malice parties in the wireless networks?
- which are other security flaws related to the cognitive radio networks specifically?
- what kind of countermeasurements the users or regulatory bodies take?

Firstly, I want to talk about why is the security important. As I repeatedly told that the work principle of the cognitive radio technology relies on the informations which are collected through observations. Then, cognitive radios decide how to act according to these informations. So, the first reason why is security important that with the security flaws the informations cognitive radio gets can be damaged or changed, and it would lead to the wrong decisions with higher probability. For instance, when the licensed user is present on the channel, the false informations can make the cognitive radio starts its transmission without setting the interference level even in the concurrent dynamic access systems where both licensed users and unlicensed users can transmit at the same channel. This interference would disturb the licensed users'

communication. The second reason why is the security important, other than damaging and twisting the information, malicious parts can steal the information and use it for their own good. This leads inefficiencies and so many other problems in the network. Other than the observation informations, the users sending their private informations in the transmission. The security of these datas are also very important issue. We can expand the list of why the security important, however, these two basic reasons is sufficient for ust to understand how important it is.

Next, I want to talk about what is the security in the networks. One of the main process for security is the authentication. With authentication, the system aims to ensure whether the user who wants to operate in the network has the right to operate or not. In addition, there might be malicious parties who want to operate in the system, the authentication process should be robustly identify whether the request comes from authorized user or malicious parties. As we all know that the fundamental authenticaiton process can be provided by a user name and a password engaged to that username. However, with the latest technological developments and improved computers, a need to more complex and secure authentication processes is appeared. Most common new methods are: the encrpytion of the passwords and hash algorithms using softwares. The second important security measurement in the networks is providing a privacy. Over the wireless networks, in the transmission, users sending their poersonal datas and takes advantages of the services and functions provided to them by the network owners. To prevent third parties or malicious hackers to reach these private datas and function histories is the main part of the providing privacy. One of the well known, method to break privacy in the wireless networks is called eavesdropping by man in the middle attacks. The attacker which stands between the two part of the private communictaion is stealing the datas without damaging datas or the communication itself, so it is hard to tell whether privacy is broken or not. This method is so common in wireless networks since we sent our packed datas through the air which a medium everyone can reach with proper equipments. So, we need to make sure, without approved authentication, noone can steal the datas or even if they are stolen, we need to make sure to add proper encryption mechanism such that cant be broken and protect the private datas. Considering some of the datas would be related with military or the public security operations, we can understand how important to provide a proper privacy.

The three recognized methods of encryption are as follows:

- Public key infrastructure: Based on the use of the digital certificates which is known as Certificate Authority,
- A symmetric cryptographic approach: Based on a private key which is priorly known by the parts of the communication,
- Hash algorithms: They maps the data to the fixed-size values, this function is practically known one-way function for today which cant be broken even if they get caught by the malicious parts.

There are some other examples about security I want to talk about briefly. With the massively increased online shopping and digital payments options, the need to properly secure the these transactions becomes vital. The main issues are properly tracing the transactions, recording their datas accurately and securing the all private authentication informations and details of personal payment informations. As I talked about before, in the dynamic spectrum management chapter, the emerging blockchain technology which provides a transparent and secure database in one perspective, can be also used to trace the transactions and record them accurately. The one advantage of the blockchain systems that the blocks cant be changed from only one point. Huge amount of different nodes in the chain have the blocks and datas engraved on the blocks. Especially in the public chains, anyone can access to the blocks and store them as well. To change a data in the blockchain seems impossible so far. We cant say what future holds in hands, yet I am happy to witness of the growth of the blockchain technology and I belived it will bring new technological advancements can be used to improve the life of humanity. Next one I want to talk about is another important issue in the both communication networks and computer services which is denial of service(DOS) attacks. This attack prevents the authenticated user to use one of the computer resources presented to them or bought by them from the providers. The last one is the single points of failure which is a failure happened any point of the system that disturbs every parts of the system. To consider possible single point of failures is also very important while designing a cognitive network. So, I will look into more detailed way later in the chapter.

9.2 Cognitive Radio Related Security

The type of network CR chooses to use whether is interweave, underlay or overlay gives us an important classification method when it comes to security issues. We can detect badly behaved CR users or malicious third parties easily if they act outside of characteristics of the specifically created CRN. This is an example of one of the security measures we can take. Distributed networks are so much more vulnerable to attacks since they don't have a central entity, and security mechanism brings cost and complexity to the networks. If we say every CR user could have its own security mechanism, it would be a inefficient way of thinking on the security issues of CR network. If we are designing a CR only not a complete CRN and possibly it will be used in less crowded area, then it might be enough.

In interweave networks, CR users are looking for a white space to use where primary user is absent. It accesses the spectrum in a TDMA or FDMA. So, less security measurements would be enough compared to underlay and overlay networks since in these networks CR user and primary user are using the same spectrum together. CR user must keep the interferences below certain level given by regulatory policies. Relatively little changes in the power of the secondary transmission can bring serious problems to the network due to the how it would affect the primary licensed user. Lastly, it can easily be seen that Cooperative networks are under heavy security responsibilities since one security issue related to any other CR user in the network would bring stronger impact on the network by affecting every other user. So, we can say it is intriguing to create an attack on the CSS networks. CSS networks need to be much more careful about their security mechanisms.

As I pointed out earlier that the main and most important function of the cognitive radios is to collect information through observations and use these information to complete its tasks. So, the functionality and reliability of the information collected are very vital for cognitive radios. These situation offers to the malicious parts a various opportunities.

9.2.1 Physical fakes

Physical fakes are the devices which planted in the cognitive radio network with the both hardware and software cost. In addition to that, they need to know or estimate the characteristics of the cognitive radio network to keep infiltrate to the network. That means the planting a such fake is a troublesome event for the malicious part. However, if they think, planting the fake to the network is beneficial to them over this cost and trouble, they can plant the physical fake. The general behaviour of the physical fakes is to send a delayed or wrong information about whether primary user is present or not in the channel to force the cognitive radio to take wrong actions. Since these informations indicate a possible event which can be occurred in the network when the conditions meet, to suspect over an informations or to decide whether they are correct or not, is a tough issue to handle. It generally disrupt to network, either forces cognitive radio to damage to licensed user' transmission or stalls cognitive radio saying the channels are occupied by the licensed users even if they are not at the time.

To overcome the affects of the physical fakes, we need to improve the agility of the cognitive radio. Since physical fakes are planted over a network, they can only reach some of the channels cognitive radio considers to start its' transmission. So, if the all channels on the relevant spectrum are not occupied, with the more agile radios, we can get another white spaces quickly. However, it can not be possible for every network since some networks have plenty of licensed users which can use the spectrum at the same time. In addition to that, relevant to their application purposes, in the some networks, transmissions of the licensed users last longer, it might not be possible to find another vacant channel every time.

We can design robust networks which can overcome this problem, even though it is not possible for every network. For example, cognitive users can use pilot tone detectors or cyclostationary detectors if the prior and specific knowledge about the primary users can be available. Unfortunately, in the networks where there are too much primary users defined on the network, cognitive radios need to have prior knowledge about every primary user or their transmission characteristics. It brings massive hardware cost and software complexity. Another solution that can be considered is to design regulatory policies that can differentiate the rogue users and cognitive users.

9.2.2 Physical degrading of performance to stop sensing

Another way to sabotage the system is physical degrading of the performance. It can be done by increasing noise floor or the SNR wall. As I explained earlier, these would lead to poor detection probability. In fact, if we face the SNR wall, it will become impossible to detect meaningful signals. We need to improve our sensing algorithms to avoid such SNR walls and we need to develop strong denoising algorithms to increase the probability of detection. Besides the rogue users, badly behaving cognitive radios can also sabotage the network this way for their own good. Hence, compared to previous issue, we need more detailed solutions. Since it is also connected with another perspective, I will explain this issue later in this chapter.

9.2.3 Physical tampering with data

Since cognitive radios are smart radios, besides the informations they collected from observations, they also use informations from previously faced experiences and informations recorded to a database. The malicious parts can try to distort the datas on the databases. The solutions to that are using additional authenticators and policies. We also can check content integrity before using the informations.

9.2.4 The double sided coin of collaboration

Cooperation between cognitive users firstly relies on their honesty and unselfishness. However, in practice, there are malicious and selfish cognitive users in the every network. So, we need to handle with this situation. In literature, the most recognized approach for this issue is using a trust-point based networks where cognitive users get scored by the reliability of the informations they shared. We also need to consider that, without bad intentions, they can send poor and wrong informations time to time. So, we continuously should keep updating their trust scores and put additional measures. Another method can be use the check the integrity of the informations shared between cognitive users.

9.2.5 Physically tampering with CR

Cognitive radios are designed in a way that they don't need to change their hardware. We know that, they are smart radios which use various softwares and algorithms. So, time to time, we are updating their softwares if needed. One of the main reason why we might need to change their software is the updated regulatory policies. Another reason is to improve their performance according to new developments over their algorithms. There can be attacks while cognitive radios are downloading the new software. Malicious parts can change the software or can put computer viruses to the files. We need to prevent these kind of attacks with strong authentication policies. In addition we can check the data integrity of the new files. The part of the cognitive radio which gets the new software should be separated from the overall system until the reliability and validation of the files check out, so the system won't be affected directly.

9.2.6 The single points of failure

The most important parts of the cognitive radios are where the observation informations are collected and where the data transfer provided in terms of the importance of the single points. We can exemplify these parts as control channels, beacons etc. When this parts fail, cognitive radios lose their main functions. So, whole device becomes useless until eliminating the failure. I already stated that control channels are one of the biggest open issues in the cognitive radio technology. Hence, the security measurements of the control channel is also lacking in the literature. Since most of the cognitive radios are designed to fulfill different tasks, there can be found various single points of failures specified to these different cognitive radios.

From here, I going to give more detailed knowledges starting from the physical layer security.

9.3 Physical Layer Security

There are three main topics considering physical layer security I will be investigated in this part.

9.3.1 Eavesdropping

I already defined the eavesdropping which is well known attack in the wireless networks. Wyner proposed an algorithm to secure the network from eavesdropping by specially defined wire-tap channel. He defined a new metric which is secrecy rate which basically gives the performance of the channel against the eavesdropping attack. So, as we get higher secrecy rate, the security of the network increases as well. With the precise secrecy rate which is higher than the theoretical value modelled in the Wyner works, we can make our transmissions without eavesdropper theft. The evaluation logic behind secrecy rate is very simple. It equals to the difference between the capacity of the main channel and the eavesdropper channel. Like I said, the first countermeasure against such attacks keeping the secrecy rate as much as possible. However, there are some practical limitations to that and eavesdroppers can also increase capacity of their channels to a certain levels. One of the important note here, to calculate the exact secrecy rate we need to know the channel state informations of channels which is not realistic in the practice. There are some optimizations and antenna selection techniques to face this issue as much as possible. The other countermeasures against eavesdropping are as follows:

- Security Oriented Beamforming: With using directional beamforming techniques, we can reduce the achievable channel capacity of the eavesdropper channel while increasing the channel gain of our transmission.
- Relay based techniques: When we have more than one relays which transmit our signals, we can choose the ones with higher secrecy rates to forward our messages. Or from another perspective, under the assumption of not knowing the CSI of the eavesdropping channel, we can just choose the relays with higher channel capacities. There are two main relay forwarding techniques as AF and DF which I defined them in the cooperative spectrum sensing chapter. The disadvantage of the AF is that it also amplifies the noise power levels as well. On the other hand, the disadvantage of the DF is that, it is much more complex since it requires signal decoding algorithms in the relays.
- Antenna selection Techniques: In mimo systems, we can choose the antenna/antennas which can give more channel gain in order to increase the secrecy rate.

- Adding Artificial Noise: We can add artificial noise which can be easily decoded at our receiver. This noise adds interference to the eavesdropping channel which decreases the secrecy rate. The disadvantage of the method that, we need to consume much more power.

9.3.2 Jamming

In the jamming, the malicious parts aim to decrease the SNR at the receiver of our communication. It can be used to disrupt both primary users' communication and cognitive users' communication. However, in the cognitive radio networks, it is generally used to prevent cognitive users to find spectrum opportunities. There are three recognized jamming methods categorized as follows:

- Sweeping Attack: The attack does not evaluate whether there is an activity in the channel or not. If the channel is vacate from both primary users and cognitive users, the attacker wastes its' resources.
- Fixed Strategy Jamming: On the contrarily, in these attacks, the attackers first evaluate whether there is an activity on the channel or not. Then, if they sensed activity, they would attack the channel.
- Cognitive Jamming: In the cognitive jamming, attackers wont just simply attack, they also updates their strategies according to the observations on the channels and on the functions of the transceivers in the network like cognitive radios. So, we can define this jamming as smart jamming.

We can list the countermeasures against jammings as follows:

- Use of directional antennas: Improves the energy efficiency and increases the SNR.
- Spread spectrum techniques: Using pseudo codes, frequency hopping techniques, channel hopping techniques etc. The disadvantage of these hopping techniques that they require multiply different informations. In addition to that, during the attack, we need to change either the channel used or the radio spectrum range used. This brings additional cost to the system. Especially, in the channel hoping techniques, the channel throughput faces a massive decrease. So, instead of the reacting to the attacks, we need to sense where can the attacks come from and to predict the attacks beforehand. If possible we can locate the jammers to simply destroy them.

9.3.3 PUE attack(The primary user emulation)

As the name suggests attackers emulate the primary user. It decreases the network throughput as well. However, for our concern, the biggest effect of such attacks that it blocks the spectrum opportunities to the cognitive radios by stating the channels occupied even when primary users vacate. The attacks depend on the confusing the cognitive radios by sending them a power above the detection threshold like primary users send. So, in the networks where cyclostationary or pilot tone detectors can be used, these attacks become useless. However, in the energy detection based sensing networks, to implement such attacks are very easy. We can list the countermeasures are as follow:

- Channel hopping,
- Radio fingerprinting: Even if we dont use cyclostationary detectors, with the prior knowledge of the some features of the transmission's of the primary users, we can possibly differentiate the attackers and primary users. However, this brings massive cost and unnecessary complexity,
- Cryptographic approaches: We can use some sort of authentication mechanism which the details of it would be coded to the received signal. However, these codes need to be decoded by the primary users. However, FCC stated that, cognitive users can exploit spectrum opportunities at the licensed users' channel without loading them any kind of tasks or additional works. Under this regulatory policy, we cant use this method. So, this is still open and challenging issue.
- Location Based: If the primary users are static and located at known places, even without radio fingerprinting, we can estimate some of the features of the primary signals. However, most of the networks have moving primary users. In addition to that, there would be a huge scalability issue in the larger networks. However, one example of such networks are the ones deployed in the IEEE 802.22 standart where geolocation databases are used.

Attacks to the Learning Engines: Learning engines are still in the early stage of development. This attack could disrupt communications of smart devices in the Internet of Things. So, until the massive deployment of the smart devices, we need to investigate what kind of attacks can be damaged to the learning engines and how can be take countermeasures.

9.4 Link Layer Security

Byzantine Attack: This attack depends on capturing some of the authenticated devices in the network. In the literature concerned about cognitive radio networks, this attack is also defined as spectrum sensing data falsification (SSDF). The most used case of such attacks are cooperative networks. They simply capture some cognitive radios and send wrong sensing information to the fusion center or the neighbouring devices. The countermeasure to such attacks is exposing the anomalies in the sensing information. However, we need reference information to expose the anomalies, which is a challenging issue in practice. One additional issue here is that, cognitive radios can send wrong or missing information even without malicious contents due to channel conditions, shadowing/fading etc. In the literature, the proposed countermeasure is using trust-based networks where cognitive radios are scored according to the reliability of their reported information. This might put cognitive radios with worse channel conditions in a very bad position. More solid algorithms need to be proposed. There is still no standardization about this.

9.5 Conclusion of Security

Other than the traditional countermeasures defined in the chapter, we can use the learning abilities of the cognitive radios which depend on strong and adaptive reasoning to maintain security. In practice, generally we need to make tradeoffs between security and performance. So, in order to get secure networks we need to compensate it from some performance merits which should not be the most important ones in the application of interest. As a last word, the most important thing while designing a cognitive radio network, we need to consider the security from the very beginning instead of putting security measurements afterwards. Putting them afterwards, much more challenging and generally impossible to completely implement them.

Table 9.1: List of Security issues in the CRN.

Layer	Threat	Countermeasures
Physical	Eavesdropping	Beamforming/relays/MIMO/artificial noise
Physical	Jamming	Channel Hopping/location of attacker
Physical	PUE	Fingerprinting/cryptography/location of attacker
Physical	Learning	Traning a secure environment
Link Layer	Byzantine	Trust schemes/ Game theory
Link Layer	Selfishness	Trust schemes/ Game theory
Application Layer	Threats to SDR	Secure software download and execution

10. PROPOSED ALGORITHM AND RELATED EXPRESSIONS

10.1 Introduction to the Algorithm

In this last chapter, I want to give my algorithms and simulated results. However, through the previous chapters, I did not give many mathematical expressions and equations. So, in the first part of this chapter, I am going to give the basic models used in the networks, the mathematical expressions and theoretical equations related to the my algorithms. As I already referred them in their parts through this thesis work, any other mathematical expressions and theoretical equations do not directly related to the my algorithm can be found on the references given.

10.2 Energy Detection based Spectrum Sensing

Like I already defined the energy detection, it depends on the energy computation of the received signal. Then, let me start with the fundamental model of the energy detection. The model depends on the classical binary hypothesis. There are two options which are presence of the signal and the absence of the signal. When primary user is present, cognitive radio receives both energy of the primary signal and the energy of the noise. On the other hand, when primary user is absent, cognitive radio only receives the energy of the noise. We can model this as classical binary hypothesis test as follows:

$$H_0 : y(n) = w(n) \qquad H_1 : y(n) = x(n) + w(n) \qquad (10.2.a)$$

Where $y(n)$ is the received signal at the cognitive radio. $w(n)$ represents the noise signal while $x(n)$ represents the primary user signal. So, H_0 is the where cognitive radio decides the primary user is absent. Contrarily, H_1 is where cognitive radio decides the primary user is present. Hypothesis test tells us that we need to define a test statistic(Λ) to make this decision over N number of samples.

Then we are comparing this test statistic to a pre-determined or calculated threshold level(λ).

$$\Lambda \underset{H_0}{\overset{H_1}{\gtrless}} \lambda, \quad (10.2.b)$$

In the energy detection, we can determine this test statistic by actually defining the energy detector;

$$\Lambda_E = \frac{1}{N} \sum_{n=0}^{N-1} |y(n)|^2 \quad (10.2.c)$$

The test statistic of energy detector is widely covered in the literature and threshold levels for different networks are given. So, the ROC performance results are also widely covered according to the success of the binary thesis through simulations and theoretical derivations. I am going to give some of the related ones in this chapter. We know that, we are expressing the ROC performance of the spectrum sensing with three main merits which are probability of detection, probability of false alarm, probability of miss-detection. Hence, I will mainly express this merits and explain the differences with different models.

Now, I want to continue with energy detector expressions.

As the number of samples used in the energy detector increases, with the usage of the central limit theorem, the test statistic approximates as Gaussian:

$$T = \Lambda_E; \quad (10.2.d)$$

$$H_0 : T \sim N(N\sigma_w^2, 2N\sigma_w^4)$$

$$H_1 : T \sim N(N(\sigma_w^2 + \sigma_x^2), (2N(\sigma_w^2 + \sigma_x^2))^2) \quad (10.2.e)$$

Probability density function(PDF) of the received samples can be derived as:

$$p(y|H_0) = \frac{1}{(\sqrt{2\pi\sigma^2})^N} e^{-\frac{\sum_{i=1}^N y_i^2}{2\sigma^2}}$$

$$p(y|H_1, s) = \frac{1}{(\sqrt{2\pi\sigma^2})^N} e^{-\frac{\sum_{i=1}^N (y_i - s_i)^2}{2\sigma^2}} \quad (10.2.f)$$

where s presents the amplitudes of the unknown signals.

Both using this PDFs and the generalized likelihood ratio test approach, we can give the distributions of the energy detector as follows:

$$P_{T|H_0}(x) = \frac{1}{\theta_0^{k_0} \Gamma(k_0)} x^{k_0-1} e^{\frac{-x}{\theta_0}}, \quad x \geq 0$$

$$P_{T|H_1}(x) = \frac{1}{\theta_1^{k_1} \Gamma(k_1)} x^{k_1-1} e^{\frac{-x}{\theta_1}}, \quad x \geq 0 \quad (10.2.g)$$

where k is a shape parameter $k_0=N/2$ and the $\theta_0=2/N$ is the scale parameter. So, they have showed that the PDF of the energy detector under absence hypothesis follows a chi-square distribution or a gamme distribution. On the other hand, the PDF of energy detector under presence hypothesis follows a Gamma distribution with $k_1=N/2$ and the $\theta_0=2/N(1+\gamma)$ where $\Gamma(.)$ denotes the complete Gamma function.

According to this test statistic expressions, we can give the local probability of detection and probability of false alarm as follows:

$$P_d = \Pr(y > \lambda/H_1)$$

$$P_f = \Pr(y > \lambda/H_0) \quad (10.2.h)$$

Also we can give probabilities of the energy detector as follows:

$$P_f = Q\left(\frac{\lambda - N\sigma_w^2}{\sqrt{2N\sigma_w^4}}\right)$$

$$P_d = Q\left(\frac{\lambda - N(\sigma_w^2 + \sigma_x^2)}{\sqrt{2N(\sigma_w^2 + \sigma_x^2)^2}}\right)$$

$$P_m = 1 - P_d \quad (10.2.i)$$

To understand this expressions, I want to remind you that σ_w^2 represents the energy of the noise signals calculated or estimated by cognitive radio while σ_x^2 represents the energy of the primary signal calculated or estimated by the cognitive radio. So, we can show the Signal-to-noise ratio(SNR) measured by the cognitive radio as follows;

$$SNR = \gamma = \frac{\sigma_x^2}{\sigma_w^2} \quad (10.2.j)$$

Q is the marcum Q -function which is a widely used function in the communications networks. Details and derivations outside of the cognitive radio theme can be found in [19,20]

10.3 Cooperative Spectrum Sensing

10.3.1 Hard decision

In the hard decision based networks, every cognitive user first takes its' local decision based on their own observations on the channel or based on the received signal features like energy, power or cyclostationary features. Then the local decisions will be sent through reporting channels to the fusion center. In the fusion center, combination of the local decisions gives us a global decision. There are various method to combine the local decisions in the fusion center. However, the most common and traditional methods are logical rules based methods like 'AND' and 'OR'. There is one another generalized method which names as k -out-of N rule. N is the number of cognitive radios in the cooperation who sends local decisions to the fusion center. If number of k users or more users decide there is not a presence of the primary user in the channel, then fusion center decides like that as well and allow cognitive users to use the channel. Contrarily, if less than number of k users decide there is not a presence of the primary user in the channel, then fusion center cant accept that since there is a increased probability of interference to the primary user according to the scheme. We can say this decision is a recessive decision which directs the cognitive radios more safe way. As I already mentioned once that, as the logical rules suggest, 'AND' rule means that to take a global decision(H_1), every cognitive radios should agree with each other. They should have the same same local decision. 'OR' rule means that to take a global decision(H_1) only one local decision from cognitive radios is sufficient. So, 'AND' rule is actually a special case of k -out-of N rule where k equals to N . On the other hand, 'OR' rule is a special case of k -out-of- N rule where k equals to 1. First, I want to give the generalized ROC equations of these rules.

Test statistics of the k-out-of-N rule as follows where D_i is the local decision of the i -th cognitive radio:

$$T = \sum_{i=1}^N D_i < k \text{ for } H_0$$

$$T = \sum_{i=1}^N D_i \geq k \text{ for } H_1 \quad (10.2.k)$$

When there is a common threshold for each cognitive radio, we can express the global probability of detection, probability of missdetection and global false alarm rate as follows:

$$\begin{aligned} Q_d &= \sum_{i=k}^N \binom{N}{i} P_d^i (1 - P_d)^{N-i} \\ Q_f &= \sum_{i=k}^N \binom{N}{i} P_f^i (1 - P_f)^{N-i} \\ Q_m &= 1 - \sum_{i=k}^N \binom{N}{i} P_d^i (1 - P_d)^{N-i} \end{aligned} \quad (10.2.l)$$

So, we can also express the rates for special cases of k-out-of-N scheme which are the logical ‘OR’ and ‘AND’ rules:

$$\begin{aligned} Q_m^{OR} &= (P_m)^N, \\ Q_d^{OR} &= 1 - (P_m)^N \\ Q_f^{OR} &= 1 - (1 - P_f)^N \end{aligned} \quad (10.2.m)$$

$$\begin{aligned} Q_m^{AND} &= 1 - (1 - P_m)^N \\ Q_d^{AND} &= (1 - P_m)^N \\ Q_f^{AND} &= (P_f)^N \end{aligned} \quad (10.2.n)$$

I repeatedly pointed out that, in the cognitive radio networks, the most important performance metrics are ROC curves of probability of detection and probability of false alarm. There are two common ways to make a performance model for cognitive radio networks. First one is the, increasing the probability of detection which also corresponds to a decreasing of the probability of misdetection. Second is the, decreasing the total error rate which corresponds to a decreasing of the sum of the probability of false alarm rate and the probability of the misdetection.

$$P_d = 1 - P_m \quad Q_d = 1 - Q_m \quad (10.2.o)$$

Total Error Rate for Single Radio :

$$E_{total}^P = P_m + P_f \quad (10.2.p)$$

Total Error Rate for Cooperation :

$$E_{total}^Q = Q_m + Q_f = \sum_{i=k}^N \binom{N}{i} P_f^i (1 - P_f)^{N-i} + 1 - \sum_{i=k}^N \binom{N}{i} P_d^i (1 - P_d)^{N-i} \quad (10.2.r)$$

First way can also be separated into two parts. We know from the explanation in cooperative sensing chapter that, probability of false alarm rate indicates the throughput of the network. On the other hand, probability of detection rate indicates the measure of the interference of the system. So, we can increase the throughput and decrease the interference by optimizing these indicators. Since we are investigating the cooperative network related to k-out-N decision rule. We should make this optimizations subject to the k. We can express the optimization models as follows to understand it better. First optimization is the solution of the throughput problem. So we are minimizing the false alarm rate. Second optimization is the solution of the interference problem. So, we are maximizing the detection rate. Before expressing the optimizations models, I want to remind the relation between the threshold and the false alarm-detection rates. In the decision test, we are comparing test statistics to the threshold. Under the assumption of constant test statistic, if we were to increase the threshold the detection probability would decrease.

On the contrarily, if we were to decrease the threshold, the false alarm rate would increase. In mathematical terms, it has been shown that Q_d is a monotonically decreasing function of the threshold while Q_f is a monotonically increasing function of the threshold.

$$\begin{aligned}
& \min_{k, \text{Threshold}} Q_f(k, \text{Threshold}) \\
& \text{subject to } Q_d \geq b, \quad 1 \leq k \leq N \\
& \max_{k, \text{Threshold}} Q_d(k, \text{Threshold}) \\
& \text{subject to } Q_f \leq c, \quad 1 \leq k \leq N
\end{aligned} \tag{10.2.s}$$

We can solve this optimization problems for different setups with different methods. For one example, neglecting effects of other parameters, we can find what is the optimum number of k by using the optimization with exhaustive search algorithms. This means we are searching for an answer for how many cognitive users in active cooperation gives us better performance in this setup.

10.3.2 Proposed algorithm and performance results

After giving the basic equations for both the energy detection and cooperative spectrum algorithms, now I want to move on to the my proposed algorithm. Most of the work toward cooperative spectrum sensing algorithms consider the model where the noise uncertainties are neglected. I already mentioned that two important things should be considered when you want to model a network with noise uncertainties. First, increasing of the noise uncertainty makes it difficult to estimate the noise variance. In fact, in [19], they have proved that with the certain level of noise uncertainty, we would hit a SNR wall where the detection of the primary signal becomes impossible since we cant have a optimal threshold level due to the obscurity of noise variance. Even if we do not hit the SNR wall, we would have deteriorated SNR levels due to the uncertainty levels are different from the zero. So, from the theoretical literature perspective, it is convient to model the networks neglect noise uncertainties. However, we also should consider practical models with noise unceratinities. In fact, in 2011, [27], they have proved that even if we cant estimate noise variance completely, unless accuracy of the noise power estimator does not

decrease with the measurement time, we won't hit a SNR wall. Also, in estimation schemes, with the increased number of samples or the sensing time, the accuracy generally improves. It has been shown in so many works. I will give the basic simulation results to show how the increased number of samples improve the performance of the energy detectors depend on the estimation of the noise variance.

To get better estimation of the noise variance, noise only samples should have been collected. In practice, it is hardly possible. One of the recognized and in use method is using aforementioned two step sensing schemes. IEEE 802.22 standard has been made depending on the usage of such scheme. As you can see from the next figure, it has two different sensing algorithms. One is fine sensing with longer sensing times. The second one is the fast sensing with smaller sensing periods. To make sure we get noise only samples, instead, we can make sure that we don't get any primary signal samples. It can be possible with more complex and sophisticated detection algorithms. One such example is to use cyclostationary detection algorithm in the fine sensing. We know that, usage of the cyclostationary detection requires more conditions to use it robustly comparing the energy detection. However, it gives so much better detection performances under the assumption of it provides the conditions required. So, when the detection test of the cyclostationary detection tells it got noise only samples(H_0), we can use it to estimate the noise power for the fast sensing part. In fast sensing part, generally more simpler energy detection algorithms will be employed. The shorter sensing time needed for the fast sensing gives the opportunity of the detect the primary signal as fast as possible. While fine sensing part has longer sensing times, it also has lower period levels. So, we are kinda managing the costs it could bring to the network by adjusting the period levels. The last thing I want to mention here that, the most practical and efficient way of the estimation of the noise variance is using the maximum likelihood criterion when we are certain that we can get noise only samples. So, in my proposed algorithm, I assumed that we can get noise only samples thanks to the two step sensing scheme, and I used maximum likelihood method to estimate the noise variances. So, even if it is not completely practical, my algorithm is suitable for IEEE standard.

Even though traditional energy detection algorithms are so much simpler, the performance results suffer at the low SNR regions. However, in cooperative networks, some proposed mechanism which improve the traditional detection schemes has showed that, with the increased number of users participating the cooperation, we can get convenient performance results.

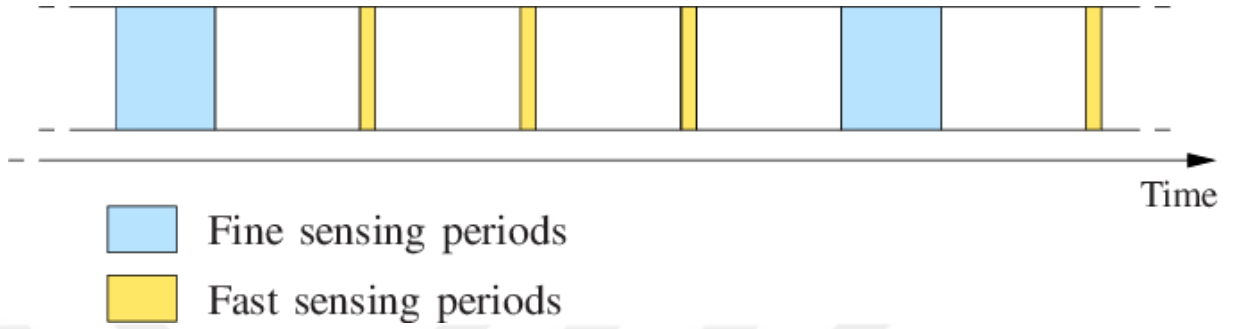


Figure 10.1: Periods of two staged sensing schemes.

In 2015, Verma Pankaj and Singh Brahmjit, [2] proposed a model using double threshold based energy detection instead of single threshold based traditional energy detection. In cooperative sensing, fusion of the datas or the decisions been made by the individual cognitive radios are the another important part in addition to the detection algorithm. So, they used hard decision based fusion technique where the individual cognitive radios make their own local decisions and send it to the fusion centre. However, to increase the reliability of the global decision and the network, taking into account the loss of some information, they have determined the thresholds are considering noise uncertainty parameter(p) as follows and made the simulations under the assumption of perfect estimaton or knowledge of the noise uncertainty can be known.

$$Threshold_{main} = Q^{-1}(P_{fa})\sqrt{2N\sigma_w^4} + N\sigma_w^2$$

$$Threshold_{upper} = (1 + p)Threshold_{main}$$

$$Threshold_{lower} = (1 - p)Threshold_{main} \quad (10.2.t)$$

where $p \geq 1$, however, in my algorithm I arranged the lower limit of range of noise uncertainty parameter as $0 \leq p$. You can visualize this as, when $p=0.01$, it roughly equals to the 1 percent of noise fluxcations and $p=0.1$ means 10 percent.

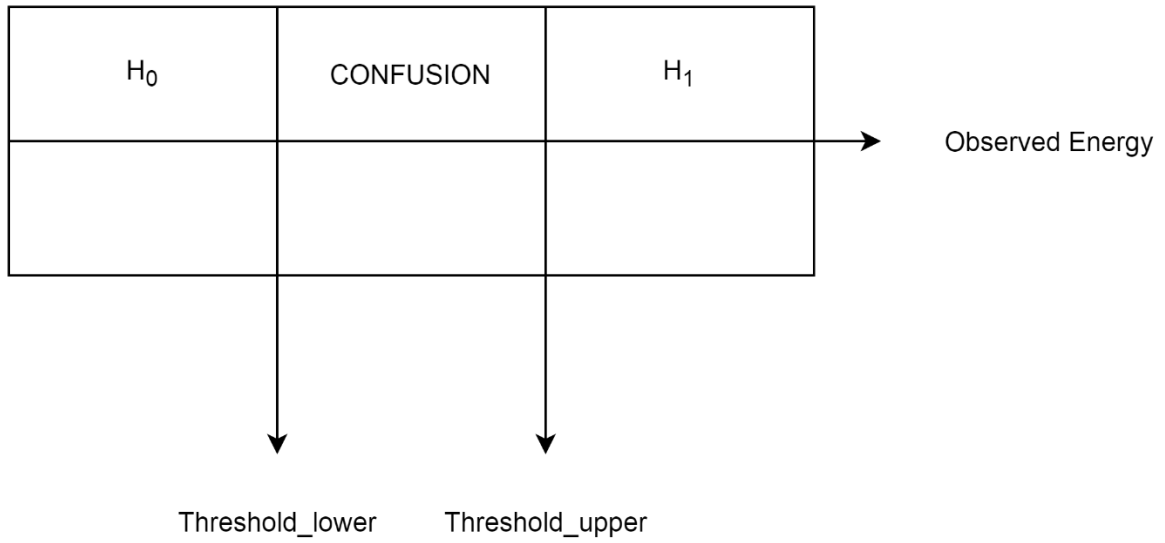


Figure 10.2: Double Threshold Scheme.

So, if the test statistic which is the estimation of the noise power falls to the H_0 or H_1 regions, the individual cognitive radios take the local decisions and send it to the fusion center. However, if the test statistic falls in the confusion region, unlike traditional hard decision schemes, the individual radios don't take local decision, instead they would send the estimated noise power to the fusion center. Comparing with the traditional way, it increases the cooperative overhead a little bit by forcing FC to process the estimated noise powers. Another problem is the reporting channels. Instead of transmitting one bit decisions, they should transmit bigger data blocks. In both this paper and my proposed algorithm, we are assumed that we have error-prone reporting channels and we neglected the issues might arise from reporting channels to give a sight to another part of the theoretical work. In the fusion center, they have employed a method based on traditional OR scheme. Before employing the OR scheme, first fusion center should have processed the data sent due to the confusion region. The processed mechanism used here is very simple. Fusion center averages the estimated noise powers, then compares it with the main threshold to take another decision like local decisions. In the last stage, the local decision sent by individual radios and the decision in the fusion center are combined by the traditional OR scheme to take a global decision. This averaging part causes the loss of information. However, it will increase the reliability of the global decision and the network. They have showed that, their proposed algorithm gives compatible performance results under good SNR

conditions. However, their proposed algorithm gives better results under bad SNR regimes compared to good SNR conditions.

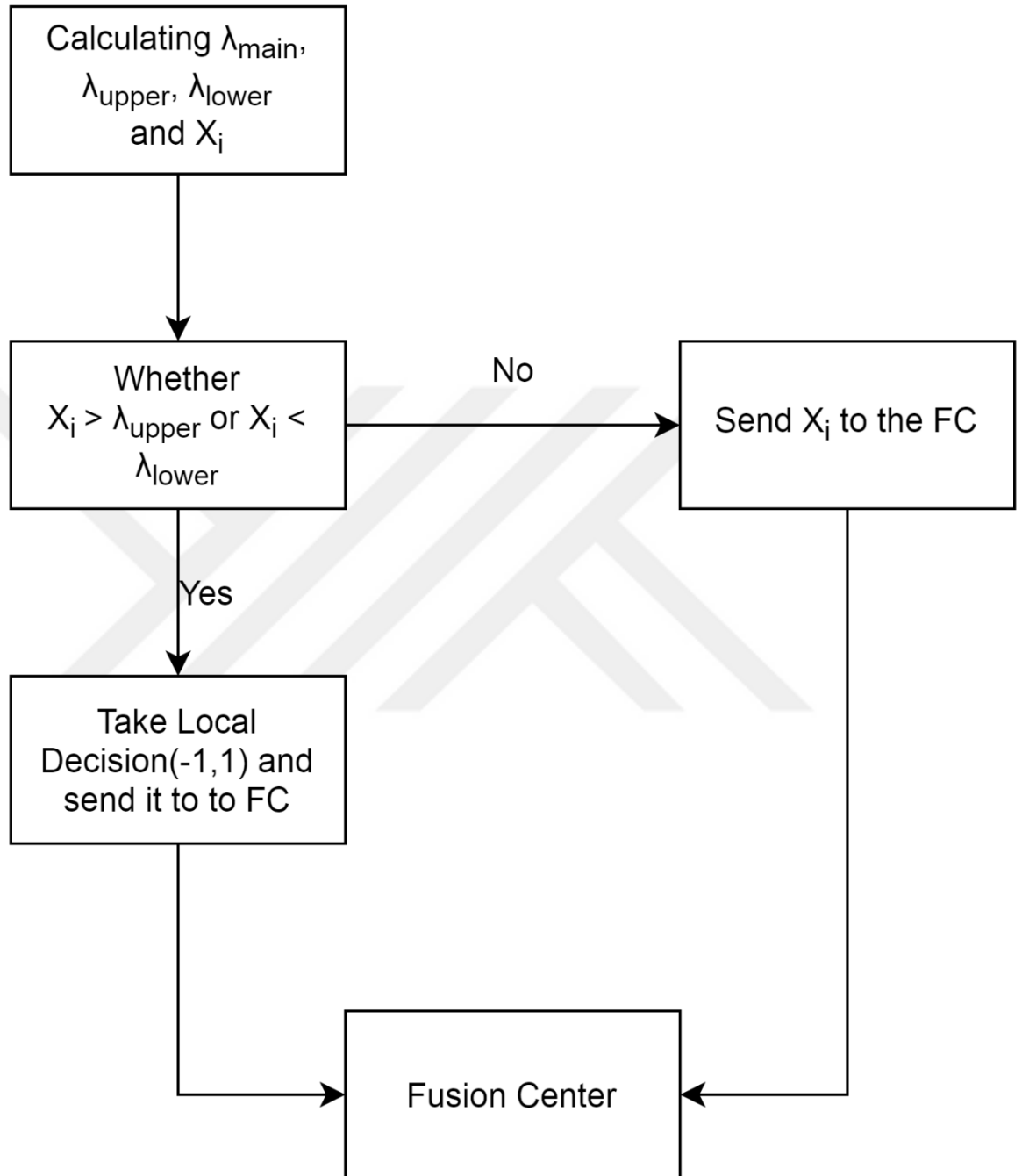


Figure 10.3: Algorithm of Double threshold scheme.

At this point, I decided to investigate this model which determines the threshold level according to the noise uncertainty rate under more practical approach. I tested the both conventional method and proposed method in (2), under the path loss effect which deteriorates the performance massively. They both affected significantly. So, to overcome this issue, I proposed an weighted based fusion scheme at the fusion center instead of conventional OR method, using same double threshold model. The local decisions of cognitive radios are weighted according to how much signal power they get received. Too closer to the primary user, too higher received power one cognitive radio gets since path loss effects grow with the distance between the cognitive user and licensed user. After averaging the received powers come from the confusion region, I assigned it to a single weight. It means without considering how much cognitive radio falls into confusion region, I added their effects as one. From simplistic perspective, this leads loss of information. However, it actually increases the reliability of the detection. The local decisions made in the H_1 and H_0 areas are almost perfect since thresholds are determined considering noise uncertainty. However, confusion area gives uncertain informations. So, without completely discarding it, reducing the impact of that informations, clearly improves the both reliability and detection performance.

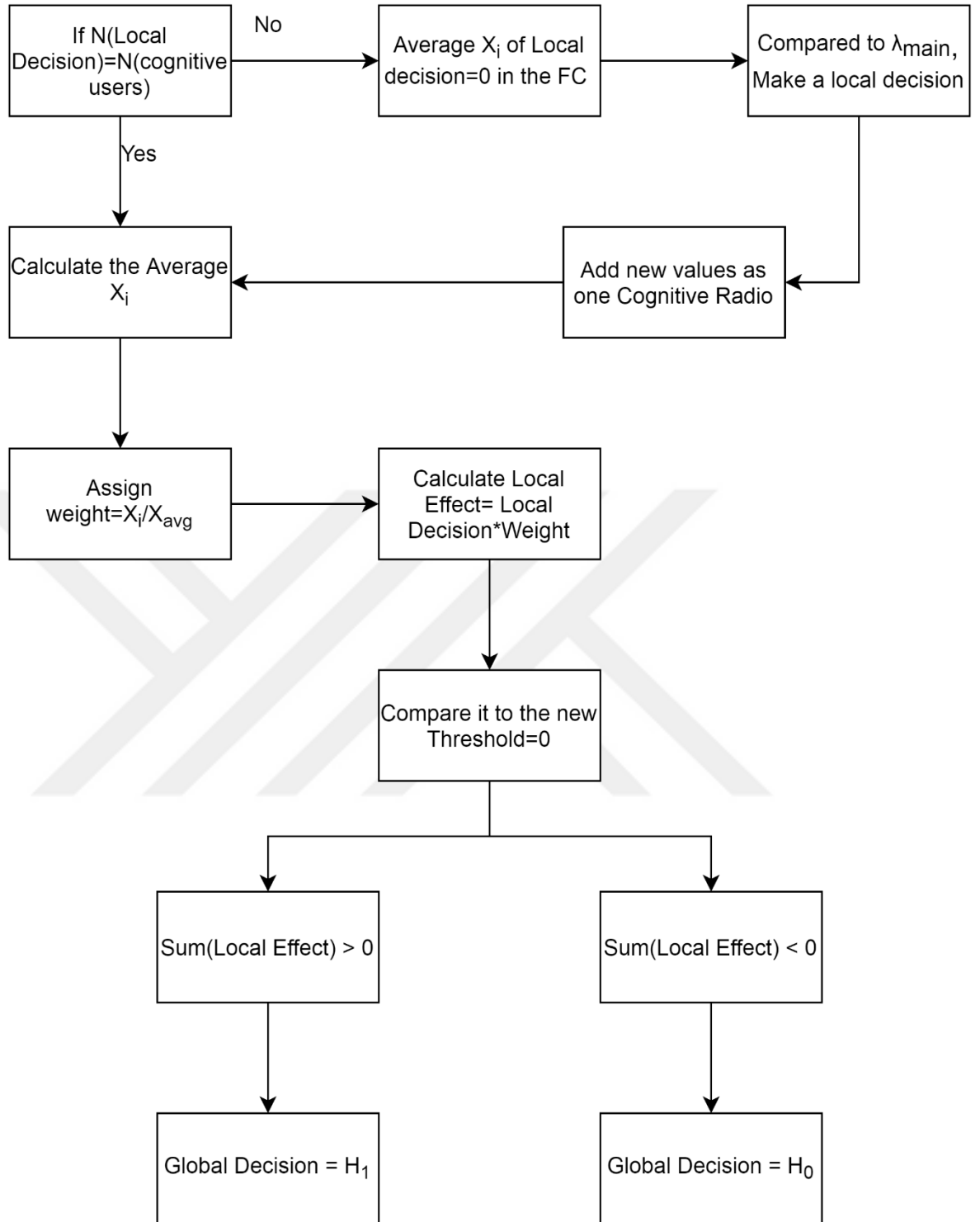


Figure 10.4: General Algorithm used in the Fusion Center.

General model of my proposed algorithm can be followed:

1) Individual cognitive users take local decisions if and only if observed energy X_i (observed energy results) lies above λ_{upper} , or below λ_{lower} ,

$$Local\ Decision = \begin{cases} +1, & X_i > \lambda_{upper} \\ -1, & X_i < \lambda_{lower} \end{cases} \quad (10.2.u)$$

2) Else, cognitive radios fall into confusion region only send the observed energy results without making any local decisions.

3) K is the number of local decisions sent to the FC, while $W = m-K$ is the number of users fall into confusion region. In the FC, these $m-K$ number of users be counted as one device. The test statistic is calculated by the averaging $m-K$ number of observed energy results. Comparing with the main threshold, a local decision has been made to add to the global decision fusion.

$$X_{avg} = \frac{1}{m-K} \sum_{i=1}^{m-K} X_i$$

$$New\ Local\ Decision = \begin{cases} +1, & X_{avg} > \lambda_{main} \\ -1, & X_{avg} < \lambda_{main} \end{cases} \quad (10.2.v)$$

4) Now, it is time to move on to the weighted fusion:

4i) If $K=m$;

$$ave_{wk} = \frac{1}{m} \sum_{i=1}^m X_i$$

$$weight_i = \frac{X_i}{ave_{wk}}$$

$$local\ effect_i = Local\ Decision_i * weight_i$$

$$New\ Test\ Statistic(NTS) = \sum_{i=1}^m local\ effect_i$$

$$Global\ decision = \begin{cases} 1, & if\ NTS > 0 \\ 0, & if\ NTS < 0 \end{cases} \quad (10.2.w)$$

4ii) If $K < m$, W is the number of users fall into confusion region;

$$total = \sum_{i=1}^K X_i + \frac{1}{W} \sum_{j=1}^W X_j$$

$$ave_{wk} = \frac{total}{K + 1}$$

$$weight_i = \frac{X_i}{ave_{wk}}$$

$$local\ effect_i = Local\ Decision_i * weight_i$$

$$New\ Test\ Statistic(NTS) = \sum_{i=1}^{K+1} local\ effect_i$$

$$Global\ decision = \begin{cases} 1, & \text{if } NTS > 0 \\ 0, & \text{if } NTS < 0 \end{cases} \quad (10.2.x)$$

I simulated my algorithms and the results show the significant improvements when we employ my proposed algorithm under different noise uncertainty levels and path loss effect. I generated BPSK primary signals for every cognitive radios with same SNR at first. Then, I added additional white gaussian noise with zero mean and also added Rayleigh slow fading effects to the channels between cognitive users and primary user. I simulated my model using Monte Carlo Simulations with 1000 simulations. Simulations has been made considering pre-determined false alarm rate to show probability of detection rates corrsesping to that false alarm rates. To add path loss effect, I simply assigned random distances between primary user and cognitive users. Model is consisting of $m=5$ number of cognitive users with one primary user, $N=200$ number of samples for fast sensing scheme. It has been proved in every CSS related work that, increased number of participant in the cooperation improves the performance results despite increased cooperative overhead due to the increased informations should be processed. Same occurs with the number of samples. Incrased number of samples, gives a chance to get better noise estimation and signal detection. However, to get higher number of samples, we need to monitor the radio channel for higher time interval which decreases the latency and some other performance merits despite of the increased detection performance. So, like I repeatedly said that trade-offs matter in the designing a model and deploying the network according to needs and conditions. So, I kept the number of cognitive radios and number of samples relatively

small to prove my algorithm clearly. Before passing the performance results of my proposed algorithm compared to the conventional method and previously proposed double threshold algorithm, you can see how N affects the local detection performance from the next figure.

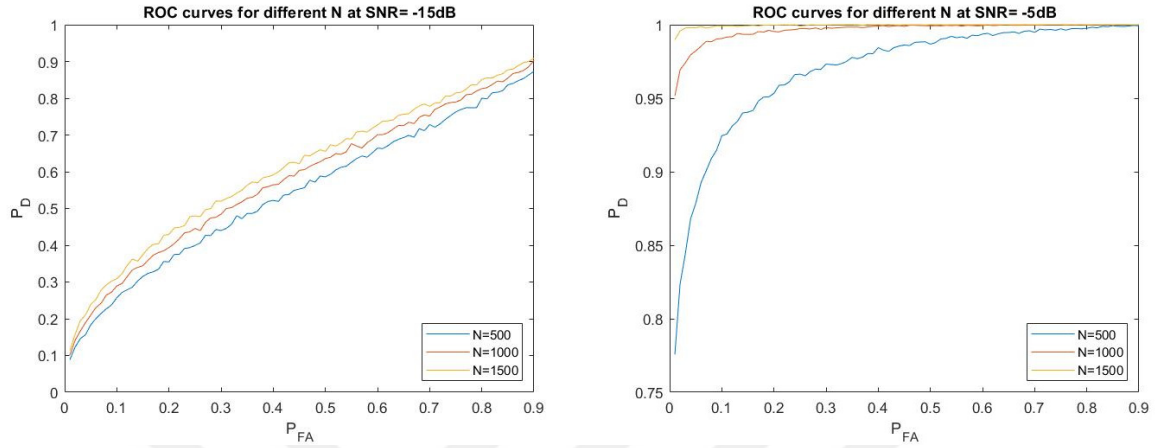


Figure 10.5: Effects of the number of samples.

In addition, the following figure shows how noise uncertainty affects the performance of a single radio.

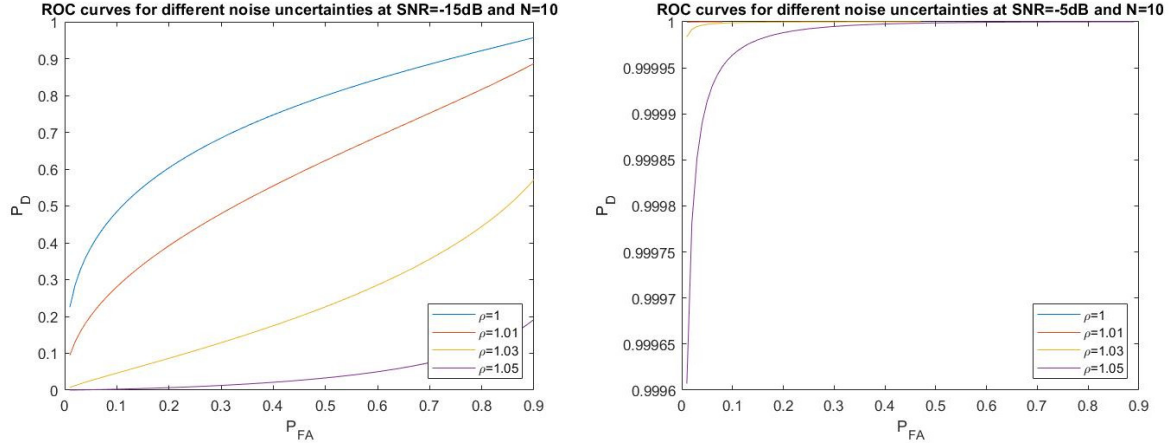


Figure 10.6: Effects of the noise uncertainty level.

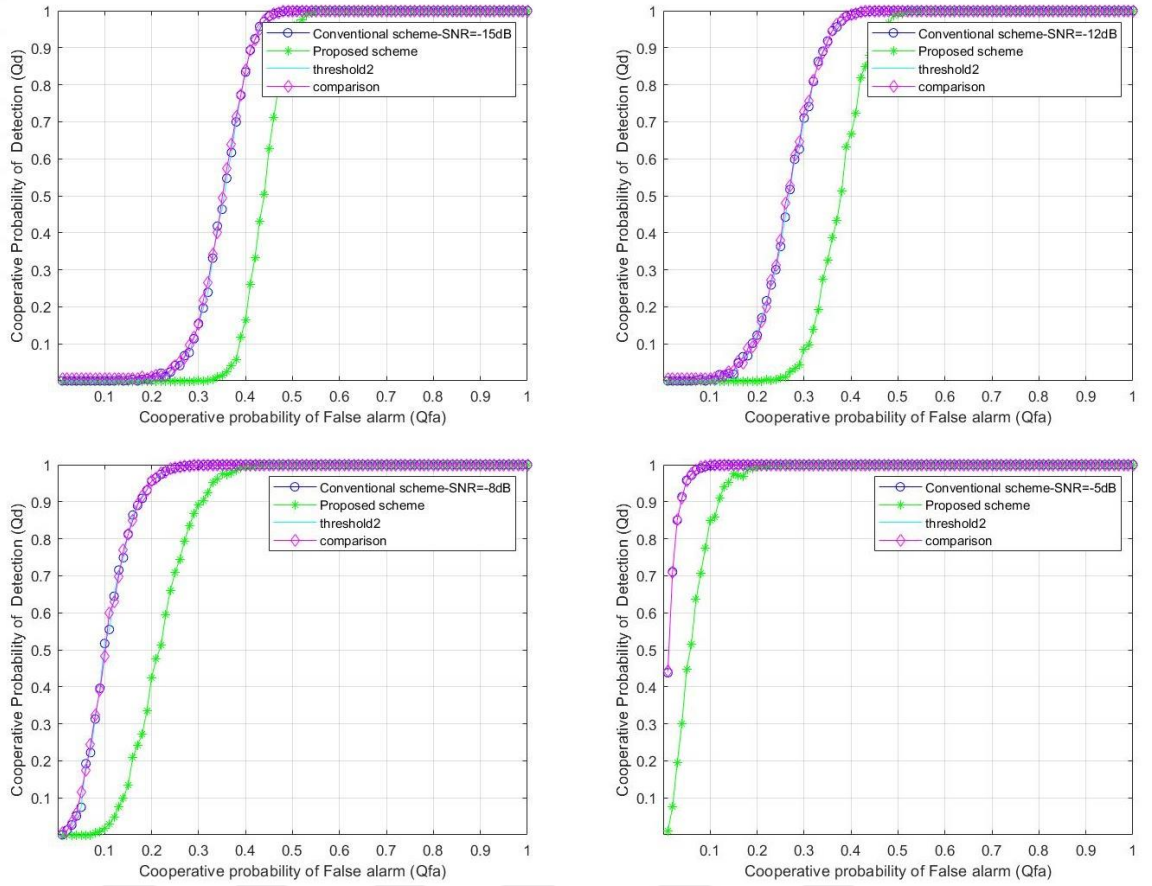


Figure 10.7: Empty model with different SNR conditions.

The figure 10.7 gives the results of the model where there is no noise uncertainty and path loss with different primary signal SNR levels. Even in this scenario, proposed scheme gives very close and compatible performance results. Clearly seen that, with the improving SNR conditions both proposed scheme and the conventional scheme gives better performance results.

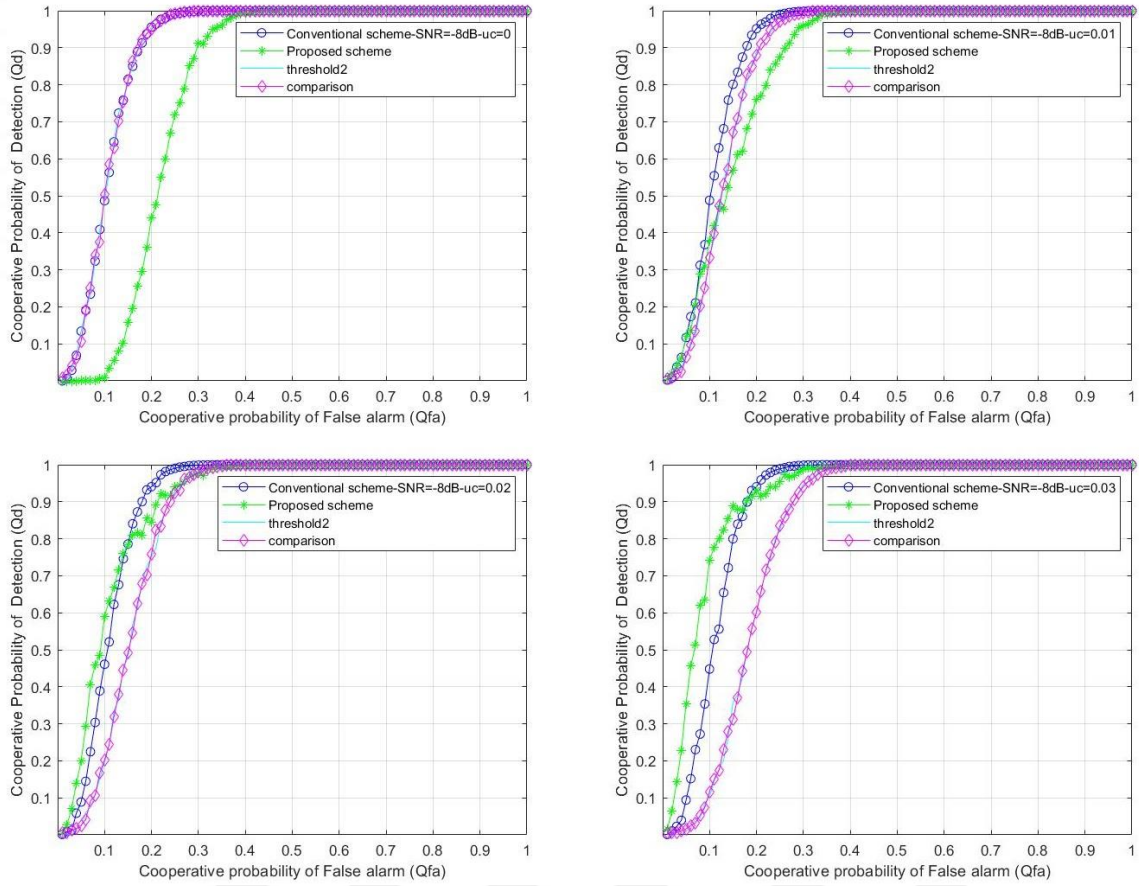


Figure 10.8: Effects of the noise uncertainty parameter to the every model.

The figure 10.8 gives the results of the model where noise uncertainty parameter changes while there is not any path loss effects with same SNR conditions. Clearly seen that, even under very small levels of noise uncertainties, the proposed scheme improves its' performance results compared to conventional method in the relatively bad SNR conditions. Moreover, with the increased level of noise uncertainty, the proposed scheme outperforms the conventional scheme and the reference double threshold scheme. As we further increase the noise uncertainty levels, the difference between the performance results keep increasing. However, since I made an assumption about knowing the certain noise uncertainty levels, it will conflict as it becomes harder to estimate this noise uncertainty level in practice with the increase. So, these levels are sufficient to prove the results. The further I increase the level, the further we go from the reality. However, I should mention here that, in practice noise uncertainty levels can go so much higher because of the issues arise in the networks. So, we need more strong and complex algorithms to estimate the noise uncertainty levels or we have to employ other detection algorithms instead of E.D.

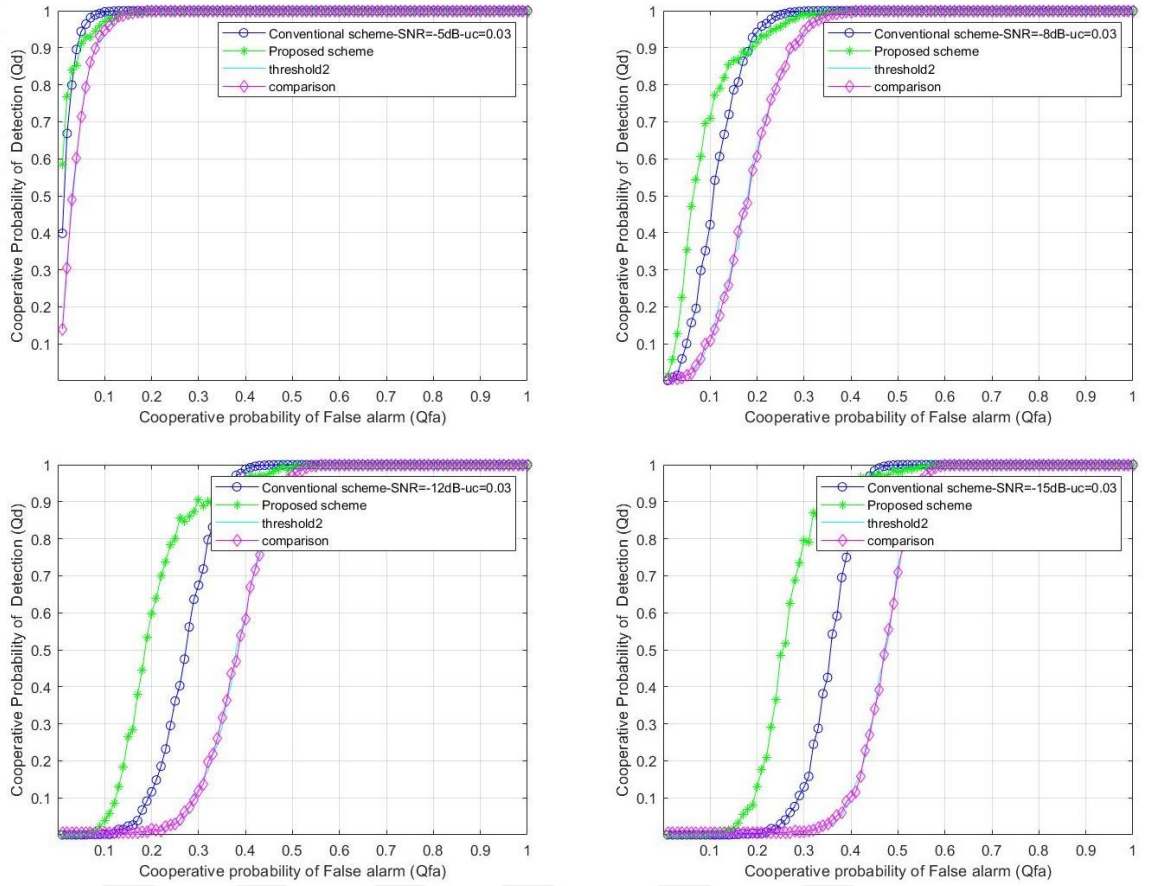


Figure 10.9: Bigger noise uncertainty level with different SNR conditions.

Figure 10.9 shows the results of the model where noise uncertainty parameter equals to the 0.03 with different SNR levels. So, in the effect of the noise uncertainty, the proposed scheme gives better performance results in the bad SNR regimes. Contrarily, as the SNR conditions improve, conventional method takes the lead in terms of the performance results even under relatively big levels of noise uncertainty.

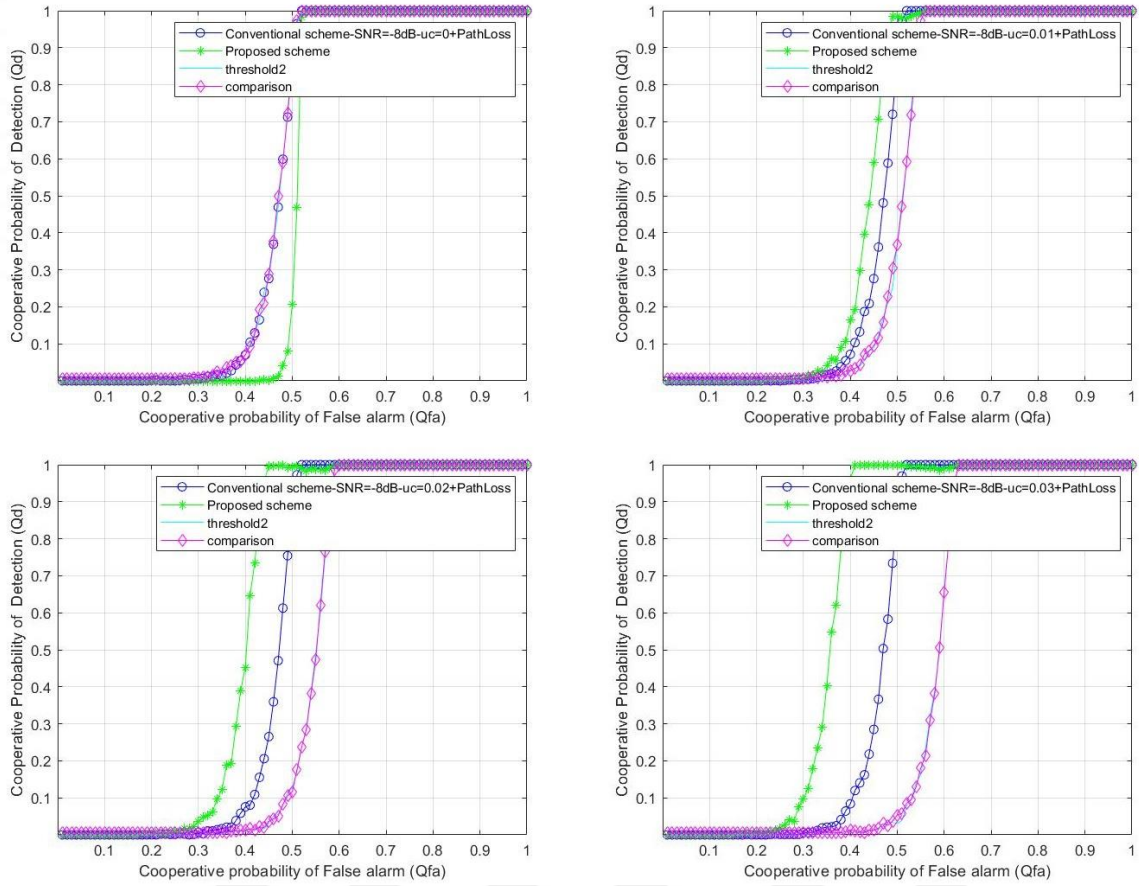


Figure 10.10: Deteriorating effects of path loss.

Figure 10.10 shows the results of the model where noise uncertainty levels change at the same SNR conditions while now model is affected by the path loss. Compared to the model where no path loss effects, we can clearly see that, the performance results of both proposed scheme and conventional scheme deteriorates massively. However, compared to conventional scheme, proposed scheme gives so much better performance results now under relatively bigger levels of noise uncertainty.

11. CONCLUSION

In my research, I explained how can we enable the dynamic spectrum management by using Cognitive Radio Technology. I explained important narratives of CR and the design issues. Then, specifically investigated the spectrum sensing function of the CR. I have built an algorithm for Cooperative Networks where multiple users make a cooperation to improve the detection probability and the reliability of the network. The proposed algorithm uses the double threshold based energy detection model for the local observations where the thresholds are determined considering to noise uncertainty level. Then, in the fusion center, a weighted global decision fusion mechanism is employed where who gets the bigger received energies have bigger impact on the global decision to increase the reliability of the detection. The proposed algorithm makes bigger performance improvements compared to the reference work under the effect of the changing noise uncertainty levels and the path loss. Compared to conventional methods, the proposed algorithm also gives compatible results in relatively good SNR conditions, while it gives better results in the bad SNR regimes.

For future work, more comprehensive framework over path loss effects can be made using proposed algorithm where the both CR users and primary user is mobile which means their locations and speeds are changing with time. As a bigger and new work, I can build a model for estimating the noise uncertainty levels using machine learning techniques. One of my ex-project is the PHY security in MIMO systems with the antenna selection algorithms in order to increase secrecy capacity, so I also want to build a framework on the security issues in the CRN where the proposed algorithm can be used.



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APPENDICES

The Matlab Code

```
clc;
clear all;
format long
C=2;
a=2; %pathloss parameters
N = 200;
snr_dB = -8; %dB
snr = 10.^(snr_dB./10);
Pf = 0.01:0.01:1;
uc = 0.01;
% BPSK Signal
L=1500;
data = round(rand(1,L)); % Data sequence
uni2bip=2*data-1; % Convert unipolar to bipolar
T=1; % Bit duration
Eb=T/2; % This will result in unit amplitude waveforms
fc=3/T; % Carrier frequency
t=linspace(0,5,1500); % discrete time sequence between 0 and
5*T (15000 samples)
K=length(t); % Number of samples
Nsb=K/length(data); % Number of samples per bit
dd=repmat(data',1,Nsb); % replicate each bit Nsb times
bb=repmat(uni2bip',1,Nsb); dw=dd'; % Transpose the rows and columns

dw=dw(:)';
%----- Convert dw to a column vector (column by column) and convert to a row vector
```

```

bw=bb';
bw=bw(:)'; % Data sequence samples
w=sqrt(2*Eb/T)*cos(2*pi*fc*t); % carrier waveform
bpsk_w=bw.*w; % modulated waveform
u=1000;
Pfa = Pf;
Dcv=zeros(5,100);
Dcv2=zeros(5,100);
Fcv=zeros(5,100);
X_avg=0;
for i =1:length(Pf)

    global_detection(i)=0;
    for j = 1:1000 % MOnter carlo döngüsü
        sum_energy = 0;
        local_etki = 0;
        weight= 0;
        new_t_i=0;

        for m=1:5
            d(m)=7+1.1*rand();
            PL=C*(d(m)^-a);
            h1=(randn(1,1)+j*randn(1,1)).*(sqrt(2));
            h=repmat(h1,1,200);
            h=h.*0.001;

            Noise = sqrt(1+uc)*randn(1,N);
            vn=var(Noise);
            Signal = sqrt(snr).*bpsk_w(1:200);
            Signal=Signal.*(abs(h)).*PL;
            vs=var(Signal);
            Recv_Sig = Signal + Noise;
            Energy = abs(Recv_Sig).^2; % Energy of received signal over N samples

```

```
Threshold_0(i) = N*vn + qfuncinv(Pf(i))*sqrt(2*N*vn^2);
```

```
Threshold_1(i) = (1-uc)*Threshold_0(i);
```

```
Threshold_2(i) = (1+uc)*Threshold_0(i);
```

```
X(m) =sum(Energy);
```

```
if X(m) >= Threshold_0(i)
```

```
    Dcv(m,i) = Dcv(m,i) +1;
```

```
end
```

```
if X(m) >= Threshold_2(i)
```

```
    Dcv2(m,i)=Dcv2(m,i)+1;
```

```
    FC(m) = 1;
```

```
elseif X(m)<=Threshold_1(i);
```

```
    Fcv(m,i)=Fcv(m,i)+1;
```

```
    FC(m) = -1;
```

```
else
```

```
    FC(m)=X(m);
```

```
end
```

```
end
```

```
K=0;
```

```
sum_energy_2=0;
```

```
sum_energy=0;
```

```
for m=1:5
```

```
    if FC(m)==1 || FC(m)==-1
```

```
        K=K+1;
```

```
        sum_energy=sum_energy+X(m);
```

```
    else
```

```
        sum_energy_2=sum_energy_2+X(m);
```

```
    end
```

```

        end
W=5-K;
X_avg=sum_energy_2./W;

if W==0
    for m=1:5
        ave_w_k = sum_energy./5;
        weight(m)=X(m)./ave_w_k;
        local_etki(m)=FC(m)*weight(m);
        new_t_i=sum(local_etki);
    end
    if new_t_i >= 0
        QFC(m)=1;
        global_detection(i) = global_detection(i) + 1;
    else
        QFC(m)=0;
    end
end

elseif W~=0
    if X_avg < Threshold_0(i)
        FC(K+1)=-1;
    else
        FC(K+1)=1;
    end
    X(K+1)=X_avg;
    for m=1:K+1

        ave_w_k=(sum_energy+X_avg)./K+1;
        weight(m)=X(m)./ave_w_k;
        local_etki(m)=FC(m)*weight(m);
        new_t_i=sum(local_etki);
    end
end

```

```

        if new_t_i >= 0
            QFC(m)=1;
            global_detection(i) = global_detection(i) + 1;
        else
            QFC(m)=0;
        end

    end

end

    QD(i)=global_detection(i)./1000; %monte carlo sayısı,kaç simülasyon
    for m=1:5
        PDcv(m,i) = Dcv(m,i)./1000;
        PDcv2(m,i)=Dcv2(m,i)./1000;
    end

end

for i=1:100
    PDcvOR(i)=1-prod(1-PDcv(:,i));
    PDcv2OR(i)=1-prod(1-PDcv2(:,i));
end

```



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