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DYNAMIC SPECTRUM ACCESS IN COGNITIVE RADIO NETWORKS:
ASPECTS OF MAC LAYER SENSING

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A thesis

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I have a great pleasure to dedicate this work to my parents who have been giving me more than I need and deserve, for their love, support and sacrifice.

Abstract

Over the past two decades wireless communication systems have been showing great revolution and rapid growth. Therefore, the standardization agencies together with wireless researchers and industry have been working on new specifications and standards to face the high demand for wireless communication systems.

One of the most critical issues regarding wireless networks regulation agencies and researchers are thinking about is how to manage the available electromagnetic radio spectrum in a way that satisfies the needs of these growing wireless systems both economically and technically especially with the recent crowding in the available spectrum. Hence, building cognitive radio systems support dynamic access to the available spectrum has appeared recently as a novel solution for the wireless system huge expansion.

In this thesis we investigate the MAC layer sensing schemes in cognitive radio networks, where both reactive and proactive sensing are considered. In proactive sensing the adapted and non-adapted sensing periods schemes are also assessed. The assessment of the pre-mentioned sensing schemes has been held via two performance metrics, achieved spectrum utilization factor and idle channel search delay.

The simulation results show that with proactive sensing adapted periods we achieve the best performance but with an observable over head computational tasks to be done by the network nodes which reflects the extent of complexity we need in our network nodes. On the other hand reactive sensing is the simplest sensing schemes with the worst achieved performance.

Keywords: *Cognitive Radio, Spectrum Sensing, Reactive Sensing, Proactive Sensing, Spectrum Utilization Factor, Idle Channel Search Delay, Sensing Periods.*

Acknowledgment

My way towards this master thesis would not have been possible without the support of various people. So it is my pleasure to take this opportunity to thank them all.

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Further, I would like to thank all colleagues and friends who made the life during my study much easier and enjoyable than it would be if they are not here! Really we made together unforgotten nice memories in this nice Sweden.

In spite it wasn't easy for them to tolerate the absence of their son all this time, they haven't stopped support, love, giving advises and praying for me, my parents who have been doing a lot for me deserve more than thanking, them and all my family.

Mohamed Hamid

Karlskrona, December 2008.

Abbreviations

1-	**CDMA**	Code Division Multiple Access
2-	**CR**	Cognitive Radio
3-	**DCS**[1]	Dynamic Channel Selection
4-	**DCS**[2]	Digital Cellular Service
5-	**ETSI**	European Telecommunication Standards Institute
6-	**FCC**	Federal Communications Commission
7-	**GSM**	Global System for Mobile communication
8-	**ISM**	Industrial, Scientific and Medical band
9-	**MAC**	Medium Access Control
10-	**OFDM**	Orthogonal Frequency Multiplexing
11-	**OFDMA**	Orthogonal Frequency Multiple Access
12-	**PDF**	Probability Density Function
13-	**PSD**	Power Spectrum Density
14-	**RF**	Radio Frequency
15-	**SDR**	Software Defined Radio
16-	**SSOH**	SenSing OverHead
17-	**SUF**	Spectrum Utilization Factor
18-	**UOPP**	Unexplored OPPortunities
19-	**UMTS**	Universal Mobile Telecommunications Service
20-	**U-NII**	Unlicensed National Information Infrastructure
21-	**UWB**	Ultra Wide Band

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Chapter 1
INTRODUCTION

1.1 Background

Recently wireless networks have been growing very rapidly both horizontally and vertically. Aiming to meet this huge growth in wireless technologies and services, researchers as well as industry have been working towards new techniques and standardizations.

The most critical consequences for that growth in wireless networks are the ones related to spectrum usage and management as electromagnetic radio spectrum comes as the most precious natural resource when we talk about wireless networks.

The existing policies of spectrum management are based on static spectrum allocation for a specific technology and service controlled by regulation agencies like FCC and ETSI. After the appearance of wireless personal communications technologies it became unreasonable to use these policies rely on static spectrum allocation for those technologies regarding economical and technical considerations. In order to solve this Industrial, Scientific and Medical (ISM) bands have been provided as a good solution to handle these types of networks. Nevertheless, after a while ISM bands got congested and over-utilized which affects the quality of communication on those bands and to overcome that software defined radio (SDR) followed by cognitive radio (CR) networks based on dynamic spectrum access have been proposed as a promising solution.

1.2 Software defined radio and cognitive radio:

Over the recent two decades, notions about radios have been evolving from pure hardware-based radios to radios with a combination of hardware and software which referred to as software defined radio (SDR). SDRs are radios with a reconfigurable behavior that radio parameters can be adapted to suit the changes in the surrounding radio environment; modulation scheme, coding scheme and transmitting power are examples of these reconfigurable parameters [1].

Cognitive radios (CRs) are basically SDRs with artificial intelligence, capable of sensing and reacting to their environment changes. This definition of CR makes it wide and contains not only dynamic spectrum access but also any reconfigure ability features such as modulation and coding adaptation, beam forming and power control. [1]. Fig. 1.1 contrasts traditional radio, SDR and CR.

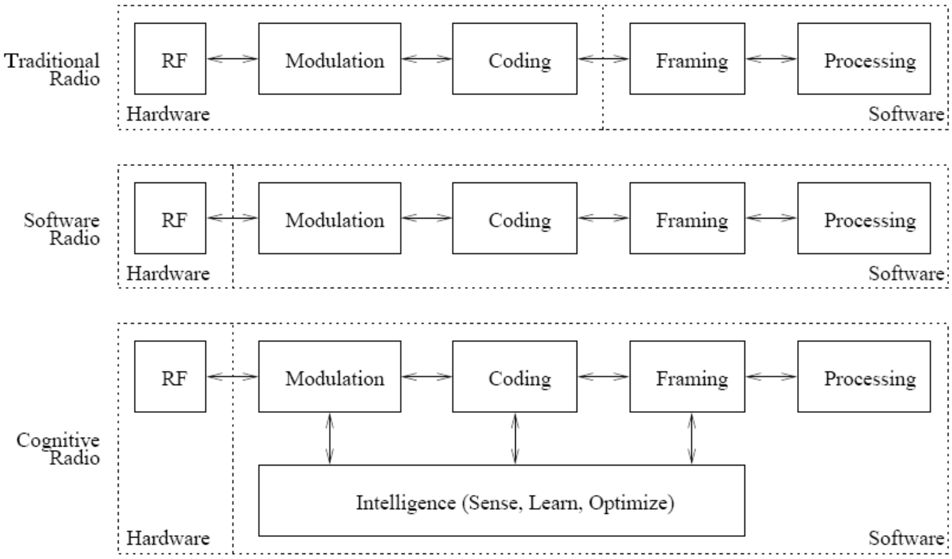

Fig. 1.1 Block diagram contrasting traditional radio, SDR, and CR

1.3 Thesis Motivation:

Cognitive radio still in the stage of research and standardization and most of this standardizations are related to physical and MAC layer as they are the expected layers to be affected more when cognitive radio become omnipresent. In this context physical layer protocols have been investigated more than MAC layer protocols. Moreover, most of the research done in the area of MAC layer have been done under the assumption that the sensing results are available but very little research have worked with sensing itself in MAC layer which is a strong motivation for people want to work in cognitive radio arena to do more investigation in MAC layer sensing including the optional sensing modes and the tradeoffs on that.

1.4 Related Work:

Joseph Mitola is regarded as the father of cognitive radio, who introduced the idea of Software Defined Radios (SDRs) in the early 1990s. In his 2000 dissertation, he took the SDR concept one step further by introducing the term cognitive radio (CR) and that was regarded as the birth of cognitive radio [2-5].

In [6] the authors presented the spectrum access policies and schemes in cognitive networks. In [7, 8] the authors investigated MAC layer sensing schemes and introduced the concepts of adaptive sensing periods in proactive sensing.

1.5 Thesis Outline:

This reminder of this thesis is structured as follows. Chapters 2 and 3 represent the part of foundation and theoretical aspects. Chapter 2 will include some concepts in the area of spectrum access and management. The aspects of MAC layer sensing will be illustrated in details in chapter 3. In addition, channel usage model concept and sensing modes will be discussed in details in this chapter. All the parts of chapter 3 will be supported by mathematical formulas and derivations. In chapter 4 the system model, simulation setup and simulation parameters will be presented. In addition, the assumptions used in the simulations will also be explained throughout this chapter.

The obtained results from the MATLAB based simulations will be presented and analyzed in details in chapter 5. Finally, chapter 6 concludes this thesis work and some recommendations for future work.

Chapter 2
SPECTRUM ACCESS RELATED CONCEPTS

In this chapter some spectrum access aspects in both traditional radio and cognitive radio and dynamic spectrum access related concepts will be discussed. Some of these concepts and terms are totally new, which they appeared when cognitive radio was suggested as a novel approach to overcome the high growth in wireless communications services and users. On the other hand some of these terms and principles already exist but they got some kinds of new meaning and usage with cognitive radio.

2.1 Radio Spectrum Regulation:

There have been different protocols of spectrum regulation rely on a static spectrum allocation policy, which is assigning a specific band to a specific service and its users and whenever this band is assigned to this service then it is fully dedicated for *just* the users of this service. This static allocation policy has some limitations especially with the huge growth in wireless services and technologies and to overcome that a new policy of distributing the spectrum dynamically is provided in cognitive radio networks.

2.1.1 Licensed Spectrum:

With licensed spectrum a frequency band is sold for being used by a specific service and consequently this sold band can be accessed by the users of that service whenever they want. There are two types of licensed spectrum; licensed spectrum for exclusive and licensed spectrum for shared usage [6].

- Licensed spectrum for exclusive: the regulator protects the spectrum usage. For exclusive usage rights one example is the bands assigned and sold for UMTS. Exclusive access rights have the advantage of preventing potential interference and then providing robust communication.
- Licensed spectrum for shared usage: in this case the spectrum is restricted to a specific technology and inside this technology the spectrum can be shared among many service providers or operators. The frequencies assigned to GSM are an example for that kind of licensed spectrum. This model is the most used licensing model. Regulator takes care of emission parameters like transmission power and interference to neighboring frequencies in order to achieve as high communication reliability as possible. Limited support of coexistence capabilities in this model can be found such as Dynamic Channel Selection (DCS)

2.1.2 Unlicensed Spectrum:

Unlicensed Spectrum is the open frequency bands to be utilized by an unlimited number of users. The utilization of unlicensed Spectrum is regulated in a way that spectrum usage is allowed whenever certain standards and rules are satisfied by the device utilizing the spectrum. Keeping these standards aims to eliminate potential interference; examples of these rules are the limitation of transmission power or advanced coexistence capabilities.

The basic and eldest unlicensed spectrum is Industrial, Scientific and Medical (ISM) bands at 900 MHz and 2.4 GHz which has been supported later by unlicensed bands at 5 and 5.8 GHz which are known as Unlicensed National Information Infrastructure (U-NII) bands.

TV bands are often under-utilized which led the FCC to propose to allow the unlicensed usage of these bands by unlicensed systems in 2004 [9]. These bands are (54-72 MHz, 76-88 MHz, 174-216 MHz and 470-806 MHz). This principle has been known as overlay vertical spectrum sharing which will be discussed more in section 2.3.3.

In 2004 another unlicensed band allocated in 3650-3700 MHz has been opened by the FCC for fixed and mobile devices transmitting at higher power. The users of this band use 'contention-based' protocols to minimize interference between fixed and mobile nodes. Also some power constrains are used to minimize interference among nodes [10].

In fact, unlicensed spectrum demand is extremely high due to the high growth in wireless technologies and therefore, unlicensed spectrum is getting over-used and thus less usable for all if we take into account spectrum usage restriction with generated interference which is increased by increasing of the number of users in the same band.

2.2 Interference Temperature

For a specific radio system the transmitted power is designed taking into account the noise floor that should be satisfied at a certain distance from the transmitter. However, unpredictable appearance of new sources of interference may make the noise floor to rise, thus the signal coverage is degraded. To prevent the occurrence of such possibility, a paradigm shift in interference assessment has been recommended by the FCC. The recommendation is based on a new metric called the interference temperature. Interference temperature is intended to manage the sources of interference in a radio environment. The specification of an interference-temperature limit provides a "worst case" characterization of the RF environment in a particular frequency band and at a particular geographic location. The recommendation satisfies two key benefits:

1. The interference temperature at a receiving antenna provides a measure for the acceptable level of RF in the frequency band of interest; any transmission in that

band is considered to be "harmful" if it would increase the noise floor above the interference-temperature limit.

2. Given a particular frequency band in which the interference temperature is not exceeded, that band could be made available to be utilized by un-serviced user. Regulatory agencies would be responsible for setting the interference-temperature limit taking into account the conditions of the RF environment that exists in the frequency band under consideration [11].

The concept of interference temperature is identical to that of noise temperature, so it can be defined as a measure of the power and bandwidth occupied by interfering signals. Average interference power and Interference temperature are related by [1]

$$P_I(f_c, B) = kBT_I(f_c, B) \tag{2.1}$$

Where $P_I(f_c, B)$ is the average interference power in Watts centered at f_c covering bandwidth B measured in Hertz, Boltzmann's constant k is $1.38 * 10^{-23}$ Joules per Kelvin degree, $T_I(f_c, B)$ is the interference temperature in Kelvin.

In case of non-perfect overlapping between licensed and unlicensed signal the amount of overlapping band determines the interfering power as illustrated in Fig. 2.1 and in this case B will be the overlapping band.

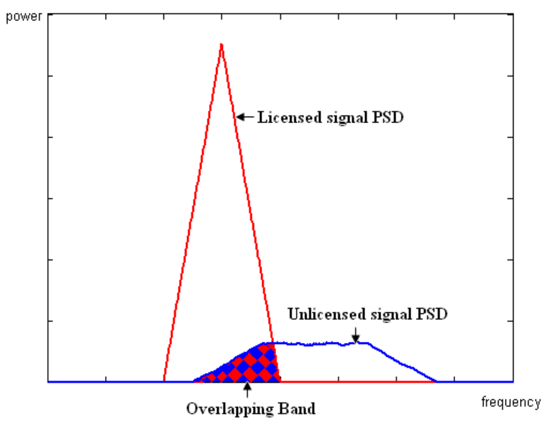

Fig. 2.1 Example of unlicensed signal partially overlaps a licensed signal

2.3 Spectrum Sharing:

The spectrum access and sharing among licensed and unlicensed users is regulated in a way that the unlicensed or secondary user, access of the spectrum shouldn't affect the degree of satisfaction of the licensed users' requirements.

2.3.1 Underlay Spectrum Sharing:

Underlay spectrum sharing is the availability of access the radio spectrum with minimal transmission power that wouldn't arise the interference temperature above its pre-designed thresholds. Underlay sharing is permitted even in some bands those are licensed for a dedicated technology. The technique used in underlay spectrum sharing is to spread the unlicensed signal over a large band of spectrum so it can be seen by the licensed radio device as an undesired signal below the noise and interference floor. Spread Spectrum, Multi-Band Orthogonal Frequency Division Multiplex (OFDM) and Ultra-Wide Band (UWB) are examples of technologies use underlay spectrum sharing. Fig. 2.2 demonstrates the underlay spectrum sharing concept [6].

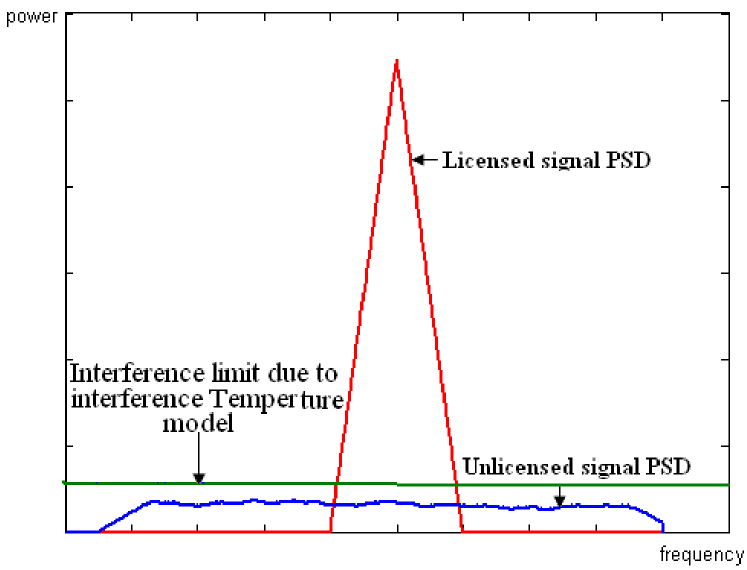

Fig. 2.2 Underlay Spectrum Sharing

2.3.2 Overlay Spectrum Sharing:

Overlay Spectrum sharing is the technique in which unlicensed users can utilize a spectrum band for the fraction of time in which this band is under-utilized by the licensed users as shown in Fig. 2.3. Cognitive radio uses flexible spectrum access techniques to identify under-utilized spectrum and to avoid harmful interference to other radios using the same spectrum [6].

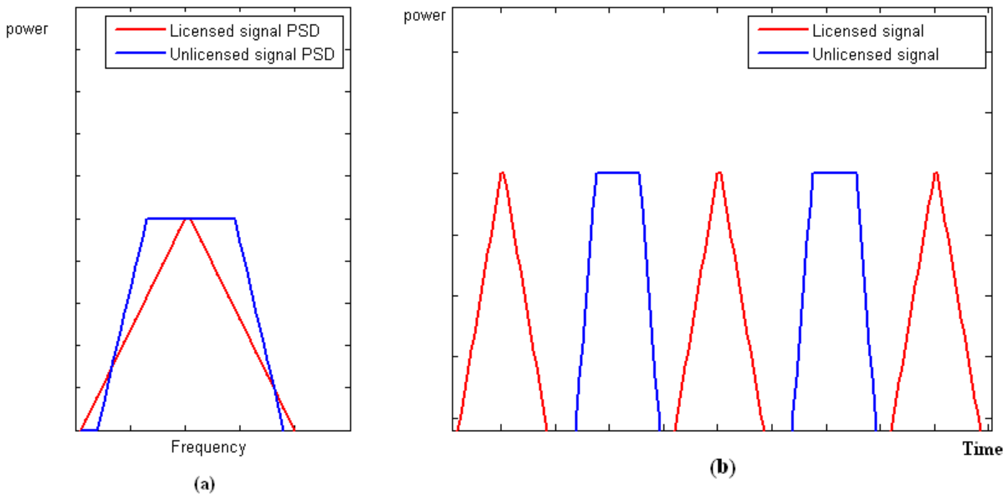

Fig. 2.3 (a) Licensed and Unlicensed signals PSD (b) Overlay Sharing

- **Opportunistic spectrum usage and spectrum holes**

Under-utilized spectrum is referred to as spectrum opportunity and for that white spectrum and spectrum hole can be used. The concept of spectrum holes is illustrated in fig 2.4. A spectrum opportunity is defined by location, time, and frequency and transmission power. A spectrum opportunity can be defined as a radio resource that either:

I. Not used by licensed radio device, or
II. Used by licensed radio device with a predictable pattern such that idle intervals can be detected and predicted.

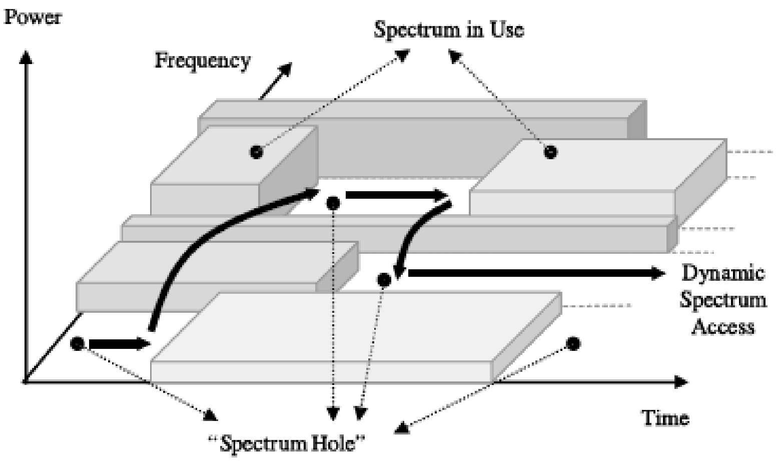

Fig. 2.4 Spectrum holes concept

2.3.3 Horizontal and vertical spectrum sharing

Cognitive radio can share spectrum with either

i. Unlicensed radio system with coexistence capabilities which is referred to as horizontal spectrum sharing. Both cognitive radio and the unlicensed systems are allowed to operate together in spite that they will interfere with each other. The unlicensed system itself could be another cognitive radio.

ii. Licensed radio system designed for using spectrum exclusively. This concept of spectrum sharing is known as vertical spectrum sharing.

The concept of horizontal and vertical spectrum sharing is illustrated in Fig. 2.5 where the cognitive radio system can share spectrum with either the WLAN at 5 GHz which represent the unlicensed system or the TV and radio broadcast at 700 MHz which is the exclusively spectrum Licensed radio system.

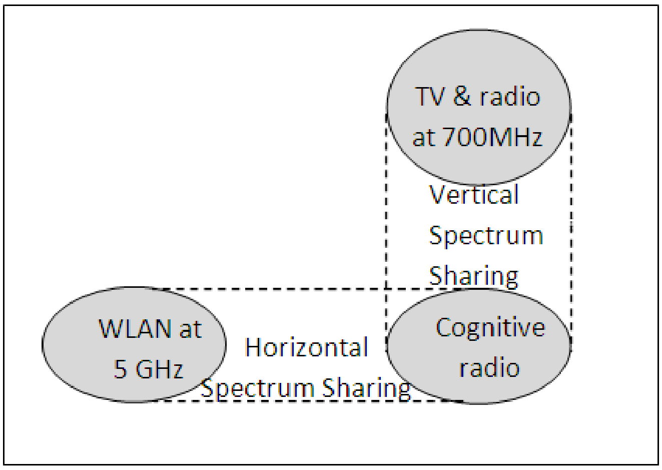

Fig. 2.5 Cognitive radio sharing spectrum with different radios horizontally and vertically

In both horizontal and vertical spectrum sharing identifying spectrum opportunities is needed. In order to avoid harmful interference licensed radio system may assist cognitive radios to identify spectrum opportunities in vertical sharing scenario which is called ’’operator assistance’’ [6].

- **IEEE 802.22**

  In TV broadcasting, every broadcast site has to serve a large coverage area which imposes the usage of high transmission power in order to guarantee robust reception for faraway receivers; this high transmission power enables cognitive radios coexistence through vertical spectrum sharing techniques in spite of the interference they may cause. In addition, in some areas some TV bands are absent which can be treated as a spectrum holes. The working group 802.22 of IEEE is working towards standardization of the unlicensed secondary access to TV bands. Fig. 2.6 presents such scenario of TV bands access [6].

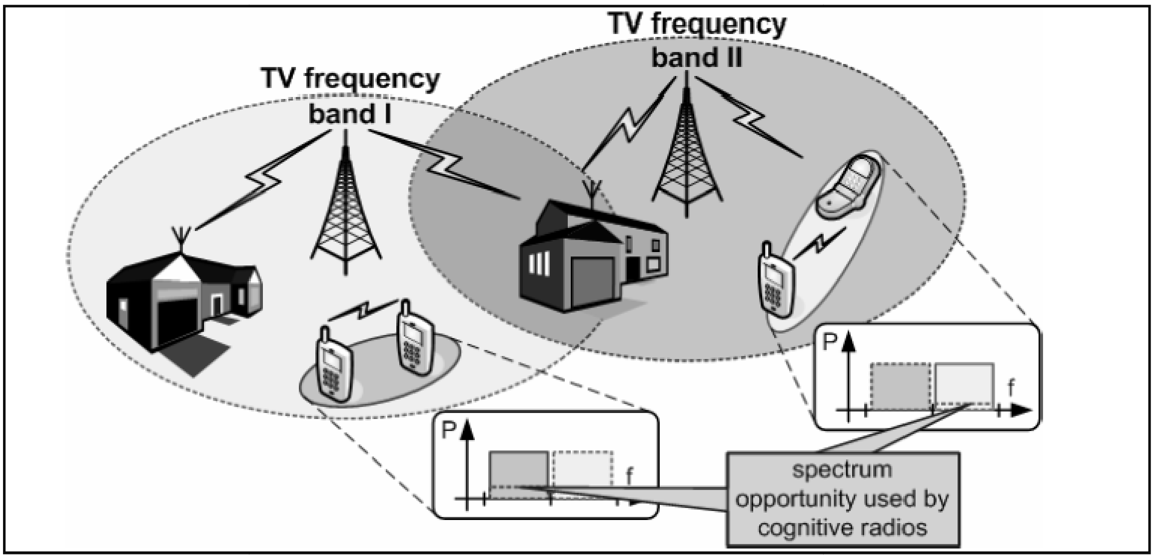

Fig. 2.6 Cognitive radios operates in TV broadcasting bands, as a basis of IEEE 802.22

- **Determination of Spectrum Availability for secondary usage :**

  Vertical spectrum sharing can be realized through either a beacon signal at a foreseen frequency for permission of secondary usage of spectrum or a common control channel. The FCC proposal identify three possible techniques for determining spectrum availability for secondary usage at a specific location as follows

  - A listen-before-talk-based passive sensing to detect any licensed user reappearance.
  - Providing a location-based database of used frequencies to check whether secondary spectrum usage is allowed.
  - Using dedicated beacon transmitters to indicate which spectrum is unavailable in a given location.

2.3.4 Frequency Agility

One important term related to spectrum sharing and cognitive radio networks is the Frequency Agility which means the ability of radio to change its operating frequency in order to optimize its use in adapting to the environment [6].

In fact Frequency Agility is not a new concept and many existing radios support this feature, one example of such systems is second generation mobile systems where mobile equipments can switch between GSM band in 900 MHz and DCS band in 1800 MHz. However, changing the channel inside the operating band and handover are not considered as a part of Frequency Agility context.

In cognitive radio networks there will be wide range of bands to be utilized and the switching between radios is expected to happen frequently. Therefore, Frequency Agility is one of the basic features and concepts related to cognitive radio and should be highly considered in manufacturing processes taking into account these characteristics of cognitive radio networks.

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Chapter 3
MAC LAYER SENSING

In order to adopt spectrum-agile feature required by cognitive radio, an enhancements in physical and MAC layers protocols are needed. The basic idea of dynamic spectrum access and allocation is to allow unlicensed users to access licensed spectrum bands when they are unutilized by their licensed users. To achieve this goal the unlicensed user should monitor the licensed channels to identify the spectrum holes and utilize them. When unlicensed user discovers a channel to be utilized without causing a harmful interference to the licensed users, this channel can be assigned to a wireless data link at that time. The unlicensed users are responsible for monitoring the channels in order to release them whenever any licensed user return to utilize these channels or one of them. Hence, sensing the spectrum is commonly recognized as the most fundamental part in dynamic spectrum access due to its role in discovering spectrum holes.

The task of sensing in physical layer is the adaptation of modulation schemes and parameters for measuring and detection the licensed users signals on different channels. There have been several proposed physical layer detection methods so far; among them the following three are the most likely ones to be used:

i. Energy detection
ii. Matched filter
iii. feature detection

The channel sensing outcome could be one of the following three possibilities:

i. The channel is idle
ii. The channel is occupied by a licensed user but can be utilized by the unlicensed user with some power constraint in order not to increase the tolerable interference limit to the licensed user.

iii. The channel is not available to the unlicensed user.

For the pre-mentioned possible outcomes of physical layer sensing to be available, one important fundamental question arises: how and when unlicensed users should sense the channels availability? This is the responsibility of MAC layer and is the main concern of the remaining parts of this chapter.

3.1 Channel Usage Pattern:

3.1.1 Alternating ON/OFF channel usage model

Channels are modeled as ON/OFF model or 0/1 state, 0 for free channel and 1 for occupied channel by either licensed or other unlicensed user under the assumption that there are no priority considerations among the unlicensed users. This 0/1 alternating model is referred to as channel usage pattern where unlicensed users can utilize only portions of the OFF periods to communicate with other nodes. Channel usage pattern is demonstrated in Fig.3.1.

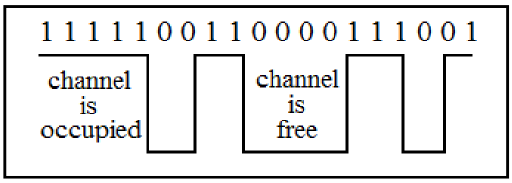


Fig. 3.1 Alternating ON/OFF channel usage pattern

Now we assume a radio system with N channels and each channel is addressed as i where $i=1,2,3,\ldots,N$; the lengths of $ON\ (Y^i)$ and $OFF\ (X^i)$ periods are described by their corresponding random probability density functions (pdf) $f_Y^{\,i}(y)$ and $f_x^{\,i}(x)$. If we assume these ON and OFF periods to be exponentially distributed with means of $E_{Yi}\ (y)$ and $E_{Xi}\ (x)$ respectively, then we will end up with distributions of ON and OFF periods as:

$$f_{Y^i}(y) = \lambda_{y^i} e^{-\lambda_{y^i} y} \quad (3.1)$$

$$f_{X^i}(x) = \lambda_{x^i} e^{-\lambda_{x^i} x} \quad (3.2)$$

where

$f_{Y^i}(y)$: PDF of the ON periods of channel *i*

$f_{X^i}(x)$: PDF of the OFF periods of channel *i*

$\lambda_{y^i} = 1/E_Y^i(y)$

$\lambda_{x^i} = 1/E_X^i(x)$

3.1.2 Channel utilization factor:

Channel utilization factor of channel ***i*** (u^i) is defined as the fraction of time (***t***) in which channel has been utilized by its licensed users throughout enough long time period (i.e. $t \to \infty$).

From the above definition of channel utilization factor we can derive a relationship between channel utilization and it random distribution parameters as follows

$$u^i = \frac{\int_0^\infty \lambda_{y^i} e^{-\lambda_{y^i} y} dy}{\int_0^\infty \lambda_{y^i} e^{-\lambda_{y^i} y} dy + \int_0^\infty \lambda_{x^i} e^{-\lambda_{x^i} x} dx} \quad (3.3)$$

From 3.3

$$u^i = \frac{E_{Y^i}(y)}{E_{Y^i}(y) + E_{X^i}(x)} \quad (3.4)$$

and in terms of λ_{y^i} and λ_{x^i} it can be expressed as

$$u^i = \frac{\lambda_{x^i}}{\lambda_{y^i}+\lambda_{x^i}} . \tag{3.5}$$

3.2 MAC Layer Sensing Modes:

From the MAC layer point of view, the availability of a particular channel to the unlicensed user can be sensed either *reactively* or *proactively.* To asses and compare these two sensing modes we will consider two performance metrics as addressed below.

1. **Spectrum utilization factor**: this is the portion of the available spectrum that hasn't been utilized by the licensed users and then can be utilized by the unlicensed user.
2. **Idle channel search delay**: this is the time unlicensed user needs to detect the first idle channel to utilize.

Throughout the remaining sections of this chapter these assessment performance metrics will be discussed in details and explained more in MAC layer sensing context.

3.2.1 Reactive Sensing

Reactive sensing is on demand sensing scheme, that is, the available channels are sensed when the unlicensed user has a packet to be sent or received; otherwise, the unlicensed user sleeps. During sensing, if any idle channel is found then it will be utilized and the wireless link between the unlicensed user and the other entity will be established. After completing sensing of all channels if no idle channel is found then the unlicensed user will sleep for a short period of ***t*** seconds and then resume sensing till finding one idle channel to utilize. According to the channels utilization factors the channels are sensed in a random order since there is no any prior-knowledge about channels utilization factors. During utilizing any channel the unlicensed user use Listen-Before-Talk mechanism to check licensed users presence, and if any licensed user appearance is detected then the channel should be released and start sensing procedure from the beginning. The procedure of reactive sensing is illustrated in Fig. 3.2.

3.2.2 Proactive Sensing:

In this type of sensing unlicensed user periodically sense the channels besides the on demand sensing when communications is needed. The purpose of the periodically sensing is to estimate the channel usage pattern in order to determine the most desirable sensing order for on demand sensing. This most desirable sensing order is governed by estimated channel utilization factors order aiming to reduce the idle channel search delay as much as possible. Hence, the on demand sensing part is the same as reactive sensing except that the channel are sensed in a specific order rather than in a random order. Fig.3.3 describes proactive sensing procedure.

- **Adapted and Non-adapted Sensing Periods Proactive Sensing**

Wireless communication channels have not perfect stationary status and so when they have been proactively sensed their sensing periods may need to be adapted according to the changes that they may face. The change we mean here is the change in channel utilization factor. In fact adaptation sensing periods is an additional computational overhead which may be traded off with the benefits from this adaptation represented by our achieved spectrum utilization and idle channel search delay. However, the degree of stationarity the channels determine whether to use proactive sensing with adapted sensing periods or with non-adapted sensing periods. Proactive sensing with adapted sensing periods is demonstrated in Fig. 3.4.

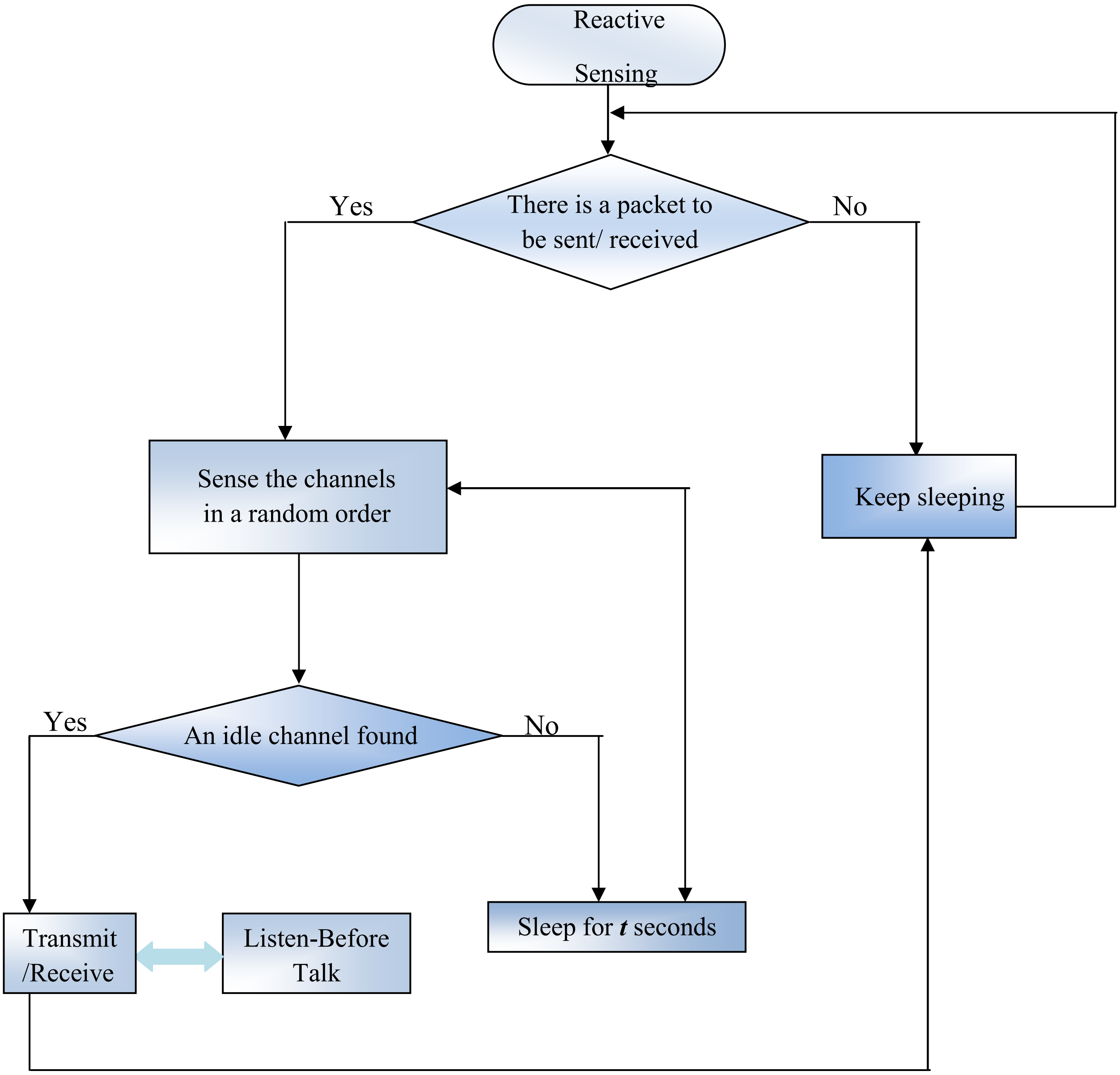


Fig. 3.2 System Flow Diagram of Reactive Sensing Procedure

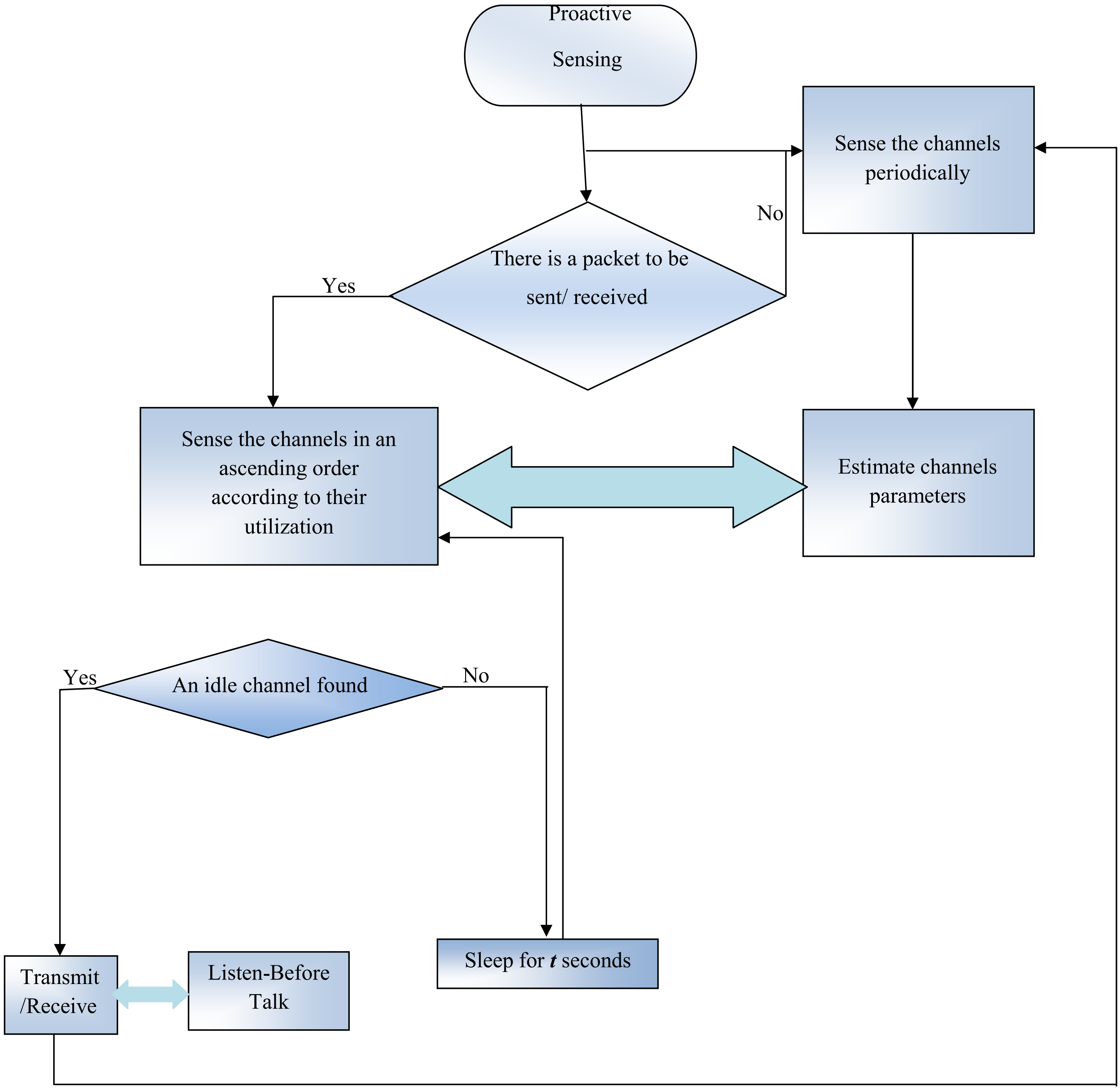


Fig. 3.3 System Flow Diagram of Proactive Sensing Procedure

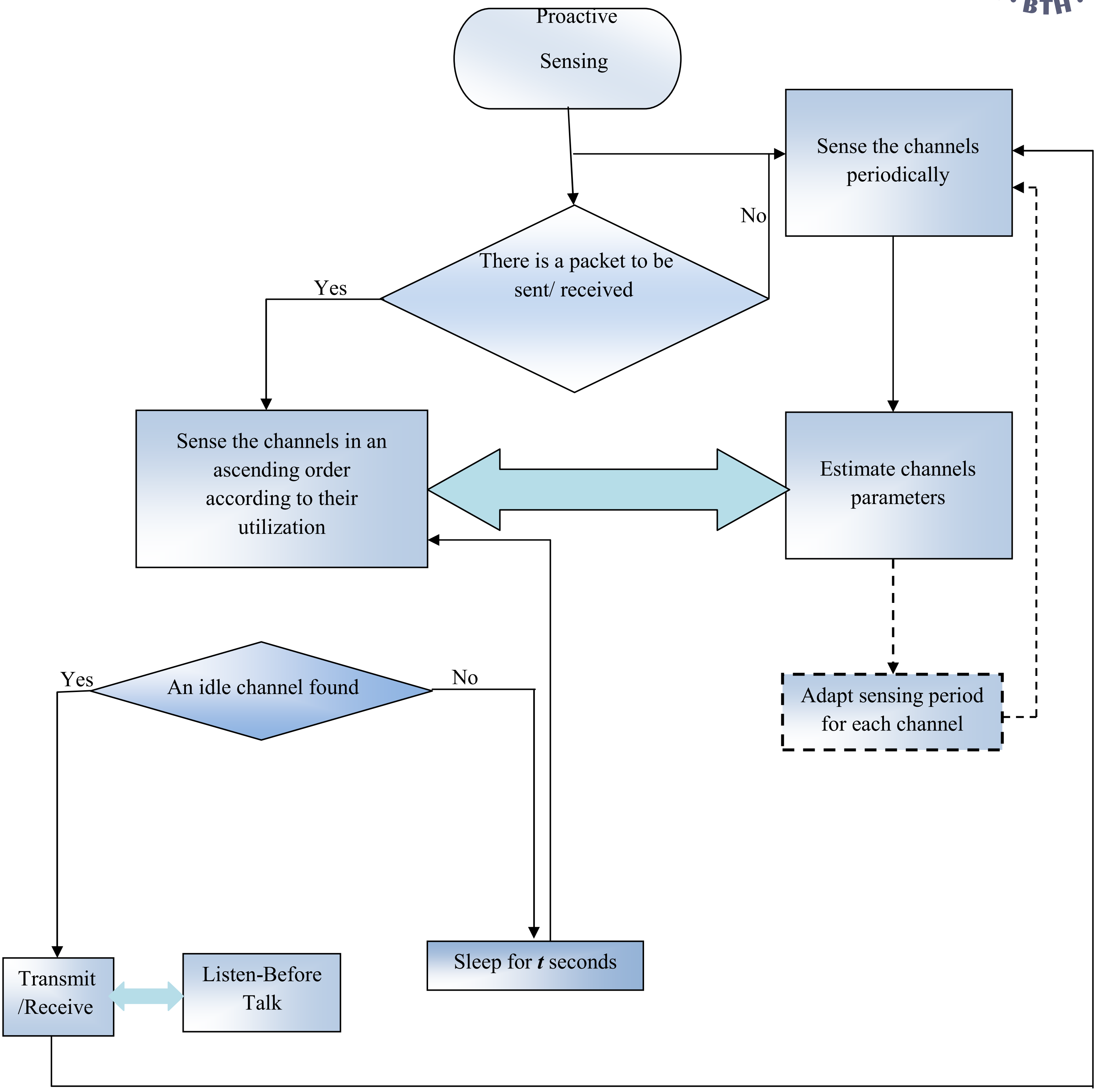


Fig. 3.4 System Flow Diagram of Proactive Sensing with Sensing Periods Adaptation Procedure

- ## Unexplored Opportunities and Sensing Overhead:

In proactive sensing the channel is sampled discretely in time and thus it is not possible to identify when an opportunity (spectrum hole) begins and ends exactly which may result in missing some opportunities. These missed opportunities increase with the increasing of sensing periods, however reducing the sensing periods blindly is not desirable either as it will increase the sensing overhead. Hence, we need to tradeoff between these two impacts of the value of sensing period.

Here we introduce two terms *Unexplored Opportunities and Sensing Overhead*

➢ ***Unexplored Opportunities ($UOPP^i$)*** is defined as the fraction of time during which channel *i* opportunities are not discovered.

➢ ***Sensing Overhead ($SSOH^i$)*** is defined as the average fraction of time during which channel *i* discovered opportunities cannot be utilized due to the sensing of other channels. In the context of *SSOH* an important assumption should be taken into account: that is the unlicensed user node is equipped with *one wide band tunable antenna*. This assumption serves in two areas:

i. The unlicensed user can operate in all available channels and utilize any one of them (i.e. to support spectrum agility requirements).

ii. The secondary user must stop utilizing a discovered channel while it is sensing one of the other channels.

Fig. 3.5 describes the concept of SSOH graphically for two channels.

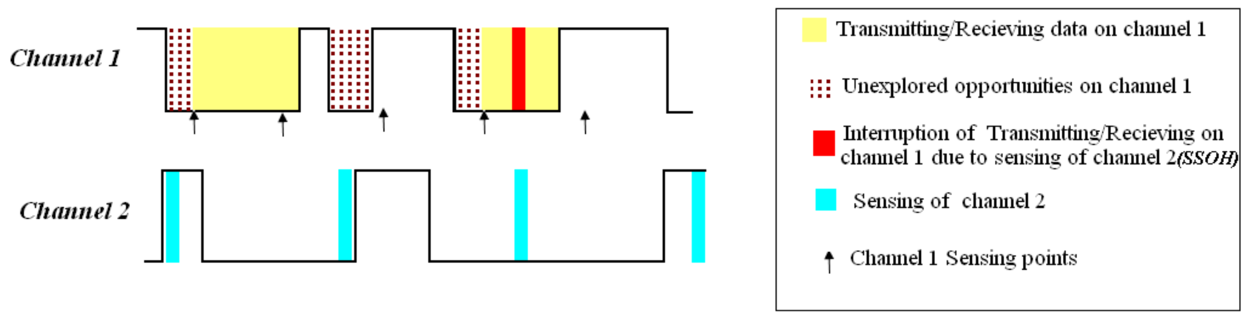


Fig. 3.5 Example of Unexplored Opportunities (*UOPP*) and Sensing Overhead (*SSOH*) in two channels radio system

- **Optimization of Sensing periods in adapted -sensing periods proactive sensing**

As introduced in section 3.2.2, a tradeoff between *UOPP* and *SSOH* regarding sensing periods should be carried out. At first we assume the time needed to sense channel *i,* which is referred to *listening interval,* to be (T_I^i). In addition, the *sensing period* of channel *i* is (T_P^i). T_I^i is determined by physical layer sensing since it depends on the used modulation scheme, sample duration, sample energy and other physical layer characteristics. Thus, our task in MAC layer is to optimize T_P^i in order to utilize our available spectrum as much as possible. In Fig. 3.6 T_I^i and T_P^i are shown for two channels.

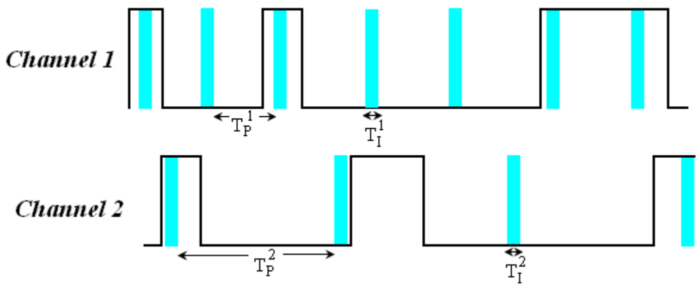


Fig. 3.6 Example of Sensing Period (T_P^i) and Listening Interval (T_I^i) in two channels radio system

As introduced in section 3.1.2, channel *i* utilization factor u^i is defined as the average fraction of time during which channel *i* is busy. Hence, the average total sum of opportunities is (1- u^i) per unit time. In Fig 3.7 the amount available spectrum for the unlicensed users is shown for two cases: if we assume short period of time such that the value of u^i can be considered as a constant value as in Fig. 3.7(a), and if relatively large period of time is assumed where the variation of u^i is considered as shown in Fig. 3.7 (b).

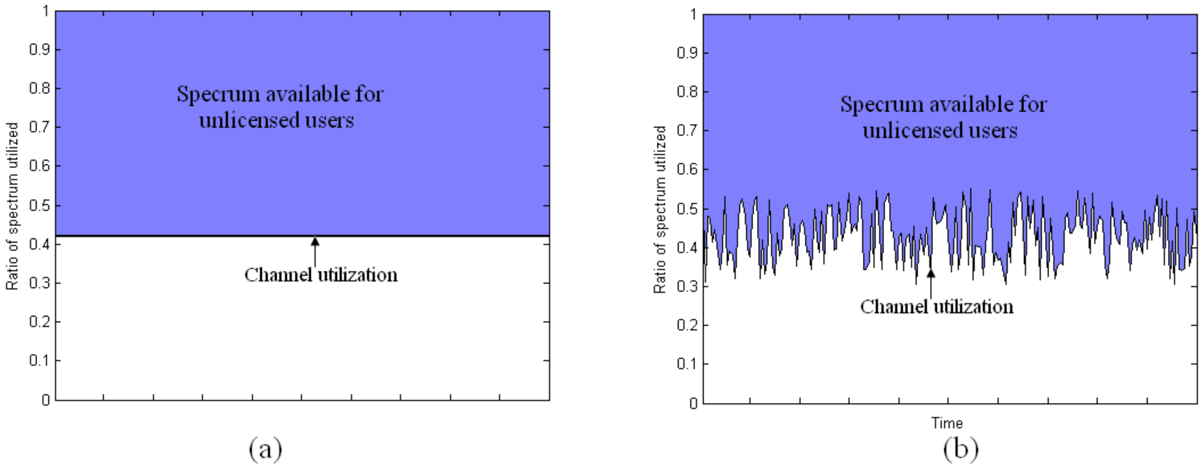


Fig. 3.7 Available spectrum for unlicensed users related to the channel utilization taken in: (a) Short period of time. (b) Relatively large period of time

For a radio system with N channels our objective function is:

$$\boldsymbol{T_P} = (T_P{}^{1}, \ T_P{}^{2}, \ \ldots., \ T_P{}^{N})$$

Then our task is to find T_P such that

$$\underline{T_P^*} = \arg\max_{T_P} \left\{ \sum_{i=1}^{N} \{ (1 - u^i) - SSOH^i - UOPP^i \} \right\} \qquad (3.6)$$

Since $(1 - u^i)$ is not related to $\underline{T_P^*}$; then (3.6) can be converted into 3.7 as follows

$$\underline{T_P^*} = \arg\min_{T_P} \left\{ \sum_{i=1}^{N} \{ SSOH^i + UOPP^i \} \right\} \qquad (3.7)$$

where $\underline{T_P^*}$ is the optimal sensing periods vector

To drive a mathematical expression for $SSOH^i$ and $UOPP^i$ a couple of assumption should be dealt with to simplify the problem as illustrated below.

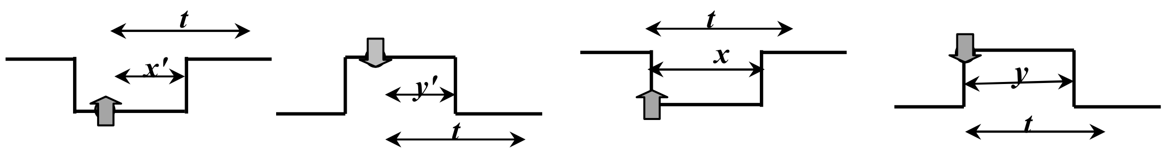
i. In case there exist simultaneous opportunities on multiple channels, unlicensed users can assign them simultaneously to one or more data links using multi-carrier OFDM technique [13].

ii. Each unlicensed user performs consistent transmission. That is, there always exists an incoming/outgoing packet from/to any unlicensed node. So, in this case, every discovered idle channel is assigned to one of the data links and is utilized until its current idle period end.

iii. The end of an idle period could be detected by the *LISTEN-before-TALK* policy. That is, a secondary user is responsible for detecting any licensed user's reappearance on the channel before transmitting the next packet.

- ### Analysis of $UOPP^i$:

Let $T_d^i(t)$ to be the average opportunities on channel *i* through a period lies between *t* and $t+t_s$, where t_s is the sensing point and *d* is either 0 or 1 given that a sample d is captured at time t_s. t_s can be an end or start of idle period so in that case we use $\tilde{T}_d^i(t)$ instead of $T_d^i(t)$; then we have four possible cases, those are: $\tilde{T}_0^i(t)$, $\tilde{T}_1^i(t)$, T_0^i and T_1^i as illustrated in Fig. 3.8



$\tilde{T}_0^i$ $\tilde{T}_1^i$ T_0^i T_1^i

Fig. 3.8 $T_d^i(t)$ **and** $\widetilde{T_d^i}(t)$

Let $\tilde{X}^i$ to be the remaining time of an OFF period at the sensing time t_s. The distribution of $\tilde{X}^i$ is given by (3.8a) [22]

$$f_{\tilde{X}^i}(x) = \frac{\mathcal{F}_x(\tilde{X}^i)}{E(x^i)} \tag{3.8a}$$

where: $\mathcal{F}_x(\tilde{X}^i) = 1 - F_x(\tilde{X}^i)$.

Similarly for an ON period (3.8b) is valid

$$f_{\tilde{Y}^i}(y) = \frac{\mathcal{F}_y(\tilde{Y}^i)}{E(y^i)} \tag{3.8b}$$

Where: $\mathcal{F}_y(\tilde{Y}^i) = 1 - F_y(\tilde{Y}^i)$

Since we are interested in calculating $UOPP^i$, we need to find $\tilde{T}_0^i(t)$ and $\tilde{T}_1^i(t)$, respectively. This can be achieved by applying the renewal theory concepts [22, 8], which results in the following:

$$T_0^i(t) = t\int_t^\infty \frac{\mathcal{F}_{x^i(x)}}{E(x^i)}dx + \int_0^t \frac{\mathcal{F}_{x^i(x)}}{E(x^i)}\left(x + \tilde{T}_1^i(t-x)\right)dx \tag{3.9}$$

$$T_1^i(t) = \int_0^t \frac{\mathcal{F}_{y^i(y)}}{E(y^i)}\tilde{T}_0^i(t-y)dy \tag{3.10}$$

$$\tilde{T}_0^i(t) = t\int_t^\infty f_{x^i}(x)dx + \int_0^t f_{x^i}(x) + \left(x + T_1^{\sim i}(t-x)\right)dx \tag{3.11}$$

$$\tilde{T}_1^i(t) = \int_0^t f_{y^i}(y)T_0^{\sim i}(t-y)dy \tag{3.12}$$

Then applying Laplace transforms, we get

$$E(x^i).T_0^{i^*}(s) = \frac{\mathcal{F}_{x^{i^*}}(0) - \mathcal{F}_{x^{i^*}}(s)}{s^2} + \mathcal{F}_{x^{i^*}}(s)T_1^{\sim i^*}(s) \tag{3.13}$$

$$E(y^i).T_1^{i^*}(s) = \mathcal{F}_{y^{i^*}}(s)T_0^{\sim i^*}(s) \tag{3.14}$$

$$T_1^{i^*}(s) = f_{y^{i^*}}(s)T_0^{\sim i^*}(s) \tag{3.15}$$

$$T_0^{\sim i^*}(s) = \frac{f_{x^{i^*}}(0) - f_{x^{i^*}}(s)}{s^2} + f_{x^{i^*}}(s) T_1^{\sim i^*}(s) \quad (3.16)$$

This leads to:

$$T_0^{i^*}(s) = \frac{1}{E(x^i).s^2}\left[\mathcal{F}_{x^{i^*}}(0) - \mathcal{F}_{x^{i^*}}(s).\frac{1 - f_{x^i}^*(0) f_{y^i}^*(s)}{1 - f_{x^i}^*(s) f_{y^i}^*(s)}\right] \quad (3.17)$$

$$T_1^{i^*}(s) = \frac{\mathcal{F}_{y^{i^*}}(s)}{E(y^i).s^2}\left[\frac{f_{x^i}^*(0) - f_{x^i}^*(s)}{1 - f_{x^i}^*(s) f_{y^i}^*(s)}\right] \quad (3.18)$$

As introduced in section 3.2.2, $UOPP^i$ is defined as the average fraction of time during which utilizable opportunities on channel i are not discovered taking into account that the maximum value of $UOPP^i$ is $(1\text{-}u^i)$. Furthermore, an opportunity means 0 in our channel usage pattern which makes it mathematically expressible to define $UOPP^i$ as the '*length*' of undiscovered zeros in channel usage pattern between the last captured 1 and next captured symbol as a ratio of $(1\text{-}u^i)$. Hence $UOPP^i$ is found to be

$$UOPP^i = \left(1 - u^i\right).\left[\frac{1}{T_p^i}\int_0^{T_p^i} \frac{\mathcal{F}_{x^i}(x)}{E(x^i)} \tilde{T}_1^i\left(T_p^i - x\right) dx\right] \quad (3.19)$$

And if we consider radio system with exponentially distributed values of the ON and OFF periods as in (3.1) and (3.2) then our $UOPP^i$ is expressed as

$$UOPP^i = \left(1 - u^i\right)\left[1 + \frac{1}{\lambda_{x^i} T_p^i}\left(e^{-\lambda_{x^i} T_p^i} - 1\right)\right] \quad (3.20)$$

Hence, $UOPP^i$ and T_p^i are related as can be shown in Fig. 3.9.

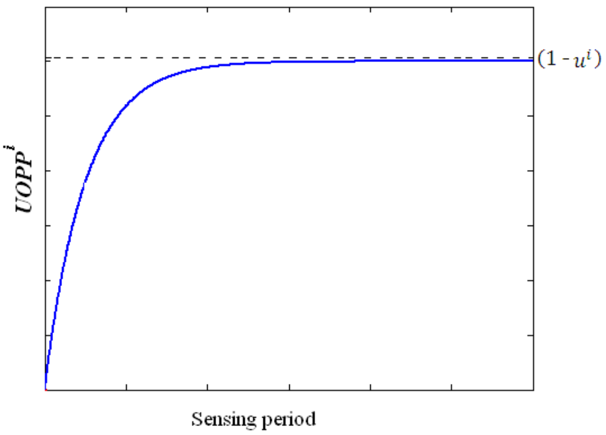


Fig. 3.9 Relationship between $UOPP^i$ and T_p^i with respect to u^i

- **Analysis of $SSOH^i$:**

As introduced earlier, SSOH^i is the average fraction of time during which the pre-discovered opportunities can't be utilized during the sensing of another channel under the assumption that the unlicensed user node is equipped with *one wide band tunable antenna* to perform on task at a time, either sensing or utilizing discovered opportunity by sending/receiving data. From this definition, it can be stated that SSOH^i is an entire radio system dependant as it depends on sensing of the other channels rather than channel *i* itself; such situation is shown in Fig. 3.5.

Since the unlicensed user has no way to detect whether the channel is free or not continuously, then any unlicensed user constructs its own channel usage pattern extracted from the discrete sensing procedure introduced earlier. This new constructed channel usage pattern is referred to as *observed channel usage pattern* as illustrated in Fig. 3.10.

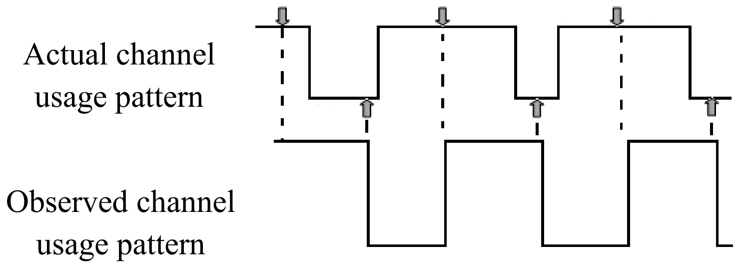


Fig. 3.10 Actual and observed channel usage pattern

Using observed channel usage pattern there will be a new value of the channel utilization factor $\tilde{u}^i$ as

$$\tilde{u}^i = u^i + UOPP^i \qquad (3.21)$$

From this new value of the channel utilization factor $\tilde{u}^i$ the $SSOH^i$ can be calculated as

$$SSOH^i = \left(1 - \tilde{u}^i\right) \sum_{\substack{j=1 \\ j \neq i}}^{N} \left(\tilde{u}^i . \frac{T_I^j}{T_P^j} \right) \qquad (3.22)$$

Blekinge Tekniska Högskola

Karlskrona, December 2008

Chapter 4
SYSTEM MODEL, SIMULATION SETUP AND SIMULATION PARAMETERS

A MATLAB based simulation has been implemented to simulate and assess the MAC layer sensing schemes in a certain cognitive radio network. This chapter will show the structure of cognitive radio network used to carry out the simulation. In addition to, the performance metrics used to assess our system will be discussed in details and their mathematical expressions will be derived and presented in this chapter. Moreover, the simulation procedure will be explained throughout this chapter. Simulation parameters to apply the MAC layer sensing aspects shown in chapter 3 will be illustrated at the end of this chapter.

4.1 Simulated Cognitive Radio Network Topology:

A wireless multi-hop ad-hoc network supporting data transfer among its nodes is considered to represent the unlicensed users' network. The network consists of a group of nodes and the licensed radio network to be shared spectrum with has N channels. Even though the network is a multi-hop network, but data transmission in the unlicensed network should be done hop-by-hop basis as the channel usage pattern of each channel may be seen differently from the unlicensed users depending on their location; this is governed by power and interference constrains and the propagation characteristics in the wireless environment the licensed and unlicensed networks built in [8].

Fig. 4.1 shows the topology of the unlicensed network where an unlicensed node N_0 is surrounded by M neighbors $N_1, N_2, \ldots, N_M$. A total number of N licensed channels can be utilized by N_0 when they are unoccupied by their licensed users. A data link L_j $(j=1,2,\ldots, M)$ is assigned for communication between N_0 and N_j. One important assumption regarding the unlicensed nodes that they are equipped with one wideband tunable antenna to support spectrum agility feature in order to be able to utilize any channel of the available *N* channels and to reduce nodes complexity, and to assure that one task can be performed at a time (either sensing one channel or transmitting/receiving data on another channel). When N_0 wants to communicate with any other node N_j, both N_0 and N_j should exchange their sensing results via control channels and then assign the appropriate channel(s) to a data link with the aid of *Unlicensed Users Coordination mechanisms* [8].

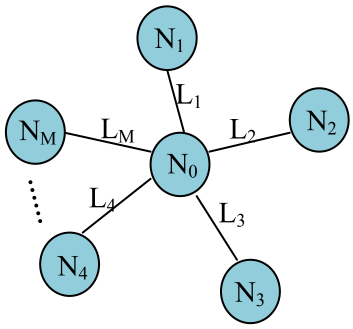


Fig. 4.1 Simulated Cognitive Radio Ad-hoc Network Topology

Regarding the available N channels we assumed them to have an exponential distribution of their ON/OFF periods

4.2 Performance Metrics:

As presented earlier, we considered two performance metrics in our simulation and assessment: spectrum utilization factor and idle channel search delay.

4.2.1 Spectrum utilization factor:

Spectrum utilization factor (SUF) is considered for proactive sensing as reactive sensing is on demand sensing. For an exponentially distributed ON/OFF periods channel with parameters shown in (3.1) 1nd (3.2) the spectrum utilization factor can be evaluated as:

$$SUF = \left(1 - u^i\right) - \left(SSOH^i + UOPP^i\right) \tag{4.1}$$

Both $SSOH^i$ and $UOPP^i$ mathematical expressions have been derived in section 3.2.2 and shown in (3.19) and (3.21), respectively. By substituting (3.19) and (3.21) in (4.1) results

$$SUF = \left(1 - u^i\right)\left[\frac{1}{\lambda_{x^i} T_p^i}\left(e^{-\lambda_{x^i} T_p^i} - 1\right)\right] - \left(1 - \tilde{u}^i\right)\sum_{\substack{j=1 \\ j \neq i}}^{N}\left(\tilde{u}^i . \frac{T_I^j}{T_P^j}\right) \tag{4.2}$$

where $\tilde{u}^i$ is explained in (3.20).

4.2.2 Idle Channel Search Delay:

Idle channel search delay for proactive sensing (T_{idle}^P) and reactive sensing (T_{idle}^R) is defined as the time required for the unlicensed user to locate the first free channel.

- **Idle Channel Search Delay in Proactive Sensing:**

Proactive sensing sorts the channels in an ascending order according to the channel utilizations. Then we can put in the following relation

$$(1 - u^1) \geq (1 - u^2) \geq \cdots \geq (1 - u^N)$$

Therefore, channel 1 is sensed for a time of T_I^1: if it is free, with a probability of $(1 - u^1)$, then it will be assigned to a data link; if not, channel 2 will be sensed for a time of T_I^2 and if it is free then it will be assigned to a data link, with a probability of of $(u^1)(1 - u^2)$, where channel 1 is occupied and channel 2 is free. This process will go on through all channels; if all channels are occupied then the packet will be buffered and sent later, with a probability of $u^1u^2 \dots u^N$. Consequently, T_{idle}^P can be expressed as follows:

$$T_{idle}^P = T_I^1.(1-u^1 \dots u^N) + T_I^2.u^1(1-u^2 \dots u^N) + \cdots$$

$$+T_I^N.u^1 \dots u^{N-1}(1-u^N) + \sum_{i=1}^{N} T_I^i.u^1 \dots u^{N-1}$$

$$= T_I^1 + u^1T_I^2 + u^1u^2T_I^3 + \cdots + u^1 \dots u^{N-1}T_I^N$$

$$= T_I^1 + \sum_{i=2}^{N} \left\{ \left(\prod_{j=1}^{i-1} u^j \right) T_I^i \right\} \tag{4.3}$$

- **Idle Channel Search Delay in reactive Sensing:**

In the case of reactive sensing there is now sorting in channels, so according to their utilizations channels are sensed randomly. Hence $N!$ possible orders of channels should be considered with equal probabilities. Let s_m to be the m^th set of ordered channels from the total of $N!$ possible sets, $s_m(i)$ to be the channel number i in s_m. As all the $N!$ sets can be chosen equally-likely with probability of $\frac{1}{N!}$ then T_{idle}^P can be expressed as follows:

$$T_{idle}^R = \sum_{m=1}^{N!} \frac{T_{idle}^{s_m}}{N!} \tag{4.4}$$

where

$$T_{idle}^{s_m} = T_I^{s_m(1)} + \sum_{k=2}^{N} \left\{ \left(\prod_{i=1}^{k-1} u^{s_m(i)} \right) T_I^{s_m(k)} \right\} \tag{4.5}$$

Then

$$T_{idle}^{R} = \frac{1}{N!}\sum_{m=1}^{N!}\left\{T_I^{s_m(1)} + \sum_{k=2}^{N}\left\{\left(\prod_{i=1}^{k-1} u^{s_m(i)}\right)T_I^{s_m(k)}\right\}\right\} \qquad (4.6)$$

4.3 Simulation Setup:

4.3.1 Simulation Structure

The constructed MATLAB based simulation has been implemented in three stages

1. Licensed network behavior simulation stage

This stage deals mainly with generation of randomly exponentially distributed ON/OFF periods for our channels according to the pre-defined means for both ON and OFF periods. The generated ON/OFF periods are then converted to a 0/1 sequences to emulate the sensing procedure. This stage is responsible for simulating physical layer sensing as it provides us with the sensing results.

2. MAC layer spectrum sensing in the unlicensed network simulation stage

This stage represents the core part of our simulation as we simulate a real scenario in cognitive radio network regarding the MAC layer sensing schemes.

3. Comparison and assessment stage

In this stage two comparisons have been performed as follows

a) Reactive sensing has been compared with proactive sensing in terms of the idle channel search delay for a different numbers of available channels in each case.

b) The proactive sensing adapted sensing periods scheme has been compared with non-adapted sensing periods scheme with respect to the spectrum utilization factor.

Fig. 4.2 shows a system diagram for the simulation scenarios.

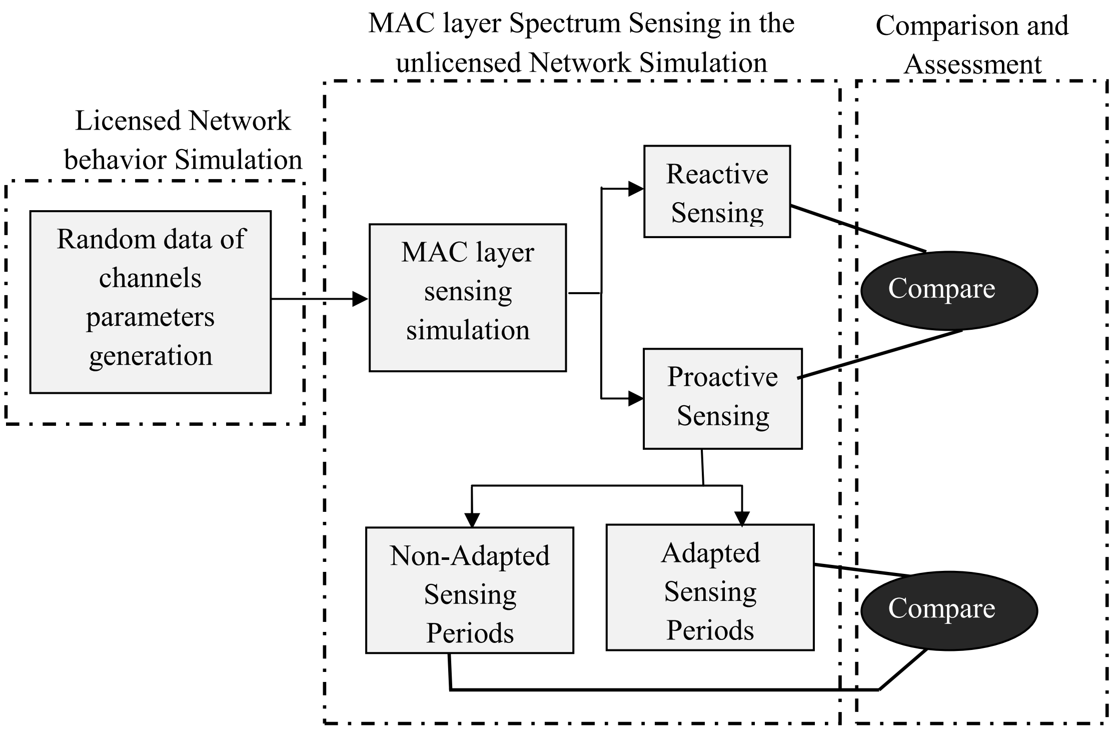


Fig. 4.2 Full Simulation Scenario

4.3.2 Channel parameters Estimation

In order to calculate our performance metrics for any sensing scheme and to apply the formulas of calculating $UOPP^i$, $SSOH^i$ and the optimal sensing periods vector at any time and update this vector accordingly we need to estimate our channels parameters: channel utilization factor, u^i and channel exponential ON/OFF periods distribution parameters λ_x^i and λ_y^i for each channel in our system.

- **Channel utilization factor Estimation**

Suppose we have collected r^i symbols$(b_1, b_2, \dots, b_{r^i})$ from channel usage pattern of channel *i*. As introduced earlier the channel utilization factor can be expressed as: $u^i = E_{Y^i}(y)/\left(E_{X^i}(x) + E_{Y^i}(y)\right)$

Then to estimate $u^i \Rightarrow \widehat{u^i}$ we can use sample mean estimator method which gives us

$$\widehat{u^i} = \frac{1}{r^i}\sum_{j=1}^{r^i} b_j \qquad (4.7)$$

which is unbiased estimator and its unbiasedness can be shown by

$$E\{\widehat{u^i}\} = \frac{1}{r^i}\sum_{j=1}^{r^i} E\{b_j\} = u^i \qquad (4.8)$$

- **Channel exponential ON/OFF periods distribution parameters λ_x^i and λ_y^i**

Estimation:

We can estimate either λ_x^i or λ_y^i, and then use it to estimate the other knowing $\widehat{u^i}$.

Suppose we estimate λ_x^i then we can use (4.9) derived from (3.5)

$$\widehat{\lambda_y^i} = \widehat{\lambda_x^i}\left(\frac{1-\widehat{u^i}}{\widehat{u^i}}\right) \qquad (4.9)$$

So now we need to estimate λ_x^i

To estimate λ_x^i Maximum Likelihood Estimator (MLE) is an appropriate estimator to be used. Suppose we have k^i OFF periods among our collected r^i symbols with lengths of Len_j (j=1,2,…,k^i) then the estimated $\lambda_x^i \Longrightarrow \hat{\lambda}_x^i$ is given by (4.10) [21].

$$\hat{\lambda}_x^i = \frac{k^i}{\sum_{j=1}^{k^i} Len_j} \qquad (4.10)$$

After estimating channels parameters then we can adapt the sensing periods if we are working with proactive sensing with adapted sensing periods. The whole process is illustrated in Fig. 4.3.

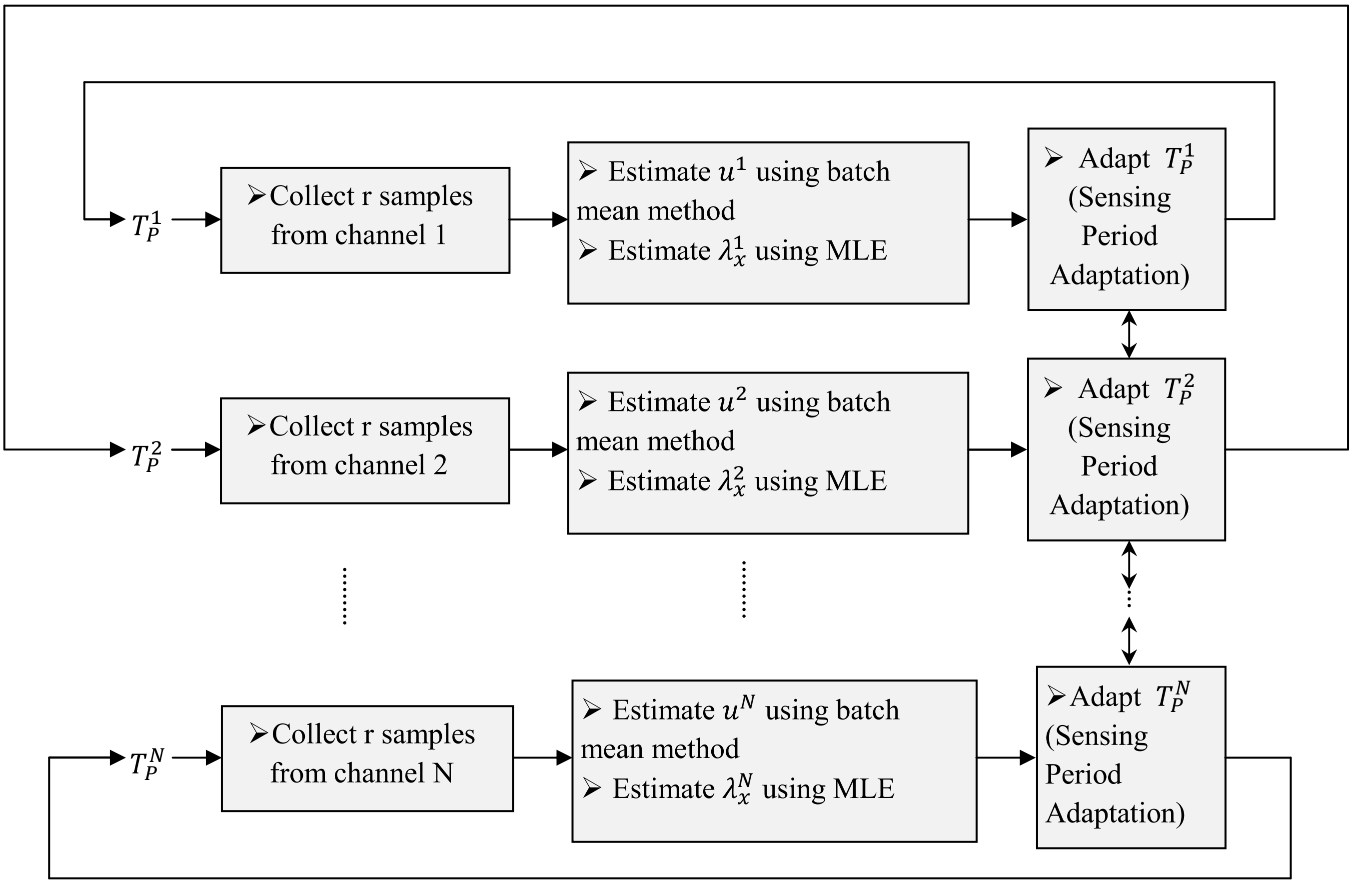


Fig. 4.3 Sensing Periods Adaptation Scenario

4.4 Simulation Parameters:

Here are the parameters used in our MATLAB based simulation. Table 4.1 shows the Fundamental Simulation Parameters while table 4.2 shows our channels Parameters used to build our simulation.

Table 4.1 Fundamental Simulation Parameters

Parameter	Notation	Value
N	Number of channels	5 channels
T_I^i	Listing Interval (For all channels)	20 ms
r^i	Collected symbols in each estimation cycle for each channel	1000 symbol

Table 4.2 Channel Parameters used in Simulation

Channel⇩ Parameter⇨	$E_{X^i}(x)$	$E_{Y^i}(y)$
Channel 1	5.00s	1.00s
Channel 2	2.50s	1.25s
Channel 3	1.67s	0.50s
Channel 4	1.25s	0.75s

Chapter 5
RESULTS AND INTERPRETATION

Our obtained results will be shown and analyzed in this chapter. The results will be classified into four categories:

1. UOPP+SSOH for our channels which reflects the wasted available spectrum due to sensing.
2. Channel parameters estimation
3. Adapted sensing periods and impact on that in achieved spectrum utilization factor for each channel.
4. Comparison of sensing modes and this mainly contains two parts.

a) Comparison between reactive and proactive sensing modes in term of idle channel search delay.

b) Comparison between adapted and non-adapted sensing periods proactive sensing in term of achieved spectrum utilization factor.

5.1 The wasted available spectrum due to sensing

Figures 5.1 to 5.5 illustrate the obtained values of UOPP+SSOH for our channels.

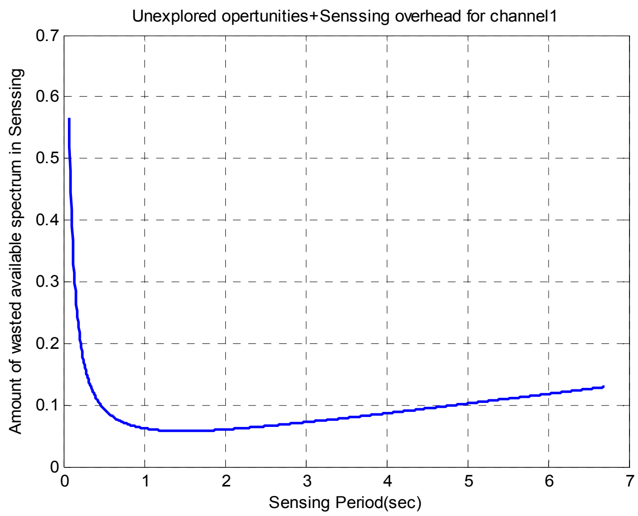


Fig. 5.1 UOPP+SSOH for channel 1

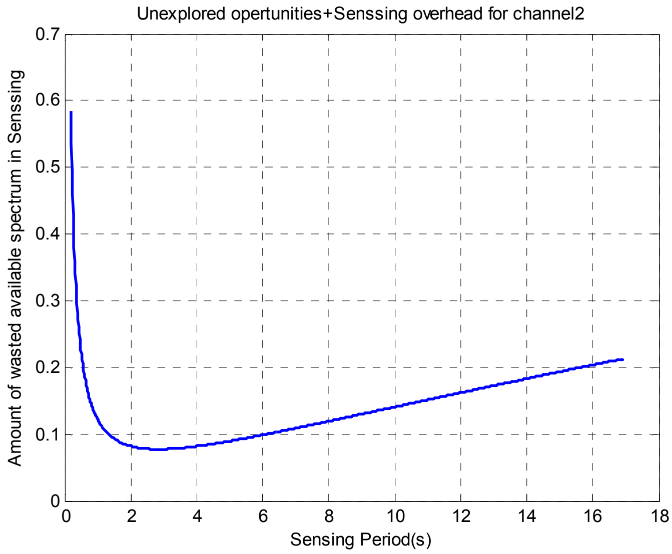


Fig. 5.2 UOPP+SSOH for channel 2

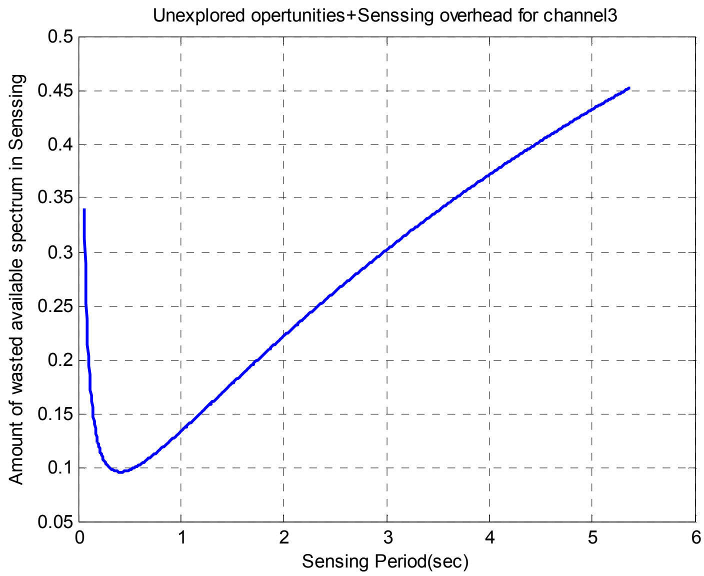


Fig. 5.3 UOPP+SSOH for channel 3

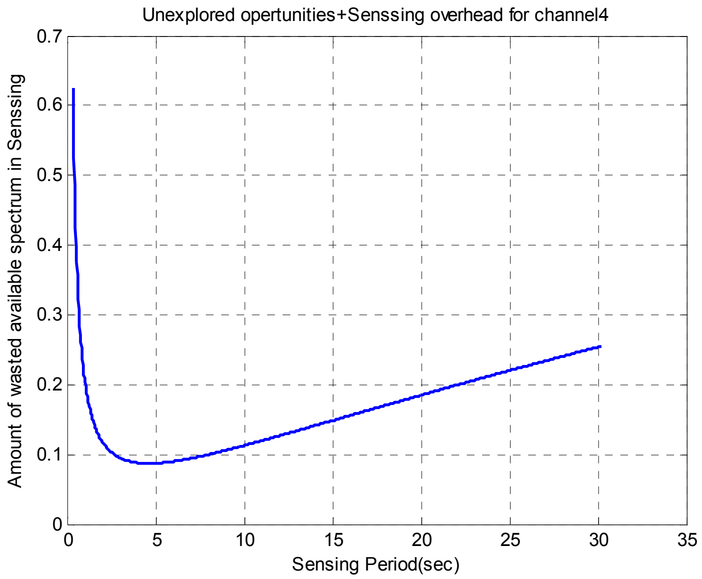


Fig. 5.4 UOPP+SSOH for channel 4

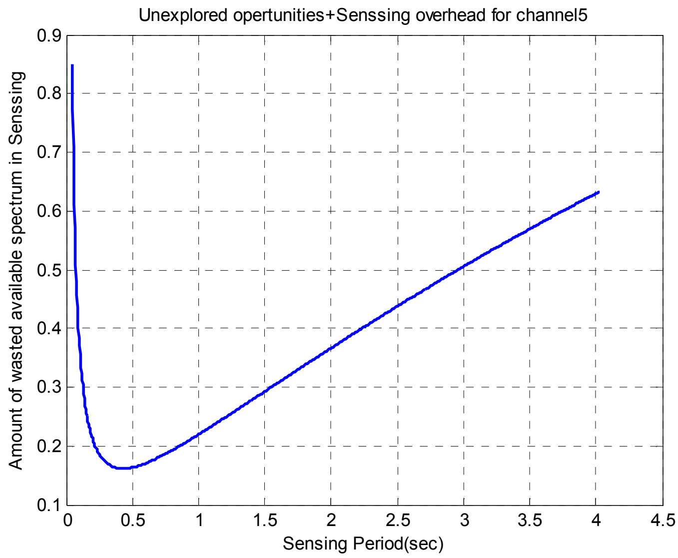


Fig. 5.5 UOPP+SSOH for channel 5

Figures 5.1 to 5.5 provide us with the optimal sensing period for each channel and the corresponding achieved spectrum utilization factor as summarized in table 5.1.

Table 5.1 Optimum sensing periods and Spectrum utilization factors

Channel	Optimum sensing period	$\frac{UOPP + SSOH}{(1-u)}$	SUF
Channel 1	1.51 sec	5.8%	94.2%
Channel 2	2.56 sec	7.8%	92.2%
Channel 3	0.43 sec	9.7%	90.3%
Channel 4	4.00 sec	8.7%	91.3%
Channel 5	0.48 sec	8.1%	91.9%

5.2 Channels Parameters Estimation:

Here we present the estimated values of channels utilization factors $\boldsymbol{u}$ and the exponential distribution parameter, $\boldsymbol{\lambda_x}$, for OFF periods for each channel.

5.2.1 Channels utilization factor estimation:

Fig. 5.6 shows the estimated values for our channels utilization, where the dashed lines illustrate the values calculated from the 'injected' means $E_{X^i}(x)$ and $E_{Y^i}(y)$.

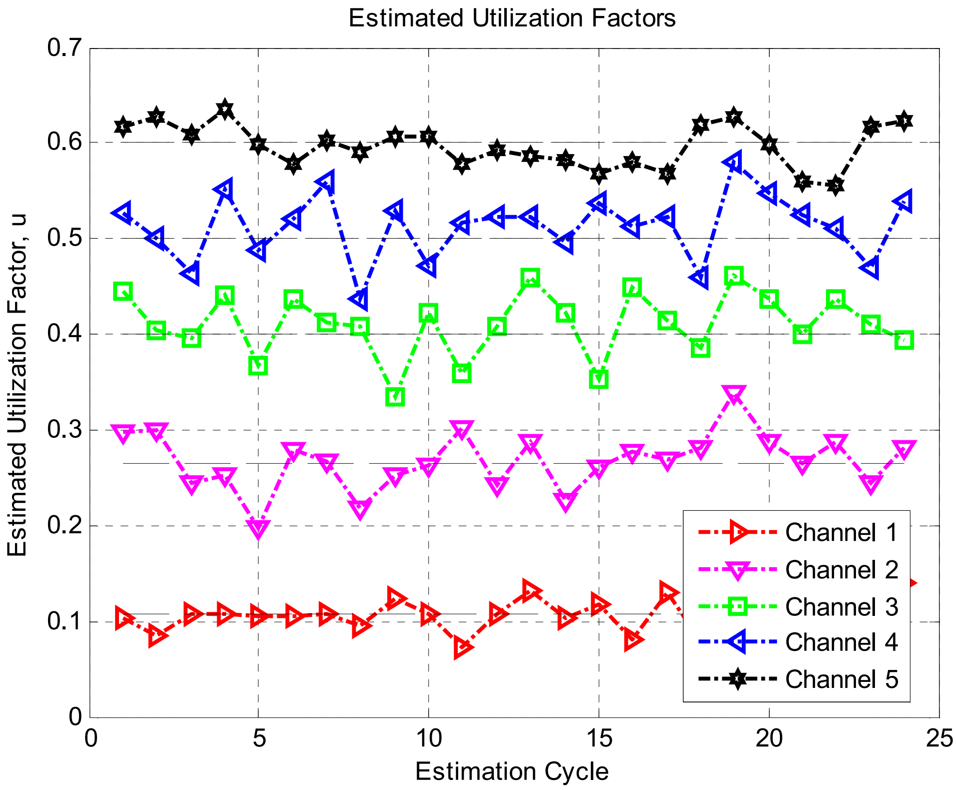


Fig. 5.6 Estimated utilization factors, $\hat{u}$, for the 5 channels

Fig. 5.6 insures that the utilization estimator we have used, sample mean estimator, is unbiased where the estimated utilizations $\hat{u}$ follow the actual ones which is represented by the dashed lines closely for all channel.

5.2.2 Channels OFF periods Distribution parameter, $\widehat{\lambda_x}$ estimation:

Fig. 5.7 shows the estimated values for our channels distribution parameter λ_x,, where the dashed lines illustrate the value calculated from the 'injected' means $E_{X^i}(x)$ and $E_{Y^i}(y)$ and the calculated u shown in Fig. 5.6.

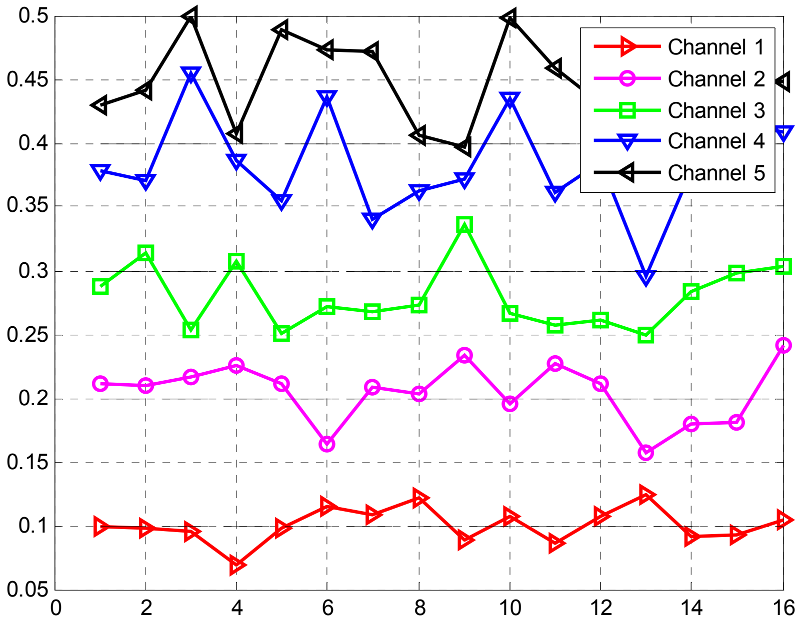
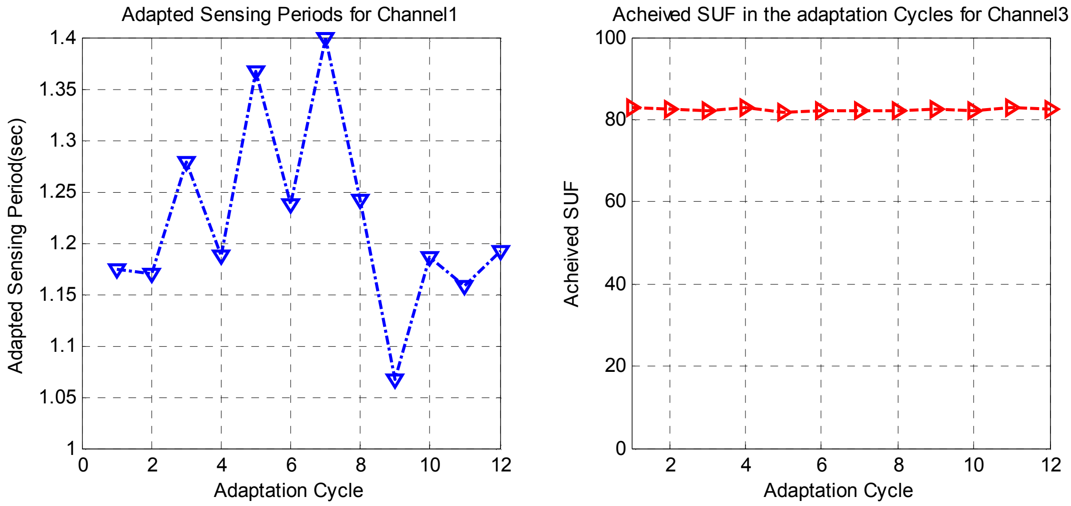


Fig. 5.7 Estimated $\widehat{\lambda_x}$ for the 5 channels

Fig. 5.7 reflects the estimated values of $\widehat{\lambda_x}$ which follow the actual ones represented by the dashed lines, even though one can observe the biasness in our used estimator, MLE, that is the estimation accuracy differ from channel to channel as it was the best in channel 1 and the worst case has been faced with channel 5.

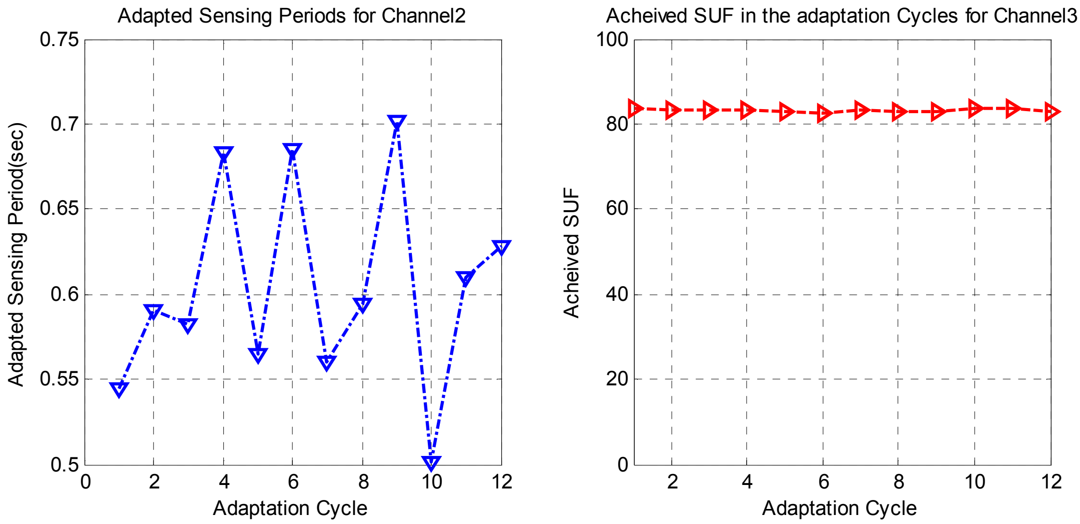
5.3 Adapted sensing periods and achieved spectrum utilization factor for each channel.

During operation, the adapted sensing periods and corresponding achieved spectrum utilization factors are illustrated in figures 5.8 to 5.12.



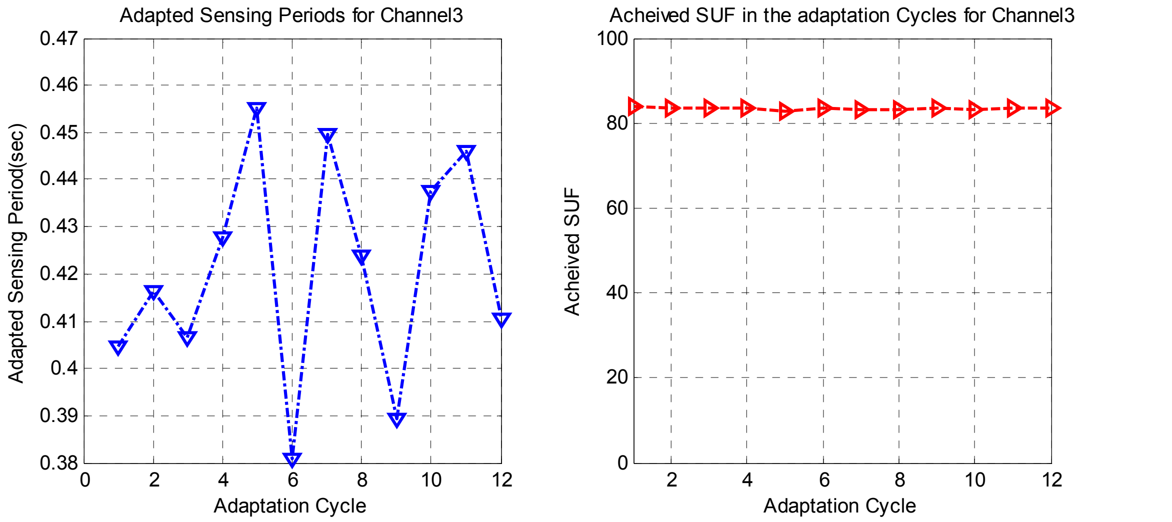
(a) **(b)**

Fig. 5.8 (a) Adapted sensing periods, (b) corresponding achieved spectrum utilization factor for channel 1 during operation



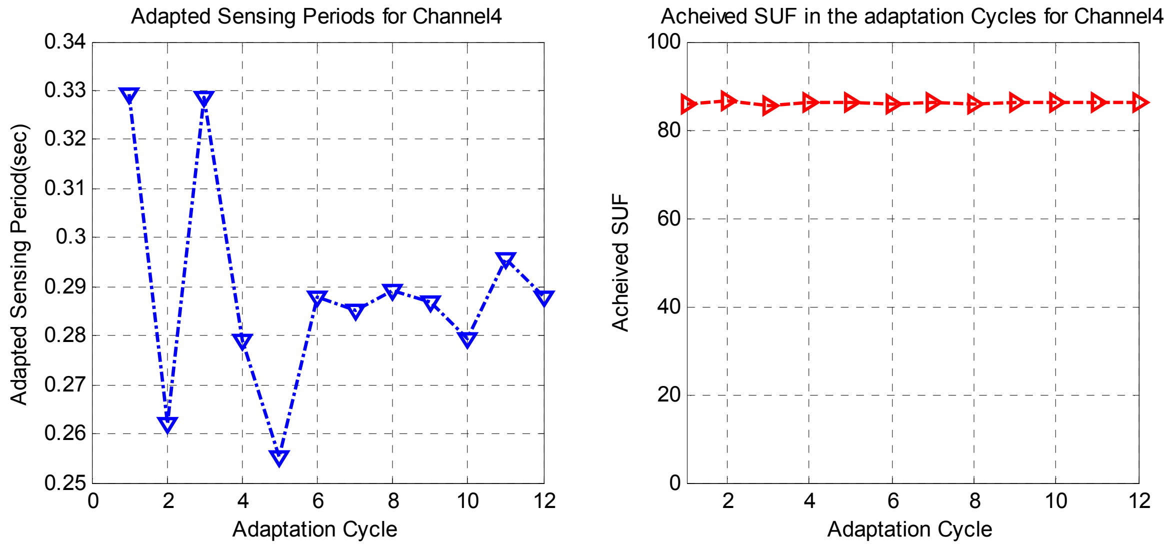
(a) **(b)**

Fig. 5.9 (a) Adapted sensing periods, (b) corresponding achieved spectrum utilization factor for channel 2 during operation



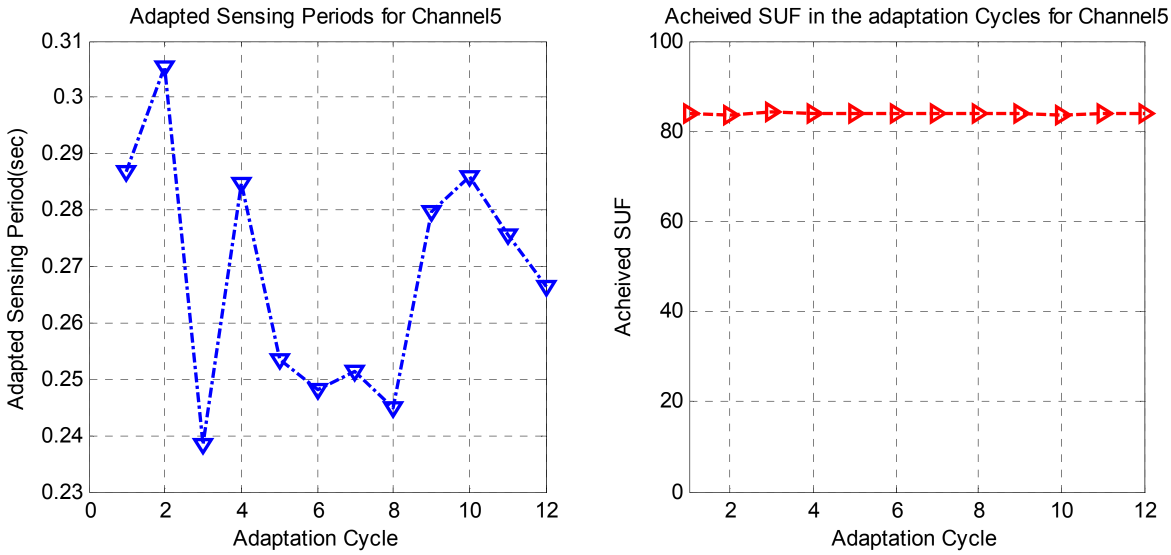
(a) **(b)**

Fig. 5.10 (a) Adapted sensing periods, (b) corresponding achieved spectrum utilization factor for channel 3 during operation



(a) **(b)**

Fig. 5.11 (a) Adapted sensing periods, (b) corresponding achieved spectrum utilization factor for channel 4 during operation



(a) **(b)**

Fig. 5.12 (a) Adapted sensing periods, (b) corresponding achieved spectrum utilization factor for channel 5 during operation

From figures 5.8 to 5.12 we observe that the achieved spectrum utilization is almost consistent in each channel and in all cases it is more than 80%. This consistent achieved spectrum utilization is an advantage of the adapted sensing periods' mode over the non-adapted ones which will be discussed and explained more in section 5.4.2.

5.4 Sensing modes Comparison and tradeoffs:

In this part we will provide two sensing modes comparison obtained results

5.4.1Reactive versus Proactive regarding Idle Channel Search delay:

We defined three cases concerning the radio environment congestion:

1. Uncongested radio environment where $\mathbf{0.5}>u^i>\mathbf{0.1}$
2. Congested radio environment where $\mathbf{0.7}>u^i>\mathbf{0.4}$
3. Highly congested radio environment where $\mathbf{0.9}>\mathrm{u}^i>\mathbf{0.5}$

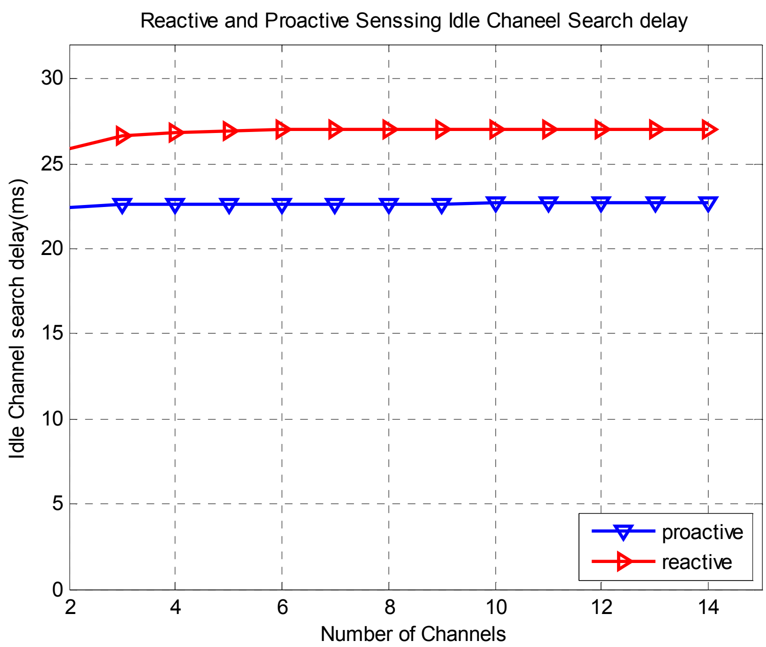


Fig 5.13 Idle Channel Search Delay in Proactive and Reactive Sensing in an uncongested environment

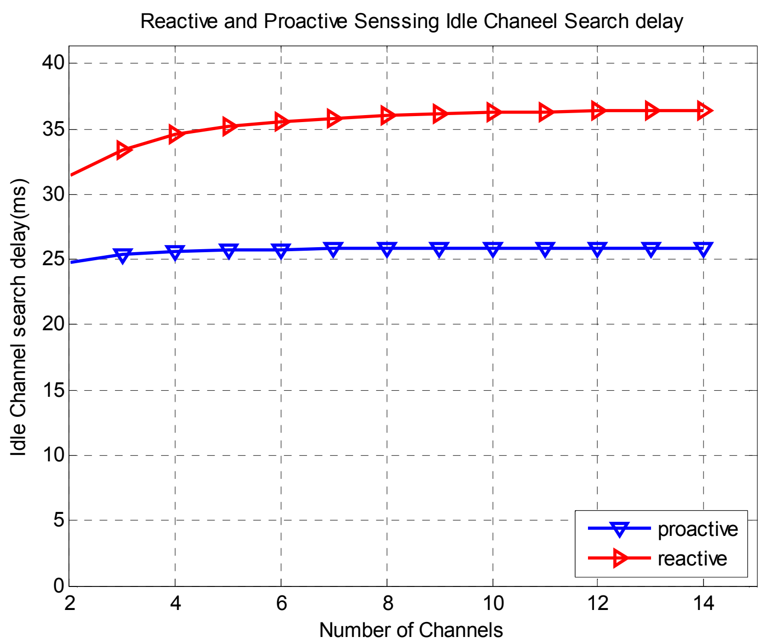


Fig 5.14 Idle Channel Search Delay in Proactive and Reactive Sensing in a congested environment

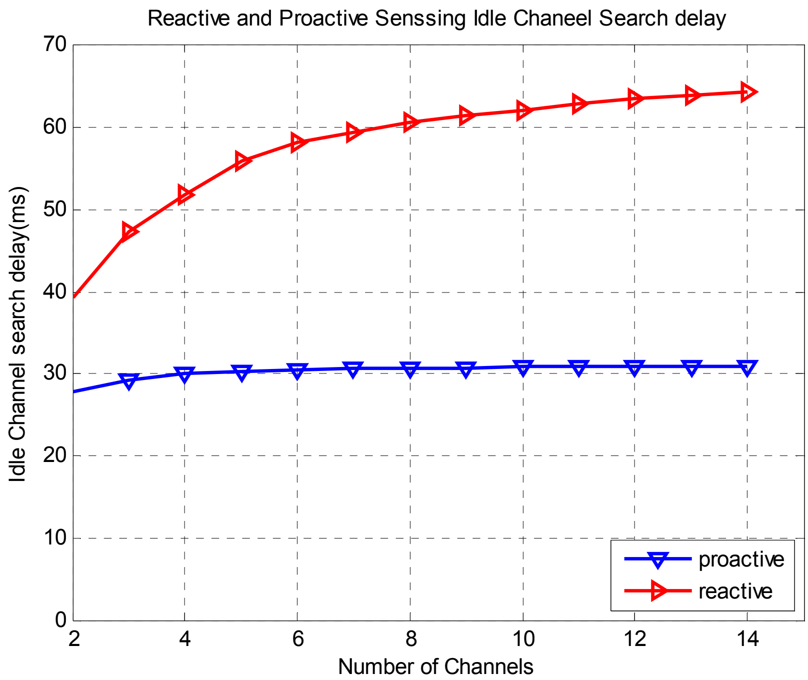


Fig 5.15 Idle Channel Search Delay in Proactive and Reactive Sensing in a highly congested environment

Figures 5.13, 5.14 and 5.15 are analyzed and the following conclusions can be stated:

1. In all cases idle channel search delay in proactive sensing is affected much less with the number of channels than in reactive sensing.
2. Reactive sensing in uncongested radio environments is better to be used as it is idle channel search delay is not much higher than Proactive sensing. Consequently, a tradeoff between the idle channel search delay and simplicity would end up with selecting reactive sensing for such environments.
3. With the increase of congestion in our radio environment, using of proactive sensing becomes more desirable to decrease idle channel search delay.

5.4.2 Impact of sensing periods' adaptation on Achieved Spectrum Utilization factor SUF in Proactive sensing:

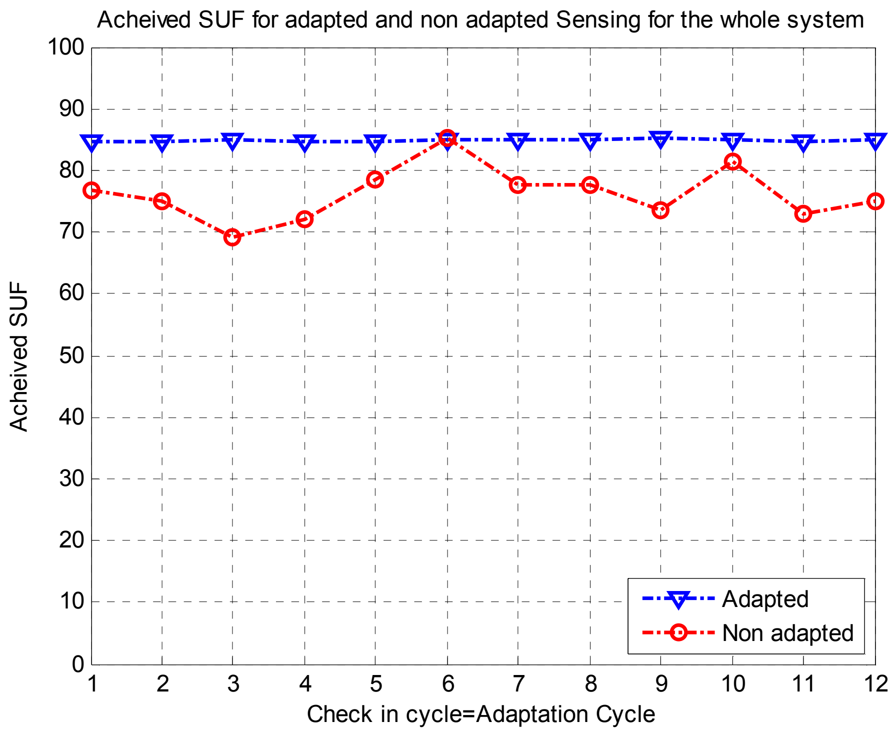


Fig. 5.16 SUF for the whole system in Adapted and Non-adapted sensing periods proactive sensing

Fig. 5.16 demonstrates the Achieved Spectrum Utilization factor SUF for the whole system which reflect how much amount of the available spectrum on the all channels the unlicensed users can utilize in both adapted and non-adapted sensing periods proactive sensing, the figure concludes that adapted sensing periods mode is more robust regarding the achieved SUF and has more consistent SUF.

Chapter 6
CONCLUSION

The ongoing increasing demand for wireless based services nowadays makes it necessary to define new policies and standards in order to manage the available electromagnetic radio spectrum in a way that makes the wireless environment applicable to match this high evolution in wireless devices and technologies.

In this thesis we considered dynamic spectrum access in cognitive radios as a new trend and a novel solution to face this wireless technologies explosion. We mainly worked with spectrum sensing in MAC layer in cognitive radio networks based on overlay spectrum sharing policy. Throughout the thesis we have illustrated the aspects of MAC layer sensing in cognitive radio networks covering the sensing modes and the performance metrics. We also presented MATLAB based simulation results and analyzed them.

Our results show that to grantee as high spectrum utilization and as low idle channel search delay as possible. Proactive sensing with adapted sensing periods is the best candidate to be used: However, proactive sensing with adapted sensing periods is the most costly mode in terms of nodes complexity needed to perform the required computational tasks. Hence it is a matter of tradeoff which is governed by the nature of the licensed and unlicensed networks as described in our results analysis.

As introduced earlier, cognitive radio is one of the newest fields in radio communications and thus considerable research is required on this interesting new technology. For future work, it is highly recommended to work with different types of both licensed and unlicensed networks and to study the impact of the network nature and characteristics on the sensing modes performance. For instance, to study the effects of inter-arrival packet rate and packet departure rate on different sensing modes performance. Moreover, more complicated types of networks can be considered such as; prioritized nodes networks and networks with centralized units. Furthermore, design and implementation of a transceiver supports one or more of the MAC layer sensing modes would be an interesting and important study related to our work. Finally, it is important for future studies to merge the area covered by this thesis with some other related issues in cognitive radio like to consider unlicensed users coordination problems.

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