İSTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF SCIENCE AND TECHNOLOGY

PRIORITY BASED COOPERATIVE SPECTRUM SHARING IN COGNITIVE RADIO NETWORKS

M.Sc. Thesis by

Gülnur Selda UYANIK

Department : Computer Engineering

Programme : Computer Engineering

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Gülnur Selda UYANIK
(504081527)

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Supervisor (Chairman) : Prof. Dr. Sema OKTUĞ (ITU)
Members of the Examining Committee : Assist. Prof. Dr. Feza BUZLUCA (ITU)
Assoc. Prof. Dr. Özgür B. AKAN (KU)

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BİLİŞSEL RADYO AĞLARDA ÖNCELİK TABANLI, KOOPERATİF SPEKTRUM PAYLAŞIMI

YÜKSEK LİSANS TEZİ
Gülnur Selda UYANIK
(504081527)

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Tez Danışmanı : Prof. Dr. Sema OKTUĞ (İTÜ)
Diğer Jüri Üyeleri : Yrd. Doç. Dr. Feza BUZLUCA (İTÜ)
Doç. Dr. Özgür B. AKAN (KÜ)

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FOREWORD

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May 2011 Gülnur Selda Uyanık

Computer Engineer

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ABBREVIATIONS

Wi-Fi	: Wireless Fidelity
WiMax	: Worldwide Interoperability for Microwave Access
FCC	: Federal Communications Commission
TRSR	: Traffic Request Satisfaction Rate
COR	: Channel Occupancy Rate
ISM	: Industrial, Scientific and Medical
CR	: Cognitive Radio
CRAHN	: Cognitive Radio Ad Hoc Networks
PU	: Primary User
RF	: Radio Frequency
SU	: Secondary User
OSI	: Open Systems Interconnection
QoS	: Quality of Service
UWB	: Ultra Wide Band
xG	: Next Generation
DSAP	: Dynamic Spectrum Access Protocol
CCC	: Common Control Channel
SINR	: Signal to Interference plus Noise Ratio
VCG	: Vickery Clarke Groves
SC/MC-ADP	: Single/Multiple Channel Asynchronous Distributed Pricing
MAC	: Medium Access Control
NE	: Nash Equilibrium
CI	: Collision Index
DSA	: Dynamic Spectrum Access
GCP	: Graph Coloring Problem
KB	: Knowledge Base
FOL	: First Order Logic
ANN	: Artificial Neural Network
OFDM	: Orthogonal Frequency Division Multiplexing
AWGN	: Additive White Gaussian Noise
SS	: Spectrum Sharing

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SUMMARY

Wireless communication is a widespread technology preferred by many of the commonly used applications. Wireless signals are used at many scales of communication networks. From personal area networks like Bluetooth and infrared signals, to cellular networks, television broadcasts, local area Wi-Fi networks, sensor networks and to long-range communications in wide area networks like WiMax, applications use wireless communication. Therefore, wireless applications take place at both high, moderate and low frequencies sweeping the whole spectrum map. However, the spectrum demands of these varieties of wireless applications follow different patterns on spectrum bands; their spectrum usages are not continuous. Therefore, static spectrum band assignments are becoming infeasible.

Cognitive radio technology is a promising technology inspired from the observation that the spectrum bands are not used efficiently and the band utilization ranges from 15% to 85%. Basically, cognitive radio technology aims to enable its users to employ the available spectrum portions, which are not used, by any of the primary users who have licenses to use these specific bands. In order to achieve this goal in a broadband communication manner, advanced mechanisms for spectrum analysis, spectrum decision, spectrum usage coordination and spectrum mobility for preventing any harm on licensed users are required. These form the basic functionalities of a cognitive radio system.

In this thesis, it is aimed to work on spectrum sharing functionality in cognitive radio networks. The spectrum sharing mechanisms are explored which distribute spectrum opportunities among secondary users who can be treated as having equal rights because all do not have any license or payment right on the spectrum. This distribution’s form directly affects the overall secondary network performance. Many different problem solution aspects for this optimization problem are considered. Then, a novel spectrum sharing mechanism is proposed and tested.

Proposed scheme in the thesis is related to the spectrum sharing process, providing a method for distributing available spectrum opportunities among secondary users. A distributed spectrum sharing mechanism is proposed that is based on individual spectrum decisions, priority and messaging mechanism between cognitive radio users. Messaging among secondary users is achieved via common control channel. Cognitive radio users in the system model of the proposed study work in a distributed manner. Messaging framework achieves cooperation and priority chaining ensures fairness among these users. In addition, a messaging topology is modeled that represents the deficiencies in the common control channel.

The network model and proposed spectrum sharing system is simulated via MATLAB Simulink environment and the following performance metrics are extracted: Traffic Request Satisfaction Rate, Channel Occupancy Rate and Fairness among cognitive radio users. The obtained results are compared with other techniques employing rule based channel selection strategies as selfish and random channel selection. Performance results are studied in variety of environments and it is observed that the proposed system performance outperforms other schemes at many cases especially when the number of broken messaging links is remained at a certain level.

BİLİŞSEL RADYO AĞLARINDA, ÖNCELİK TABANLI, KOOPERATİF SPEKTRUM PAYLAŞIMI

ÖZET

Kablosuz haberleşme, sık olarak kullanılan pek çok uygulamada tercih edilen, yaygın bir teknolojidir. Haberleşme ağlarında, kablosuz sinyaller, pek çok ölçekte kulanılmaktadır. Bluetooth, kızılötesi sinyaller gibi kişisel alan ağlarından, hücresel ağlar, televizyon yayınları, yerel alan WiFi ağları, duyarga ağları ve WiMax gibi uzun menzilli haberleşme sağlanan geniş alan ağlarına kadar birçok uygulamada, kablosuz haberleşme kullanılmaktadır. Bu nedenle, kablosuz haberleşme kullanan uygulamalar, yüksek, orta ve düşük frekanslarda, tüm spektrum haritasını tarayacak şekilde yer alırlar. Fakat, bu değişik uygulamaların ihtiyaçları değişik tiplerde olduğundan, spectrum kullanımları süreklilik göstermemektedir. Bu nedenle, statik spektrum bant ataması efektif olmaktan çıkmaktadır.

Gelecek vadeden bir teknoloji olan bilişsel radyo ağlar, spekrum bantlarının efektif olarak kullanılmadığının ve bant verimliliğinin %15 - %85 arasında değişim gösterdiğinin gözlemlenmesinden doğmuştur. Temel olarak, bilişsel ağ teknolojisi, belirli spektrum alanlarının kullanım hakkı için ücret ödemiş olan birincil kullanıcıların kullanmadıkları spektrum alanlarını, kendi kullanıcılarınan sunmayı amaçlamaktadır. Bu amacı genişbantlı haberleşme kapsamında gerçekleştirebilmek için, gelişmiş spektrum analizi, spektrum kararı, spektrum kullanımı koordinasyonu ve birincil kullanıcılardan herhangi birine zarar gelmesini önlemek amacı ile spektrumu terk etme mekanizmaları gerekmektedir. Bu mekanizmalar, bilişsel radyo ağlarının temel fonksiyonlarını oluşturmaktadır.

Bu tez çalışmasında, bilişsel radyo ağlarda, spektrum paylaşım fonksiyonu üzerinde çalışılması amaçlanmıştır. Spektrum olanaklarını, herhangi bir lisans veya ödeme yapmadıkları için kendi aralarında eşit haklara sahip olduğu düşünülen ikincil kullanıcılar arasında dağıtan spektrum paylaşım mekanizmaları incelenmiştir. Bahsedilen paylaşımın yapısı, ikincil ağın performansını doğrudan etkilemektedir. Bu optimizasyon problemi için önerilen değişik çözüm yaklaşımları değerlendirilmiştir. Bunun ardından, özgün bir spektrum paylaşım mekanizması önerilmiş ve test edilmiştir.

Bu tez çalışmasında önerilen yöntem, ikincil kullanıcılar arasında spektrum olanaklarının paylaşımını sağlayan bir method olduğu için spektrum paylaşımı ile ilgilidir. İkincil kullanıcıların bireysel spektrum kararları, öncelik değerleri ve mesajlaşma mekanizmasına dayanan, dağıtık bir spektrum paylaşım yöntemi önerilmiştir. İkincil kullanıcılar arasındaki mesajlaşma ortak kontrol kanalı aracılığı ile gerçekleştirilmektedir. Önerilen sistemdeki ağ modelinde, bilişsel radyo ağ kullanıcıları, dağıtık bir prensip ile çalışmaktadırlar. Mesajlaşma mekanizması kullanıcılar arasındaki iş birliğini, öncelik değerlerinin çevrel olarak ilerletilmesi ise kullanıcılar arasındaki adaleti sağlamaktadır. Bunun yanında, mesajlaşma topolojisi yardımıyla ortak kontrol kanalındaki mesajlaşma eksiklikleri modellenmektedir.

Ağ modeli ve önerilen spektrum paylaşım yöntemi MATLAB Simulink ortamında simule edilmiş ve ilgili performans metrikleri incelenmiştir: Trafik İsteği Karşılanma Oranı, Kanal Kaplama Oranı ve kullanıcılar arası Adalet. Elde edilen sonuçlar, kural tabanlı çalışan, bencil ve rasgele spektrum paylaşım stratejileri ile karşılaştırılmıştır. Performans metrikleri çeşitli ortamlarda incelenmiş ve önerilen sistemin performansının pek çok ortamda, koparılan mesajlaşma bağlantılarının belirli seviyenin üstüne çıkmadığı durumlarda, diğer yöntemlerden daha yüksek olduğu gözlemlenmiştir.

1. INTRODUCTION

Wireless communication is used at many scales of communication networks. From personal area networks to wide area networks, wireless spectrum is in use. Especially the mobile devices’ pervasion increased the preference of wireless communication and spectrum map is getting crowded at latest decades. Wireless spectrum’s free portion scarcity has encouraged the researchers to work on how to use this valuable resource more effectively. Cognitive radio is a new communication model, different from the traditional communication standards, not working at a certain spectrum interval, rather than trying to utilize all by embracing the spectrum as much as possible.

Cognitive radio technology is a communication paradigm whose main intent is to explore the wireless spectrum band in a wide and intelligent manner and use it efficiently by giving its users the opportunity to use the licensed and/or unlicensed spectrum bands when there is no activity at a specific moment, at that portion of the band. Need of this technology rose from the observation that the spectrum bands are used sporadically and there exists some unused times and/or frequencies in the bands decreasing the utilization of the spectrum. FCC also reported that the temporal and geographical variations in the utilization of the assigned spectrum range from 15% to 85% [1]. This implies that the static assignment of the spectrum policy may drop the overall spectrum efficiency significantly. Even if no licensed user is using a specific spectrum portion at a specific time, no other user can utilize it by the traditional static spectrum assignment policy. However, if it were achieved to serve these opportunities to other users, overall spectrum utilization would obviously increase. This idea comes up with a cognitive radio technology paradigm. At this point, it has to be pointed out that the traffic demands of CR users are said to be delay tolerant. Although, currently QoS is a topic of interest in CR networks, in this work, CR users are thought to have low QoS requirements. Considering CR users have not paid any fee on any spectrum right, it is not usually guaranteed for them to achieve all their traffic requirements even at a certain level.

Distributing the available spectrum among secondary users that have no specific right on these bands, while protecting the licensed users' (primary users) communication service demands is the key concept of cognitive radio technology. Protecting the primary users is vital in these networks considering the secondary users are thought to have no specific rights on any band, whereas primary users at each band has paid for his rights.

The IEEE 802.22 is a standard for wireless regional area network, which will operate using the white spaces in the TV spectrum (TV signals at 54 to 862 MHz). The white spaces are the unused spectrum portions in the TV broadcasts. This standard is a first standard using cognitive radio rationale such that the white spaces that occurred from geographical losses from TV broadcasts are used for secondary users' communications. Secondary users are allowed to communicate on these opportunities, however, their interference to primary users are defined to be kept below a strict level. Besides interference restrictions and timing requirements, the error at detection of primary signal is defined within a certain bound as well.

Since the main idea of cognitive radio technology includes communicating on a wide range of frequencies, many implementation challenges exist. Hardware support for switching from and to variety of frequencies, ability to work with different communication parameters, related problems at physical and data link layer and upper layer challenges like routing and receiver node's synchronization with sender's working frequency are some of these challenges. Because the spectrum management functionalities are in continuous relation within each other, usually cross layer solutions are proposed for cognitive radio systems.

Spectrum opportunity detection is the basic step in this technology. After determining the available spectrum portions, spectrum sharing mechanisms distribute these spectrum opportunities among secondary users. In this thesis, spectrum sharing algorithms are considered and a distributed, cooperative and priority based spectrum sharing mechanism is proposed.

1.1 Purpose of the Thesis

Spectrum opportunities arise from the lack of primary users' communication at certain times and frequencies. As well as detection of these opportunities, it is important to decide which CR user/s can use them. It is also crucial which set of these users' spectrum usage is more profitable for the overall spectrum utility. Spectrum sharing algorithms come up at this point, handling this optimization problem. Since all CR users in the system work with a similar approach of utilizing available spectrum, these users can be seen as competitors competing for almost the same resources. Spectrum sharing mechanisms provide the distribution of commonly detected spectrum opportunities among these coexisting CR users. Therefore, spectrum sharing is one of the challenging functionalities of the cognitive radio systems and is studied in this thesis.

Main purpose of this thesis is to understand research, work on the spectrum sharing mechanisms, and increase the overall system performance in cognitive radio networks. Different spectrum sharing algorithms existing in literature are examined. Then, a priority based spectrum sharing mechanism is proposed, simulated and its performance is analyzed.

Proposed scheme aims to overcome the collisions among the secondary users who discovered and will attempt to utilize the same spectrum holes. In order to increase the overall system utility, a priority and messaging based approach is introduced. Messaging framework achieves cooperation among CR users helping to increase the overall system utility. Priority chaining provides a method of scheduling CR users while protecting the fairness among them. CR users are said to communicate on a common control channel for the control messages of the spectrum sharing process. However, a messaging topology is modeled that represents the deficiencies in the common control channel which prevents some CR users from hearing some other/s's messages from the CCC.

The network model and the proposed spectrum sharing system are simulated via MATLAB Simulink environment and the following performance metrics are extracted: Traffic Request Satisfaction Rate, Channel Occupancy Rate and Fairness among cognitive radio users. Proposed scheme's performance is compared with basic, distributed, rule regulated spectrum sharing techniques called selfish and random channel selections. Since the proposed method is a cooperative scheme using the advantage of communication among CR users, messaging environment is varied in order to see how the connectivity of the nodes affects the proposed scheme's performance.

1.2 Organization of the Thesis

Chapter 2 presents the cognitive radio technology and its basic functionalities in its subchapter 2.1, and then chapter 2.2 covers the selection of spectrum sharing mechanisms that have been examined as a literature search.

Proposed spectrum sharing scheme is presented in Chapter 3 in detail, including the network model description, spectrum decision and sharing subsystems' explanations, definitions of the performance metrics, and model implementations and verifications in MATLAB Simulink environment.

Performance evaluations of the proposed scheme and comments to simulation results are given in Chapter 4.

Chapter 5 is the review of the thesis and the conclusion.

2. SPECTRUM SHARING IN COGNITIVE RADIO NETWORKS

2.1 Cognitive Radio Technology and the Basic Functionalities

In a traditional communication paradigm, except the open spectrum intervals (also called *spectrum commons*) like ISM band, spectrum users pay and obtain specific and strict rights on their spectrum usages. *"Primary User"* is the term referring to such users that have license to use specific part of the spectrum. Some unused spectrum opportunities arise from the fact that these licensed users do not use their channel resources continuously. FCC also reported that (in the report dated November 2002) in many bands, spectrum access is a more significant problem than scarcity of spectrum [2].

As seen in Figure 2.1.a, some frequencies are in sparse or medium use whereas some are in heavy use. Especially sparsely used frequencies, and with some restrictions the medium used ones, matching with the rudiments of a cognitive radio technology, can be considered as unused spectrum portions. *"Spectrum Hole"* concept that comes from this observation is described in [2] as: "A spectrum hole is a band of frequencies assigned to a primary user, but, at a particular time and specific geographic location, the band is not being utilized by that user".

The spectrum opportunities may be arisen from empty slots varying in both frequency and time domain as seen in Figure 2.1.b. Spectrum hole concept is also denoted as *"White Space"* as in [2] or *"Spectrum Opportunity"* as in [3]. Besides, in [2], author also defined *"Grey Space"* portions that are spectrum bands partially occupied by low power interferers. However, in most of CR technology studies, it is preferred using only white spaces. The reason is that due to the imperfections on spectrum status characterization, these gray spaces may not be detected precisely and grey space usage can come up with a PU disturbance with an higher probability than a white space's miss detection such that in fact a PU was in an active state. In the proposed work of this thesis, CR users in the network model also try to use only the white spaces of the primary users' communication bands.

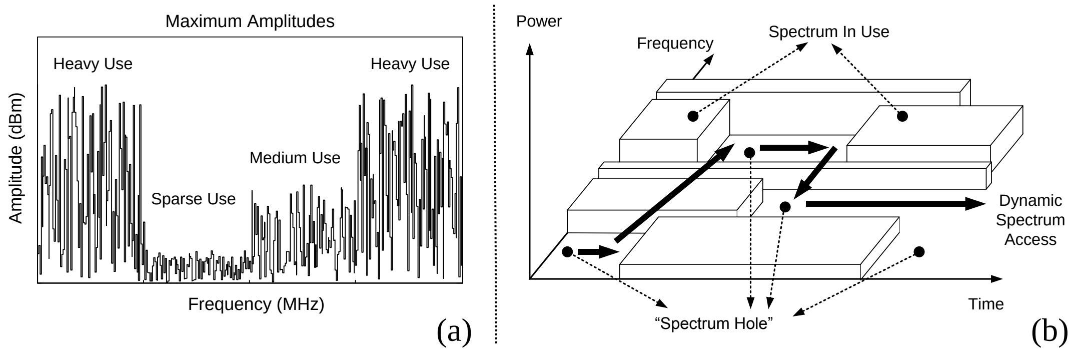


Figure 2.1 : Spectrum utilization and spectrum hole concept: (a)Utilization. (b)Spectrum holes varying in both f and t domain, adapted from [1].

Cognitive Radio Technology for that there also exist other technical terms such as Next Generation Networks or Dynamic Spectrum Access [1] [3], inspired from the observation that the spectrum bands are not used efficiently and they are used sporadically such that the band utilization drops due to the spectrum holes. Basically, CR technology aims to enable its users to use these available spectrum portions (spectrum holes). In other words, main idea of CR technology is to get benefit from the varying spectrum opportunities. Since these spectrum holes alternate, the selection mechanism that passes through these variety of spectrum holes, aims to find the optimal available spectrum portion to communicate on. Meaning, cognitive radio equipment should be able to communicate on different kinds of spectrum portions, frequencies and possibly with different properties on transmission parameters like coding, bandwidth etc. That is why the CR technology has risen on top of the previously proposed concept of "*Software Defined Radio*" technology that enables a radio equipment to work on different spectrum bands and ensures it a property of being configurable or programmable.

Network topology of Cognitive Radio Networks can be both infrastructure-based, or can exist with an ad hoc manner. The network model of the proposed spectrum sharing in this thesis also consists of CR users working with ad hoc principles. "Cognitive Radio Ad Hoc Networks" term represents ad hoc networks of CR users. Ad hoc quality comes from the inexistence of a centralized entity like a CR base station. Moreover, since a CR user can utilize variety of spectrum parts from availability in different bands, these users are usually capturing sets of both licensed and unlicensed bands. CRAHN architecture can be seen in Figure 2.2 with two licensed and an unlicensed band and without any infrastructure of the secondary network.

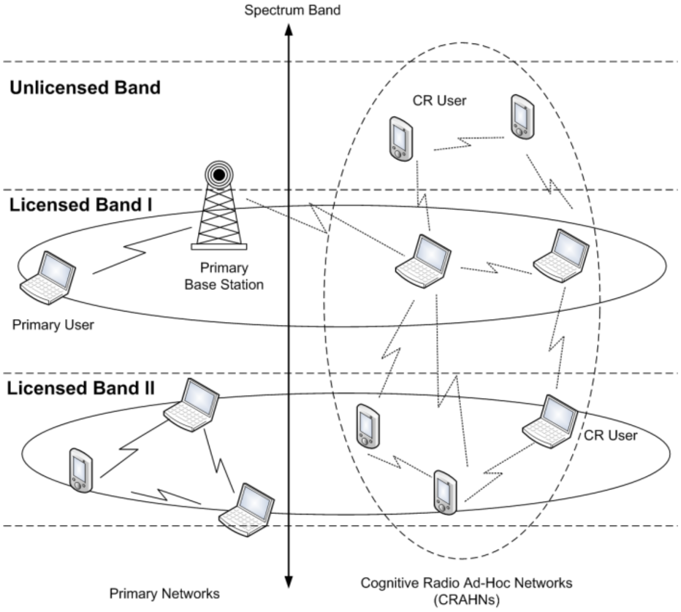


Figure 2.2 : CRAHN architecture, adapted from [5].

Cognitive radio users need to determine and be aware of the spectrum opportunities as a first step. Then, the spectrum holes need to be analyzed in order to decide the gain of the CR user if they are used. After finding and choosing the most suitable spectrum hole/s, the dynamic behavior of the primary user activity necessitates the CR user to leave the band if a PU (PU have a highest priority) comes up. That principle constitutes the main obligation of the cognitive radio technology of causing no (or at an acceptable level) harm on primary users. Meaning that, the information provided by the spectrum sensing block is not stable for a long period and needs to be reconsidered at each spectrum decision.

Four functionalities of the spectrum management in CR networks can be summarized as follows:

- **Spectrum Sensing:** Spectrum Sensing is the process of detecting the spectrum holes. Many physical layer implementations like filter detection, energy detection, interference-based detection etc. are proposed and used in this phase. The spectrum monitoring capability of the CR users is crucial also for other functionalities' performances. The wider of the spectrum range that a CR user can capture, more likely it is to capture more or higher quality spectrum holes, increasing the spectrum utilization of secondary users.

- **Spectrum Management:** Spectrum management process tries to capture the best available channel for a specific CR user. Thus, this process is related to more upper layers. First, the spectrum analysis should be performed to determine or predict the capabilities of the detected spectrum hole, and then the spectrum decision mechanism provide a mechanism to choose band/s from the available ones in a wide range of spectrum. This process seems similar to spectrum sharing, nevertheless, the spectrum sharing is more alike to MAC protocols in traditional networks considering the coordination among secondary users rather than deciding a specific spectrum portion for a specific CR user according to its selfish interests.

- **Spectrum Sharing:** Since there would possibly be more than one CR user in the system, and some set of spectrum holes they detect will possibly overlap, these users can be seen as competitors competing for almost the same resources. Spectrum sharing mechanisms, then, are methods to provide fair scheduling scheme between these coexisting CR users. Spectrum sharing is the main topic of this thesis. Chapter 2.2 analyses this functionality in detail and gives the selected algorithms on this functionality.

- **Spectrum Mobility:** Spectrum mobility can be regarded in two different cases like transition to a better available spectrum or leaving the band on the occurrence of PU activity [1], [4]. First approach may be avoided for some cases due to the switching cost versus switched channel’s gain over the previous one. However, latter condition for spectrum mobility is critical not to break the main rule of cognitive radio technology about not disturbing the primary users of the system.

Figure 2.3 represents the basic functionalities and their relationships; *spectrum sensing* observes RF stimuli and decides whether there exists spectrum hole or not. *Spectrum decision* uses this information and sensed RF signal to characterize the spectrum hole in order to qualify its quality for an SU usage. After the spectrum decision, if the decision is proper (reflecting a spectrum opportunity), SU starts its transmission with the help of the output provided by *spectrum sharing* block. Besides this abstract manner, spectrum sharing block usually takes into account more complex parameters like other SUs’ spectrum usages, spectrum demands etc. This functionality is analyzed in detail in Chapter 2.2. *Spectrum mobility*, on the other hand, ensures the protection of PUs; if any PU detection has occurred, it triggers spectrum decision block so that SU stops transmission.

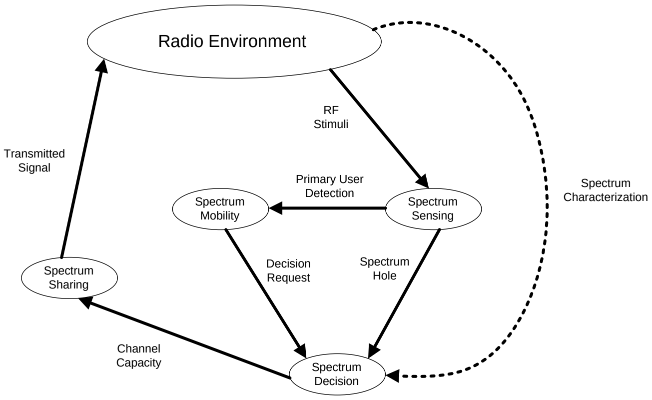
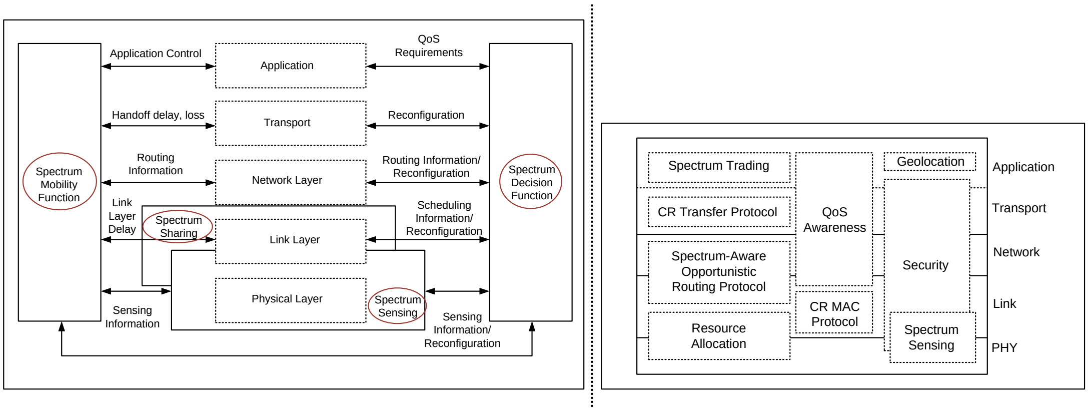


Figure 2.3 : Cognitive cycle illustrating spectrum sensing, management and sharing functionalities, adapted from [5].

Figure 2.4.a visualizes interactions within CR functionalities and their relations with communication layers at the OSI model. As can be noticed, many of CR functionalities need to be designed as cross layer approaches since they rely on or provide input/output from/to multiple layers.

Authors of [6] extended this sketch by adding security, QoS awareness, spectrum trading and location knowledge at application layer, transport protocol, security in all layers, and routing at network and link layer as seen in Figure 2.4.b. Again, many blocks have cross layer designs because of their interactions and dependence among different layers' data.



(a) (b)

Figure 2.4 : Spectrum management functions and the architectures of CR in the layered model: (a)Architecture adapted from [4]. (b)Architecture adapted from [6].

2.2 Spectrum Sharing in Cognitive Radio Networks

Spectrum sharing functionality of CR is the main functionality that is worked on throughout the thesis.

Dynamic spectrum access techniques are classified in [3] and the cognitive radio technology is under *Hierarchical Access Model*. The idea is to open the spectrum bands to *"Secondary Users"* who are ordinary users except from licensed primary users while limiting their interference on PUs. Hierarchical Access Model encapsulates *Spectrum Overlay (Opportunistic Spectrum Access)* and *Spectrum Underlay (Ultra wide band)* approaches. The underlay approach strictly limits the SUs' transmission powers such that they are perceived by PUs as equivalent to natural noise sources. For achieving high data rate with low transmission powers SUs are said to be work in a UWB. Since this limitation is strict enough, there is no spectrum sensing and decision functionalities in this scheme. In overlay approach, on the other hand, SUs are limited not on their transmission power levels but on time and frequency selections. Therefore, SUs need to exploit spatial and temporal spectrum white spaces according to their local and instantaneous spectrum observations [3].

After the spectrum sensing and decision processes, detected or predicted spectrum holes need to be utilized by the CR users conforming to specific principles. Spectrum sharing mechanisms provide scheduling in order to achieve this joint spectrum utilization among CR users.

Classification of spectrum sharing algorithms can be performed considering spectrum decision algorithm's architecture, CR users' spectrum allocation behaviors and spectrum access technique as seen in Figure 2.5.

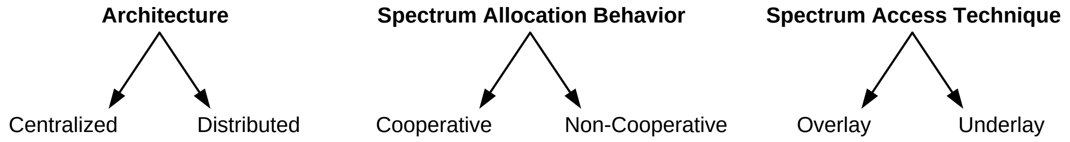


Figure 2.5 : Classification of spectrum sharing in xG networks, adapted from [1].

Architecture classification is related to whether spectrum allocation and access algorithm is performed by a central entity or in a distributed manner where each CR user decides its own decision. When a centralized entity exists, all CR users are said to be able to communicate with this center. This topology brings advantages of running centralized algorithms based on the whole network knowledge. Both spectrum sensing and decision algorithms can take this advantage. By retrieving the sensing information of all users, center can construct a whole spectrum status map of network. Moreover, center can eliminate some of the outlier decisions and lead to a more proper decision. Spectrum sharing is an optimization problem of assigning available spectrum opportunities among CR users in order to achieve maximum profit based on overall spectrum utilization or SU gains. This optimization can also take advantage of the centralized solutions. Schemes like bargaining and overall optimization approaches usually prefer a centralized manner.

Cooperativeness of a spectrum sharing algorithm reflects the consideration of other CR users' spectrum usages during a CR user's own spectrum decision.

Overlay and underlay approaches as also stated earlier, differs from each other by CR users' transmission opportunities. Overlay approach allows a CR user to use channel only if PU is inactive while in the underlay approach, CR users can transmit non-intrusively as long as they obey the restrictions on its transmission power limit.

Spectrum sharing process can may performed both with an intra or inter network manner. When SUs are organized under several operators throughout specific regions that can overlap on both location and spectrum, these operators should assent on their spectrum usages to provide non-conflicting service to their SUs. As seen in Figure 2.6, inter-network spectrum sharing algorithms deal with sharing among CR operators, whereas intra-network spectrum sharing algorithms provide scheduling between CR users in the same network.

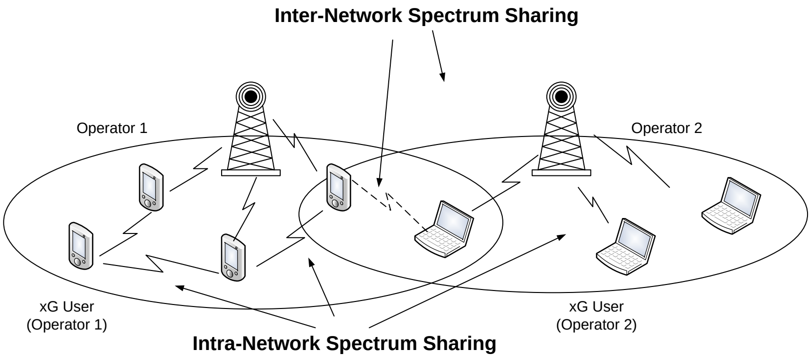


Figure 2.6 : Inter-network and intra-network in xG networks, adapted from [1].

“Common spectrum coordination channel” etiquette protocol that is proposed for coexistence between IEEE 802.11b and 802.16a networks is an example of inter-network spectrum sharing mechanism, in which users determine their channel selection based on broadcasted messages in order to prevent interference, additionally perform interference power adaption if the channel selection is not sufficient [1]. “Central spectrum policy server” is another example of inter-network spectrum sharing mechanism that collects the spectrum demands of the CR operators and distributes available spectrum among them utilizing the total benefit [1].

A distributed spectrum access protocol so called DSAP is an intra-network spectrum sharing mechanism similar to spectrum policy server; a centralized entity retrieves sensing and demand information from SUs and distributes spectrum accordingly [1]. Moreover, it constructs a *Radio Map* from retrieved sensing information and uses it in spectrum sharing mechanism [1]. Intra-network spectrum sharing algorithms that can be categorized with classification shown in Figure 2.5 are to be analyzed in detail in latter sections.

Spectrum sharing challenges include; usage of CCC (common control channel among which all important message exchanges take place and for which all CR users can access), connectivity change due to chosen operating frequencies and spectrum unit that is described as *“channel”* (referring to a configuration of transmission parameters and capacity issues) in many works [1].

Dynamic nature of spectrum sharing problem provide the basis for different solutions like graph coloring analogy, auctioning based approaches or even a water filling approach that is used in information theory. Some schemes try to benefit from the learning mechanisms to be able to adapt the dynamic environment in which CR users work and many learning schemes are proposed for this purpose. The strategic behaviors of the cognitive radio users competing for the available spectrum opportunities are also modeled as different kinds of games and game theoretic approaches are proposed as solutions. Latter sections describe these different kinds of spectrum sharing algorithms.

2.2.1 Non Cooperative Rule or Policy Based Spectrum Sharing Approaches

Zheng and Cao has proposed in [7], a device centric spectrum management in which SUs access the channel/s due to some predefined rules that require only local information. Therefore, this spectrum sharing mechanism stays under the distributed solutions at architecture classification. Cooperativeness, since the users work according to predefined rules not considering other users’ channel decisions, is said to be not used directly. However, the rule definitions try to implement a scheduling considering fairness among all users. A kind of cooperativeness is also achieved by letting neighbors exchange the available channels.

In [7], *Poverty Line* concept is defined as minimum amount of spectrum that is given to an SU and formulated proportional to the number of all available channels over node degree (number of neighbors) of a user. Users work according to the predefined five spectrum rules labeled from A to E:

- Rule A implies that each SU selects exactly fixed number of channels that equals the lowest poverty line value of SUs in the system.
- Rule B sets this limit as poverty line of each SU user itself. Moreover, it gives ability to an SU to grab channels from its users if it has less idle channels than its poverty line.
- Rule C limits number of channels to be borrowed from richer neighbors.
- Rules D and E are selfish channel selections in which SUs select channels with highest throughput values.

Distributed rule regulated spectrum sharing is proposed in [8], where CR users act based on predefined five spectrum sharing rules similar to [7]. They showed both analytically and with simulations that by using these rules, system converges in finite steps and each CR user takes at least a guaranteed amount of spectrum allocation that is defined again as “Poverty Line”. First three rules specify limits on number of channels that a CR user can select exactly or at most proportional to the poverty line of users. Rules B and C, as an addition, enable poorer nodes to grab channels from richer nodes, which necessitate each user to learn its neighbors’ channel selections, and produce excessive messaging. Rules D and E make a CR user take channel selections selfishly as selecting channel/s with highest throughput. The difference between them is the value of maximum number of channels that a CR user can select.

2.2.2 Auctioning Based Approaches in Spectrum Sharing

Auctioning based approaches get the intuition from the economy model that is used to determine the value of the desired commodity. *Payoff* for each user is the value of the gain each retrieves when he grabs a certain portion of the commodity. *Bidders* are the competitors for the common resource, announcing the value of their payment and the related payoff they will gain if they obtain some or all of the resource they demand. An auction is called efficient if it maximizes total payoff of all bidders. Thus, in many auctioning schemes, mechanisms like the Vickery-Clarke-Groves are proposed to increase auctioning efficiency [9]. In an auctioning mechanism adaptation, CR users should announce that how much gain each of them will get when they utilize a specific spectrum hole and the amount of the pay they can supply. Then a central mechanism collects whole information, performs auction rules, and distributes the available spectrum holes depending on the CR users' demands and supplies. Grouping based or *local bargaining* mechanisms also exist for implementation of a bargaining process in a distributed way. However, since the more effective assignment in an auctioning market needs more information on the users' payoffs and payments, excessive messaging schemes are needed for retrieving this kind of information among CR users working with a distributed manner.

Huang et al. in [10] proposed an auction based spectrum sharing scheme in which SUs submit their bids according to their received SINR values and the interference they will provide when a certain transmission power is assigned to them. PU in that scheme allocates each SU a transmission power value according to these bids while protecting overall power interference constraint (underlay approach). VCG auctioning mechanism was not used due to its computational complexity for finding optimum allocation, instead, they modeled two different auction mechanisms in which PU decides a reserve power and reserve bid and then SUs submits new bids accordingly. One dimensional auction with pricing and power auctions are analyzed by giving auctioning mechanisms in detail and their finite state analysis. Additionally, an iterative and distributed bid updating algorithm is proposed in order to overcome the prior knowledge of SUs about others' utility functions and all channel gains [10].

Local bargaining is another example of auction based spectrum sharing but in a distributed scenario. It is a cooperative scheme that needs information exchange among SUs. The main principle is grouping SUs into local groups in which a separate local bargaining procedure will be held [11]. This grouping progress is an important part of the algorithm, which can introduce an implementation problem. It is said to be performed by SUs automatically when they are affected by any mobility effect. Grouping procedure uses control messages between SUs. Bargaining procedures are defined with two variants as one to one and feed poverty bargaining [11]. The evaluations revealed that local bargaining could closely approximate centralized graph coloring approach at a reduced complexity [1]. This produces a middleware approach between a fully distributed network model and centralized solutions.

Single and multiple channel and asynchronous pricing (SC/MC-ADP) models are proposed for determining transmission power of SUs. Each node transmits their interference price to other nodes, retrieving these messages; a node selects a channel and adjusts its transmission power accordingly. Users may use different and/or same channels but with different transmission powers [1].

2.2.3 Game Theory Based Spectrum Sharing Techniques

Spectrum is a common resource that is to be utilized by SUs. Therefore, the SUs that are in common region of the available spectrum portions can be regarded as competitors for these spectrum opportunities. The issues like protecting the balance between acting selfishly or cooperatively to improve overall system utility, how SUs spectrum decisions, cost and their profits affect each other, makes researchers easier to come up with a game theory analogy. Additionally, the theory behind game analogy to the different systems makes it possible to analyze and decide optimality and ability to define an equilibrium criterion in such interactive decision processes.

Book chapters [9] and [12] present the game theoretic approaches for cooperation in cognitive radio networks. Basically, the CR users are treated as game players that try to maximize their own profit. Though, if all work with a selfish manner, the overall spectrum utilization drops due to the collisions among them. Therefore, users need to consider, guess or think about the leaving users' channel usages and decide accordingly.

Game is mainly a set of players, strategies and pay off or utility functions. Strategies are the actions that players can take. Pay off or utility functions define what players gain when they perform a specific action in a specific status of the environment. A fundamental advantage of modeling spectrum management in CR networks with a game theoretical framework is the opportunity to find an equilibrium state of the network in which CR users have no attempt to change their status. In detail, finding a Nash Equilibrium is not an easy process and methods like 'Direct Application of Definition (Greedy Search)', 'Improvement Deviations', 'Iterative Elimination of Dominated States' and 'Best Response Analysis (eliminate intermediate improvement states)' exist for this purpose.

Game Theory Analogy of a CR System: *Players* are the CR Users (and Primary Users), *Actions* can be defined as which channels can be used with which configurations, Outcomes can be defined as the overall network state. *Utility Functions* can reflect the QoS parameters targeted by SUs. After making this analogy adequately precise, the choice of the game type, indeed the formulation and model of the CR system, is the most important topic to be considered. There exists many models, used in CR adaptation like 'Normal form (strategic form) games', 'Synchronous single-shot games', 'Repeated games (extensive form game)', 'Myopic repeated games', 'Mixed (Probabilistic) strategy games', 'Potential games', 'Super modular games', etc. They are not considered in detail but each of them supports different qualities that have to be considered when one of them is to be implemented.

A basic, multiple access game, consisting of two users in a wireless medium is formulated as a game and solved as an illustrative example in [9]. In [12], two variants of game models as coalitional game theory and non-cooperative game frameworks are given. Game theoretical formulization of cooperative distributed MAC protocol: slotted Aloha, game model of available channel distribution to SUs with respect to their QoS requirements and a spectrum aware routing with a congestion game model are given in [12].

Channel selection and additionally transmission power adjustment is performed according to a potential game model in [13] where they showed their model converges to a NE. SUs and PUs (they call lower and higher priority users) can both use same channel but with adjusting their transmission parameters. Joint power allocation and channel selection problem is modeled as a potential game aiming minimizing overall interference among users and user awards are reflecting their throughput [13].

In [14], a selfish (non-cooperative) game-theoretic approach for cognitive radio networks with dynamic spectrum sharing is proposed with an example game including two players' case and then a generalization phase. Collision Index (CI) term is also proposed to reflect the probability (the mixed strategy) that the assigned bandwidth is taken by PU. Nash Equilibrium theorem of the game they propose and its proof is also given in the paper.

In reference paper [15], a game theoretic, DSA-driven MAC strategy is proposed for CR networks. The authors' aim is to combine the intelligence of the game theoretic approaches and the utility gains of DSA strategies. Their mechanism consists of DSA algorithm: deriving the spectrum access strategy for data communication, negotiation mechanism: coordinating players to follow the right game policy, clustering algorithm: limiting the negotiation within one cluster for scalability and collision avoidance mechanism: eliminating collisions among clusters.

In [16], a comparison of resource allocation schemes in cognitive radio networks is performed. One of them is a game theory based and the other is a heuristic based approach. Their simulation results showed that the heuristic usage performs better than the game theoretic scheme in their environmental set up.

2.2.4 Graph Coloring Analogy to Spectrum Sharing Problem

Graph Coloring Problem is basically a problem of assigning each vertex one of the colors such that the connected vertices do not have the same color. In wireless systems, many problems are transformed into GCP like setting the base stations' working frequencies. In cognitive radio networks, the scheme is a little bit different since the available frequency set (equivalent to color set) differs for each node (vertex). The reason is that the available frequency set is determined by the primary user activity on the frequencies a node is monitoring.

The *interference graph* is generated as having vertices of CR users and conflicting edges between users if they have conflicting channels available. Conflicting channels are the channels, which make CR users conflict if they both use. Each node represents a CR user. Every node has a set of colors denoting its available channels.

Figure 2.7.a represents *interference/conflict graph* of the network for channels/colors A and B. As an example of a link of interference, Nodes 2 and 3 both have A on their color list therefore they have an edge on A because they will interfere if both of them use A. Then the problem is decomposed into finding a k-colored graph-coloring problem. This model is also named after *color sensitive GCP* by some references since the available channel (color) list changes from node (vertex) by node on the interference graph. Then GCP algorithm assigns colors to nodes not violating conflict properties. After GCP assignment, some nodes, like node 3 in Figure 2.7.b, may not be able to be assigned with any color due to their interference relationships and available channels.

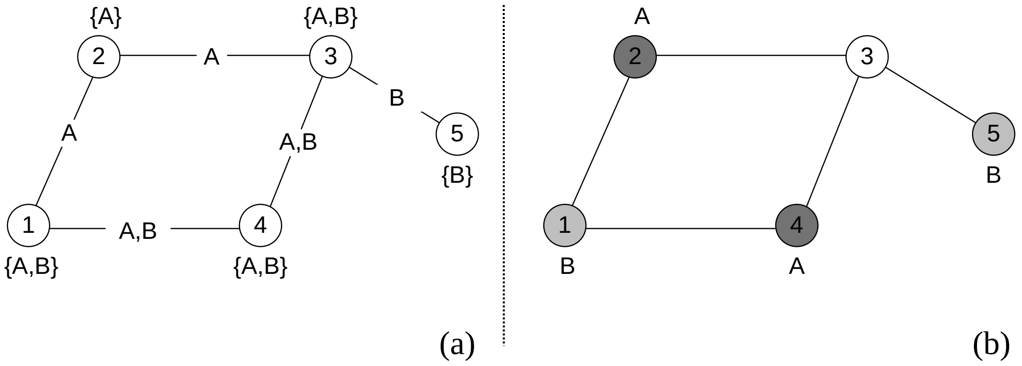


Figure 2.7 : Interference graph representation: (a)Conflict Graph of a network with channels A and B. (b)Proper 2-Coloring of the Conflict Graph, adapted from [9].

Traditional graph coloring algorithms minimize the number of colors used to mark each vertex. The best strategy is coloring the most difficult vertices first. Since the optimal assignment problem is NP complete, the approximations are used like defining labels to each node, representing their priority [9]. Like performed in [17] and [18], ruling formulas can be changed to ensure different quality metrics like overall system utility, fairness, max min fairness or proportional fairness among CR users. Actually, several heuristics aiming at different performance metrics (their performances are best according to their each targeted performance metric but most probably below average when another metric is measured) can be combined with a hyper-heuristic concept and an average performance on all heuristics (the metrics they are trying to optimize) can be gained. Unfortunately, finding a proper heuristic sequence via a hyper heuristic approach needs an evaluation of a search (population based or tabu search) that may highly decrease system's response time about distributing spectrum holes and may not be useful when the spectrum status changes at a high rate. A project on hyper-heuristic implementation on three heuristics (each maximizes fairness, total throughput of CR, and minimum bandwidth assigned to a CR user) with a discrete event simulator written in C++ is performed about this concept in the earlier stages of this thesis work.

Hierarchical approach is also applied in spectrum sharing process. SUs are grouped under cluster heads and spectrum sharing is performed in two stages in the low complexity, hierarchical spectrum sharing scheme proposed in [19]. First, spectrum sharing is performed among cluster heads, as distributing spectrum holes between them in a fair and distributed method in which interference graph is constructed and list-coloring method similar to graph coloring is used [19]. Then, cluster head performs spectrum sharing among cluster members. A heuristic based maximum matching method among member SUs are used at this step [19].

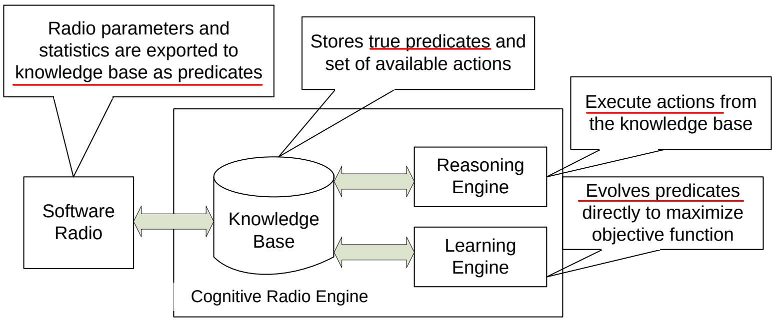
2.2.5 Using Artificial Intelligence Concepts in Spectrum Sharing

Assuming the activity of PUs or status of the spectrum environment follows a certain pattern, learning approaches are thought to be more profitable for SUs for utilizing spectrum in a more intelligent way. Learning approaches like decision tree based, reinforcement learning techniques, or knowledge based reasoning approaches are proposed on top of this idea. It is remarkable that machine learning techniques can discover different relationships and correlations that are hidden within large amounts of data.

Reasoning is processing the available information (*knowledge base*), in order to take reasonable decisions. Reasoning can be achieved with different interference rules on different representations of the knowledge base. For example, Bayesian networks are the specialized representations showing conditionally independency between predicates ensuring making queries or optimal decisions.

Learning can formally be described as: “a computer program is said to learn from experience E with respect to some class of tasks T and performance measure P, if its performance at tasks in T, as measured by P, improves with experience E”. Assuming the spectrum status follows a certain pattern, CR users' are thought to get benefit from learning the environment they are working in, in order to increase their performance.

Combinations of reasoning and learning schemes are also used in cognitive radio spectrum sharing problem. Many different learning schemes exist in the literature. Knowledge based learning methods are focused at this section. In [20], Clancy et al. proposed the application of knowledge based learning schemes for CR systems. Their system's drawback is that they suppose the radios work in a policy based manner and they have hard coded rules. Their goal is to incorporate results of learning engine into calculus based reasoning engine. Figure 2.8.a visualizes their structure of CR user model consisting of knowledge base driven learning and reasoning engines. KB represents the long term memory of CR user, Learning Engine stores the new predicates (logical expressions that form the rules of KB) and Reasoning Engine determines whether an action is applicable or not. Actions have preconditions that should be derived from KB (interference process) to decide whether it is applicable or not and post conditions. Learning engine's duty is to enlarge the list of actions to the CR user and determine which action will ensure the best benefit. Action definition is illustrated in Figure2.8.b and Figure2.8.c show how predicates can be used in such logical expressions (in detail: FOL representation is used) and how they are applied to knowledge base, respectively.



(a)

action: decreaseModulationRate
precond: $(\mathrm{modRate}(\mathrm{QPSK}) \wedge \mathrm{snr}(\leq 8\ \mathrm{dB})) \wedge$
postcond: $(\neg \mathrm{modRate}(\mathrm{QPSK}) \wedge \mathrm{modRate}(\mathrm{BPSK}))$

(b)

KB' = KB postcond
= $(\mathrm{modRate}(\mathrm{QPSK}) \wedge \mathrm{snr}(5\ \mathrm{dB})) \wedge$
$(\neg \mathrm{modRate}(\mathrm{QPSK}) \wedge \mathrm{modRate}(\mathrm{BPSK}))$
= $(\mathrm{modRate}(\mathrm{BPSK}) \wedge \mathrm{snr}(5\ \mathrm{dB}))$

(c)

Figure 2.8 : Clancy et al.'s CR model: (a)Model visualization. (b)Example action. (c)KB status after applying example action, adapted from [20].

Clancy et al. implemented their proposed scheme in two benchmarks: capacity maximization using different coding and modulation types, given different SINR values of the channels and DSA in which center frequencies, bandwidths and times when CR user transmits are tried to be considered while maximizing capacity and minimizing interference. Thus, learning mechanism tries to learn where and where others are transmitting. Several action definitions like ‘notOverlap’, ‘moveBand’ and signal detections are given in terms of the predicates in the same format that KB uses. That is the hardest part of their proposal to implement and the DSAP benchmark case is also not implemented in the paper.

Another approach proposed in [21], titled as ‘Spectrum access games and strategic learning in cognitive radio networks for delay critical applications’, combines a game theoretic approach with a knowledge based learning scheme. Figure 2.9 visualizes the proposed approach. Their proposed scheme contains the special mathematical framework that enables to design, analyze and optimize dynamic multi-user environments as markets; meaning that spectrum access is governed by market driven rules. Interactions are modeled as stochastic or repeated games played over time based on dynamic changes in environment. They implemented three learning schemes: myopic adaptation, simple reinforcement learning and auction based learning.

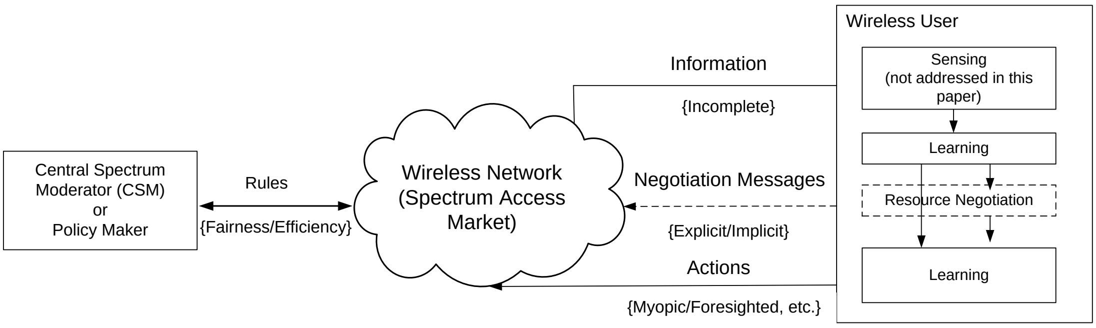


Figure 2.9 : Shaar et al’s knowledge-based wireless networking paradigm, adapted from [21].

In [22], Tsagkaris et al proposed *neural network* based learning schemes for cognitive radio systems. They use similar structure as Clancy et al used which is demonstrated in Figure 2.8 such that cognitive engine has a knowledge base, learning and a reasoning engine to control the software defined radio structure. The difference in this work is the implementation of the learning engine. They proposed an ANN based learning scheme for the learning engine. The neural network structure is used to predict the achievable data rate in a certain configuration: a specific value combination of the transmission parameters taking into account recent information sensed, as well as the past experience and knowledge.

Another example of an ANN usage in CR is [23], in which researchers implemented a Cognitive Controller for dynamic channel selection in IEEE 802.11 wireless networks and made performance evaluations in a test bed environment.

ANN usage can also be performed on the primary user activity modeling. In addition, the spectrum sensing block’s performance may be increased using the predictions on PU activities by this trained ANN. A simple project on MATLAB about this concept is also implemented in the earlier stages of this thesis work.

2.2.6 Nature Inspired Solutions in Spectrum Sharing

Even though it may take improper values with respect to spectrum dynamics for nature inspired, population based solutions to converge to optimum values, many biologically inspired solutions are proposed for spectrum sharing problem. Likewise, in [24], channel allocation optimization problem is modeled and solved with a multi objective genetic algorithm. Population adaptation, variable quantization and variable adaptation techniques are also proposed in order to try decreasing settling time of the algorithm [24].

Ant colony optimization is basically a heuristic and distributed solution where ants construct solutions, grade them and show their solutions’ qualities via pheromones as a signal for leaving ants for latter decisions. This scheme is also used in spectrum allocation problem: SUs are modeled as ants and with designed ant colony optimization algorithm as an adaptive task assignment, these ants select spectrum bands with a distributed manner. In [25], authors showed that by their model and performed simulations, 100 runs were enough for optimum spectrum assignment.

Evolutionary algorithm is the term combining genetic programming, evolutionary strategies, differential evolution, grammatical evolution and memetic algorithms. Swarm intelligence also includes ant colony optimization and particle swarm optimization techniques. Binary particle swarm optimization from swarm intelligence and genetic algorithm from evolutionary algorithms are used for spectrum management in multi user OFDM based cognitive radio network in [26].

They observed that particle swarm optimization performs better than the genetic algorithm based engine [26].

3. PROPOSED PRIORITY BASED SPECTRUM SHARING SCHEME

Spectrum access/sharing problem is the decision of a CR user to decide which spectrum portion he/she will operate on. This decision can be taken both selfishly considering only self-interests and taking into account the global concerns like overall system utility or fairness among other CR users. Latter approach is implemented in the proposed scheme in this thesis.

Proposed scheme is related to the spectrum sharing process, providing a method for distributing available spectrum opportunities among secondary users. It is a distributed spectrum sharing mechanism that is based on individual spectrum decisions, priority and messaging mechanism between CR users.

Priority mechanism is used only for the purpose of scheduling among CR users. Meaning that, there is no actual priority class definitions among SUs. Each SU has equal rights on spectrum usage. Actually, the priority values in the proposed system can be organized in a way that a certain class of SUs are favored or otherwise.

All users work in a distributed manner; sense and decide the channel occupancy, then, decide to use which channel/s by themselves. Cooperation is acquired by messaging framework that enables each user retrieve its neighbors' channel decisions and priorities from the CCC. Priority chaining mechanism helps to provide fairness between these SUs.

In the proposed method, a *messaging topology* is modeled that represents the deficiencies in CCC. On the other hand, *interference graph* of the CR users is said to be fully connected for the first implementation sets meaning that any SU will interfere with another on same channel. Then, an interference graph that models the interference constraints with respect to distances between SU transmitters and leaving SU receivers and the frequencies of each channel is also added.

Note: Paper titled "A Priority Based Cooperative Spectrum Utilization Considering Noise in Common Control Channel in Cognitive Radio Networks" including the proposed spectrum sharing method is accepted as a presentation and publishment in Conference Proceedings (which will be included in IEEE Xplorer) of IWCMC 2011 The 7th International Wireless Communications and Mobile Computing Conference, Cooperative and Cognitive Networks Workshop section.

The network model and proposed spectrum sharing system is simulated using MATLAB Simulink tool in terms of the following performance metrics: *Traffic Request Satisfaction Rate, Channel Occupancy Rate* and *Fairness* among CR users. Performance metrics' definitions are given in Chapter 3.5.

The results obtained are compared to those of the techniques employing rule based channel selection strategies similar to [8] as selfish and random channel selection.

The value of maximum number of channels to be selected by a CR user denoted as "*n*" is chosen as one and three. The environment that proposed scheme is tested is varied in by changing messaging topology of the CR users. Test environments and the results are presented in Chapter 4.

3.1 System Model

Each CR user senses same portions of the spectrum (e.g. channel_i) which the PU couples are using for their communication. However, each pure PU traffic signal is added with different noise source for representing each CR user's channel monitoring qualities. CR users' spectrum decisions may differ on same channels due to these noise factors. However, there is still a strong probability that more than one SU decide that the same spectrum portion is available at the same instance. Since the users work in a distributed manner, users that capture the same spectrum hole will all try to use the same channel simultaneously. The proposed priority and messaging based spectrum sharing mechanism aims to overcome the condition that causes collision among SUs and consequently lowers overall spectrum utility.

Priority mechanism ensures that each CR user has a unique priority value at a time. By an abstract manner, the idea is to enable only the CR user having the highest priority to use channel/s over the users that also have data to send and decided that the spectrum is available. However, messaging imperfections on CCC may still lead to some collisions among SUs due to the lack of knowledge of CR user about its conflicting neighbors and their priority values. At some predefined intervals, the priority values of CR users are incremented by a chaining manner concerning the fairness of secondary users.

By the messaging framework, a CR user learns its neighbors' spectrum decisions, their current priority values and their candidate channel/s. Candidate channels are the channels a CR user is intended to use. That is, CR user decided that the channel/s is/are available and he has data to send meaning that its traffic queue is not empty. Messaging topology represents for each node, which neighboring nodes can be heard from CCC. Spectrum decision phase in the proposed system can also be implemented via a cooperative scheme since all users' spectrum decisions are also available from messages retrieved from CCC.

The simulation environment consists of eight primary users with Poisson traffic patterns (with different λ values in interval of [1 5] sim.timeUnit^{-1}) and a cognitive radio network of ten CR users in two different messaging topologies as random and fully connected. Actually, there is no correlation between traffic pattern of primary users and the proposed spectrum sharing mechanism's behavior. Meaning that proposed scheme will also work properly with other traffic patterns of primary users.

All of ten CR users monitor all PU channels. Messaging environment represents the deficiencies in CCC. In an ideal scenario, since all CR users have access to the CCC, they perfectly hear each other without any loss and equivalent messaging topology is fully connected. However, due to the possible channel noise, some of the CR users may not hear all other CR users' messages. This is represented in the network model by a randomly created messaging topology. Moreover, since this deficiency's degree is also important, a parameter denoted as *"m"* is defined. *"m"* represents, for each CR user, the number of neighboring nodes whose messages cannot be heard from CCC by that user. Parameter m is varied starting from one to five in the simulations. The neighbor/s for each CR whose messages will be lost is/are selected randomly but stay still for each run. Meaning, the messaging topology stays still for a same run, whereas each set up is run 50 times to represent 50 different messaging topologies for each m.

Messaging topology affects the messaging properties of CR users and performances of them directly: e.g. in a random topology, user$_i$ may not be connected with user$_j$ meaning that user$_i$ cannot hear user$_j$'s messages. Lack of user$_i$'s knowledge about user$_j$ prevents him to take spectrum decisions considering user$_j$. Accordingly, they may try to use the same channel simultaneously, and they will interfere.

The *interference graph* is said to be fully connected in both messaging topologies meaning that if more than two CR users decide to use the same channel, they interfere. Any interference with another CR user results in failure for both of them.

Another interference relationship is also modeled and explained in Chapter 3.7. The interference relations among CR users are extended in a way that if the receiver of a corresponding CR transmitter and another CR transmitter on same frequency are distant enough (such that the receiver perceives other transmitter’s signal below a certain noise level), that transmitter’s transmission on same frequency will not result in a failure. However, any CR transmitter pair on the fully connected interference graph are said to interfere with each other and their equivalent channel selections results with a failure for both of them.

Each PU couple is communicating on a different channel; therefore, there could be zero to eight channels available at an instance for CR users. All channels are said to have equal communication parameters.

All CR users listen to each channel with different noise parameters and have their own spectrum decisions based on their personal observations. CR users are behaving in a distributed manner. That is, each user has its own spectrum sensing and decision models. Figure 3.1 visualizes the CR user model for the environment consisting of ten secondary users. Each user has at most nine neighboring CR user. Therefore messages are labeled as from/to_n1 to from/to_n9. CR user model has separate subsystems for “*Spectrum Sensing and Decision”* and “*Priority Based Spectrum Sharing and Message Handling”* that includes message preparation and spectrum usage decision (message analysis) blocks.

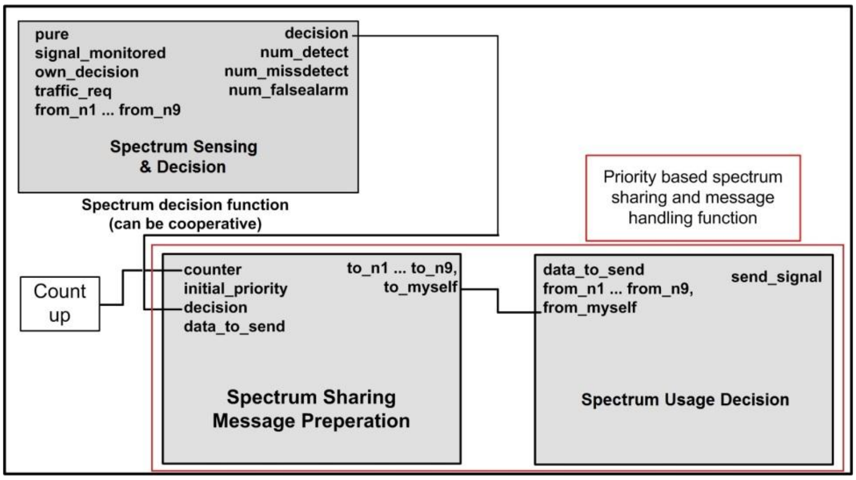


Figure 3.1 : CR user model for environment consists of ten CR Users.

“Spectrum sensing and decision” block actually comes later than an individual sensing block that takes the sensed signal and decides that the channel is empty when the sensed signal is below a certain signal threshold. Spectrum sensing and decision is the spectrum decision functionality of a CR user. Therefore, its inputs include pure signal of PU users in order to calculate the spectrum sensing block’s performance, CR user’s own decision after its own sensing module and messages for their decision fields. These decision fields can be used in cooperative spectrum decision algorithms. However, in the CR model of the proposed scheme, no such cooperation is used.

In “priority based spectrum sharing subsystem”, first block, “spectrum sharing message preparation”, prepares messages based on candidate channel/s that are evaluated from spectrum sensing and decision block, priority value and user's traffic request. Then, each CR user's “spectrum usage decision” block analyzes the retrieved messages and decides its spectrum usage accordingly.

CR users’ traffic demands are also modeled as Poisson with different λ parameters in interval of [1 5] sim.timeUnit^{-1}. CR users have queues of infinite length, for their traffic. Poisson traffic generator inserts the traffic requests of CR user into the queue. When the spectrum is available and CR user has decided to use some channel/s according to the retrieved messages, queue is decremented by one or more (by at most n).

If a CR user has data to send and has detected more than one spectrum channel opportunity, it has to be decided whether to use just one channel or multiple channels at the same time. “*n”* parameter is the predetermined and fixed value representing how many channels a CR user can use at most in this system. In the simulations, it is set with two variants as “n = 1” and “n = 3”. Note that, for “n = 3”, we assume that a CR user can transmit simultaneously from all three channels matching with their transmission parameters. Similarly, corresponding CR receiver is said to be synchronized and be able to receive from the same three channels with same communication parameters.

Each subsystem of the CR model is described in the following subchapters.

3.2 Spectrum Sensing and Decision Model

All CR users monitor all eight channels that PUs are transmitting. However, each CR user senses the spectrum activity as PU’s pure activity added with a different noise source. AWGN noise sources with different variance values (0.1, 0.2 or 0.3) are added to the pure channel activity providing each CR user a sensed spectrum status. Because spectrum sensing block’s performance directly affects the spectrum sharing block’s performance, a simple spectrum decision model is implemented for preventing both favor and disfavor. This block’s outcome probabilities are set at a certain level by tuning the channel noise parameters. Decision model that is implemented is a simple and distributed method in which a CR user decides that the spectrum is available whenever sensed signal is below a certain threshold (0.5). Remark that, the AWGN parameters are set accordingly with this threshold value. Pure signal’s value is also one.

3.3 Priority Chaining Mechanism

Priority chaining mechanism as also stated earlier, tries to provide fairness among CR users. Considering the highest priority always provide corresponding user an excessive right on spectrum usage than other CR users, this privilege should not always stand at a certain CR user, rather it has to pass users with equal possibilities. In the proposed method, this is accomplished by chaining the priority values periodically.

At every 10% of simulation time (chosen as 1000 units), priorities are increased by one using modulus of number of the CR users (10). The progress of the priority values for each CR user is seen in Figure 3.2. Period for changing the priorities of users is chosen as 100 time units. It is remarkable that at any time instance, CR users’ priority values are unique.

Priority chaining mechanism’s drawback comes from the initial priority and increase periods’ synchronization issues. In the simulations, the synchronization is achieved by giving all CR users internal up-counters (counting from zero to nine) with same periods (equals to priority change period) and initial priorities are chosen to be the “node_id” values of CR users. Current priority values are calculated as this counter value added with CR user’s initial priority modulus number of CR users. In the field implementations, it is thought to be achieved by a short communication at network set up phase, with a center, in order to retrieve timer frequency and initial priority value.

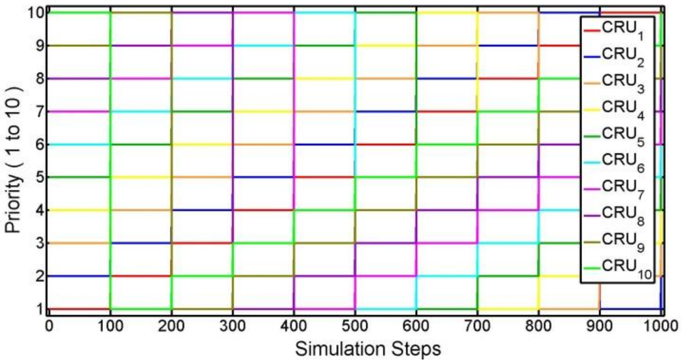


Figure 3.2 : Priority chaining mechanism for a network containing ten CR users.

These priority values will ensure some privileges to the CR users on spectrum sharing process. That is, these values will help to schedule CR users' transmissions on available spectrum opportunities according to some principles that will be explained in latter chapters.

Each SU has equal rights on spectrum usage although their priority quantities are different at an instance of network status. Actually, the priority values in the proposed system can be organized in a way that certain classes of SUs are favored. Several number of "priority" classes in terms of QoS requirements can be implemented. For example, fixed and higher than chained priority values can be assigned for some class of SUs. This will give excess right on spectrum usage to these higher qualified users again with the proposed spectrum sharing mechanism.

Node addition or loss resulting from topology changes or other reasons will cause some discontinuities at these priority values. Especially, node addition may cause an equivalency at the priority values. Algorithm may randomly choose on priority equivalences but preventing this situation will decrease the possible collusions with a higher rate. Therefore, even if the priority values are chained from one to ten at the simulations, it is thought that this limitation can be relaxed for possible node additions. For example, priority values can be given uniquely from one to twenty to ten users (again chained one by one). Then, when a node is added to the network, one of empty priority values can be assigned to him.

3.4 Messaging and Traffic Decision Phase

Proposed scheme's cooperativeness comes from the messaging phase in the model. Since CR users retrieve information about others' channel behaviors, the decisions they take are more intelligent and intended to increase the overall system performance.

CR users in the proposed scheme, send messages containing their spectrum decisions, traffic requests and candidate channel/s through CCC. *Candidate channel* is a term defined for a channel for a specific CR user, representing the channel is intended to be used by that user. That is, the channel is thought as a spectrum opportunity and that CR user wants to use it (i.e. user has some data to send). In other words, candidate channels are the channels for which spectrum sensing block decided that there is no PU activity at the moment and which can be used for SU communication.

Due to spectrum variety and possible interruptions from PUs in chosen channels, control messages that are used pre-routing, pre-spectrum decision etc. processes are usually said to be sent via CCC in CR networks. However, the CCC mechanism may not provide perfect communication between all CR users. That is, one CR user may not hear a set of other users from CCC. In proposed scheme, this situation is modeled with the messaging topology. Fully connected topology represents an ideal CCC, whereas a random topology represents possible noise in the CCC. Random topology, as also stated earlier, has variants by m parameter representing the number of neighboring nodes that cannot be heard from CCC. For implementing a messaging deficiency, messages also contain an additional field representing their validity. CR users are fully connected at each model. For implementing m parameter, related communication link between two or more CR users (from CCC) should be broken. This is implemented with turning the corresponding message into an invalid message by resetting its validity bit.

CR users sense and decide channels' status during the spectrum sensing process. After completing the sensing and decision process, each CR user prepare a message containing its priority, its channel decisions and candidate channels. Note that, since the users also send each other their channel decisions, "Channel Decision" phase can be implemented in a cooperative manner like applying AND, OR, or MAJORITY rules. Then, if a CR user has data to send (i.e. its current queue size > 0), retrieved messages from neighboring users are analyzed in order to decide which channel/s are to be used.

Besides its validity bit, a message consists of three basic fields:

- Channel Decisions
- Candidate Channel/s (channel/s ids that are decided to be free and can be used by that user)
- Priority Quantity (priority value of the sender CR user)

The outcomes of the spectrum sharing message preparation sub system are the messages prepared for the consecutive decisions of neighbors. Later, spectrum usage decision block decides whether to use channel/s or not. This process is also called as traffic decision. Thus, this block's outcome is the traffic-outgoing link. Inside, if a CR user has traffic request, it analyzes retrieved messages and decides to use at most n channels. This decision relies on below conditions to be satisfied:

For channel_i to be chosen by CR user_k:

- CR user_k has data to send (its queue has a positive length)
- CR user_k decided that the channel_i is available
- CR user_k thinks that it has the highest priority in a group of users who also satisfy the first two conditions, (i.e. no neighboring message has higher priority value and has channel_i in its candidate channel values.)
- Alternatively, there exists a user that has a higher priority value and both satisfies the first two conditions but it has fulfilled the number of channels to be used (i.e. it has already n channels available before channel_i and will not attempt to choose channel_i).

Remark that, because channel signal qualities are not considered and all empty channels are equivalent in terms of communication parameters in the proposed scheme, choice principle between available more than n channels is starting to choose from channel that has smallest channel id. Moreover, algorithm is written accordingly. Last itemized rule states that even if there exists another higher priority user that has data to send and detected $\mathrm{channel}_i$ is available, that user (with lower priority) can still use $\mathrm{channel}_i$ under relation:

"$i > n$ & $\exists\, n$ available channels in $\{channel_1 \ldots\ldots channel_{i-1}\}$". Because, the higher priority user will select n channels from the set of previous available channels than i, fulfill its channel usage capacity and will not attempt to choose $\mathrm{channel}_i$.

Pseudocode for the above-described behavior of spectrum decisions is given below (Algorithm channelUsageDecisions).

Algorithm channelUsageDecisions: Procedure for channel usage decisions

```
Input               : Spectrum sensing vector of channel status ($s_1 \ldots\ldots s_8$),
                      Neighboring messages ($m_1 \ldots\ldots m_9$).
Output              : Channel usage decisions ($t_1 \ldots\ldots t_8$).
Constant parameter  : n: number of channels to be selected (at maximum)

if there is data to send in the traffic queue
{$t_1 \ldots\ldots t_8$} ← {1, ……, 1}
    for all channels do
        if "channel is sensed as empty" ($s_i == 0$)
            for all messages do
                if "neighbor_j with higher priority has channel_i in its candidate channel
                    list's first n entries" (check corresponding fields of $m_j$)
                    $t_i$ ← 0
                    break
        else $t_i$ ← 0
    if sum ({$t_1 \ldots\ldots t_8$}) > n
        Eliminate more than n opportunities, select first n channels to send
else {$t_1 \ldots\ldots t_8$} ← {0, ……, 0}
```

CR messaging topology directly affects the collision probability between CR users. If a fully connected topology can be achieved in the field (perfect CCC), all users will be aware of the priority and candidate channel information of all other users meaning that each user can perfectly guess its neighbors channel usage decisions and thus, no user will choose the same channel at the same time. This prevents the collisions among secondary users and highly increases system utility. Though, for a more realistic scenario, random topologies with the help of m parameter are also employed and simulated.

3.5 Performance Metrics Defined for Evaluating System Performance

Spectrum sensing block’s efficiency directly affects the spectrum sharing algorithm’s performance. In the proposed system, sensing block was implemented as a simple threshold based spectrum decision maker as explained in Section 3.2.

Percentage of detection, miss detection and *false alarm* terms are reflecting the sensing block’s performance. Percentage of detection is the right decisions’ rate of sensing block about PU existence or non-existence. Miss detection rate reflects at which rate sensing block’s hypothesis about PU is wrong such that PU is active unlike it says inactive. Similarly, false alarm percentage is the ratio of sensing block decisions that says PU is active whereas he actually is inactive. It is to be denoted that false alarms, since some spectrum holes are missed, will only decrease system utilization whereas miss detections may lead to a more serious problem of a conflict with a strict policy of CR technology that is preventing any harm on PU communication.

In the systems simulated, these percentage values are also noted and tuned for a reasonable sensing block performance. It should be not too close to ideal as well as not excessively poor for preventing both favor and disfavor to the spectrum sharing sub system. Also stated in Chapter 4.1, the rates of detection, miss detection and false alarm are 87, 6.5 and 6.5 percent in the studied environments respectively.

Performance of the spectrum sharing process is examined with different metrics designed. Latter sections describe each of them sequentially.

3.5.1 Traffic Request Satisfaction Rate

Traffic Request Satisfaction Rate metric defined as in Eqn. 3.1 for CR user$_i$ is the ratio of the CR user’s channel usages over its traffic requests.

$$TRSR_i = \frac{channel\ Usages_i}{traffic\ Requests_i} \tag{3.1}$$

This metric reflects how his obtained rights to use the spectrum with respect to its traffic demand satisfy a CR user. This traffic demand for each CR user is also modeled with a Poisson traffic pattern.

It is important to remind that the traffic request of a CR user is not only blocked by primary user, but also by another CR user with higher priority. Moreover, the collisions among CR users results with an unsuccessful attempt of communication. Although, a traffic request is dequeued from the traffic queue, if it is not performed successfully (any collision with a PU - can only occur on miss detection - or another SU), this does not counted as a proper *channelUsage* in the calculation of TRSR metric of that user.

3.5.2 Channel Occupancy Rate

$$COR_i = \frac{channelUsages_i}{\sum_{k=1}^{N} channelUsages_k} \qquad \textbf{(3.2)}$$

Eqn. 3.2 defines the channel occupancy rate metric for CR user$_i$. N is the number of CR users in the system and in the system simulated it is ten.

CR user’s *channelUsages* quantity is again the amount of time slots it successfully used the channel. That is, it has decided to use the channel and neither any PU nor any other CR user was transmitting at the same time on that channel. The successful channel usages of a CR user are divided by the sum of time slots used by all CR users without any conflict.

COR metric, since it is basically the ratio of the CR user’s spectrum hole usage over summation of all users in the system, gives an idea about how the spectrum holes are distributed among the CR users. That is, this metric also gives an idea about fairness among CR users. Expected COR value for a system in which a complete fairness is achieved and all CR users have similar traffic patterns, is 0.1 for 10 users (total of COR values is 1.0 and for 10 users that are expected to have equal COR values, this value is calculated as 0.1).

3.5.3 Fairness

Fairness index is calculated according to the Jain’s fairness index [27] which gives a value in the interval [0 1]. Fairness variable as seen in Eqn.3.3 is taken as TRSR of N CR users in the system.

$$f(CR_1, CR_2 ... CR_N) = \frac{(\sum_{i=1}^{N} TRSR_i)^2}{N \sum_{i=1}^{N} {TRSR_i}^2} \tag{3.3}$$

COR values also give idea about fairness but it is not enough for a CR user to take equal part with other users on the spectrum opportunities. In addition, the ratio between its traffic demand and its gained spectrum is important. This is reflected by TRSR value and the fairness in terms of TRSR values is important as well.

3.5.4 System Utility

System utility is the ratio of the successfully used spectrum portions in the system, over all available spectrum opportunities. This metric reflects at how much degree spectrum is used efficiently meaning that; with which rate the secondary users successfully used spectrum holes.

Because, the proper channel usages are again taken in the system utility formulation, system utility is highly correlated with the PU activities producing spectrum holes and at which rate the collision avoidance is achieved among CR users.

$$SystemUtility = \frac{NumOfAllSpectrumHoles}{\sum_{i=1}^{N} channel\ Usages_i} \tag{3.4}$$

Spectrum sharing algorithms are the multi-objective optimization algorithms. That is, the overall system utility, fairness and each user’s TRSR values are all to be maximized for a perfect efficiency of the spectrum resource. The proposed scheme is not an optimization implementation but its performance on these metrics is analyzed in order to see if each stays at an acceptable level.

3.6 MATLAB Simulink Model Development and Verification

Network model and spectrum sharing mechanisms are implemented in MATLAB Simulink environment. As seen from Figure 3.1, each CR user is modeled as separate subsystems for spectrum sensing that has a threshold based spectrum decision, message preparation and spectrum decision.

First, the communication system of primary users is modeled. Primary users’ traffic is implemented as signal generators for transmitters triggered by time based entity generators to model Poisson traffic pattern. Then AWGN noise added channels are modeled for each user reflecting how they will sense the communication channels of PUs. Each of the eight channels are input to ten adders that adds channel’s pure activity with different AWGN noise sources for producing ten different sensed signals for each of ten SUs for each eight channels.

Queuing systems for CR users’ traffic demands are modeled as integrators whose input is retrieved from traffic generators and decreasing by the traffic-outgoing link. Since a CR user is allowed to use multiple channels at the same time, the decrement of the queue is the summed up traffic on eight channels. When n parameter is set to three, the number of channels that can be used simultaneously by a CR user are two or three. If three of the channels are used, traffic queue is decremented by three, considering each channel’s capacity as equal.

Then, message format is prepared according to the described fields in Chapter 3.4 and related bus connections of proper sizes are implemented. For ease of model implementations, in all models, the CR users are connected at a fully connected manner and a validity bit is added for modeling messaging imperfections based on m parameter. When m is set to a certain number (one to five), each user puts invalid sign to m random messages at the message preparation step. This randomness is at the first message, meaning that the broken links stays same for the same run for protecting the stability of the interference graph.

Traffic patterns of both PUs and SUs, spectrum usage decisions, queue sizes etc. are recorded as matrices from the Simulink model via ‘toWorkspace’ elements and post processing files are written for calculations of all probabilities, performance metrics, successful transmissions etc.

In order to check the correctness of the model behaviors, some test cases are implemented as basics of the network model. The imperfect situations of the described network model are implemented systematically and the behavior of the model is examined. These test cases are described at the following chapters.

3.6.1 Ideal Environment

In order to eliminate the spectrum sensing block’s effect on spectrum sharing subsystem, first, perfect sensing scenario is implemented. That is, all SUs monitor the channel signals as equivalent to the real transmission signal of PUs. No AWGN noise source is added to any channel.

Appendix A, Table A.1 and Appendix B, Table B.1 first eight rows titled as “Ideal” represent fairness, system utility, average TRSR and PU disturbance values for “n = 1” and “n = 3” cases respectively. Any attempt of SU while any PU is active, even if it is not an successful communication for an SU, is counted as a disturbance for PU. It is remarkable that PU disturbance is zero due to the perfect sensing scenario. Utility values represent the utilization of the spectrum holes. Since the spectrum holes are identically detected without any error, utilization only is affected by the spectrum sharing mechanism. If SS mechanism cannot prevent some of the collisions among CR users (no collision with a PU occurs due to perfect sensing), utilization drops remembering only successful transmissions are counted at system utility calculation. The fully connected scheme reached the highest achievable system utility value (1.0) as expected; reflecting a fully messaging topology with the proposed scheme prevents collisions among SUs with a hundred percent.

Since selfish channel selection ranks the channel SINR values, then chooses the best and in this environment, all users will sense PU activity with 1.0, and 0.0 signal values for inactive PUs, this scheme’s performance is zero in terms of all metrics. All of ten users see the available channels identically and all try to use same empty channel and their collision results in failure for all of them.

Note that at this environment, SUs’ traffic demands are thought to be Poisson but not kept in a queue. When there is no available spectrum to meet a request, this request is lost. Therefore, TRSR values are formed as 40% at most. Appendix A, Table A.2 and Appendix B, Table B.2 first eight rows titled as “Ideal” represent the TRSR and COR values and their standard deviations of each CR user in detail. TRSR values decrease when m is increased due to the messaging imperfections and lack of knowledge about neighboring nodes made the SS mechanism take less intelligent decisions. Another trend of increase of TRSR values, when n number is increased from one to three, is also seen.

3.6.2 Channel Noises with AWGN Models

The channel noises are then added to the previous model titled as ideal, in order to measure the sensing block’s effect on overall system. Each channel is added with different noise parameters for each CR user like explained in Chapter 3.2. Appendix A, Table A.1 and Appendix B, Table B.1 rows 9 to 16, titled as “~Ideal” represent fairness, system utility, average TRSR and PU disturbance values for “n = 1” and “n = 3” cases respectively of this environment. PU disturbance is positive due to channel noises. Appendix A, Table A.2 and Appendix B, Table B.2 rows 9 to 16, titled as “~Ideal” represent the TRSR and COR values of each CR user in detail. General trend of decrease in TRSR values due to increase of m holds in these simulations as well. Again, “n = 3” cases have higher TRSR values.

3.6.3 Implementing a Queue Mechanism for the Traffics of SUs

Then a queue management for keeping the SUs traffic requests is implemented. For its pure effect on the system, channels are turned back to ideal case, that is, perfect sensing is achieved in all CR users. Appendix A, Table A.1 and Appendix B, Table B.1 rows 17 to 24, titled as “~Ideal” represent fairness, system utility, average TRSR and PU disturbance values for “n = 1” and “n = 3”. Again, PU disturbance is zero due to the perfect sensing. However, average TRSR values are higher due to the queue management keeping the traffic requests of CR users.

In previous models, if there is no spectrum opportunity, traffic request of CR user is lost. However, by keeping the traffic requests at a queue, we gain advantage of serving them when a spectrum hole is captured. At this point, traffic requests of SUs are thought to be delay tolerant. Again, “n = 3” values are higher than “n = 1” equivalents and increasing m decreases the systems performance.

The next model is containing both two variants on queue implementation and channel noise implementation. This is the environment described with the network model of the proposed scheme, having both imperfections. Its analysis is given in detail in Chapter 4.1.

3.7 Distance Based Interference Constraints’ Addition to the Proposed Scheme

The interference graph is said to be fully connected in the environments. Meaning, the labels on all edges of the interference graph representing the conflicting channels were containing the whole channel set. That is, any attempt of using the same channel of any two or more SUs results in a failure for all of them. This graph is extended according to the CR users’ and receiver of these users’ physical locations.

Because, if a CR user and another's receiver are distant enough, that CR user can use the same channel with the receiver's corresponding transmitter. Its transmission signal is considered by the receiver as an acceptable noise.

Eight communication channels of PUs' frequencies are denoted as $f_1 \ldots f_n$. The CR users' locations are Tx_1, Ty_1 ... Tx_n, Ty_n. SUs in the system are thought to be transmitters and corresponding receivers are assigned to each of them for this interference relations' implementation. Corresponding receivers' locations are Rx_1, Ry_1 ... Rx_n, Ry_n. In order to define the interference relations, besides these terms of frequency and location, path loss formula, transmitter users' transmission powers and the noise floor of the CR receivers are needed. For simplicity, a simple one way in free space path loss model is chosen regardless of the receivers' antenna types (considering between two isotropic antennas), environment's characteristics etc.

$$\mathrm{L} = 20 \log_{10}\left(\frac{4\pi \mathrm{d}}{\lambda}\right) \qquad \textbf{(3.5)}$$

Where L is the path loss (in dB), d is the distance between transmitter and the receiver of the other transmitter. λ is the wavelength and defined as:

$$\lambda = \frac{f}{c} \qquad \textbf{(3.6)}$$

where c is the speed of light.

The CR users (the transmitters) are to be placed randomly for their physical locations. Then each receiver is also to be placed randomly. However, the receivers need to be placed near enough to hear corresponding CR transmitter whenever it chooses any of the eight communication channels. Therefore, at first step the frequency assignment to communications channels and calculations of their ranges should be performed.

For the maximum range calculations, transmitters' powers and the receivers' noise floor values are to be examined. The maximum distance for a receiver can be calculated from Equation 3.5 (this calculation is also called *link budget* analysis of the communication systems) where L is the maximum allowable signal loss (transmitter's transmission power subtracted with noise floor of receiver) and calculated d is the maximum allowable distance. Actually, in addition, transmitter antenna's gain is to be added to the transmission power and the antenna gain of receiver power. In the implemented interference graph, the range values from [28], which are based on typical budget analysis on several wireless standards, are used.

Table 3.1: Frequencies of each communication channel and their maximum distances for receivers

Channel Id	Frequency (f_i)	Maximum Distance for a Receiver
1	5 GHz (802.11.a)	90 ft. ~ 27 m
2	2.4 GHz (802.11.b)	250 ft. ~ 76 m
3	2.4 GHz (802.11.g)	100 ft. ~ 30 m
4	2.4 GHz (Homer RF)	150 ft. ~ 46 m
5	5 GHz (802.11.a)	95 ft. ~ 29 m
6	2.4 GHz (802.11.b)	275 ft. ~ 84 m
7	2.4 GHz (802.11.a)	92 ft. ~ 28 m
8	5 GHz (802.11.b)	300 ft. ~ 91 m

Table 3.1 shows the channel assignments and the related maximum allowable distances for a receiver. Note that, the lower frequencies like TV or GSM bands or shorter-range 2.4 GHz protocols like Bluetooth are not chosen for preventing outliers in the distance values. Similar frequencies are chosen but different distance values from the ranges in [28] are given for different channels.

CR users' (transmitter users') physical coordinates are given randomly at a 2D terrain of 100 m * 100 m. Receiver coordinates are again chosen randomly but with a restriction of not farther from corresponding receiver than 27 m. Reason is, even its transmitter uses channel$_1$, they should be able to communicate. The assigned coordinates of the CR users are given in Appendix C, Table C.1 including the distances between them.

Interference definition is a little bit tricky because it is not directly defined between transmitter couples. Principle is that; if any transmitter$_j$ is close enough (in the range of frequency which transmitter$_i$–receiver$_i$ couple is using) to receiver$_i$, it causes interference to transmitter$_i$–receiver$_i$ couples' transmission. Meaning transmitter$_j$ can not use that frequency simultaneously with transmitter$_i$.

Distances of transmitter CR users to other receiver CR users and on which channels CR transmitters cause interference are given in Appendix C, Table C.2. Note that, there can be cases where CR transmitter_i is interference to CR transmitter_j but the reverse is not true because of the positions of their corresponding receivers. Therefore, different from the example interference graph in Figure 2.7, the interference graph's links are to be drawn with directed edges from CR transmitter_i to transmitter_j. Channels on this directed edge represents which channels they will interfere when transmitter_i transmit on. Corresponding interference graph is not visualized with one graph for it is not readable due to the number of links. It has a complex structure nearly like having fully connected links. However, the conflicting channel list on each link is not the list of all channels as it was in the previous fully connected interference graph approach. Therefore, the interference graph is separated to the channels and interference relationships are visualized channel by channel, a graph for each channel. These interference graphs can be seen from Appendix D, Figure D.1. Channels with higher ranges as channel_2, channel_6 and channel_8 has more complicated interference graphs as expected.

The hard coded interference graph implementation to the model is preferred because the channel assignment, transmitter powers and related distance calculations are affecting only the interference relationships of the CR users in the network perspective considered. The performance metrics are extracted from the model by a post processing work and these interference relations are added to this post process. The addition of more realistic channels with their more communication parameters and CR user's physical locations can be seen as a future work of this study.

4. PERFORMANCE ANALYSIS of PROPOSED SCHEMES

4.1 Priority Based Spectrum Sharing Scheme's Performances When the Interference Graph is Fully Connected

Designed spectrum sharing scheme is compared with two variants of distributed rule regulated spectrum sharing methods that are proposed in [8], and explained in Section 2.2.1. These are similar but simpler rule regulated schemes as *selfish channel selection* and *random channel selection*.

Described system is modeled and its performance is studied using MATLAB Simulink environment. Figures 4.1, 4.2 and 4.3 represent the results within 95 percent confidence interval values. Variety in simulated models comes from the messaging topology (m = 0 to 5 with 0 meaning fully connected), spectrum sharing subsystem (priority based, selfish and random) and the maximum number of channels to be used instantaneously (*n* parameter) differences. Two types for messaging topologies as random and fully connected are implemented. Random topology is tested via different m parameters, which represents the number of neighboring nodes that cannot be heard from CCC. Spectrum sharing subsystem is implemented for different schemes as *selfish channel selection* in which each CR user selects at most n channels that provide highest throughput, *random channel selection* that represents n random channel selections from available channels and *priority based spectrum sharing* which is the proposed scheme.

Spectrum sensing block directly affects spectrum sharing mechanism's performance. Therefore, we implemented a simple threshold based spectrum sensing scheme. It is observed that detection, miss detection and false alarm rates are about 87, 6.5 and 6.5 percent in the studied environments respectively. Remark that, since only AWGN noise models are used for modeling the monitored signals of PU's for CR users, the error in detection is similar for both incorrect decisions about PU activity. That is, the equivalence of probability of miss detection and false alarm is meaningful because AWGN noise’s probability of making a 1 below 0.5 (a miss detection) and 0 over 0.5 (a false alarm) is identical.

Table 4.1: Fairness indexes and system utility values with different spectrum sharing mechanisms, *m* and *n* values

SS Mechanism	Messaging Topology	m	Fairness Index		Utilization	
			n = 1	n = 3	n = 1	n = 3
Priority Based	Fully Connected Top.	0	0,998	0,997	0,891	0,890
	Random Top.	1	0,971	0,974	0,670	0,775
		2	0,995	0,955	0,525	0,666
		3	0,962	0,954	0,446	0,564
		4	0,957	0,941	0,364	0,500
		5	0,947	0,943	0,290	0,437
Random	-	-	0,999	0,999	0,371	0,362
Selfish	-	-	0,996	0,996	0,303	0,195

Table 4.1 includes the fairness index values calculated according to Eqn. 3.3 and the system utility values (definition is given in Chapter 3.5.4 and calculation in Eqn. 3.4) for each environment simulated. “*System Utility*” is the ratio of the successfully used spectrum portions in the system over all available spectrum opportunities.

Appendix A, Table A.1 and Appendix B, Table B.1 last 8 rows titled as “Sim Environment for Paper” also has these entries with additional columns of average TRSR value, primary user disturbance ratio and the standard deviations of each performance metric for “n = 1” and “n = 3” variations respectively. Note that primary user disturbance is counted as any attempt of CR users’ communication, whether they collide within each other or not. Actually, any collision with primary user was not counted as an successful communication for secondary user in the performance metrics.

Fairness among CR users is said to be achieved in all systems as seen from the fairness index values for each system is over 0.9. Proposed scheme specially uses priority chaining for this purpose whereas selfish channel selection and random channel selection schemes’ fairness are directly affected by the selected channel and spectrum sensing block which determines the set of available channels to be selected. Moreover, fairness and system utility values should be considered together for a better system performance. Selfish channel selection, for example, may be fair in all cases but its lower system utility value decreases the network performance.

As seen from the lines about utility for both “n = 1” and “n = 3” cases, as m increases, (m is 0 for the fully connected phase) in proposed scheme, system utilities decreases as expected. As m increases, the deficiencies in CCC increase. In parallel, as number of neighboring nodes that cannot be heard from CCC increases, the probability of collision between neighboring nodes increases due to the lack of knowledge about their spectrum usage preferences. This obviously decreases overall system utility value due to the collisions that are not prevented in the proposed scheme.

As n increases, CR users get the right to select more than one channel. This may or may not increase their spectrum usage rates and overall system utility according to the spectrum sharing scheme. In our scheme, as seen in Table 4.1, increasing n value increased overall system utility in partially connected topologies like m = 1 to 5. No significant change in fully connected topology is also meaningful because increasing n only ensures emptying the traffic queue in a faster way by taking three packets if spectrum opportunities are more than three (also can take one or two packets if the number of available channels is one or two). However, overall spectrum hole utilization stays still since fully connected scheme fully utilizes spectrum opportunities according to the CR users traffic demands. “n = 1” case also utilizes all opportunities again with respect to CR users traffic demands but the queue length in this scheme decreases in a slower manner. Selfish and random channel selection rules on the other hand shows lower performance when “n = 3”. This is reasonable because these schemes do not consider other users’ channel selections and more channel selection selfishly or randomly increases collision probability between CR users. Especially selfish channel selection’s system utility decreases dramatically as n increases because even if CR users’ channel sensing status are different, their chosen best channels overlap and as the number of chosen channels increases, this collision probability also increases.

Figure 4.1 and Figure 4.2 visualizes the percentages of traffic request satisfaction rates of the CR users when “n = 1” and “n = 3” cases. X-axis represents the different spectrum sharing schemes and different environments represented by different m values for the priority based scheme. Each set up has ten bars reflecting each CR user’s TRSR value from CR $user_1$ to CR $user_{10}$ with its confidence interval plot. Confidence intervals are calculated with 95%. Y-axis represents TRSR values over hundred for each CR user at each set up. These values are actually average of fifty runs for each set up.

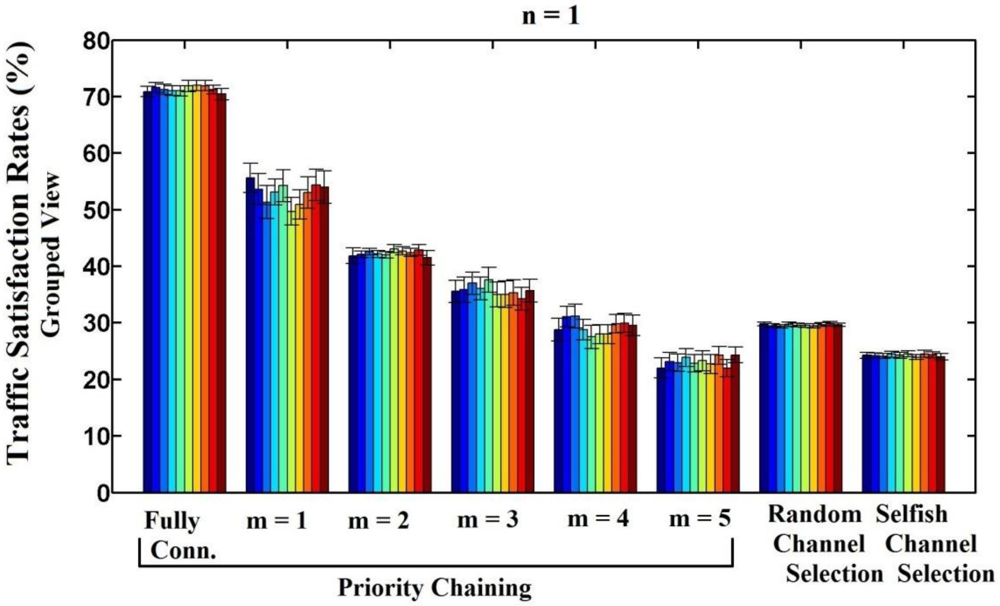


Figure 4.1 : Traffic request satisfaction rates, when n = 1.

Appendix A, Table A.2 and Appendix B, Table B.2, last 8 rows titled as “Sim Environment for Paper” also have detailed TRSR and COR values (average values for each user and related standard deviations from 50 runs) of each CR user for “n = 1” and “n = 3” set ups.

In Figure 4.1, highest performances are gained with the proposed scheme at the environment which has a fully connected messaging topology (m = 0). Then performance drops due to the increase of m. It is also seen that selfish channel selection’s performance stays between the priority based scheme at environment with “m = 4” and “m = 5” configurations. Moreover, random schemes’ performance stays between “m = 3” and “m = 4” configurations for “n = 1” set up.

For the proposed scheme, for both cases for n, as seen from the Figures 4.1 and Figure 4.2, as m increases TRSR values decrease, due to the messaging imperfections and lack of knowledge about neighbors. Remark that TRSR values are calculated based on real spectrum usages meaning that the collision among any CR user makes that transmission not counted in the TRSR calculation, lowering TRSR values of the users.

As seen from Figure 4.2, when “n = 3”, TRSR values are slightly higher than “n = 1” equivalents that can be seen from Figure 4.1. The reason is that users can select more channels and if collisions among them can be prevented at a certain level, this brings advantage to overall system utility and users’ TRSR values. System utility and users’ TRSR values are highly correlated in the network model. Therefore, Table 4.1 also shows that increasing n, increased system utility in the proposed scheme.

Proposed scheme, with all m values, outperform random and selfish channel selections when “n = 3” that can also be seen from Figure 4.2.

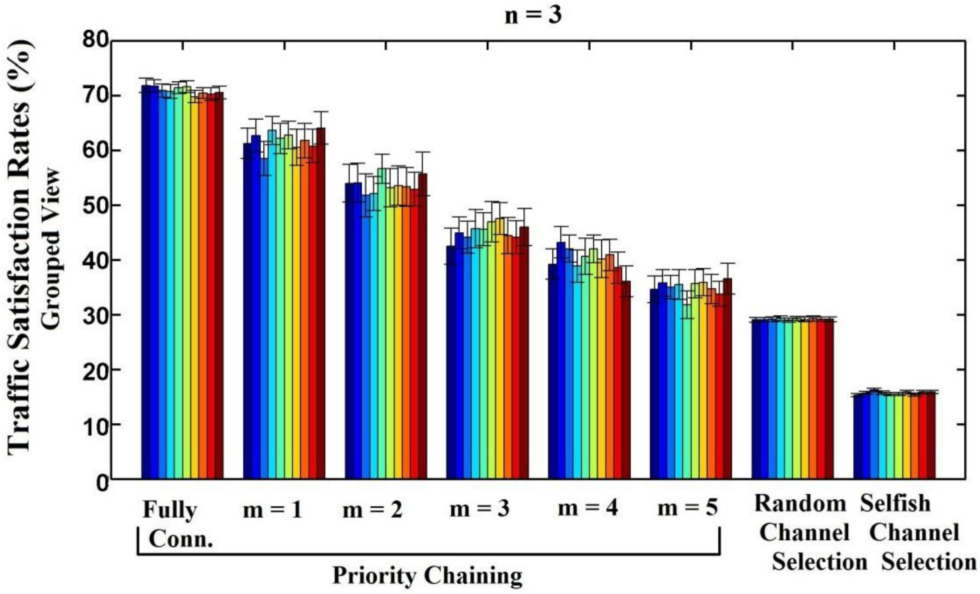


Figure 4.2 : Traffic request satisfaction rates, when n = 3.

Proposed spectrum sharing scheme has the highest TSRS values reflecting each CR user satisfies its traffic request up to about 70 percent in both environments of n. Increasing m, decreases our scheme’s performance but if connectivity can be achieved for a certain level at the environment like m is at most 2 or 4, our scheme can reflect its advantageous sides and increase overall system utility, protecting fairness between users.

Stacked view of channel occupancy rate values also gives an idea about the fairness among CR users. COR values represent the percentage of the specific user’s channel usage over other users. The fairness seen from this plot is a sign of how fair the distribution of the spectrum holes is achieved regardless of the CR users’ traffic demands or the gain they retrieve.

Figure 4.3.a and Figure 4.3.b visualizes the channel occupancy rates for “n = 1” and “n = 3” environments respectively. X-axis again represents the different spectrum sharing schemes and different m values for the priority based scheme. Each set up has a stacked view of 10 values reflecting each CR user’s COR value (CR user 1 at the bottom of the stack, 10 at the top) within its confidence interval plot. Confidence intervals are calculated with 95%. Y-axis represents COR values (cumulated by each user’s value) over 1.0 for each CR user at each set up. Total value of the COR values for a same set up is 1.0 by definition.

For nearly all schemes, COR values are similar providing high fairness between users. COR values are reflecting fairness between users in terms of the spectrum hole distribution and this fairness is achieved in all cases. Note that calculated fairness index value is based on TRSR values of the users in order to look at fairness based on a different metric, about how fair the traffic requests of CR users are provided.

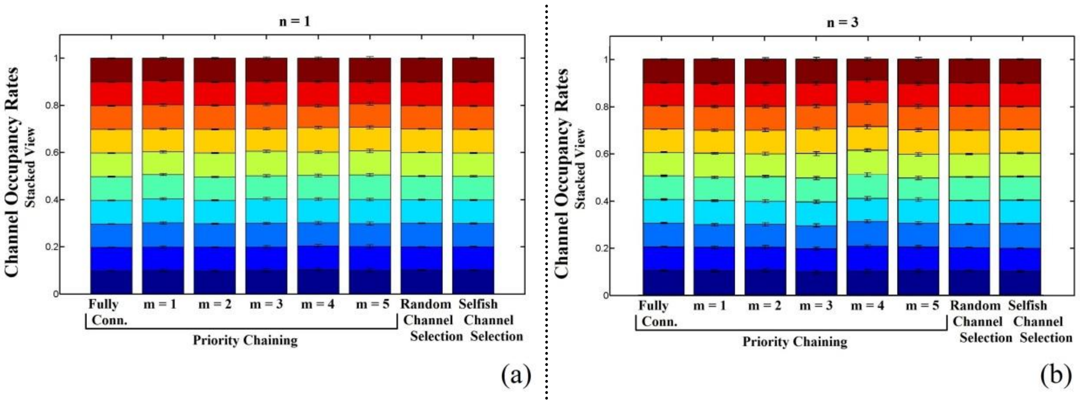


Figure 4.3 : Channel occupancy rates: (a)When n = 1. (b)When n = 3.

4.2 Priority Based Spectrum Sharing Scheme’s Performances When Distance Based Interference Constraints are Added

When the distance based interference relationships are added to the network model, this addition decreases the number of collisions among CR users on some channels. As described at Chapter 3.7, the conflicting neighbors of CR users differ according to their physical locations and used frequencies.

Table 4.2: Fairness indexes and system utility with different spectrum sharing mechanisms, *m* and *n* values (with the distance based interference relations)

SS Mechanism	Messaging Topology	m	Fairness Index		Utilization	
			n = 1	n = 3	n = 1	n = 3
Priority Based	Fully Connected Top.	0	0,998	0,997	0,891	0,885
	Random Top.	1	0,994	0,990	0,827	0,832
		2	0,995	0,978	0,785	0,784
		3	0,991	0,978	0,772	0,723
		4	0,988	0,969	0,748	0,672
		5	0,984	0,967	0,730	0,610
Random	-	-	0,989	0,985	0,736	0,794
Selfish	-	-	0,978	0,991	0,704	0,298

The fairness index and the system utility values for each environment can be seen from Table 4.2. Fairness is said to be achieved in all cases. System utility decreases as m increases in the proposed scheme, identical with its trend in the previous interference graph implementation. However, the random scheme's performance is much higher with the implemented interference graph. With the fully connected interference graph, random channel selection was resulting with more number of collisions decreasing the TRSR and system utility values. The implemented interference relations are looser and the random channel selections' choices may not result in a failure for some channels in this case. Selfish channel selection on the other hand, shows its poorer performance when n value is set to three.

TRSR values of CR users can be seen from Figure 4.2.a for "n = 1" and Figure 4.2.b. for "n = 3" cases. Fully connected messaging topology again outperforms all other schemes. However with the interference relations implemented, other schemes' performance are also acceptable when "n = 1". Random channel selection, indeed, performs between "m = 4" and "m = 5" when "n = 1". The reason of this schemes' higher performance is the range relations of the transmitters.

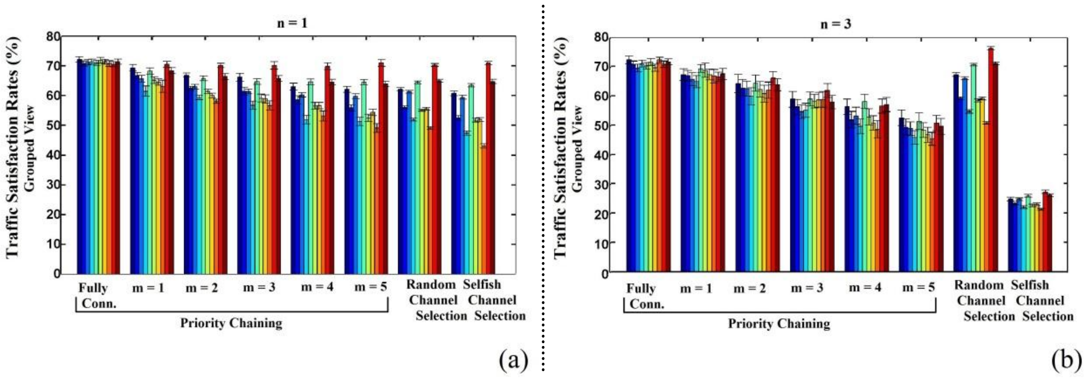


Figure 4.4 : Traffic request satisfaction rates (with the distance based interference relations): (a) When n = 1. (b) When n = 3.

It is also seen that CR users 1,9 and 10 has higher TRSR values. When the interference graphs visualized at Appendix D, Figure D.1 are considered, it can be seen that these nodes have less interference relations with other users. This makes the probability of their transmissions of resulting in a failure decrease. Therefore, their system performances increase.

With this sample of interference relations implementation, it is seen that the proposed method’s advantageous sides are more affective when the probability of collision among CR users is high like it was in the fully connected topology. Proposed scheme’s main target is preventing the collisions among CR users and if the interference relationships exist in such a way that even a random channel selection does not result in a failure for the transmissions, proposed scheme cannot reflect its benefit on eliminating collisions among CR users.

In the implemented interference graph, the terrain was set to 100 m * 100 m, meaning that a receiver and the disturber transmitter can be at most $100\sqrt{2}$ meters (approx. 141 m.) distant. If the channels’ transmission ranges are equal or more than this value, the results will be identical with the first scenario where no distance based interference relations is taken into account. In the interference graph implementation, as seen from Table 3.1, the ranges of the channels are much shorter, reducing the possibility of collisions among SUs whose channel selections are random.

5. CONCLUSION

Cognitive radio network is a promising technology that enables secondary users to utilize the unused spectrum portions of the primary licensed users. Spectrum sharing problem is a challenging functionality of these networks for distributing the detected spectrum holes between secondary users. This thesis' main subject is to research and work on spectrum sharing algorithms. At the first, stage spectrum sharing algorithms from literature are examined. Then, a priority based spectrum sharing mechanism is proposed. Proposed priority based spectrum sharing scheme aims to overcome the collisions among the secondary users intending to choose the same spectrum holes. In order to increase system utility, a priority and messaging based approach is introduced. Two variants of the interference graph among CR users are implemented as a fully connected and a location and channel frequency based interference relations. Simulation results showed that the collaboration between CR users increases system utility and performance. With the proposed model, there may still be some decisions causing collisions. The reason behind such an event is that in the network model employed, users can collide with other users whose messages cannot be heard. In other words, messages provided by CR users may not be read by every other user from CCC due to the environmental imperfections. This imperfection is implemented via m parameter representing the number of neighboring nodes that cannot be heard from CCC and m is varied systematically to see its effect on the proposed spectrum sharing method. The scheme works on the spectrum sharing process and system performance can still be improved with an underlying MAC protocol that also prevents leaving collisions or with a more accurate spectrum sensing algorithm. The priority values' adaptation according to the QoS classes of SUs with the aim of providing service levels, exploring different traffic patterns of PUs in the system, adaptation and the effect of routing as well as how the dynamic nature of CR users' connectivity affect the spectrum sharing scheme and overall system performance can be noted as future work of this spectrum sharing work.

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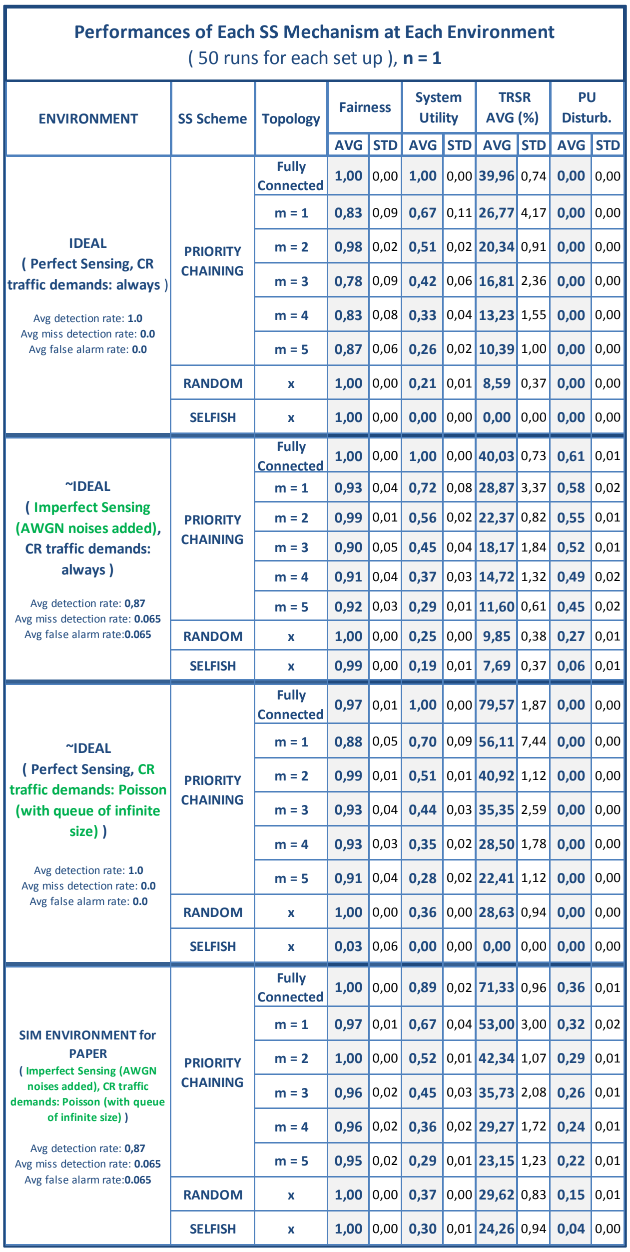
APPENDICES

APPENDIX A

Table A.1: Performances of each SS mechanism at each environment (n = 1)



Performances of Each SS Mechanism at Each Environment
(50 runs for each set up), **n = 1**

ENVIRONMENT	SS Scheme	Topology	Fairness		System Utility		TRSR AVG (%)		PU Disturb.	
			AVG	STD	AVG	STD	AVG	STD	AVG	STD
IDEAL (Perfect Sensing, CR traffic demands: always) Avg detection rate: **1.0** Avg miss detection rate: **0.0** Avg false alarm rate: **0.0**	PRIORITY CHAINING	Fully Connected	1,00	0,00	1,00	0,00	39,96	0,74	0,00	0,00
		m = 1	0,83	0,09	0,67	0,11	26,77	4,17	0,00	0,00
		m = 2	0,98	0,02	0,51	0,02	20,34	0,91	0,00	0,00
		m = 3	0,78	0,09	0,42	0,06	16,81	2,36	0,00	0,00
		m = 4	0,83	0,08	0,33	0,04	13,23	1,55	0,00	0,00
		m = 5	0,87	0,06	0,26	0,02	10,39	1,00	0,00	0,00
	RANDOM	x	1,00	0,00	0,21	0,01	8,59	0,37	0,00	0,00
	SELFISH	x	1,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
~IDEAL (Imperfect Sensing (AWGN noises added), CR traffic demands: always) Avg detection rate: **0,87** Avg miss detection rate: **0.065** Avg false alarm rate:**0.065**	PRIORITY CHAINING	Fully Connected	1,00	0,00	1,00	0,00	40,03	0,73	0,61	0,01
		m = 1	0,93	0,04	0,72	0,08	28,87	3,37	0,58	0,02
		m = 2	0,99	0,01	0,56	0,02	22,37	0,82	0,55	0,01
		m = 3	0,90	0,05	0,45	0,04	18,17	1,84	0,52	0,01
		m = 4	0,91	0,04	0,37	0,03	14,72	1,32	0,49	0,02
		m = 5	0,92	0,03	0,29	0,01	11,60	0,61	0,45	0,02
	RANDOM	x	1,00	0,00	0,25	0,00	9,85	0,38	0,27	0,01
	SELFISH	x	0,99	0,00	0,19	0,01	7,69	0,37	0,06	0,01
~IDEAL (Perfect Sensing, CR traffic demands: Poisson (with queue of infinite size)) Avg detection rate: **1.0** Avg miss detection rate: **0.0** Avg false alarm rate: **0.0**	PRIORITY CHAINING	Fully Connected	0,97	0,01	1,00	0,00	79,57	1,87	0,00	0,00
		m = 1	0,88	0,05	0,70	0,09	56,11	7,44	0,00	0,00
		m = 2	0,99	0,01	0,51	0,01	40,92	1,12	0,00	0,00
		m = 3	0,93	0,04	0,44	0,03	35,35	2,59	0,00	0,00
		m = 4	0,93	0,03	0,35	0,02	28,50	1,78	0,00	0,00
		m = 5	0,91	0,04	0,28	0,02	22,41	1,12	0,00	0,00
	RANDOM	x	1,00	0,00	0,36	0,00	28,63	0,94	0,00	0,00
	SELFISH	x	0,03	0,06	0,00	0,00	0,00	0,00	0,00	0,00
SIM ENVIRONMENT for PAPER (Imperfect Sensing (AWGN noises added), CR traffic demands: Poisson (with queue of infinite size)) Avg detection rate: **0,87** Avg miss detection rate: **0.065** Avg false alarm rate:**0.065**	PRIORITY CHAINING	Fully Connected	1,00	0,00	0,89	0,02	71,33	0,96	0,36	0,01
		m = 1	0,97	0,01	0,67	0,04	53,00	3,00	0,32	0,02
		m = 2	1,00	0,00	0,52	0,01	42,34	1,07	0,29	0,01
		m = 3	0,96	0,02	0,45	0,03	35,73	2,08	0,26	0,01
		m = 4	0,96	0,02	0,36	0,02	29,27	1,72	0,24	0,01
		m = 5	0,95	0,02	0,29	0,01	23,15	1,23	0,22	0,01
	RANDOM	x	1,00	0,00	0,37	0,00	29,62	0,83	0,15	0,01
	SELFISH	x	1,00	0,00	0,30	0,01	24,26	0,94	0,04	0,00

Table A.2: TRSR and COR values of each user with each SS mechanism at each environment (n = 1)

TRSR and COR Values of User with Each SS Mechanism at Each Environment

(50 runs for each set up), **n = 1**

ENVIRONMENT	SS Scheme	Topology	TRSR 1 (%)		TRSR 2 (%)		TRSR 3 (%)		TRSR 4 (%)		TRSR 5 (%)		TRSR 6 (%)		TRSR 7 (%)		TRSR 8 (%)		TRSR 9 (%)		TRSR 10 (%)	
			AVG	STD	AVG	STD	AVG	STD	AVG	STD	AVG	STD	AVG	STD	AVG	STD	AVG	STD	AVG	STD	AVG	STD
IDEAL (Perfect Sensing, CR traffic demands: always) Avg detection rate: 1.0 Avg miss detection rate: 0.0 Avg false alarm rate: 0.0	PRIORITY CHAINING	Fully Connected	40,20	1,30	39,93	1,29	39,78	1,21	39,74	1,09	39,83	1,00	39,88	1,09	39,81	1,02	40,05	1,10	40,14	1,09	40,22	1,17
		m = 1	27,13	12,41	29,09	12,04	26,48	12,93	26,37	13,82	26,82	11,75	26,70	11,46	23,81	13,55	25,38	12,21	25,75	12,29	30,15	9,84
		m = 2	20,72	6,24	20,56	2,41	20,36	1,04	20,22	0,59	20,25	0,79	20,07	0,79	20,20	1,22	19,88	1,75	20,41	3,20	20,76	3,17
		m = 3	16,90	9,58	15,26	10,22	16,74	10,15	15,89	11,74	17,37	9,24	14,82	8,94	18,54	8,66	17,67	8,21	18,38	8,22	16,53	9,31
		m = 4	12,82	6,18	12,74	6,08	13,04	6,23	12,81	6,65	13,01	6,75	12,99	5,96	13,47	6,18	12,84	5,71	15,02	8,01	13,57	6,66
		m = 5	10,98	4,54	10,88	4,12	10,10	4,20	9,85	4,02	9,74	3,45	10,29	4,58	10,79	4,15	10,75	4,29	10,61	4,14	9,95	4,55
	RANDOM	x	8,56	0,38	8,61	0,40	8,59	0,40	8,59	0,37	8,51	0,44	8,52	0,47	8,61	0,45	8,64	0,47	8,61	0,43	8,63	0,49
	SELFISH	x	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
~IDEAL (Imperfect Sensing (AWGN noises added), CR traffic demands: always) Avg detection rate: 0,87 Avg miss detection rate: 0.065 Avg false alarm rate:0.065	PRIORITY CHAINING	Fully Connected	39,64	2,17	39,97	1,76	40,15	1,96	40,11	2,13	40,05	1,60	40,18	1,56	40,01	1,61	39,94	1,52	40,15	1,72	40,05	1,93
		m = 1	29,08	9,45	29,42	8,51	29,36	8,20	28,72	8,37	29,72	7,20	28,42	9,33	28,20	9,07	28,54	7,79	28,54	8,10	28,72	7,53
		m = 2	22,61	5,71	22,62	1,43	22,36	1,11	22,33	0,92	22,44	1,18	22,40	1,09	22,13	1,16	22,15	1,47	22,33	2,03	22,36	2,29
		m = 3	17,47	5,99	19,12	5,40	16,67	6,21	17,23	6,33	17,41	5,91	19,81	7,23	17,99	6,71	18,95	6,09	18,98	6,74	18,11	7,13
		m = 4	15,00	5,01	15,16	5,12	14,60	4,63	14,71	5,04	14,99	4,87	15,35	5,33	13,65	4,53	14,23	4,37	14,35	5,12	15,15	5,07
		m = 5	11,67	3,58	11,80	3,15	11,18	3,38	11,79	3,59	12,97	3,52	11,76	3,69	11,23	3,13	11,11	2,78	11,93	3,42	10,58	3,26
	RANDOM	x	9,85	0,45	9,84	0,43	9,85	0,51	9,84	0,50	9,85	0,40	9,91	0,51	9,74	0,47	9,87	0,44	9,84	0,46	9,86	0,46
	SELFISH	x	7,63	0,74	7,82	0,71	7,77	0,70	7,64	0,88	7,72	0,78	7,59	0,79	7,61	0,79	7,59	0,68	7,89	0,69	7,67	0,68
~IDEAL (Perfect Sensing, CR traffic demands: Poisson (with queue of infinite size)) Avg detection rate: 1.0 Avg miss detection rate: 0.0 Avg false alarm rate: 0.0	PRIORITY CHAINING	Fully Connected	99,86	0,51	89,87	1,92	79,88	1,76	70,59	2,33	63,85	4,07	61,63	4,01	66,33	4,82	74,88	6,25	90,10	6,12	98,74	2,87
		m = 1	66,07	24,96	57,24	22,34	51,73	17,37	45,06	16,96	48,13	14,80	49,46	13,15	50,39	15,57	57,36	22,16	63,44	24,99	72,20	22,74
		m = 2	42,82	7,75	40,17	2,20	38,84	2,33	39,23	2,13	38,94	2,49	40,46	3,18	40,93	3,27	42,57	4,21	43,11	5,42	42,11	5,69
		m = 3	36,10	9,31	33,84	9,95	35,32	11,92	35,91	9,07	33,81	10,22	36,56	9,33	36,44	10,31	35,58	9,84	36,85	12,67	33,11	9,57
		m = 4	27,48	9,14	29,14	8,39	28,18	6,76	26,30	6,99	28,87	8,25	29,29	8,48	30,28	8,18	29,79	8,41	27,22	7,86	28,49	10,06
		m = 5	23,53	7,26	23,77	8,27	21,31	6,63	24,49	8,04	21,41	7,14	19,15	7,27	21,58	6,38	23,82	7,57	22,18	6,54	22,83	7,91
	RANDOM	x	28,53	1,12	28,60	1,19	28,55	1,31	28,76	1,28	28,55	1,35	28,69	1,53	28,61	1,18	28,63	1,50	28,81	1,26	28,60	1,25
	SELFISH	x	0,00	0,00	0,00	0,02	0,00	0,00	0,00	0,01	0,00	0,01	0,00	0,00	0,00	0,01	0,00	0,00	0,01	0,03	0,00	0,01
SIM ENVIRONMENT for PAPER (Imperfect Sensing (AWGN noises added), CR traffic demands: Poisson (with queue of infinite size)) Avg detection rate: 0,87 Avg miss detection rate: 0.065 Avg false alarm rate:0.065	PRIORITY CHAINING	Fully Connected	70,89	3,17	71,62	3,03	71,27	3,25	71,06	3,05	71,01	3,12	71,86	3,57	71,95	3,31	71,95	3,08	71,25	2,81	70,42	3,46
		m = 1	55,62	9,16	53,64	9,64	51,35	10,22	53,14	8,13	54,24	9,84	49,69	8,60	50,93	9,02	53,06	9,82	54,39	9,86	53,95	10,12
		m = 2	41,86	5,02	42,11	1,86	42,56	1,96	42,18	2,21	42,03	2,08	43,11	2,42	42,72	2,60	42,43	2,61	42,85	3,46	41,50	4,46
		m = 3	35,56	6,83	35,85	7,84	36,98	7,03	36,06	7,08	37,62	7,69	34,99	7,75	35,04	8,24	35,31	7,91	34,22	7,06	35,67	6,98
		m = 4	28,77	7,00	31,06	6,38	31,22	7,40	28,80	6,29	27,51	7,29	28,00	5,86	28,00	5,85	29,83	5,77	29,98	5,85	29,56	6,48
		m = 5	22,01	6,19	23,15	5,84	22,96	5,39	23,88	5,61	22,85	5,36	23,31	6,22	22,72	5,80	24,27	5,60	21,99	5,39	24,32	4,88
	RANDOM	x	29,82	1,21	29,51	1,32	29,38	1,06	29,73	1,42	29,59	1,13	29,53	1,14	29,47	1,34	29,67	1,20	29,86	1,27	29,65	1,10
	SELFISH	x	24,24	1,84	24,21	1,59	24,14	1,54	24,45	1,84	24,26	1,83	24,52	1,85	23,94	1,52	24,48	2,18	24,34	1,96	24,05	2,02

ENVIRONMENT	SS Scheme	Topology	COR 1 (over 1.0)		COR 2 (over 1.0)		COR 3 (over 1.0)		COR 4 (over 1.0)		COR 5 (over 1.0)		COR 6 (over 1.0)		COR 7 (over 1.0)		COR 8 (over 1.0)		COR 9 (over 1.0)		COR 10 (over 1.0)	
			AVG	STD	AVG	STD	AVG	STD	AVG	STD	AVG	STD	AVG	STD	AVG	STD	AVG	STD	AVG	STD	AVG	STD
IDEAL (Perfect Sensing, CR traffic demands: always) Avg detection rate: 1.0 Avg miss detection rate: 0.0 Avg false alarm rate: 0.0	PRIORITY CHAINING	Fully Connected	0,10	0,00	0,10	0,00	0,10	0,00	0,10	0,00	0,10	0,00	0,10	0,00	0,10	0,00	0,10	0,00	0,10	0,00	0,10	0,00
		m = 1	0,10	0,05	0,11	0,05	0,10	0,05	0,10	0,05	0,10	0,05	0,10	0,04	0,09	0,05	0,09	0,04	0,09	0,04	0,11	0,04
		m = 2	0,10	0,03	0,10	0,01	0,10	0,00	0,10	0,00	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,02	0,10	0,01
		m = 3	0,10	0,05	0,09	0,06	0,10	0,06	0,10	0,08	0,10	0,06	0,09	0,05	0,11	0,05	0,10	0,04	0,11	0,05	0,10	0,05
		m = 4	0,10	0,04	0,10	0,04	0,10	0,05	0,10	0,05	0,10	0,05	0,10	0,04	0,10	0,04	0,10	0,04	0,11	0,05	0,10	0,05
		m = 5	0,10	0,04	0,10	0,04	0,10	0,04	0,09	0,04	0,09	0,04	0,10	0,04	0,10	0,04	0,10	0,04	0,10	0,04	0,10	0,04
	RANDOM	x	0,10	0,00	0,10	0,00	0,10	0,00	0,10	0,00	0,10	0,00	0,10	0,00	0,10	0,00	0,10	0,00	0,10	0,00	0,10	0,00
	SELFISH	x	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
~IDEAL (Imperfect Sensing (AWGN noises added), CR traffic demands: always) Avg detection rate: 0,87 Avg miss detection rate: 0.065 Avg false alarm rate:0.065	PRIORITY CHAINING	Fully Connected	0,10	0,00	0,10	0,00	0,10	0,00	0,10	0,00	0,10	0,00	0,10	0,00	0,10	0,00	0,10	0,00	0,10	0,00	0,10	0,00
		m = 1	0,10	0,03	0,10	0,03	0,10	0,03	0,10	0,03	0,10	0,02	0,10	0,03	0,10	0,03	0,10	0,02	0,10	0,03	0,10	0,02
		m = 2	0,10	0,02	0,10	0,00	0,10	0,00	0,10	0,00	0,10	0,00	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01
		m = 3	0,10	0,03	0,11	0,03	0,09	0,03	0,09	0,03	0,10	0,03	0,11	0,04	0,10	0,03	0,11	0,03	0,10	0,04	0,10	0,04
		m = 4	0,10	0,03	0,10	0,03	0,10	0,03	0,10	0,03	0,10	0,03	0,10	0,03	0,09	0,03	0,10	0,03	0,10	0,04	0,10	0,03
		m = 5	0,10	0,03	0,10	0,03	0,10	0,03	0,10	0,03	0,11	0,03	0,10	0,03	0,10	0,03	0,10	0,02	0,10	0,03	0,09	0,03
	RANDOM	x	0,10	0,00	0,10	0,00	0,10	0,00	0,10	0,00	0,10	0,00	0,10	0,00	0,10	0,00	0,10	0,00	0,10	0,00	0,10	0,00
	SELFISH	x	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01
~IDEAL (Perfect Sensing, CR traffic demands: Poisson (with queue of infinite size)) Avg detection rate: 1.0 Avg miss detection rate: 0.0 Avg false alarm rate: 0.0	PRIORITY CHAINING	Fully Connected	0,12	0,01	0,11	0,01	0,10	0,01	0,09	0,01	0,08	0,01	0,08	0,01	0,08	0,01	0,09	0,01	0,11	0,01	0,12	0,01
		m = 1	0,12	0,04	0,10	0,04	0,09	0,03	0,08	0,03	0,08	0,03	0,09	0,03	0,09	0,03	0,10	0,04	0,11	0,04	0,13	0,04
		m = 2	0,10	0,02	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01
		m = 3	0,10	0,03	0,09	0,03	0,10	0,03	0,10	0,02	0,10	0,03	0,10	0,03	0,10	0,03	0,10	0,03	0,10	0,03	0,09	0,03
		m = 4	0,10	0,03	0,10	0,03	0,10	0,02	0,09	0,02	0,10	0,03	0,10	0,03	0,11	0,03	0,11	0,03	0,10	0,03	0,10	0,04
		m = 5	0,11	0,03	0,11	0,04	0,10	0,03	0,11	0,04	0,10	0,03	0,08	0,03	0,10	0,03	0,11	0,03	0,10	0,03	0,10	0,03
	RANDOM	x	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01
	SELFISH	x	0,00	0,00	0,05	0,18	0,00	0,00	0,02	0,11	0,04	0,19	0,00	0,00	0,04	0,18	0,00	0,00	0,03	0,15	0,02	0,12
SIM ENVIRONMENT for PAPER (Imperfect Sensing (AWGN noises added), CR traffic demands: Poisson (with queue of infinite size)) Avg detection rate: 0,87 Avg miss detection rate: 0.065 Avg false alarm rate:0.065	PRIORITY CHAINING	Fully Connected	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01
		m = 1	0,10	0,02	0,10	0,02	0,10	0,02	0,10	0,02	0,10	0,02	0,09	0,02	0,10	0,02	0,10	0,02	0,10	0,02	0,10	0,02
		m = 2	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01
		m = 3	0,10	0,02	0,10	0,03	0,10	0,02	0,10	0,02	0,11	0,02	0,10	0,02	0,10	0,02	0,10	0,02	0,10	0,02	0,10	0,02
		m = 4	0,10	0,02	0,11	0,02	0,11	0,03	0,10	0,02	0,09	0,02	0,10	0,02	0,10	0,02	0,10	0,02	0,10	0,02	0,10	0,02
		m = 5	0,09	0,03	0,10	0,02	0,10	0,02	0,10	0,02	0,10	0,02	0,10	0,03	0,10	0,02	0,10	0,02	0,10	0,02	0,10	0,02
	RANDOM	x	0,10	0,01	0,10	0,01	0,10	0,00	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01
	SELFISH	x	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01

APPENDIX B

Table B.1: Performances of each SS mechanism at each environment (n = 3)

Performances of Each SS Mechanism at Each Environment
(50 runs for each set up), **n = 3**

ENVIRONMENT	SS Scheme	Topology	Fairness		System Utility		TRSR AVG (%)		PU Disturb.	
			AVG	STD	AVG	STD	AVG	STD	AVG	STD
IDEAL (Perfect Sensing, CR traffic demands: always) Avg detection rate: **1.0** Avg miss detection rate: **0.0** Avg false alarm rate: **0.0**	PRIORITY CHAINING	Fully Connected	1,00	0,00	1,00	0,00	40,04	0,75	0,00	0,00
		m = 1	0,88	0,11	0,88	0,11	35,36	4,45	0,00	0,00
		m = 2	0,76	0,16	0,75	0,16	29,95	6,41	0,00	0,00
		m = 3	0,64	0,19	0,59	0,19	23,40	7,83	0,00	0,00
		m = 4	0,49	0,22	0,38	0,20	15,21	7,80	0,00	0,00
		m = 5	0,35	0,18	0,17	0,11	6,85	4,39	0,00	0,00
	RANDOM	x	1,00	0,00	0,05	0,00	2,18	0,17	0,00	0,00
	SELFISH	x	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
~IDEAL (Imperfect Sensing (AWGN noises added), CR traffic demands: always) Avg detection rate: **0,87** Avg miss detection rate: **0.065** Avg false alarm rate:**0.065**	PRIORITY CHAINING	Fully Connected	1,00	0,00	1,00	0,00	39,92	0,86	0,75	0,01
		m = 1	0,89	0,10	0,87	0,11	34,67	4,64	0,74	0,01
		m = 2	0,84	0,11	0,77	0,13	30,94	5,23	0,74	0,01
		m = 3	0,66	0,15	0,53	0,15	21,27	5,82	0,74	0,01
		m = 4	0,57	0,16	0,37	0,14	14,87	5,54	0,74	0,02
		m = 5	0,51	0,15	0,19	0,10	7,59	4,06	0,74	0,01
	RANDOM	x	1,00	0,00	0,07	0,00	2,97	0,12	0,42	0,01
	SELFISH	x	0,80	0,07	0,00	0,00	0,18	0,04	0,41	0,02
~IDEAL (Perfect Sensing, CR traffic demands: Poisson (with queue of infinite size)) Avg detection rate: **1.0** Avg miss detection rate: **0.0** Avg false alarm rate: **0.0**	PRIORITY CHAINING	Fully Connected	0,91	0,02	1,00	0,00	80,40	2,10	0,00	0,00
		m = 1	0,88	0,04	0,91	0,05	73,20	4,88	0,00	0,00
		m = 2	0,88	0,04	0,79	0,08	63,95	6,33	0,00	0,00
		m = 3	0,88	0,04	0,67	0,08	53,68	6,46	0,00	0,00
		m = 4	0,89	0,04	0,55	0,05	43,81	3,90	0,00	0,00
		m = 5	0,90	0,04	0,45	0,03	36,25	2,58	0,00	0,00
	RANDOM	x	1,00	0,00	0,34	0,00	27,78	1,09	0,00	0,00
	SELFISH	x	0,99	0,01	0,11	0,01	9,21	0,65	0,00	0,00
SIM ENVIRONMENT for PAPER (Imperfect Sensing (AWGN noises added), CR traffic demands: Poisson (with queue of infinite size)) Avg detection rate: **0,87** Avg miss detection rate: **0.065** Avg false alarm rate:**0.065**	PRIORITY CHAINING	Fully Connected	1,00	0,00	0,89	0,02	70,92	1,17	0,30	0,01
		m = 1	0,97	0,01	0,78	0,03	61,81	2,57	0,26	0,02
		m = 2	0,95	0,02	0,67	0,04	53,70	3,13	0,21	0,01
		m = 3	0,95	0,02	0,56	0,04	45,17	2,70	0,18	0,02
		m = 4	0,94	0,02	0,50	0,02	40,15	1,98	0,15	0,01
		m = 5	0,94	0,03	0,44	0,02	34,92	1,39	0,13	0,01
	RANDOM	x	1,00	0,00	0,36	0,00	29,16	1,07	0,16	0,01
	SELFISH	x	1,00	0,00	0,20	0,01	15,68	0,54	0,04	0,00

Table B.2: TRSR and COR values of each user with each SS mechanism at each environment (n = 3)

TRSR and COR Values of User with Each SS Mechanism at Each Environment
(50 runs for each set up), **n = 3**

ENVIRONMENT	SS Scheme	Topology	TRSR 1 (%)		TRSR 2 (%)		TRSR 3 (%)		TRSR 4 (%)		TRSR 5 (%)		TRSR 6 (%)		TRSR 7 (%)		TRSR 8 (%)		TRSR 9 (%)		TRSR 10 (%)		COR 1 (over 1.0)		COR 2 (over 1.0)		COR 3 (over 1.0)		COR 4 (over 1.0)		COR 5 (over 1.0)		COR 6 (over 1.0)		COR 7 (over 1.0)		COR 8 (over 1.0)		COR 9 (over 1.0)		COR 10 (over 1.0)	
			AVG	STD	AVG	STD	AVG	STD	AVG	STD	AVG	STD	AVG	STD	AVG	STD	AVG	STD	AVG	STD	AVG	STD	AVG	STD	AVG	STD	AVG	STD	AVG	STD	AVG	STD	AVG	STD	AVG	STD	AVG	STD	AVG	STD	AVG	STD
IDEAL (Perfect Sensing, CR traffic demands: always) Avg detection rate: 1.0 Avg miss detection rate: 0.0 Avg false alarm rate: 0.0	PRIORITY CHAINING	Fully Connected	39,79	2,17	40,46	2,80	39,96	2,44	39,83	2,87	40,49	2,52	40,09	2,51	40,00	2,54	40,09	2,14	39,70	1,90	40,03	2,46	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,00	0,10	0,01
		m = 1	34,99	13,24	36,21	12,39	35,40	13,42	35,41	13,42	33,56	14,97	35,96	13,55	38,70	6,12	36,35	11,13	32,73	15,65	34,27	15,23	0,10	0,04	0,10	0,04	0,10	0,04	0,10	0,04	0,09	0,04	0,10	0,04	0,11	0,02	0,10	0,04	0,09	0,04	0,10	0,05
		m = 2	30,53	16,72	30,47	16,66	29,97	17,26	28,51	18,17	31,89	15,33	32,96	14,85	27,42	18,28	27,31	18,21	28,62	17,43	31,84	16,28	0,10	0,06	0,10	0,06	0,09	0,06	0,10	0,07	0,11	0,06	0,12	0,07	0,09	0,07	0,09	0,07	0,09	0,06	0,11	0,06
		m = 3	27,35	15,25	20,82	18,38	20,85	17,82	23,34	18,12	24,60	17,51	24,78	17,65	22,33	18,11	24,45	18,08	21,32	18,32	24,19	18,11	0,12	0,09	0,09	0,09	0,10	0,09	0,09	0,08	0,10	0,07	0,10	0,07	0,09	0,09	0,11	0,09	0,10	0,09	0,10	0,09
		m = 4	15,61	16,03	15,78	15,71	14,53	15,98	13,76	15,77	17,18	15,20	15,10	16,86	15,88	15,87	16,60	15,77	13,85	15,50	13,79	16,35	0,10	0,11	0,11	0,13	0,09	0,14	0,11	0,19	0,11	0,12	0,10	0,17	0,10	0,12	0,11	0,11	0,08	0,10	0,08	0,10
		m = 5	5,34	8,54	6,35	11,30	7,49	10,28	8,63	11,35	7,85	9,98	7,32	10,36	8,11	10,60	6,55	9,16	4,50	7,90	6,30	9,92	0,09	0,18	0,08	0,14	0,10	0,15	0,11	0,15	0,11	0,15	0,10	0,17	0,10	0,14	0,10	0,19	0,06	0,11	0,08	0,13
	RANDOM	x	2,20	0,20	2,18	0,19	2,19	0,22	2,15	0,22	2,19	0,21	2,17	0,21	2,16	0,22	2,15	0,21	2,21	0,20	2,19	0,22	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01
	SELFISH	x	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
~IDEAL (Imperfect Sensing (AWGN noises added), CR traffic demands: always) Avg detection rate: 0,87 Avg miss detection rate: 0.065 Avg false alarm rate:0.065	PRIORITY CHAINING	Fully Connected	40,08	2,84	39,13	2,37	39,36	2,48	40,08	2,24	40,18	2,36	40,48	2,64	39,58	2,63	40,23	2,62	39,77	2,69	40,27	2,64	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01
		m = 1	35,66	10,70	36,06	10,80	34,95	11,37	35,71	10,78	35,10	11,59	36,67	8,43	30,83	14,81	32,73	14,31	33,95	13,28	35,02	13,54	0,10	0,03	0,10	0,03	0,10	0,03	0,10	0,03	0,10	0,04	0,11	0,03	0,09	0,04	0,09	0,04	0,10	0,04	0,10	0,04
		m = 2	26,57	15,52	32,77	12,81	31,50	13,48	27,87	16,14	30,46	14,27	30,70	14,22	31,76	12,36	32,33	12,44	32,95	12,69	32,48	13,12	0,08	0,05	0,10	0,04	0,10	0,05	0,09	0,05	0,10	0,05	0,10	0,05	0,10	0,04	0,10	0,04	0,11	0,04	0,11	0,05
		m = 3	19,17	15,38	21,72	16,07	20,90	15,24	23,93	15,32	24,27	15,32	22,85	15,49	21,30	16,34	19,89	15,14	21,68	14,66	16,99	14,75	0,09	0,07	0,10	0,08	0,10	0,08	0,12	0,10	0,12	0,08	0,11	0,07	0,10	0,08	0,09	0,08	0,10	0,07	0,08	0,06
		m = 4	16,10	13,26	14,09	13,06	13,74	12,66	18,30	14,62	14,56	12,87	17,61	13,85	14,99	13,59	10,91	12,63	13,02	12,45	15,34	13,66	0,10	0,08	0,09	0,08	0,09	0,07	0,12	0,11	0,09	0,07	0,15	0,17	0,10	0,10	0,07	0,08	0,10	0,10	0,09	0,08
		m = 5	6,50	8,63	7,34	8,73	7,68	7,84	8,55	9,06	5,57	6,53	9,15	9,35	8,92	9,32	8,77	9,25	6,59	7,50	6,85	7,72	0,08	0,10	0,10	0,12	0,11	0,10	0,11	0,11	0,08	0,09	0,13	0,14	0,11	0,10	0,11	0,11	0,08	0,09	0,09	0,09
	RANDOM	x	2,97	0,19	2,99	0,19	2,98	0,22	2,97	0,19	2,90	0,17	2,99	0,16	2,98	0,21	2,93	0,22	2,96	0,18	2,99	0,21	0,10	0,01	0,10	0,00	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,00	0,10	0,01	0,10	0,01	0,10	0,00	0,10	0,01
	SELFISH	x	0,20	0,10	0,17	0,08	0,18	0,10	0,19	0,10	0,18	0,11	0,19	0,11	0,18	0,10	0,16	0,10	0,19	0,10	0,19	0,10	0,11	0,05	0,09	0,04	0,10	0,05	0,11	0,05	0,10	0,05	0,10	0,05	0,10	0,05	0,09	0,05	0,11	0,05	0,11	0,05
~IDEAL (Perfect Sensing, CR traffic demands: Poisson (with queue of infinite size)) Avg detection rate: 1.0 Avg miss detection rate: 0.0 Avg false alarm rate: 0.0	PRIORITY CHAINING	Fully Connected	99,89	2,99	93,42	3,87	79,83	3,65	66,90	4,16	55,81	3,81	42,53	3,82	50,74	21,93	101,27	7,69	103,86	2,45	104,74	3,63	0,13	0,01	0,12	0,01	0,10	0,01	0,08	0,01	0,07	0,01	0,05	0,01	0,06	0,03	0,13	0,01	0,13	0,01	0,13	0,01
		m = 1	90,72	22,76	74,70	22,95	63,76	16,72	52,07	16,81	46,77	13,49	55,87	26,55	78,96	29,29	86,28	27,70	92,89	19,63	90,03	22,56	0,12	0,03	0,10	0,03	0,09	0,02	0,07	0,02	0,06	0,02	0,08	0,04	0,11	0,04	0,12	0,04	0,13	0,03	0,12	0,03
		m = 2	70,47	27,98	57,18	21,14	55,59	20,78	56,64	20,92	61,65	25,64	62,75	26,15	67,83	26,00	68,76	23,95	68,77	28,03	69,89	24,12	0,11	0,04	0,09	0,03	0,09	0,03	0,09	0,04	0,10	0,04	0,10	0,04	0,10	0,04	0,11	0,04	0,11	0,04	0,11	0,04
		m = 3	51,25	20,50	56,25	21,25	48,66	17,85	53,73	22,80	46,39	19,22	58,30	20,67	48,74	18,57	55,93	20,53	58,57	21,92	58,97	22,93	0,09	0,03	0,11	0,04	0,09	0,03	0,10	0,04	0,09	0,03	0,11	0,04	0,09	0,03	0,10	0,04	0,11	0,04	0,11	0,04
		m = 4	41,88	15,70	47,97	17,69	42,83	17,75	45,04	16,22	48,23	20,34	45,28	11,46	42,60	15,07	42,52	15,03	39,89	16,97	41,90	15,14	0,10	0,03	0,11	0,04	0,10	0,04	0,10	0,04	0,11	0,04	0,10	0,03	0,10	0,03	0,10	0,04	0,09	0,04	0,10	0,03
		m = 5	38,78	13,90	41,38	14,15	36,51	13,44	34,76	12,54	38,44	13,30	33,90	11,85	32,12	10,21	35,39	12,62	34,29	12,07	36,90	12,79	0,11	0,04	0,12	0,04	0,10	0,04	0,10	0,03	0,11	0,04	0,09	0,03	0,09	0,03	0,10	0,03	0,10	0,04	0,10	0,03
	RANDOM	x	27,91	1,54	27,74	1,54	27,66	1,42	27,89	1,37	28,04	1,55	27,79	1,61	27,54	1,37	27,72	1,42	27,56	1,37	27,90	1,48	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01
	SELFISH	x	8,32	1,21	9,38	1,06	10,29	1,13	8,81	1,07	8,70	0,99	8,60	1,16	9,50	1,19	8,95	0,93	10,18	1,15	9,39	1,12	0,09	0,01	0,10	0,01	0,11	0,01	0,10	0,01	0,09	0,01	0,09	0,01	0,10	0,01	0,10	0,01	0,11	0,01	0,10	0,01
SIM ENVIRONMENT for PAPER (Imperfect Sensing (AWGN noises added), CR traffic demands: Poisson (with queue of infinite size)) Avg detection rate: 0,87 Avg miss detection rate: 0.065 Avg false alarm rate:0.065	PRIORITY CHAINING	Fully Connected	71,81	4,63	71,71	3,96	70,88	4,35	70,73	4,59	71,41	3,67	71,60	3,67	69,78	3,92	70,46	3,47	70,26	4,20	70,52	4,15	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01
		m = 1	61,25	9,75	62,72	10,59	58,49	10,80	63,59	8,92	62,15	9,61	62,75	8,80	60,54	11,54	61,75	11,02	60,75	10,76	64,06	10,43	0,10	0,02	0,10	0,02	0,10	0,02	0,10	0,01	0,10	0,02	0,10	0,01	0,10	0,02	0,10	0,02	0,10	0,02	0,10	0,02
		m = 2	53,97	12,00	54,03	12,46	51,75	13,80	52,11	11,00	56,61	9,43	53,15	12,23	53,56	12,66	53,31	12,60	52,87	10,74	55,67	13,98	0,10	0,02	0,10	0,02	0,10	0,02	0,10	0,02	0,10	0,02	0,10	0,02	0,10	0,02	0,10	0,02	0,10	0,02	0,10	0,02
		m = 3	42,49	11,65	44,91	10,16	44,13	10,14	45,64	12,27	45,60	10,65	46,91	12,99	47,48	10,23	44,40	11,58	44,16	10,62	45,98	12,04	0,09	0,02	0,10	0,02	0,10	0,02	0,10	0,03	0,10	0,03	0,10	0,03	0,11	0,02	0,10	0,03	0,10	0,02	0,10	0,03
		m = 4	39,20	9,77	43,19	10,00	42,03	8,56	38,86	10,38	40,59	11,62	42,00	8,86	40,18	12,14	40,88	10,12	38,56	10,06	36,06	9,93	0,10	0,03	0,11	0,02	0,11	0,02	0,10	0,03	0,10	0,03	0,10	0,02	0,10	0,03	0,10	0,03	0,10	0,03	0,09	0,02
		m = 5	34,60	8,41	35,76	8,59	34,99	7,60	35,51	9,53	31,79	8,76	35,65	9,07	35,92	8,73	34,69	9,34	33,76	8,00	36,53	9,92	0,10	0,02	0,10	0,03	0,10	0,02	0,10	0,03	0,09	0,03	0,10	0,03	0,10	0,03	0,10	0,03	0,10	0,02	0,10	0,03
	RANDOM	x	29,05	1,52	29,07	1,44	29,13	1,48	29,32	1,51	29,00	1,39	29,28	1,30	29,13	1,46	29,28	1,84	29,19	1,44	29,14	1,54	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01
	SELFISH	x	15,30	1,00	15,72	0,98	16,22	1,17	15,69	1,16	15,50	1,04	15,47	1,10	15,86	1,19	15,35	1,06	15,85	1,21	15,86	1,07	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01	0,10	0,01

APPENDIX C

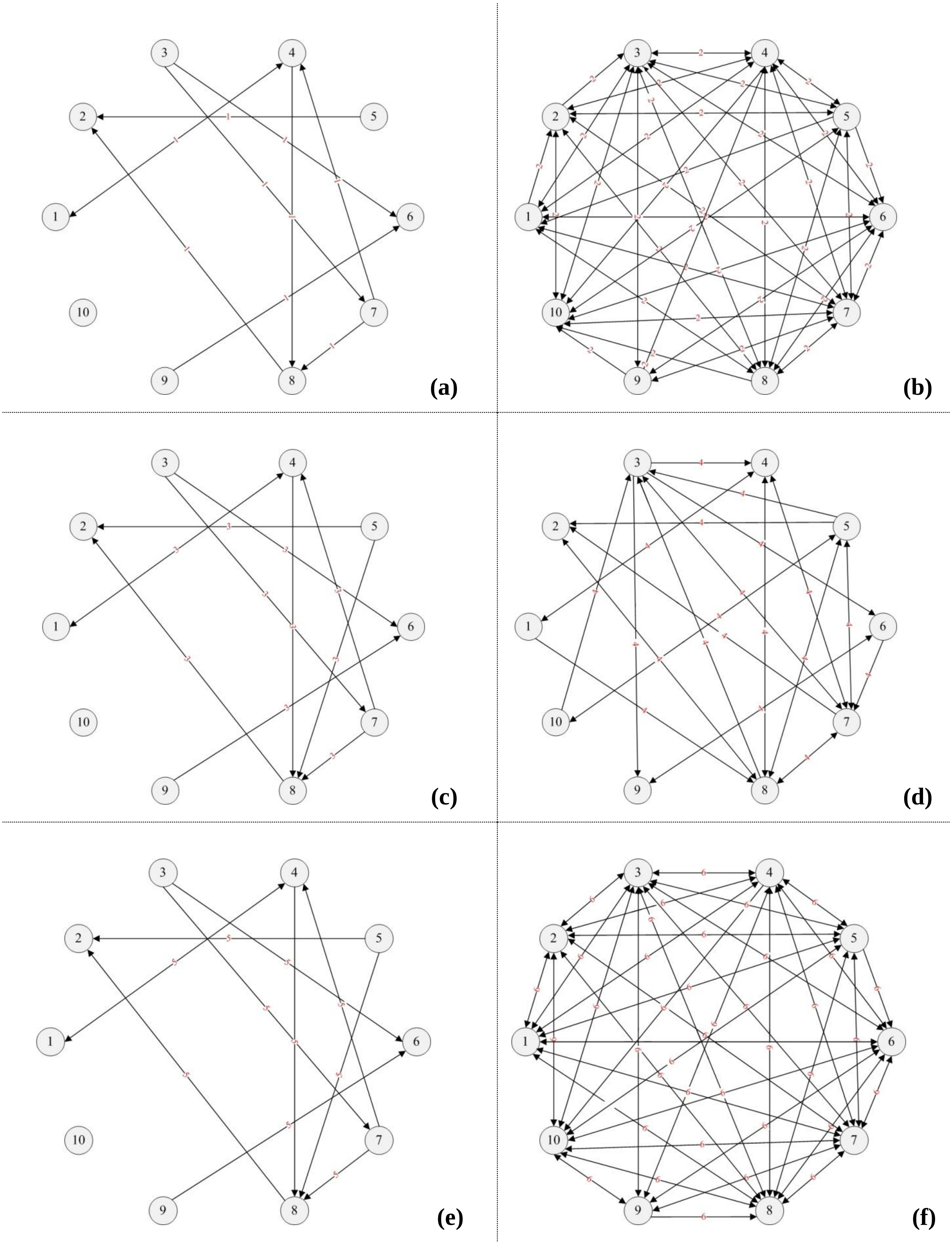
Table C.1: Chosen Coordinates for CR users and their corresponding receivers

CR User (Transmitter) Id	Location (x , y)	Corresponding CR User (Receiver) Id	Location (x , y)	Distance Between Them
1	82 , 91	1	96 , 97	15,23
2	16 , 98	2	10 , 83	16,16
3	70 , 32	3	44 , 39	26,93
4	77 , 80	4	71 , 76	7,21
5	28 , 68	5	12 , 50	24,08
6	96 , 35	6	76 , 26	21,93
7	51 , 70	7	62 , 48	24,60
8	36 , 84	8	54 , 78	18,97
9	94 , 13	9	83 , 20	15,56
10	5 , 17	10	21 , 31	21,26

Table C.2: Distance values between each transmitter and each receiver and corresponding conflicting channels list

Trx.Id	**Rcv. 1**		**Rcv. 2**		**Rcv. 3**		**Rcv. 4**		**Rcv. 5**		**Rcv. 6**		**Rcv. 7**		**Rcv. 8**		**Rcv. 9**		**Rcv. 10**	
	Dist.	Conflicting Channels	Dist.	Conflicting Channels	Dist.	Conflicting Channels	Dist.	Conflicting Channels	Dist.	Conflicting Channels	Dist.	Conflicting Channels	Dist.	Conflicting Channels	Dist.	Conflicting Channels	Dist.	Conflicting Channels	Dist.	Conflicting Channels
1	15,2	-	72,4	2,6,8	64,4	2,6,8	18,6	1,2,3,4,5,6,7,8	81,1	6,8	65,3	2,6,8	47,4	2,6,8	30,9	2,4,6,8	89	8	85,56	8
2	80	6,8	16,2	-	65,3	2,6,8	59,2	2,6,8	48,2	2,6,8	93,7	-	67,9	2,6,8	42,9	2,4,6,8	117	-	67,19	2,6,8
3	70	2,6,8	78,7	6,8	26,9	-	44	2,4,6,8	60,7	2,6,8	8,49	1,2,3,4,5,6,7,8	17,9	1,2,3,4,5,6,7,8	48,7	2,6,8	32,7	2,4,6,8	49,01	2,6,8
4	25,5	1,2,3,4,5,6,7,8	67,1	2,6,8	52,6	2,6,8	7,21	-	71,6	2,6,8	54	2,6,8	35,3	2,4,6,8	23,1	1,2,3,4,5,6,7,8	78,2	6,8	74,41	2,6,8
5	73,9	2,6,8	23,4	1,2,3,4,5,6,7,8	33,1	2,4,6,8	43,7	2,6,8	24,1	-	63,8	2,6,8	39,4	2,4,6,8	27,9	2,3,4,5,6,7,8	85,9	8	37,66	2,4,6,8
6	62	2,6,8	98,5	-	52,2	2,6,8	48	2,6,8	85,3	8	21,9	-	36,4	2,4,6,8	60,1	2,6,8	35,5	2,4,6,8	75,11	2,6,8
7	52,5	2,6,8	43	2,4,6,8	31,8	2,4,6,8	20,9	1,2,3,4,5,6,7,8	43,8	2,4,6,8	50,6	2,6,8	24,6	-	8,54	1,2,3,4,5,6,7,8	75,2	2,6,8	49,2	2,6,8
8	61,4	2,6,8	26	1,2,3,4,5,6,7,8	45,7	2,4,6,8	35,9	2,4,6,8	41,6	2,4,6,8	70,5	2,6,8	44,4	2,4,6,8	19	-	94,5	-	55,08	2,6,8
9	84	8	109	-	56,4	2,6,8	67,1	2,6,8	90	8	22,2	1,2,3,4,5,6,7,8	47,4	2,6,8	76,3	6,8	15,6	-	75,19	2,6,8
10	121	-	66,2	2,6,8	44,8	2,4,6,8	88,5	8	33,7	2,4,6,8	71,6	2,6,8	64,9	2,6,8	78,2	6,8	79,4	6,8	21,26	-

APPENDIX D



(a) (b) (c) (d) (e) (f)

Figure D.1 : Interference graphs: (a)Channel$_1$. (b)Channel$_2$. (c)Channel$_3$. (d)Channel$_4$. (e)Channel$_5$. (f)Channel$_6$. (g)Channel$_7$. (h)Channel$_8$.

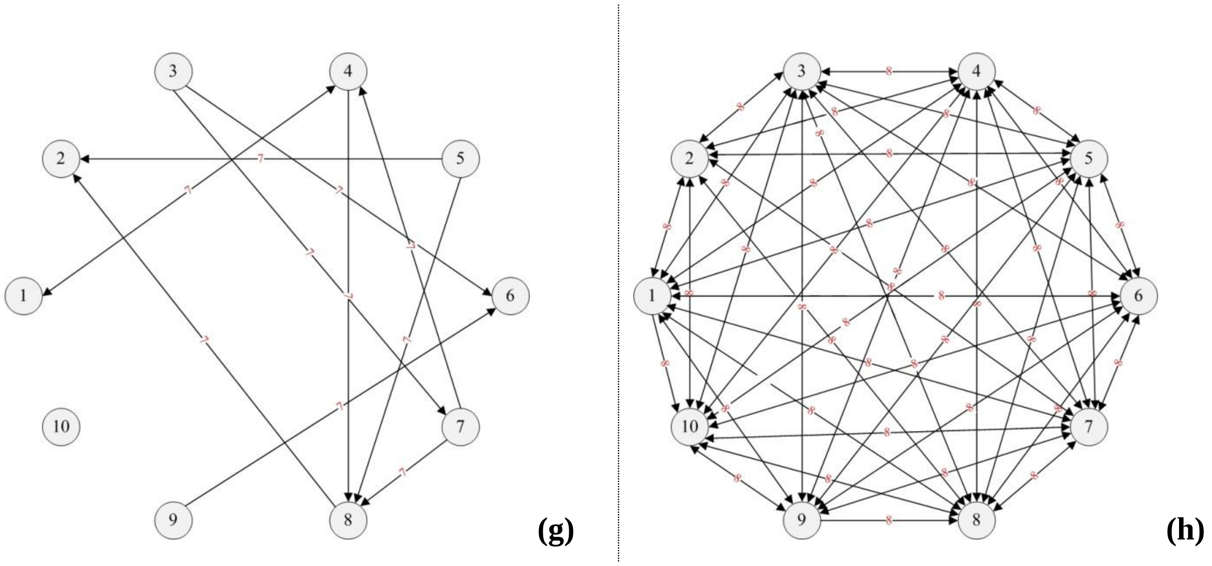


Figure D.1 (contd.): Interference graphs: (a)Channel$_1$. (b)Channel$_2$. (c)Channel$_3$. (d)Channel$_4$. (e)Channel$_5$. (f)Channel$_6$. (g)Channel$_7$. (h)Channel$_8$.

CURRICULUM VITAE

Candidate's full name : Gülnur Selda (Kuruoğlu) UYANIK

Place and date of birth : İstanbul, 04 / 09 / 1985

Permanent Address : Istanbul Technical University, Computer and
Informatics Faculty, Computer Engineering
Department, Office: 5308, 34469, Maslak / İST

Universities attended : B.Sc.: Istanbul Technical University,
Computer Engineering

Publications:

- **Kuruoglu, G.S.**, Erol, M. and Oktug, S., 2009. Localization in Wireless Sensor Networks with Range Measurement Errors, *Advanced International Conference on Telecommunications*, 0, 261–266.
- **Kuruoglu, G.S.**, Erol, M. and Oktug, S., 2009. Three Dimensional Localization in Wireless Sensor Networks Using the Adapted Multi-Lateration Technique Considering Range Measurement Errors, *GLOBECOM Workshops*, 2009 IEEE, pp. 1–5.