İSTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF SCIENCE AND TECHNOLOGY

A DYNAMIC SPECTRUM DECISION SCHEME FOR HETEROGENEOUS COGNITIVE RADIO NETWORKS

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Programme : Computer Engineering

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FOREWORD

First, I would like thank to my advisor Assist. Prof. Dr. Feza BUZLUCA for his valuable time and supervision.

This work is dedicated my beloved wife, Bilgen KAPLAN.

May 2009

Metin Kaplan

Computer Engineer

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ABBREVIATIONS

CR	**:** Cognitive Radio
DSA	**:** Dynamic Spectrum Access
SB	**:** Spectrum Broker
CAB	**:** Coordinated Access Band
AHP	**:** Analytical Hierarchy Process
FPUA	**:** Frequency of Primary User Appearance
SC	**:** Spectrum Channel
CI	**:** Consistency Index
TH	**:** Throughput

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A DYNAMIC SPECTRUM DECISION SCHEME FOR HETEROGENEOUS COGNITIVE RADIO NETWORKS

SUMMARY

In conventional spectrum management, spectrum bands are given to license holders with static policies. As there is dramatic increase in areas of wireless applications, most of the users have problems to find spectrum bands to operate on while most of the spectrum bands are not utilized. Cognitive radio is a technology which is proposed to solve this problem. Cognitive radios may operate on licenced spectrum bands which are not occupied by primary users for given time. This technique is called Dynamic Spectrum Access. When we go into details, spectrum sensing and spectrum decision are the main challenging functions that cognitive radio (CR) networks have to perform. In this paper, we focus especially on the spectrum decision problem. This problem is worsened in the presence of users with different demands and spectrum channels with different properties in a heterogeneous network. For accurate and fair spectrum management, we propose a spectrum decision algorithm for spectrum brokers that takes user type and spectrum channel properties into consideration. This approach increases both the number of users that can get proper spectrum bands and the throughput of the system. Proposed algorithm also includes a "patience" option. Users that choose the "patience" option agree to wait for a predetermined amount of time until their connection is established. Meanwhile, a better spectrum may become available. Wait option increases the chance of patient users getting a better spectrum.

BİLİŞSEL RADYO AĞLARI İÇİN YENİ BİR SPEKTRUM KARAR ALGORİTMASI

ÖZET

Geleneksel spektrum yönetiminde spektrum bantları kullanıcılara sabit kullanım hakları aracılığı ile dağıtılmıştır. Son yıllarda meydana gelen kablosuz iletişim uygulamalarındaki artış ile birçok kullanıcı spektrum bulma konusunda sorunlar yaşamaktadırlar. Oysa sabit kullanım hakları ile erişilen spektrum bantları verimsiz kullanılmaktadır. Bilişsel radyolar bu sorunları çözmek için önerilmiş bir teknolojidir. Bilişsel radyolar lisanslanmış bantlar üzerinde de birincil kullanıcılara zarar vermemek şartı ile çalışabilen cihazlardır. Bu tekniğe Dinamik Spektrum Erişimi denir. Daha ayrıntılı baktığımızda spektrum algılama ve spektrum karar verme, bilişsel radyo ağlarında yerine getirilmesi gereken iki ana işlevdir. Bu çalışmada, ana konu spektrum karar problemidir. Bu problem, kullanıcıların farklı istekleri ve spektrum kanallarının da farklı özellikleri olduğu göz önünde bulundurulduğunda daha da karmaşık bir hal alır. Daha adaletli ve verimli bir spektrum yönetimi için, bu çalışmada spektrum dağıtıcılarda kullanılması için bir algoritma tasarlanmıştır. Bu algoritma, kullanıcı tipini ve spektrum kanallarının özelliklerini göz önünde bulundurarak, kullanıcı istekleri ile kanal özelliklerini en iyi şekilde eşleştirmeye çalışmaktadır. Bu sayede hem sistemden fayda sağlayan (iletişimini istediği özelliklerde gerçekleştiren) kullanıcıların sayısı hem de sistemin toplam verimliliğinin (aktarılan toplam veri miktarının) arttığı gözlemlenmiştir. Ayrıca, algoritmaya bekleme toleransına sahip kullanıcılar için de bir ekleme yapılmıştır. Bekleme toleransına sahip olan kullanıcılar spektrum dağıtıcısına istekte bulunduktan sonra spektrum kanalına sahip olana kadar kendisinin belirttiği zaman dilimi kadar bekleyebilen kullanıcılardır. Bu eklenti sayesinde hem bekleme toleransına sahip olan kullanıcılar hem de diğerleri daha iyi bir kanal bulma şansına sahip olmaktadırlar.

1. INTRODUCTION

In conventional spectrum management strategy, huge amount of spectrum bands are assigned to license holders with static policies which are decided by governmental agencies in base of large geographical areas. According to this spectrum management strategy, only the users which have these licences to operate can access to related spectrum bands. There are only a small amount of spectrum bands that users which have no licence, can operate on [1].

However, in recent years spectrum demand increased dramatically. This is predictable as there are many new application areas using wireless technology intensively. This increase in spectrum demand resulted in the problem to find available spectrum to operate.

As a result, researches questioned whether the spectrum bands assigned using static policies are really utilized or not. Researches showed that most of the license holders cannot utilize their spectrum band [2][3]. You can see the spectrum occupancy results for Chicago in the Figure 1.1 [3].

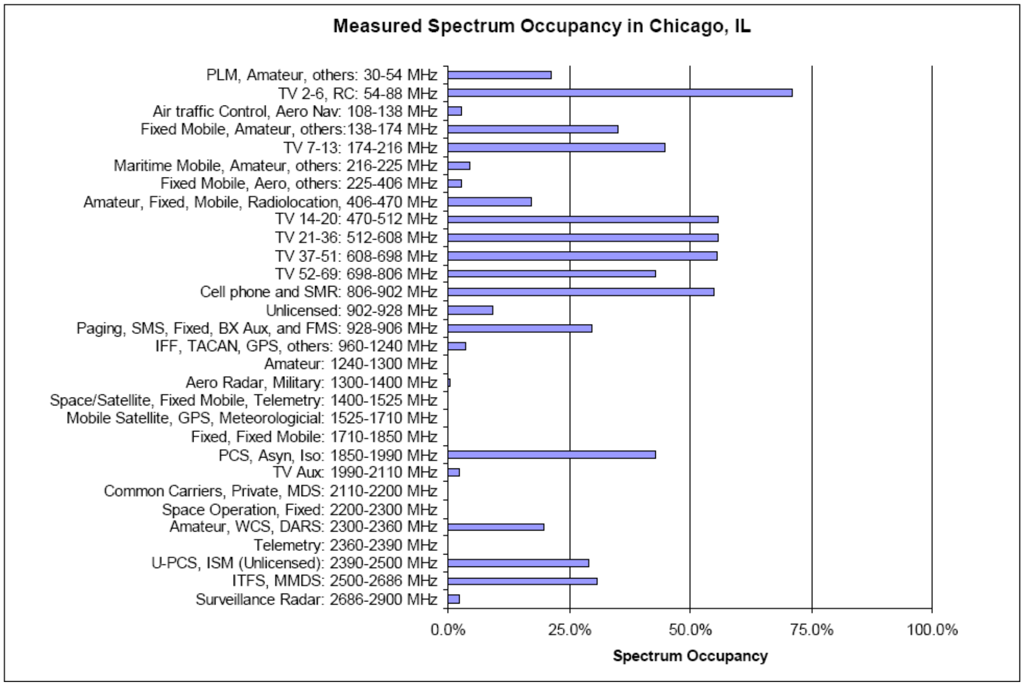

Figure 1.1 : Spectrum occupancy in each band measured in Chicago

Hence, CR and dynamic spectrum allocation techniques are introduced [4]. Cognitive Radio gives opportunity to share the wireless channel with licenced users without disturbance to primary users.

1.1 Purpose of the Thesis

The purpose of this work is to propose an efficient and fair spectrum management algorithm which can be used by Spectrum Brokers in order to assign proper spectrum channels to the users who have different needs. With this work, we propose that user type should be one of the criteria in spectrum selection in CR networks.

Another contribution we make in decision system, to take the patient users into consideration in the decision process. Patient user is a user which can wait some amount of time until a spectrum is assigned to itself. With this extension, both the patient users and impatient users have higher chance to get better spectrums.

1.2 Background

As described above, cognitive radios may use licenced spectrum bands which are not occupied by a primary user for given time. Figure 1.2 [1] illustrates how a CR uses unused spectrum bands in opportunistic way.

This opportunistic usage of spectrum is also called Dynamic Spectrum Access. In DSA, CR users are not allowed to interfere with primary users which have the static licences to operate on related spectrum band.

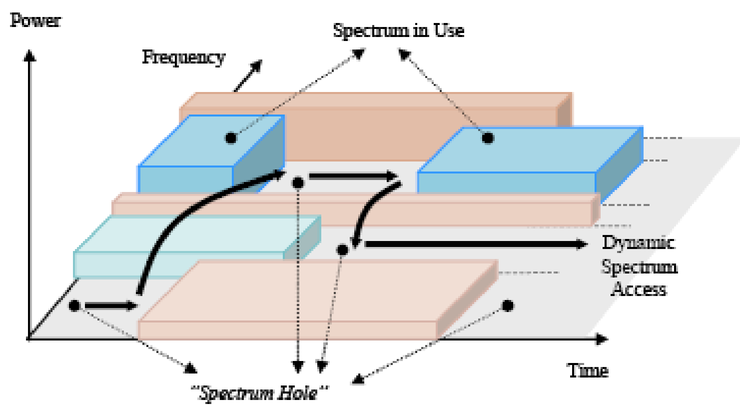

Figure 1.2 : Opportunistic spectrum usage

Every Cognitive Radio should be able to provide four functionalities, find unused spectrum bands, select the best unused spectrums, coordinate access to that channel with other users, be aware of primary users and vacate the spectrum at their appearance. This four challenging functionalities are spectrum sensing, spectrum decision, spectrum sharing and spectrum mobility respectively [1]. In addition to these functionalities, every CR has to collect statistical information about spectrum bands, in order to make proper decisions [5].

It is not easy for each radio device to support all these functionalities at the same time, as both the hardware and software of the terminals will be complicated and expensive. So centralized Spectrum Management and RSB (Regional Spectrum Broker) are introduced [1][5][6]. With this centralized entity, CR users will just send the requests to SB and wait for answer. Owing to SBs, CR terminal does not have to scan the whole spectrum, collect statistical data, make decisions, coordinate access to spectrum with other CRs.

However, the decision mechanisms to be used in spectrum brokers are still an open area to discuss. In the papers [1][5] users get the best spectrum among available spectrums. So the SB is supposed to make one preference list of available spectrum channels.

However, needs of different users in today's wireless networks are not the same. Each user type has it is own restrictions for attributes of spectrums as well as some requirements in their connections. In addition spectrum characteristics are not identical either. They may differ from each other in their attributes such as bandwidth, bit error rate, load of licensed users etc.

In conclusion, trying to find single best spectrum for all users is not a logical approach for spectrum decision.

1.3 Hypothesis

One of our motivations in this work is to introduce "Best Spectrum Channel Regarding the User Type" instead of "Best Spectrum Channel". That means best channel will be selected regarding the type of the user because of the reasons explained above.

As decision algorithm *utility function* is used. Other decision methods could be Neural Networks [7], Fuzzy logic [8], game theory [9,10] or heuristic algorithm[11], however all these mechanisms have more computational overhead. Furthermore, our aim is to see the effects of user types in decision taking, not to compare decision techniques as it is done in [12]. For utility function, the weight values are obtained using Analytic Hierarchy Process.

Price could be an additional parameter in the spectrum selection process [13]. However, in this work, we aimed to create a fair spectrum decision algorithm which does not accept the price as a decision parameter.

Moreover, in this new SB design, we define a customer-specified set-up time, referred to as *wait option,* which is a measure of the user's patience. It describes the time a spectrum request can be held until it is satisfied.

Instead of assigning an available spectrum to a user immediately, the broker may delay the decision according to the wait option of the user. With that feature, the possibility to assign a proper spectrum to user is increased, because during wait time some other users may leave the system and new spectrums may be available.

2. SYSTEM OVERVIEW

2.1 Objectives

The main focus of this chapter is to explain the differences between centralized and distributed spectrum management systems. Then we will explain why Centralized approach is better and selected to use in this work.

2.2 Centralized Spectrum Management vs. Distributed Spectrum Management

In centralized spectrum management, there are central entities to scan the environment and to make decision for each user. In contrast, in distributed spectrum management there is no central entity, so each CR user has the responsibility to scan the environment, make spectrum decision for itself and coordinate the access to the band with other CR users.

Decision of spectrum is a challenging topic in CR systems. When we examine the distributed decision, to be able to select a spectrum, a CR user should have spectrum sensing module, to scan large spectrum bands whether there is available channel or not. In order to make right decisions, also statistical information about spectrum bands should be kept [14]. This means not only expensive and complex hardware but also power consumption problems for mobile devices [5][6].

Another problem for a CR user in distributed decision system is to coordinate access to channel with the other CR users [1]. There will be race condition between users and this will reduce the efficiency of the system. There are some researches trying to address these problems [15].

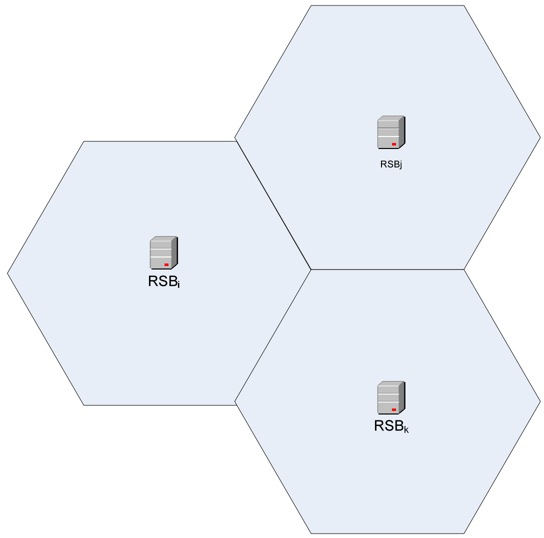

Figure 2.1 : Network structure overview

Regarding the problems described above, in the proposed system, Spectrum Brokers which, manages spectrum usage in a predefined area, are used. Spectrum Broker is a central entity which scans the environment and keeps statistical data about the environment. Users in the predefined area make requests to related SB. SB makes decisions for users and assigns them to one of the available spectrums at a given time.

To make the spectrum management easy and efficient the operation area is divided into regions as shown in Figure 2.1 and every management region has its own Spectrum Broker, namely Regional Spectrum Broker (RSB) [16,17].

Add-hoc network components [18] are not considered and detailed in this work as the main motivation is to propose a new decision algorithm.

In this study we focus on designing an efficient decision scheme. Therefore some issues about RSBs such as coordination channels [19], area overlaps [15,17] are not addressed in this particular research.

Another term that we should emphasize here is CAB. CABs are managed by SBs. SB leases CABs to users and at the end of lease time users release the CAB to SB. There are two possible usages for CAB. First one is CAB-M1. In this type only network operators can request CAB. The other type is CAB-M2, in which every mobile node can create request for CAB [20].

In our system, not only CABs but also the spectrum bands which have been used by primary users are considered.

3. BEST SPECTRUM CONCEPT REGARDING USER TYPE

3.1 Objectives

The main focus of this chapter is to explain one of our two contributions to spectrum decision algorithms which is "Best Spectrum Regarding User Type". To explain this approach, first we will examine the characteristics of wireless channels, then we will define the different user types and their needs, finally we will detail the decision mechanism which is used to find preference lists of each individual user type.

3.2 The Heterogeneous System

This study has been done for heterogeneous CR networks that include spectrum channels (SC) with different properties. In order to identify the characteristics of spectrum channels and the network infrastructure the following statistical information are kept for each SC by the RSBs:

- Bandwidth
- Delay
- FPUA

The parameter Delay is the amount of delay time caused by network model and infrastructure which is used the spectrum channel in.

We added a new attribute named FPUA that is the statistical information about the primary user appearance in the channel. It is given as a number of the primary user connections in a predetermined time interval. The FPUA is an important parameter because CR users must vacate the spectrum immediately when a primary user enters into the channel. So this attribute allows us to make an estimation of connection duration to that wireless channel.

Statistical information about these attributes of SCs should be kept in SB in order to make a better decision list for each traffic class type.

Each RSB keeps a list of available spectrums and creates a matrix of these spectrum channels, which holds available spectrum channels (SC_i) in its rows and the attributes of channels in its columns.

Spectrum channel *i* can be expressed as a vector of *k* attributes. The expression will be as,

$$s_i = [a_1 \; a_2 \; .. \; a_k] \qquad \textbf{(3.1)}$$

For *n* available spectrum channels, for given time t_0 available spectrum matrix can be expressed as:

$$S = \begin{bmatrix} s_1 \\ s_2 \\ . \\ . \\ s_n \end{bmatrix} \qquad \textbf{(3.2)}$$

Here s_j is the i.th avaliable spectrum in the system

3.3 Traffic Classes

Basic components of "Opportunistic Spectrum Access" (OSA) are spectrum opportunity identification, exploitation and regularity system. Identification is responsible for tracking the idle spectrums in both time and location and spectrums' characteristics while exploitation is responsible for getting the best spectrum [5]. In the spectrum decision process, spectrum identification is very important in order to find best matching spectrum channel to the users.

Regarding the "Best Spectrum Channel" concept, the reason to identify the spectrum characteristics is to find the best spectrum among available spectrums. However, as the needs of users are different from each other, in this paper "Best Spectrum Channel" concept is extended to "Best Spectrum Channel Regarding User Type". The first step is to define possible user types. In this paper, possible user types are traffic classes, which are introduced in 3GPP [21] as shown in Table 3.1.

Table 3.1: Traffic classes and example usages

Traffic Class	Example Usage
Streaming	Video streaming
Conversational	VoIP
Interactive	Web browsing
Background	Email download

When a CR user needs a spectrum, it sends a request that includes its type to the RSB. The RSB will use user's traffic class type to be able to select the spectrum which matches to that user at most.

3.4 Decision Algorithm

The user type and spectrum channel characteristics will be used in a decision algorithm. In this work, as decision algorithm *utility function* is used.

Utility functions generally used to define the difference in the satisfactions of different elements. A utility function is applied to elements in an object set, and this will give us the benefit received from usage of those objects. We can call this result a preference list.

To do that, every attribute of an object has weight factor on the result. Here utility functions will run on spectrum channels so spectrum channel attributes such as Delay, Bandwidth and FPUA should have weight values on the result.

Before applying the utility function, the weight factors of traffic classes (user type) must be calculated for each attribute of a Spectrum Channel (SC). These factors show that how important is an SC attribute for a traffic class. To get those weight factors for each different traffic class type Analytical Hierarchy Process (AHP) is used.

3.4.1 AHP

Analytical Hierarchy Process [22] is a technique which is used in decision making systems when decision makers may have difficulties in accurately determining the various vector weights. This process involves pair-wise comparisons. Another reason to use AHP is its consistency check in creation of weight values.

3.4.1.1 Values for AHP matrices

First step is to create an AHP matrix for each traffic class. Pair-wise comparison values for channel attributes are

Table 3.2: Meanings of values used in determination for relative importance

Value	**Meaning**
1	Equally preferred
2	Equally to moderately preferred
3	Moderately preferred
4	Moderately to strongly preferred
5	Strongly preferred
6	Strongly to very strongly preferred
7	Very strongly preferred
8	Very to extremely strongly preferred
9	Extremely preferred

This cross importance AHP matrixes shown in Table 3.3, Table 3.4 and Table 3.5 are created using the explanation of traffic classes and boundary values of traffic classes given in [21].

Table 3.3: AHP matrix for streaming traffic class

Streaming	Bandwidth	FPUA	Delay
Bandwidth	1	2	4
FPUA	½	1	3
Delay	¼	1/3	1

Table 3.4: AHP matrix for conversational traffic class

Conversational	Bandwidth	FPUA	Delay
Bandwidth	1	1/3	1/7
FPUA	3	1	½
Delay	7	2	1

Table 3.5: AHP matrix for background traffic class

Background	Bandwidth	FPUA	Delay
Bandwidth	1	1/3	1/3
FPUA	3	1	1
Delay	3	1	1

Here we should answer the question what will happen when there is a new traffic class available in the future or the characteristics of a traffic class above change. This system allows us to change the values of a matrix anytime and add a new traffic class without any dependencies to other traffic classes available. Because the values inside a matrix are independent from the values in other matrixes.

3.4.2 Calculating the weight values

First step is to get weight values, is to find sum of each column in AHP matrixes (3.3)

$$V_j^{sum} = \sum_{i=1}^{n} M_{ij}^{AHP} \qquad \textbf{(3.3)}$$

where n is the number of rows and columns in matrix, V_j^{sum} is the vector which holds the column sums.

Then for each column element, divide the value of element to column sum (3.4).

$$M_{ij}^{AHP} = \frac{M_{ij}^{AHP}}{V_j^{sum}} \qquad j = 1, .. , n \qquad \textbf{(3.4)}$$

Next step is to calculate the average values of rows (3.5).

$$V_i^{average} = \frac{\sum_{j=1}^{n} M_{ij}^{AHP}}{n} \qquad \textbf{(3.5)}$$

where $V_i^{average}$ is the vector which holds the averages of the rows.

Then we need to calculate the consistency vector as further step. To do so, we need to multiply the related AHP matrix with the vector we have created in the previous steps (3.6)

$$V_i^{consistency} = V_i^{average} \times M_{ij}^{AHP} \qquad \textbf{(3.6)}$$

$$V_i^{consistency} = \frac{V_i^{consistency}}{V_i^{average}} \qquad \textbf{(3.7)}$$

Furthermore we need to calculate λ and CI using (3.8) and (3.9) in order to calculate the consistency ratio.

$$\lambda = \sum_{1}^{n} V^{CR} \times \frac{1}{n} \quad \textbf{(3.8)}$$

$$CI = \frac{\lambda - n}{n - 1} \quad \textbf{(3.9)}$$

After applying these steps, now we have the weight values of attributes which can be used in utility function. But here we need to be sure whether the values that we have used in AHP matrixes are consistent or not. To test these values we need to do the last step and calculate the consistency ratio.

3.4.3 Consistency ratio

Consistency ratio can be obtained using (3.10)

$$cr = \frac{CI}{RI} \quad \textbf{(3.10)}$$

RI = 0,58 as in the AHP matrix there are 3 attributes

Consistency ratio is important in AHP, as it shows us how consistent the cross importance values between attributes are. If cr is less than 0.10, the values are relatively consistent.

In this work, a useful visual AHP tool [23] has been used to obtain weight values. Weight values for each traffic class can be seen in the Table 3.6 with related consistency ratio.

Table 3.6: Weight values for traffic classes

Traffic Class	Spectrum Characteristics			
	Bandwidth	FPUA	Delay	Cr
Streaming	0.5614	0.3181	0,1205	0,005
Conversational	0,0927	0.2898	0.6175	0,002
Interactive	0,1421	0,4337	0,4242	0

According to these values in the table, Bandwidth is more important than Delay for Streaming traffic, while Delay is more important than Bandwidth for Conversational traffic.

Regarding these three parameters, it is not possible to make a distinction between Interactive and Background traffic classes, as we do not use enough number of spectrum channel characteristics in decision process. So, in this paper we consider just 3 different traffic classes. For Interactive and Background the preference list will be the same.

For each traffic class, the weight vector is:

$$W^{streaming} = \begin{bmatrix} 0.4847 \\ 0.3836 \\ 0,1317 \end{bmatrix} \quad W^{conversational} = \begin{bmatrix} 0.0619 \\ 0.3145 \\ 0.6236 \end{bmatrix}$$

$$W^{interactive} = \begin{bmatrix} 0.3741 \\ 0.3995 \\ 0.2324 \end{bmatrix}$$

The general format of the utility function is as follows:

Profit **(P_i)** provided by Spectrum Channel **(SC_i)** for Traffic Class **(*TC*)** which has weight vector (W^{TC}) is

$$P_i^{TC} = \sum_{j=1}^{k} S_i \times W_j^{TC} \qquad \text{k = number of attributes} \qquad \textbf{(3.11)}$$

Here S_i is a row of spectrum channels matrix *S*, that holds characteristic values of i^{th} channel (SC_i).

In order to apply the utility function correctly the matrix of available spectrums *S* must be normalized. To do that if a parameter affects the result directly proportional formula (3.11) is used, otherwise formula (3.12) is used.

ns_{ij} *: is normalized value for* $s_{ij} \in S$

$$ns_{ij} = s_{ij} / s_j^{\max} \quad i = 1, \ldots, n \quad j = 1, \ldots, k \qquad \textbf{(3.12)}$$

$$ns_{ij} = s_j^{\min} / s_{ij} \quad i = 1, \ldots, n \quad j = 1, \ldots, k \qquad \textbf{(3.13)}$$

After applying the formula (3.12) to Bandwidth and (3.13) to Delay, FPUA the matrix *NS* which holds normalized values is generated.

$$NS\left[ns_{ij}\right]_{i=1\ldots n,\, j=1..k} \qquad \textbf{(3.14)}$$

The profit obtained from channel each SC_i for a traffic class TC ∈ {Conversational, Background, Streaming}, is calculated with the following formula:

$$NP_i^{TC} = NS_i \times W^{TC} \text{ for i= 1,2,\ldots,n} \qquad \textbf{(3.15)}$$

The spectrum that constitutes the highest value is the best spectrum for this traffic class at the moment. We have also considered the maximum and minimum values which a spectrum channel attribute can have for a specific traffic class. For example, the max delay value for conversational traffic class is 20ms. SB must not assign a spectrum channel with wait value more than 20ms to the users of conversational traffic. Therefore those spectrum channels which have not convenient values do not exist in the preference list of related traffic classes.

Figure 3.1 shows the steps in a flowchart diagram.

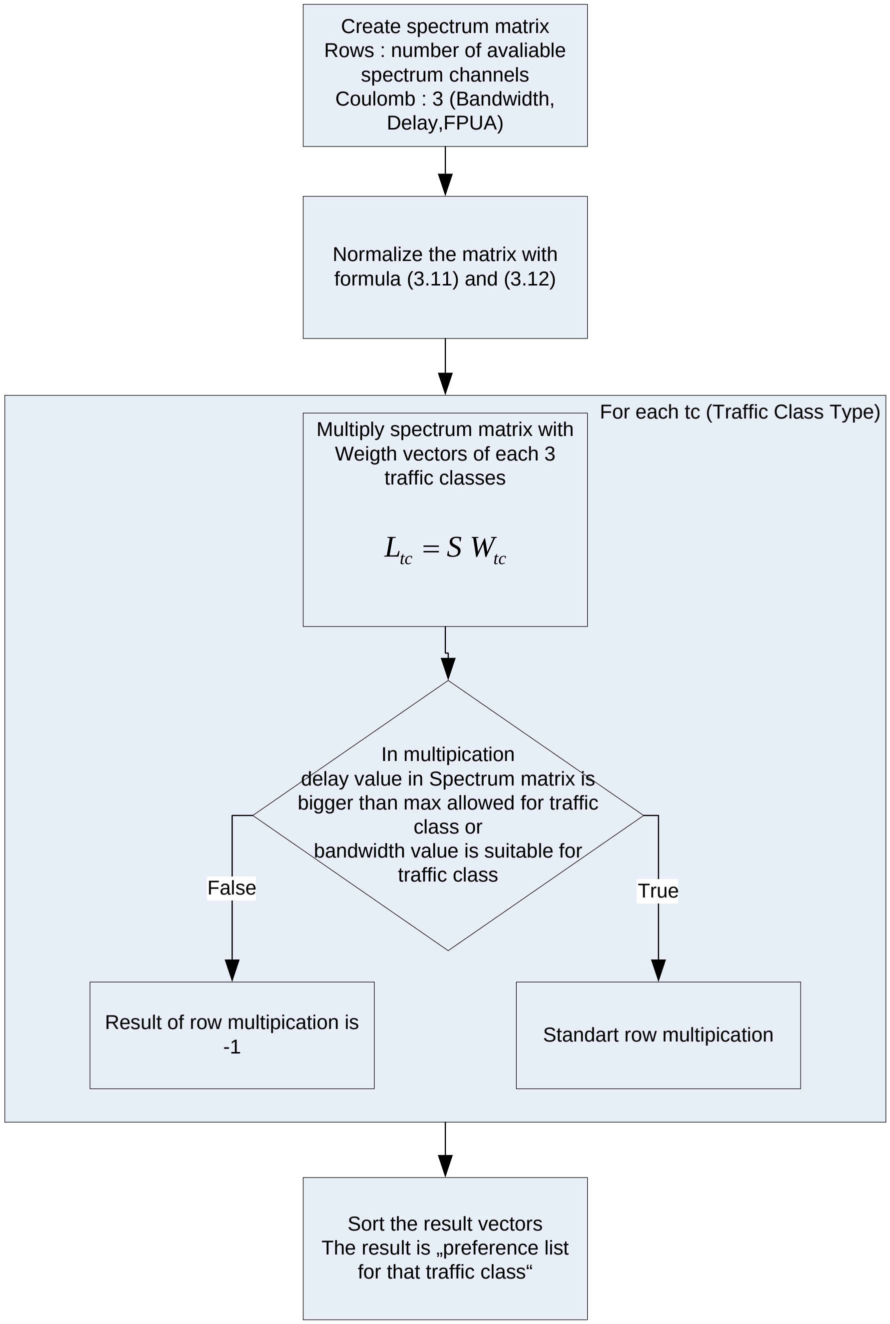

Figure 3.1 : Flowchart of preference list creation

4. USER REQUESTS with WAIT OPTION

4.1 Objectives

The main focus of this chapter is to explain the second contribution that we made with this work which is the wait option for some users. In this chapter, first the wait option will be introduced and detailed. Moreover, we will explain handling mechanism of the users with wait option.

4.2 Wait Option

For some users, the time to find a spectrum is a time critical process. Most of the users who make a request to SB are in the middle of existing communication. These users should get a spectrum to operate on as soon as possible.

On the other hand, some users can wait some amount of time until a convenient spectrum is assigned to them. Example users for that are the users which just initiate a new connection or background traffic users which do not need real time communication.

In this work we call the user which can wait for a spectrum channel, as user with wait option or patient user. This option is considered in the proposed algorithm as described in Figure 4.1.

Each request from a user to RSB has also wait parameter which shows the max amount of time related user can wait until getting a convenient spectrum. Instead of to be rejected or occupying a “better” spectrum than necessary, patient users get a proper channel and allow more users to be satisfied.

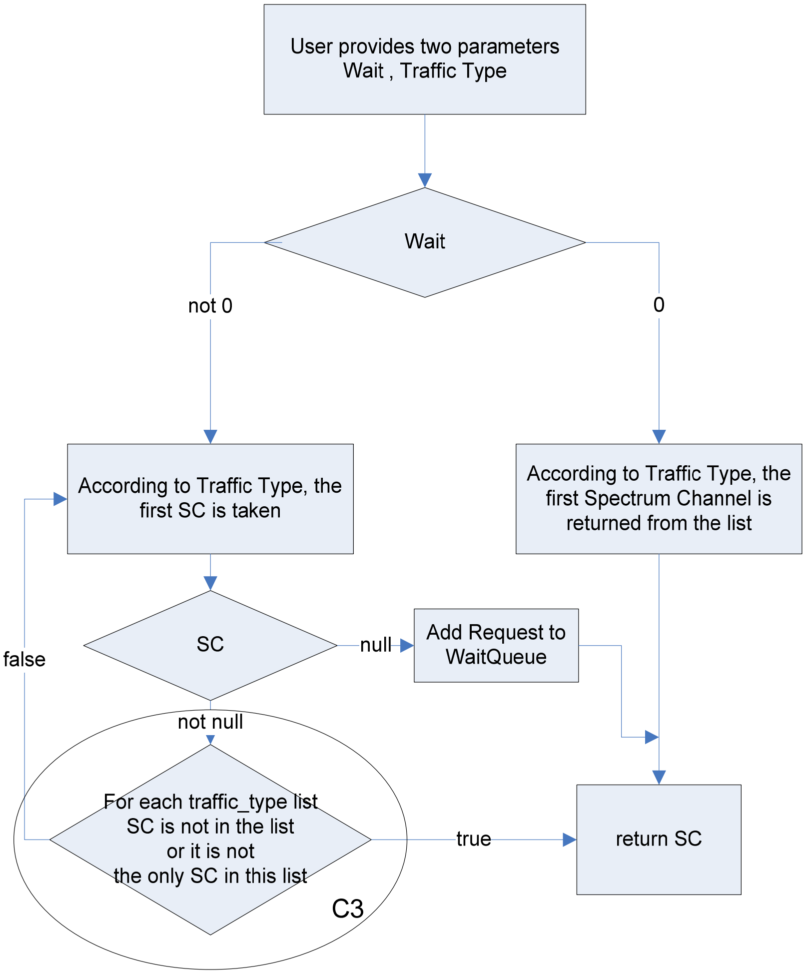

Figure 4.1 : Flowchart of spectrum selection among preference lists

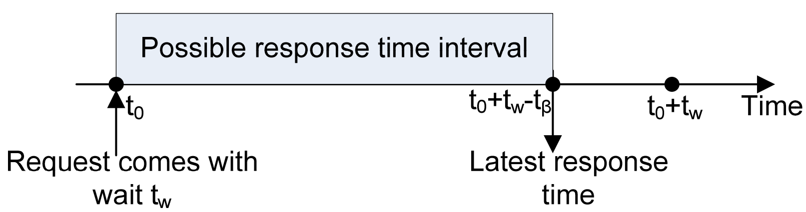

Figure 4.2 : Time-line for a request with wait option

In Figure 4.2, request with wait value t_w, comes to SB at given time t_0. This request should be answered in asynchronous at latest $t_0 + t_w - t_\beta$. Here t_β is amount of time required by system to inform user about the spectrum information.

At the time point $t_0 + t_w - t_\beta$, related user is handled as impatient user, as that user is not able to wait additional amount time.

There can be a convenient and available SC in this time interval, this spectrum has to satisfy control “C3”.

Here we should detail the C3 control in Figure 4.1. According to that control spectrum channel can be assigned to user if this channel does not exist in the preference list of a traffic class, which means this spectrum channel can not be used by other traffic class users anyway. For each preference list which includes this spectrum channel there exist at least one more spectrum channel.

The idea here is, to think other possible users who have no wait tolerance and to keep at least one reserved spectrum channel for those users.

5. SIMULATION & RESULTS

According to our design which is detailed in previous chapters, we propose a Spectrum Broker which consists of three modules. The first module is responsible to scan the environment, to collect statistical information, to update spectrum table, and update the preference lists if it is necessary. Module 2 is responsible to get requests from users and to assign them the best matching spectrum channel using the preference lists of each traffic class. The last module handles users which wait (patience) option.

During this work, a simulation program is implemented. These 3 modules are implemented to have a simulation running. As the aim of this work is not to deal with spectrum sensing, spectrum sensing related part of module 1 is not implemented. Environmental information is simulated by the class Tester which will be explained in the next chapter. User requests are also under the control of Tester. Primary user appearance in the spectrum is generated by the FPUA value of spectrum channel.

As the module 1 keeps the preference list of each traffic class updated and it is done for each spectrum allocation and reallocation, the request from users are answered faster than the other possible designs.

5.1 Implementation

Simulation code is implemented in Java using Object Oriented approach. In the next chapters you can find the class diagram of important classes.

5.1.1 Classes

5.1.1.1 Tester

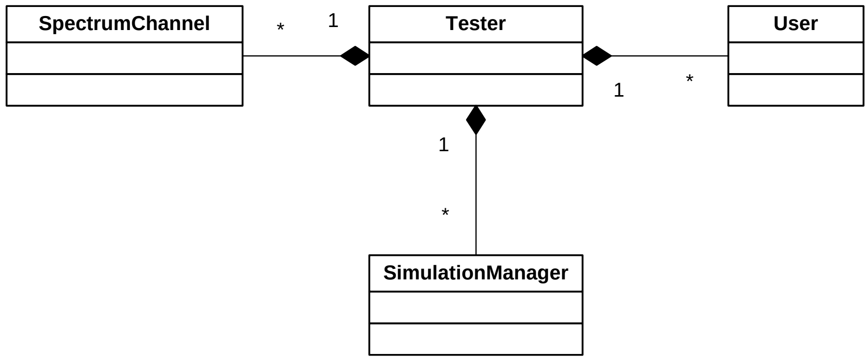

Figure 5.1 : Class diagram for Tester

Class Tester is responsible to create the test scenarios and write the results to a file. It has a SimulationManager instance which can be thought as a SB. Tester creates Users which make requests to SimulationManager. In addition to that, Tester created SpectrumChannel list and observes the usage of those channels.

5.1.1.2 SimulationManager

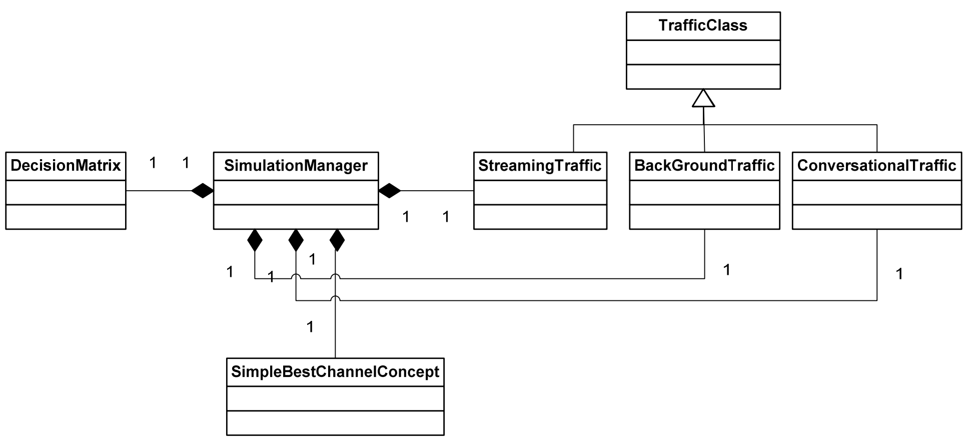

Figure 5.2 : Class diagram for SimulationManager

SimulationManager is responsible of creation preference list of spectrum channels for each traffic classes. Moreover the requests from users are handled in this class as well as the users which have wait option.

5.1.1.3 TrafficClass

TrafficClass is a abstract base class for concrete traffic classes such as StreamingTraffic, BackGroundTraffic and ConversationalTraffic. This class holds the weights values and the preference lists inside. If there is a new traffic class to add to system, new traffic class should be inherited from TrafficClass and related weight values should be added.

5.2 Theoretical Comparison of the New Desing and Basic Design

To compare with our algorithm, we built a system called basic design that also uses the utility function but without taking different traffic classes into consideration. In basic design utility function, weight values generated in AHP, user come and go procedures are the same. However, basic design does not consider the user type and does not include the patient option either.

In this part, we will make a comparison of new design which has no WO, with basic design. To do so, we try to explain the benefit gained from having different preference lists for each traffic class instead of one preference list for all types of users.

To have this comparison, we suppose at a given time there are 3 available spectrum channels as shown in Table 5.1. And also we suppose, there will be one request from each traffic type. We will compare the behaviours of two designs as the order of users' changes.

Table 5.1: Available spectrums for theoretical comparison

Traffic Class	Spectrum Characteristics		
	BANDWIDTH	FPUA	DELAY
Spectrum A	2048	50	70
Spectrum B	192	10	15
Spectrum C	128	5	25

When new design processes the available spectrums shown in Table 5.1 the preference lists of each traffic class is generated and results are in shown Table 5.2.

Table 5.2: Preference lists of traffic classes in theoretical comparison

Order	Preference List of		
	Streaming	Background	Conversational
1	Spectrum A	Spectrum C	Spectrum B
2	Spectrum C	Spectrum B	-
3	Spectrum B	Spectrum A	-

Basic design calculates its own preference list using available spectrums and the result is shown in Table 5.3.

Table 5.3: Preference list of basic design in theoretical comparison

Order	Basic Design
1	Spectrum B
2	Spectrum C
3	Spectrum A

According to these results, the behaviour of new model and basic model is the same when the order of users as following.

Table 5.4: User scenario results in the same behaviour for both of the systems

Coming Order	Spectrum given by	
	New Design	Basic Design
Conversational	Spectrum B	Spectrum B
Background	Spectrum C	Spectrum C
Streaming	Spectrum A	Spectrum A

Without the wait option, as we can see in the Table 5.4, new design and the basic design behaves exactly the same. That's the only case they behave the same.

However, with the user order scenario shown in the Table 5.5, behaviours of the systems are totally different from each other.

Table 5.5: Another possible user scenario

Coming Order	Spectrum given by	
	New Design	Basic Design
Streaming	Spectrum A	Spectrum B
Conversational	Spectrum B	Spectrum C
Background	Spectrum C	Spectrum A

When we examine the results, we see that :

- User which is type of conversational traffic could not communicate using the SpectrumC while the delay value is bigger than the max delay value allowed for conversational traffics.
- The other two users get successful convenient spectrum channels, however regarding the utilization of the system Background user get the highest band available while Streaming gets a spectrum with lower Bandwidth so total amount of the data transfer of the system is worsened with basic design.

5.3 Comparison the Proposed Algorithm with Basic Design

To have the results, Tester creates 20 tests. For each test, the procedure is:

- 50 users from random traffic classes are created randomly. Each traffic class has the same probability as we used uniform distribution in random value generation. The time difference between two users has mean value 4 seconds for this comparison.
- The system has six available spectrum channels with characteristics given in Table 5.6
- Each user makes a request for a Spectrum Channel to RSB in both new and basic design.
- Each user has wait values when it makes a request to new design. The wait value will be 0 or 5 seconds. Both have equal chance as here random generation is also uniformly distributed.
- Update the amount of total data transfer and average number of users profited by system for each technique

So in this part of test we will have the comparison of new model and basic model regarding both amount of total data transfer and number of users benefited from spectrums. Preference list of traffic classes are generated using the available spectrums shown in Table 5.6. These preference lists can be seen in the Table 5.7.

Table 5.6: Available Spectrum List Used in Tests

Traffic Class	Spectrum Characteristics		
	BANDWIDTH	FPUA	DELAY
Spectrum A	2048	20	100
Spectrum B	256	25	5
Spectrum C	11	5	40
Spectrum D	16	50	15
Spectrum E	1024	100	30
Spectrum F	128	90	40

Table 5.7: Preference lists for available spectrums

Background	**Streaming**	**Conversational**
Spectrum A	Spectrum E	Spectrum B
Spectrum C	Spectrum B	Spectrum D
Spectrum B	Spectrum F	-
Spectrum E	-	-
Spectrum D	-	-
Spectrum F	-	-

Simple design calculates its own preference list and this list can be seen in the Table 5.8. As we discussed before, basic design will just have one preference list for all user requests.

Table 5.8: Preference list of basic design

Order	Basic Design
1	Spectrum A
2	Spectrum C
3	Spectrum B
4	Spectrum E
5	Spectrum D
6	Spectrum F

When we examine results shown in Figure 5.3, we see that in every case the number of users profited by our new design is more than the basic design. The difference between two systems has the average value 6,81 and standart deviation 0,21. As we tested the system with 50 users, the gain in average %13,6.

Also the comparison between these two systems regarding the total amount of data transfered can be examined using Figure 5.4.

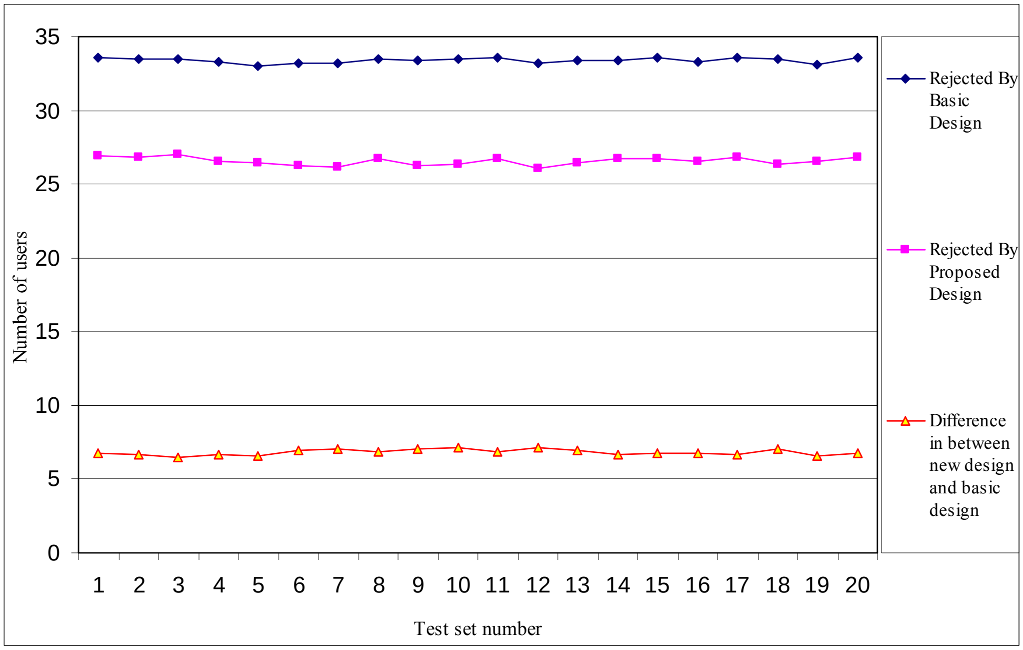

Figure 5.3 : Difference between the average number of users profited

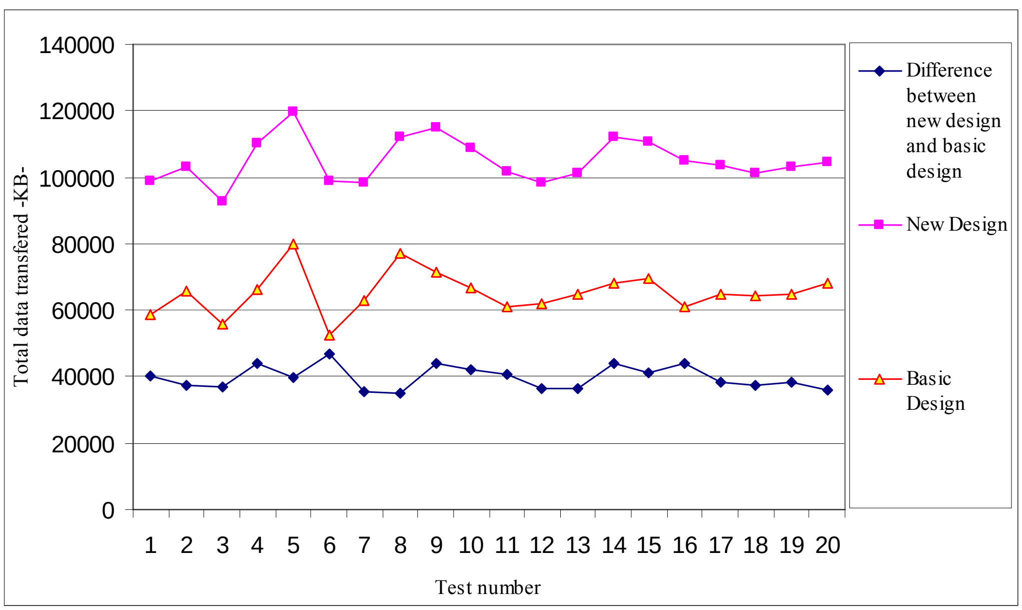

Figure 5.4 : Amount of total data transfer comparison

As it can be realized from the figures, new design provides increased number of profited users. Because we match the user needs and spectrum facts and then decide for spectrum accordingly. Knowing the user type helps us to find a more convenient spectrum channel as we know the requirements of user in Delay, Bandwidth and other parameters.

In addition to that, as it is shown in Figure 5.4, not only the number of users, which can get a useful spectrum to operate is increased, but also the amount of total data transfer in the system (utilization of spectrum bands) is advanced. According to Figure 5.3 and Figure 5.4, it is clear that management of spectrums is better when the algorithm takes the type of traffic into consideration.

5.3.1 Calculation of total data transfer

For calculation of amount of total data transfer, a simple technique is used. If a user gets a spectrum which it can operate on, regarding the parameter Delay, user utilize the spectrum as it needs. Users' needs in TH is different, however this needs are fixed in simulation for each traffic class to have a simple solution. For Conversation traffic class this value is 24 KB/sec, for Interactive this is 128 KB/sec and for Bandwidth it is the bandwidth of selected spectrum channel.

5.4 Comparison Between Models With and Without Wait Option

In the study, also the comparison between the new models with and without wait option are performed to have a clear understanding of the benefit gained from wait option.

According to Figure 5.5, the number of users profited by design considers the wait option is always greater than number of users profited by design which does not consider the wait option.

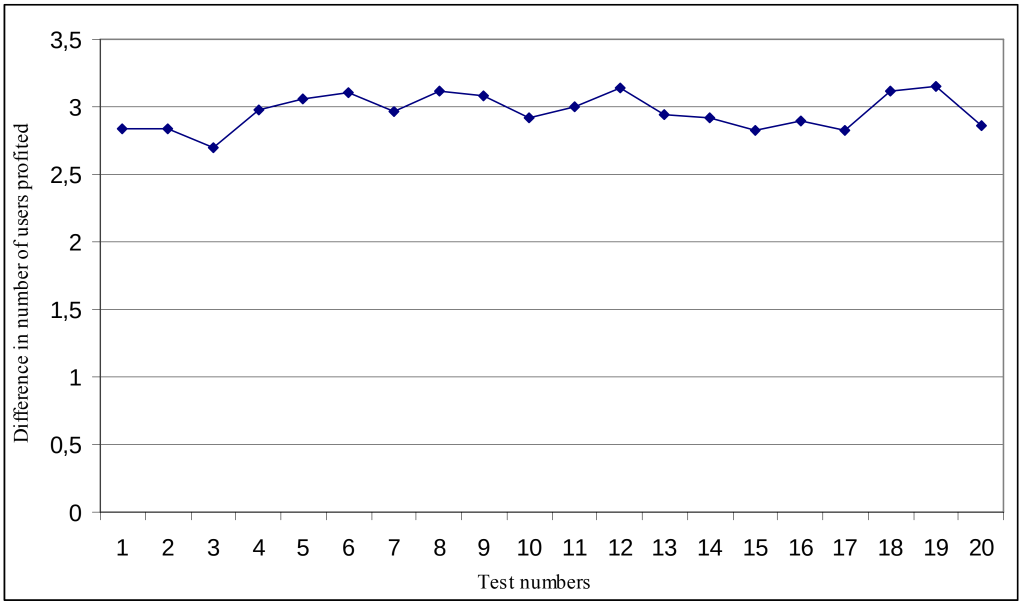

Figure 5.5 : Comparison between models with and without wait option

5.5 Stress Comparison Between New Model and Basic Model

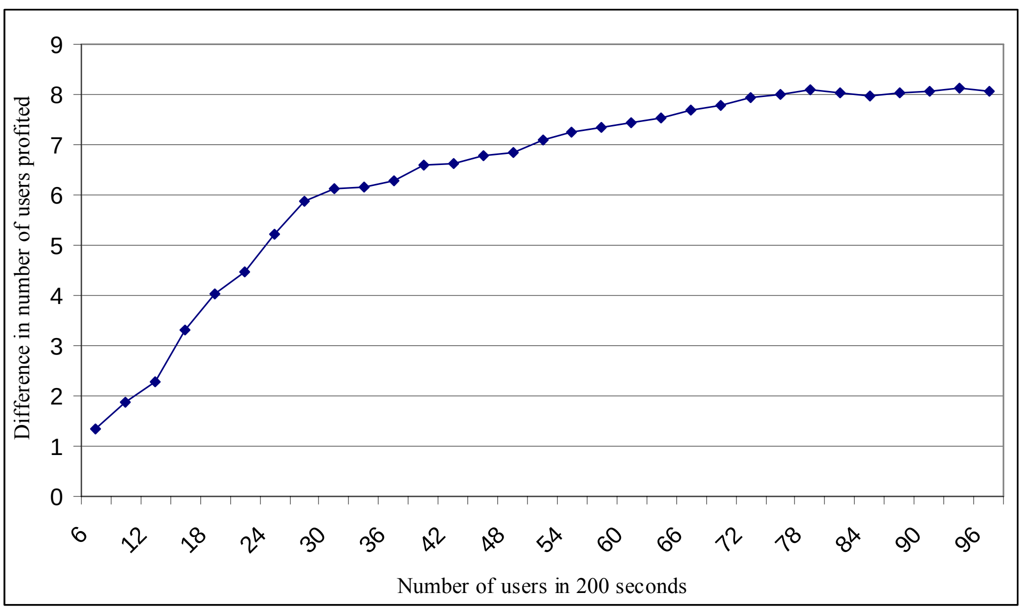

Figure 5.6 : Comparison for different number of requests in 200 sec

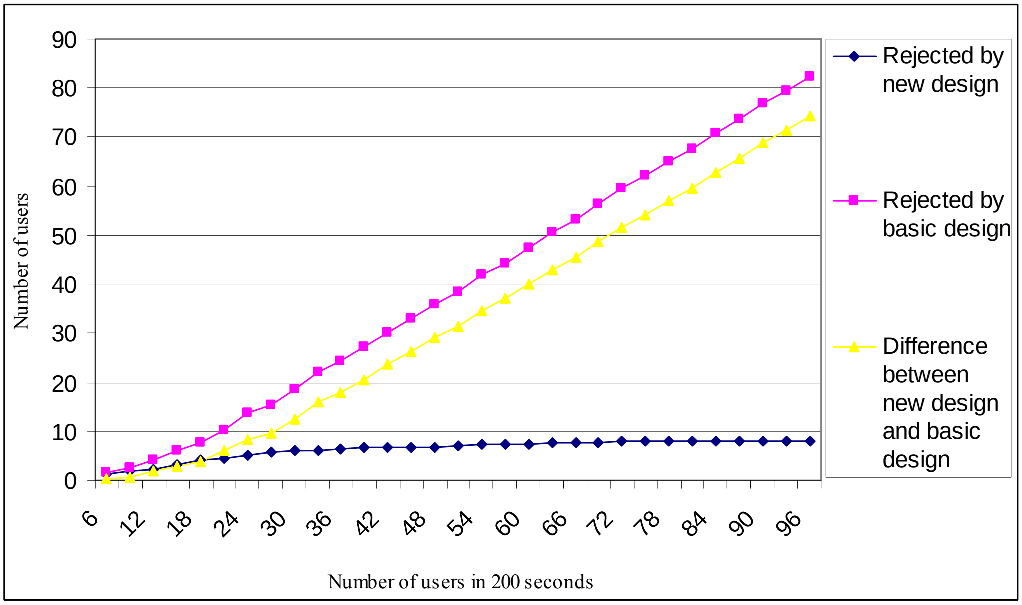

Figure 5.7 : Detailed comparison for different number of requests in 200 sec

In Figure 5.6, you can see the comparison for number of users profited between proposed new model with wait option and basic model. In these comparisons every traffic class has the same amount of users.

With the comparison shown in Figure 5.6, we see that as the number of users which are distributed in 200 seconds increases the difference between number of users profited increases. The difference value converges to a number as the number of users increases.

In Figure 5.8, Figure 5.9 and Figure 5.10 we can see the comparisons of difference in the number of users profited between new system and basic system, comparison of difference in the number of users profited between new system and new system without WO and the difference in TH between new system and basic system respectively.

Each test has 50 users which are distributed in 400 seconds. The reason to have these additional results is to have a comparison regarding the distribution time interval of users.

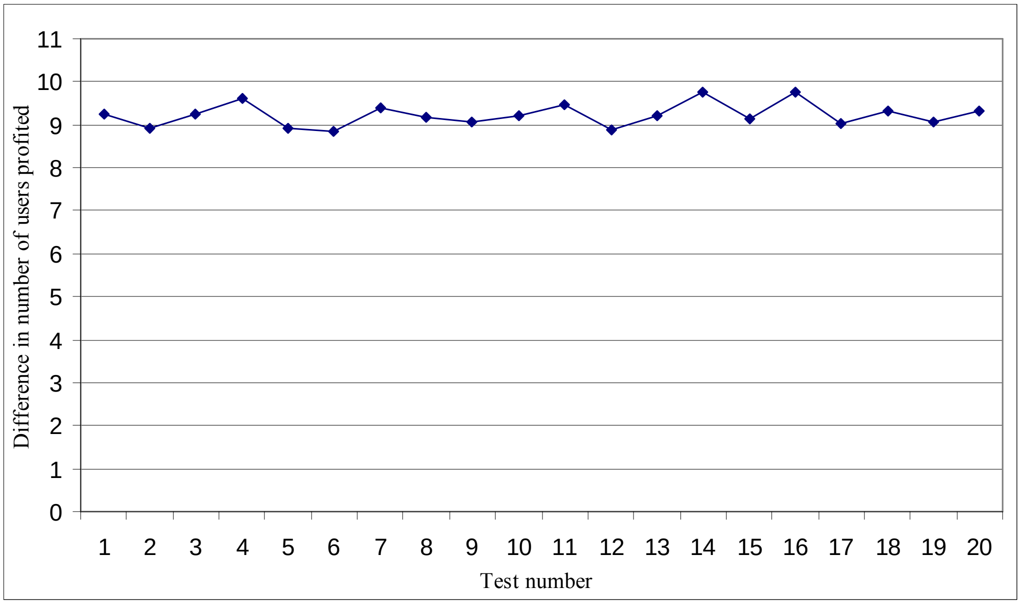

Figure 5.8 : Comparison between full-new system and basic system

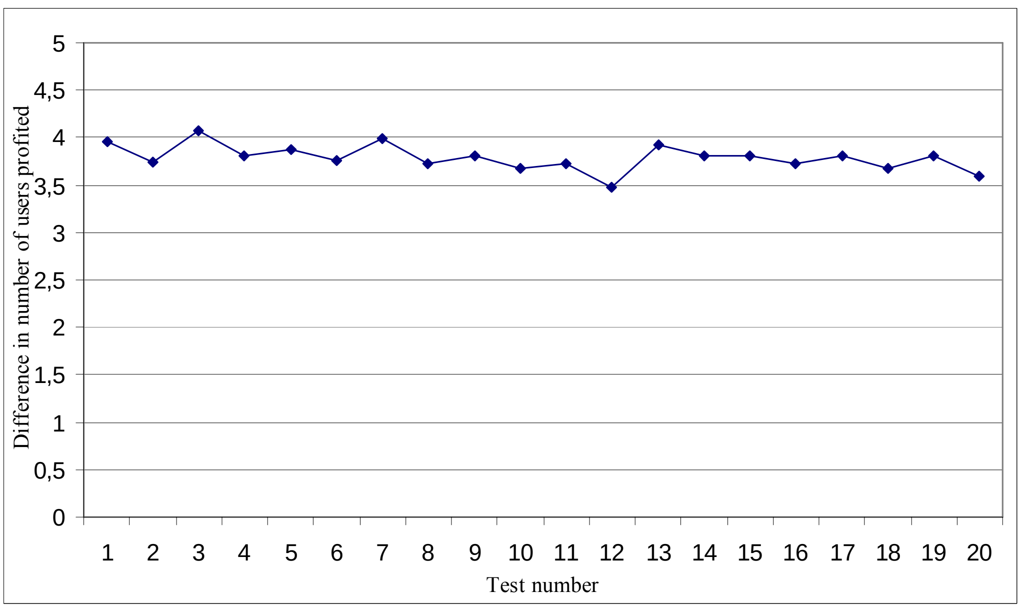

Figure 5.9 : Comparison between new designs with and without wait option

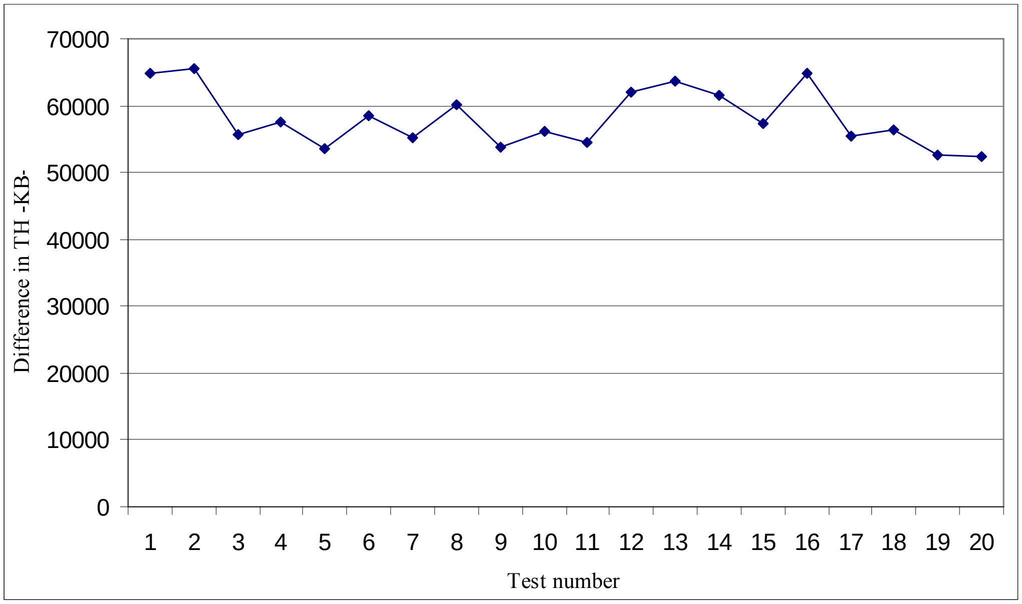

Figure 5.10 : Comparison regarding total data transfered

When the users are distributed in 200 seconds average value for the difference in the number of users profited between the proposed system and basic system is 6,81 while the same attribute has the value of 9,22 when the users are distributed in 400 seconds.

Table 5.9: Mean values of criteria regar,ding the user density in time

Criteria	User are distributed in	
	200 sec	400 sec
Number of users profitted (new vs basic)	6,81	9,22
Number of users profitted (new vs new without WO)	2,96	3,78
Difference in TH	39685	58090

As it can be seen in the figures, the results shows the same characteristics with the tests are made with 200 seconds. The values are higher than before as the change to get a spectrum is better and our system gains more chance to utilize the system.

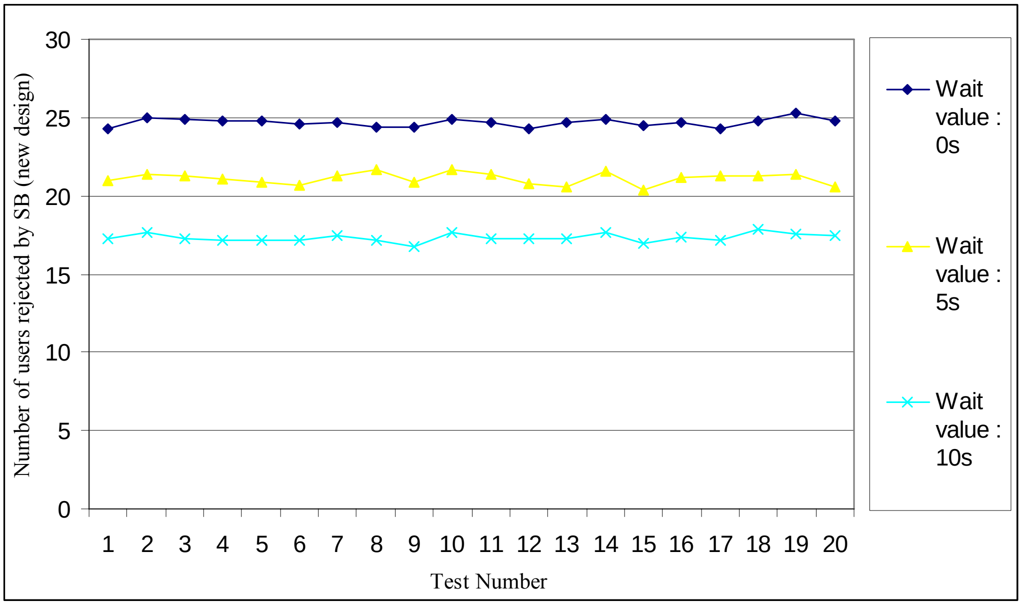

Figure 5.11 : Comparison of system behaviour with different wait values

In Figure 5.11, the result of comparison based on different wait values can be seen. In this scenario patient users and impatient users are uniformly distributed. So some users are the patient users and some of them are not. Both of them have equal chance.

For this test, 50 users from different traffic classes are created and if they are patient users, they make the same request with wait values 0, 5, and 10 seconds.

When patient users have the wait value 0 seconds, means there is no patient users in the system. So the result is the same with the new design which does not take the wait value into consideration.

The result shows that number of profited users increases as the wait value increases.

6. CONCLUSION & FUTURE WORK

In this paper, a decision algorithm is proposed for Spectrum Brokers which are used as a centralized entity in CR networks. The idea is to select a proper spectrum regarding the needs and type of related user. This brings the advantage of fair spectrum management which matches the user requirements and spectrum characteristics at most.

In addition, we extended our design for the users who have patience tolerance. Instead of to be rejected or occupying a "better" spectrum than necessary, patient users get a proper channel and allow more users to be satisfied. With that, not only users with wait option but also the users without tolerance have higher chance to get a better spectrum.

The results which have been generated by the simulation implemented for this work show that both contributions have positive effects on both spectrum utilization and number of users which have been satisfied by system.

In the future works, the decision mechanism used in this work -utility function- can be altered to another decision technique. Moreover the parameters which are used to identify spectrum channels can be extended. In addition, patient users can be grouped and handled in this way to have a more intelligent decision algorithm.

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