FLEXIBLE SPECTRUM ALLOCATION FOR NEXT GENERATION DISTRIBUTED WIRELESS NETWORKS

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ABSTRACT:

The changes in network services, technology and in the regulation have led a new era for the innovation of the network with the birth of the Next Generation (NextG).

Also NextG is afflicted by the problem of growing demand for the spectrum, but it is possible a more efficient use of the spectrum thanks to more bands and technologies.

The current model of distribution of the spectrum assigns the rights of the spectrum in frequency bands allocated to certain categories of services with the aim of avoiding interference. In this regard, two main sharing concepts are introduced: **Underlay Approach** (UWB)**, Overlay Approach** (Cognitive Radio).

Using a CR is possible to observe the spectrum, to find which frequencies are free and then to implement the best communication shape and to check that the interference is maintained at the minimum.

The target of this work is to equalize the total distribution of the allocated radio spectrum resources among more interfering devices that work in the same geographical area.
One of the intelligent principles, considered to the use of spectrum in addition to the FSU Algorithm based on SINR and Interference Threshold Approach, is the Spectrum Load Balancing, which is derived from the idea of water-filling. The goal is support the distributed QoS and in this manner will make an improvement in the spectrum efficiency.

Contents

Chapter 1

Introduction

1.1 General Framework

The changes in network services, technology and in the regulation have led to a new era for the innovation of the network with the birth of the Next Generation (NextG) [1.].

There isn't a formal definition of NextG, but its purpose is to improve the convergence of wireless communications and wireless access. The NextG is based on two key concepts, the first is the old 3G system and is its evolution, the second involves new approaches to wireless mobile and the wide band ([2.]). Its main target is ubiquitous wireless communications systems and seamless high-quality wireless services and it includes the concepts and technologies for the innovations in the architectures, in the spectrum allocations and utilizations, in the radio communications, in the networks, services and application.

Different forces had led to change the wireless infrastructure, like:

- The deregulation and competitive climate;
- The increasing customer demand for telecommunication services, indeed the increase in traffic has a significant impact on the network with to QoS (Quality of Services) parameters that the customers exepct for the services they subscribe to;

- The downward pressure on the costs.

Result of all these factors has been the adaptation by the side of the vendors of wireless systems of their offer to meet the demand of users and providers of services.

Since the spectrum is a scarce resource also NextG is afflicted by the problem of growing demand for the spectrum, but it is however possible a more efficient use of the spectrum thanks to more bands and technologies.

The spectrum that it not used in efficient manner at any frequency, geographical area and time is wasted (Spectrum Holes, Figure 1); the new technologies suffer this aspect because they are often restricted to use the high frequencies with consequent limited propagation and higher deployment costs for the coverage.

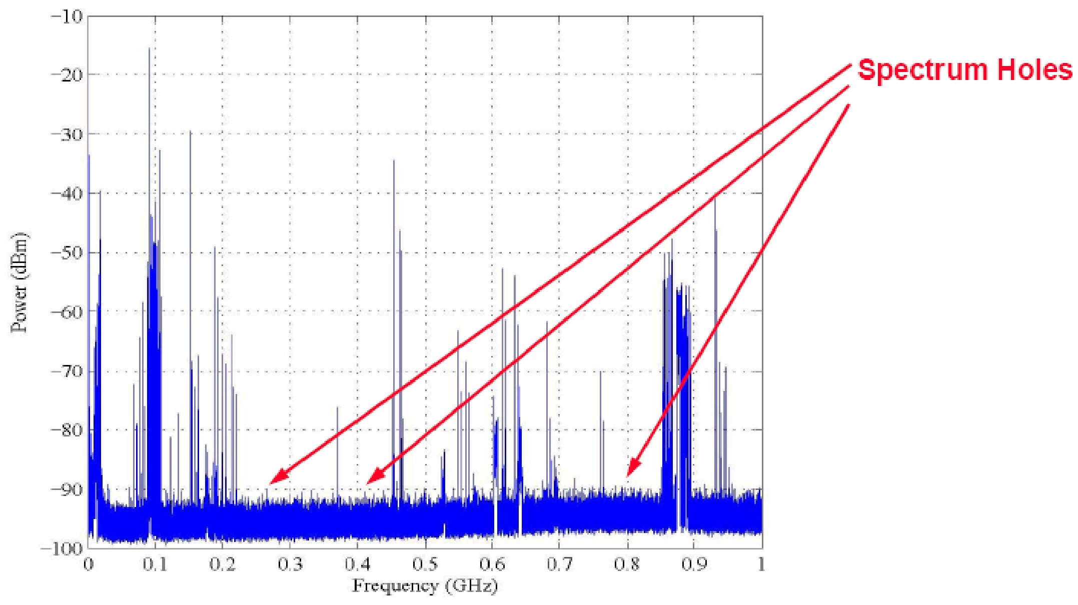


Figure 1 Spectrum utilization

The current model of distribution of the spectrum assigns the rights of the spectrum in frequency bands allocated to certain categories of services with the aim of avoiding interference ([3.][4.]).

Thanks to the introduction of Cognitive Radio (CRs) ([4.]), it is becoming possible to obtain a more efficient use of the spectrum. CR-enabled devices can be described by four adjectives: agile, smart, software-defined, intelligent. The CRs adapt their transmissions, observing the spectrum sensing where it is used and choosing to transmit respecting a set of rules to ensure a specific QoS ([5.]). Hence CR can be defined intelligent, because they know the environment in which they are operating and they use learning techniques to learn from the environment and to adapt to changes with the following aims ([6.]):

- Highly reliable communication where and when needed (ubiquitous);
- Efficient utilization of the spectrum.

It is thus possible to use and share the spectrum in efficient manner and with the dynamic access techniques it is possible to work on the best available channel.

These techniques are ([7.]):

- **Spectrum Sensing**: Determinate the available spectrum portion;
- **Spectrum Management**: Select the best available channel;
- **Spectrum Mobility**: Coordinate access to the channel when a licensed user is detected.

1.2 Thesis Motivation

The wireless networks are characterized by policies of the spectrum assignment that are fixed and by a significant amount of the spectrum used sporadically, as it are concentrated only in certain parts while in others it is unused. The increasing demand in access to the limited spectrum, the limited availability of the spectrum and the inefficiency of spectrum use lead to the need of a new paradigm of communication to exploit the spectrum in an appropriate manner.

Generally the operators of the cellular mobile networks have to obtain the resource of the dedicated spectrum from the national telecommunication regulators, and this resource is utilized independently by each operator without interference coordination, but with drawback that the dedicated spectrum allocation is reduced, the spectrum efficiency is trunked and the peak data-rate is reduced due to restricted bandwidth of each operator.

The spectrum sharing is considered important from the point of view of the effective use of available resources, while it is requested a high traffic demand and QoS. The Spectrum Sharing techniques are required to provide a high system gain especially in the indoor Local Area (LA) scenario where the coverage area is small and the mobility of users is low. When more networks are placed in the same geographical area and use the same radio spectrum, the interference is major. In the LA environment the installation of Home Node B (HeNB) can or cannot be decided by the operators and among the operators there is not cooperation hence the problem of the interference becomes important and one solution, with the aim to mitigate the interference, has to be found. Another aspect that characterized the LA is the variability of the traffic load among the HeNBs operating in the same geographical area and the same radio spectrum, and this is due to under-utilized time and/or frequency resources by a given HeNB.

This kind of scenario is considered in this work, hence it is needed to find a Flexible Spectrum Usage (FSU) mechanism, implemented in each HeNB, to balance the resource use among the HeNBs and to help to mitigate the problem of intra-system interference. A peaceful coexistence among two or more HeNBs can be obtained through:

- Time separation: the transmission is done in different time;
- Frequency separation: the transmission happens in different frequencies;

- Space separation: the path loss among the transmit antennas of one system to the receive antennas is sufficiently high to attenuate the interfering signal.

Hence the target of this work is to equalize the total distribution of the allocated radio spectrum resources among more interfering devices that work in the same geographical area.
One of the intelligent principles considered for the use of spectrum is the Spectrum Load Balancing that is derived from the idea of water-filling.
The goal is support the distributed QoS in the scenarios in which coexisting radios are present and in this manner one will make an improvement in the spectrum efficiency.

1.3 Thesis Outline

The structure of the thesis is the following:

- Introduction, where an overview of the actual state of the art of the spectrum is provided and one motivates the thesis;
- Back ground Theory, where the description of the spectrum management, the spectrum sharing, cognitive radio can be found;
- Description of the Project, in which there is the description of the scenario considered and of an algorithm thought for a fair spectrum sharing;
- Numerical Results, in which there is the description of the simulator used and the comments to the results obtained from the simulations;
- Conclusion, in which conclusions on the work are drawn and some possible future investigations are out-lighted.

Chapter 2

Background Theory

2.1 Radio Spectrum Management

In several years, the number of new uses and users of the radio spectrum is increased, but not all of it is equally usable, as some parts are good for some purposes and others are technically preferable for other purposes ([8.]).

However, a good part of higher frequencies must still be found economically useful for some applications. As a result many of the parts used tend to be seriously loaded especially in densely populated areas.

This condition without an efficient spectrum management leads to interference among the systems and reduce the total capacity of the medium.

2.1.1 National Spectrum Management

The governments are responsible of the radio spectrum management but this responsibility is important also world-wide ([8.]). If a country is a member of International Telecommunication Union (ITU) its government assures that the radio station in its jurisdiction do not cause harmful interference to the radio stations in the other countries that operate according to the international agreements. Nationwide there are different units, and each is responsible for the radio frequencies use and their work will be coordinated nationally, creating an Administration, which will manage the spectrum in the following manner:

- The radio spectrum is divided in frequency bands, that are allocated for each radio service. A table of frequencies is created and that has to be harmonized with the international table in accordance with ITU.
- Transmission of radio signal is conditioned on the release of license by the Administration. The authorization to use the spectrum for an authorized purpose can take different forms, that depend by the done use.
- The Administration checks the spectrum to detect and stop the use without license and assure the licensed use. But if a licensed user does not use the allocated frequency, denying the use to other users, the license can be withdrawn.

2.1.2 International collaboration

There is an international uniformity in the spectrum allocation to services. Radio links that are common among two different countries should be assigned frequencies that are allocated in frequency bands that are presented in both countries, hence the radio emissions used for systems that are totally within one country cannot cross frontiers.

Some frequency bands are used only world-wide or regionally by a single group of users that work under control of an international body. The choice of the frequencies within these bands for specific stations is devolved by the Administration to the international bodies, even if they themselves allocate the frequencies.

Generally the Administration cooperates with the other closest Administrations, in informal bi-lateral manner, to resolve possible problems of interference. The multi-lateral collaboration among the countries in an region can resolve broader problems.

The forum for the global collaboration in the radio spectrum usage is the ITU and through the ITU the Administrations consult the other global organizations (i.e. ICAO, IMO etc.).

2.1.3 Frequency Allocation

2.1.3.1 Frequencies Range

The used radio spectrum by the radio system extends from about 10 kHz to about 80 GHz and each year there is an extension toward higher frequencies ([8.]).

The international table of the frequencies allocation divides this range in precise frequency bands (Figure 2).

Frequency Band	Band Number	Symbol
3-30 kHz	4	VLF-Very Low Frequency
30-300 kHz	5	LF- Low Frequency
300-3000 kHz	6	MF- Medium Frequency
3-30 MHz	7	HF- High Frequency
30-300 MHz	8	VHF- Very High Frequency
300-3000 MHz	9	UHF- Ultra High Frequency
3-30 GHz	10	SHF- Super High Frequency
30-300 GHz	11	EHF- Extremely High Frequency

Figure 2 Designations of frequency ranges

The international table of frequency allocations is characterized by the division of the spectrum in frequency bands, wide or narrow, that are used for specific radio services.

The main characteristics of this table are:

- Radio services for which the bands are allocated;
- Some allocations are world-wide but for some frequency bands there are regional differences in the allocations;
- Most frequency bands are allocated for more services and are called “shared”;
- Most allocations are qualified by footnotes.

2.1.3.2 Radio Services

The existing radio services are almost 35 and are divided in different groups ([8.]):

- **Fixed Services (FS)** that are radio stations placed in specified terrestrial locations and the radio link between them. The Fixed Satellite Services (FSS) provide satellite link between stations at specified terrestrial location and include also the satellite feeder links between other services (i.e. mobile-satellite, broadcast-satellite);
- **Broadcasting Services (BS)** that include the terrestrial transmitters and their emission for direct reception by general public. The Broadcasting Satellite Services (BSS) are the corresponding transmission from satellites and also they provide the emission too for distribution for general public reception;
- **Mobile Services (MS)** that include mobile radio stations (i.e. on land vehicles, aircraft, ships etc.), stations at fixed terrestrial location that communicate directly whit them, and the radio links used for this purpose.

These services include also Mobile Satellite Service (MSS) links, Aeronautical Mobile Service (AMS) and Land Mobile Services (LMS);

- **Amateur Service (AmS) & Amateur-satellite Service (AmSS)**, for these services the spectrum is allocated for the use of authorized radio amateurs for self –training and technical investigations;
- **Technical and Scientific Services**, use radio in the course of space exploration, surveying the Earth and for similar activities (i.e. Space Research Service (SR), Earth Exploration-satellite Service (EES) etc.).

2.1.3.3 The ITU Regions

Often the allocation in a specified frequency for some services can be important for one country or for few countries and hence it cannot coincide with the agreements about the uniform world-wide allocations ([8.]). For this reason the world is divided in three regions (Figure 3), with the aim to manage the global spectrum and each region has its own set of frequency allocations ([11.]).

Figure 3 The three Regions defined by the ITU for frequency allocation purposes ([12.])

2.1.3.4 Frequency band sharing

When the same bands that are allocated for different services one talks about “Frequency band sharing” ([8.]). This sharing can give flexibility to the national usage of the spectrum but also puts some restrictions and potentially calls for the need of mandatory frequency coordination procedures. The restrictions are the limitations on the system parameters with the aim to reduce the interference. The mandatory frequency coordination is a procedure that includes a computation of prospective interference level by the Administrations before a radio station starts to use new frequencies, to assure that the interference will not be high. The international agreement for band shared among different services is not always possible. Therefore there are two kinds of allocations: primary and secondary. The emission from a secondary radio station can cause a harmful interference at receiving station in another country of a service with primary allocation.

2.1.4 Radio Spectrum Regulation

The radio spectrum regulations allow an efficient and reliable spectrum use, in fact the regulators determine how much of the band can be used, the available rights of the licensed users and of unlicensed users and define the spectrum access rules, that have the purpose to improve the public welfare and resolve the problem of underutilized spectrum.

The possible way to use the spectrum is the following [[18.]]:

- *Licensed Spectrum* for exclusive use (UMTS);
- *Licensed Spectrum* for shared use (DECT,PCS);
- *Unlicensed Spectrum* (U-NII);
- *Open Spectrum*.

The targets are ([16.]):

- A suitable QoS;
- No radio must be prevented from spectrum access and transmission for long time;
- Availability and efficient use of the spectrum;
- An adaptive use of the spectrum;
- The costs of the devices should be not increased.

2.1.4.1 Licensed Spectrum

The greater part of the radio spectrum is allotted to the licensed radio services (quasi-private property), for this reason the radio spectrum access and the spectrum sharing of the licensed spectrum are done by the regulated devices.

When there is an exclusive use of the radio spectrum, the licenses owners pay a tax to obtain this prerogative, wherefore in this manner the harmful inference can be avoided.

The licensed spectrum involves an inefficient spectrum use, due to inflexibility of the exclusive use, for instance it prohibits the radio spectrum use if this is under-utilized or unused by license holder.

Another problem is the licenses duration, in fact the regulators can intervene if the spectrum is under-utilized or wasted and they can extend or re-distribute the licenses and improve the introduction of new technologies, but the uncertainty of the future rules can prevent future investments ([18.]).

2.1.4.2 Unlicensed Spectrum

The access to the unlicensed spectrum is free, but regulated. Different users can share the same spectrum, but they must respect certain technical rules or standard with the aim to mitigate the interference.

Since different technologies can use the same radio spectrum, this spectrum can be overused and for this reason it is less usable for all.
The regulator wants to avoid that and impose limits (i.e. transmission power), but in this manner the spectrum will tend to be under-utilized, because it will not be used by all devices.

2.1.4.3 Open Spectrum

The open spectrum paradigm allows to access in any spectrum portion without license but under the constraint of fulfilling a minimum set of rules for the spectrum sharing ([18.]). The target is the liberalization of the radio communication with the aim to overcome the block in accessing the spectrum.
Hence the technologies and the standards that are supposed to work according to the spectrum sharing paradigm should be able to manage dynamically the spectrum access and the spectrum sharing ([13.]).

2.2 Spectrum Sharing

2.2.1 Spectrum Sharing and FSU

From what has been said, it is clear that due to growing demand for wireless connection and crowding of unlicensed spectrum, there is a need to define new ways to use spectrum ([17.]).
Hence, to obtain an unlicensed spectrum use for secondary users under specific requirements with the aim to limit the interference to pre-existing primary users, the new sharing concepts are introduced, as sensing and adaptation to the environment.
Two approaches are identified:

- **Underlay Approach**, that imposes strict restrictions on transmitted power levels with a requirement to operate over “ultra” wide bandwidths (UWB) and allows to use in simultaneous an uncoordinated manner the radio spectrum in the time and frequency domain.

- **Overlay Approach**, that avoids higher priority users through the spectrum sensing and adaptive allocation (Cognitive Radios, CR).

Both these approaches are a major shift from the approach in which once assigned the frequency band, no interference is allowed to the primary user, even if the total avoidance of interference is not possible.

In the Underlay Approach the transmissions are allowed in previously used bands with a low power level so that the interference is not harmful. In the Overlay Approach the spectrum is left free in fast manner to yield allowable interference. Figure 4 illustrate the transmitter power spectrum density profile in underlay and overlay spectrum sharing approach.

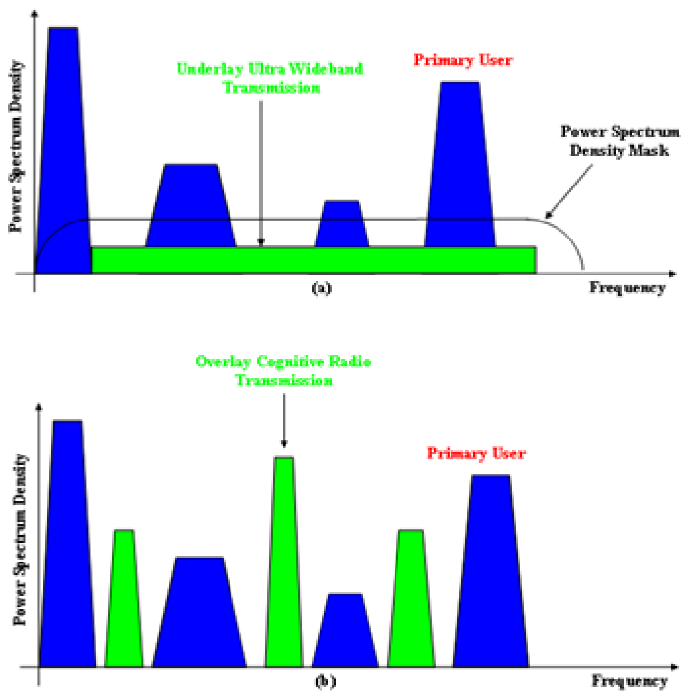


Figure 4 (a) Underlay and (b) Overlay Approach for sharing spectrum with primary users

The Spectrum Sharing implies improvements in the frequency agility and in dynamic range with the aim to accommodate the in-band primary users and new functions that include high sensitivity sensing and protocols that can use the sensing information to minimize the interference are required.

The Cognitive Radio must share the spectrum with unlicensed system and with licensed system. The first case is named *Horizontal Sharing* and the second *Vertical Sharing*. Both require identifying the spectrum in suitable way (Figure 5).

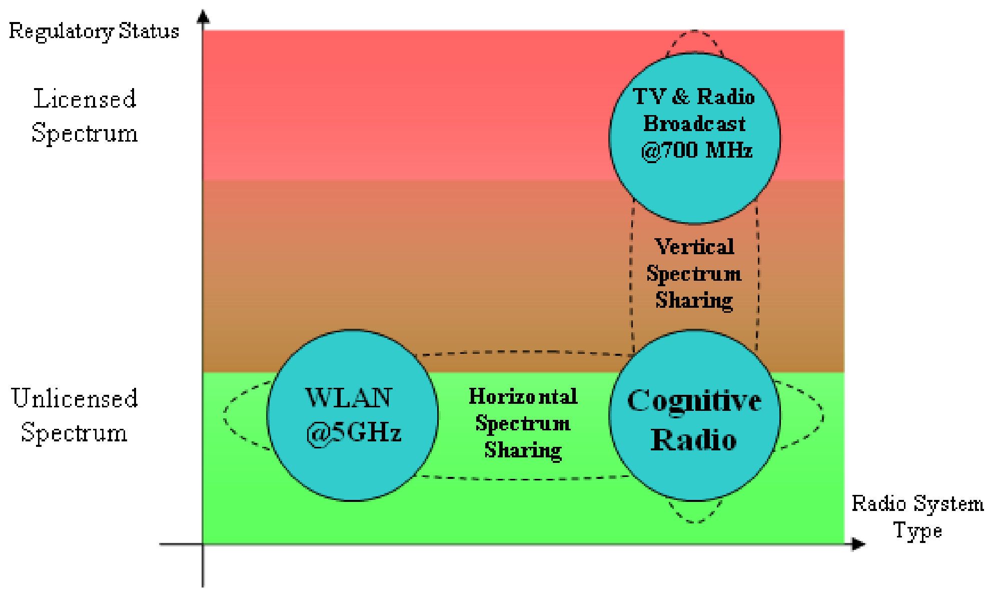


Figure 5 Cognitive radios share spectrum with different radio system

In the Vertical Scenarios, the Cognitive Radios are able to work without interference in used licensed spectrum and the licensed systems help the cognitive radios to identify the spectrum opportunities (Figure 6).

In the Horizontal Scenarios, the Cognitive Radios identify the opportunities and coordinate the use with the other Cognitive Radios in distributed manner (Figure 6).

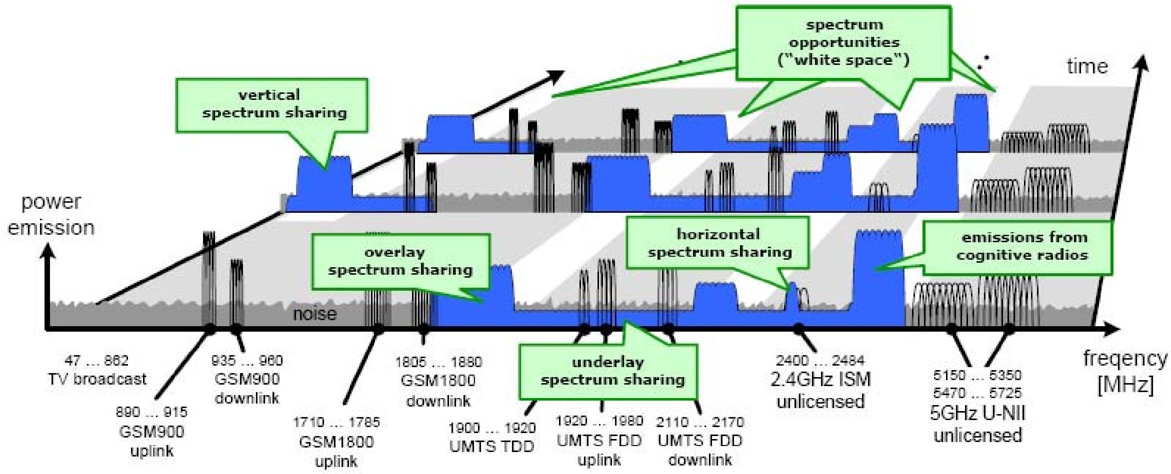


Figure 6 Underlay and Overlay Spectrum Sharing of Cognitive Radio ([18.])

2.3 SDR and Cognitive Radio

An "Agile Radio" is a Software Defined Radio (SDR) that can change the frequency use, the power and the modulation without changing its hardware. For this reason it is defined agile, since it can move around the spectrum ([5.]).

It is characterized from ([22.]):

- Interoperability;
- Transmission of multimedia flows;
- Good Quality of Service;
- Low power consumption;
- Flexibility.

The main characteristics are the re-configurability and the multi-standard operations. The re-configurability allows to extend the devices capacity without change. In this manner the following targets are reached:

- Adaptation of the radio interface to the communication environments and radio interface standards;
- The integration of new applications and services;
- Software updates and over the air download;
- Exploitation of flexible heterogeneous services provided by the radio network.

The SDR is the basic block for the new communication network and for the creation of the Cognitive Radio (CR).

The idea of CR like an aggressive solution to increase the spectrum use was born in 2002 ([17.]).

A CR is a radio, which coexists with higher priority primary users and senses their presence, modifying the characteristic of its own transmission so that there is not an harmful interference. An example of scenario where CR can be applied is the case in which the licensed primary users can use a specific frequency band and cannot be modified to allow an opportunistic spectrum use by CR. To avoid the interference to these users the CR have to protect specific geographical areas in which are present the primary receivers that should not be degraded by CR operation. The CR have to detect the white spaces with the aim to indentify the frequency bands currently available for the transmission and they have to adapt the transmission power so that the interference margin to any active primary user is not exceeded. The CR will operate in a large spectrum group (until about several GHz) in which different kinds of primary users are present with the aim to exploit the spectrum and to obtain high throughput applications. This group can be further divided in sub-channels with sufficient resolution for sensing and channel assignment coordination.

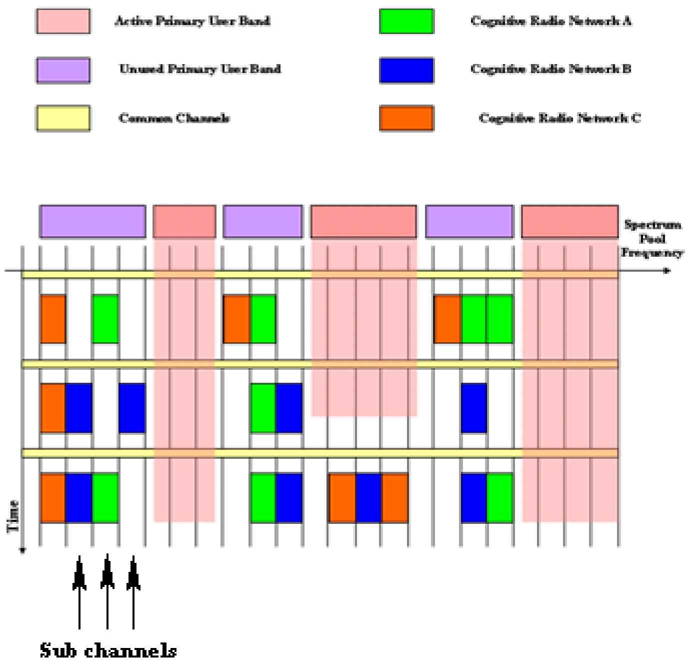


Figure 7 A time-frequency spectrum usage pattern when cognitive users share bands with primary users

Figure 7 is an example of temporal use of frequency bands where three active primary users are present in a specified location. Unoccupied primary user bands are shared by three cognitive networks (A, B, C) that are simultaneously sensing and competing for the available spectrum within the same spectrum group. The cooperation among these networks is required to perform reliable sensing and coordinated communication. The CR need dedicated channels for the exchange of control and sensing information, for this purpose there are two kinds of control channel available, namely Universal Control Channel (UCC) and Group Control Channels (GCCs).

Hence the CR is *self-aware* because it knows the surrounding environment and is able to communicate with the other devices and to exchange its own knowledge this property allows coordinating the spectrum use, when this is under-utilized. The CR is based on the *Cognition Cycle* (Figure 8). The CR observes the environment, understands, creates the plans, decides about its actions and finally acts.

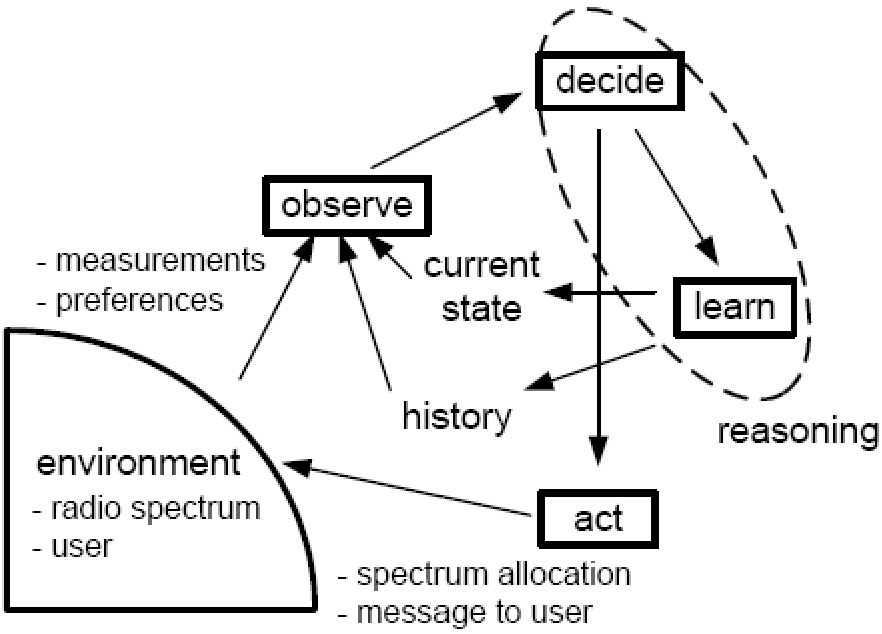


Figure 8 Cognition Cycle ([18.])

The knowledge of environment can be heavy from computational point of view, therefore the CR is characterized by:

- *sleep period*, during which the radio is not used, but has processing power that starts the learning algorithms;
- *wake period*, if in this period a stimuli is received the Cognition Cycle starts;
- *Decision phase*, during which a plane is selected;
- *Acting phase*, which starts the selected processes.

The other characteristics are the following ([18.]):

- *Frequency Agility*: the radio changes the operating frequency to optimize its use, adapting of the environment;
- *Dynamic Frequency Selection* (DFS): the radio listens to the signal from near devices to choose the optimal operative environment;
- *Transmit Power Control* (TCP): the transmission power is adapted to power bounds when it is necessary and to allow larger sharing of the spectrum;
- *Location Awareness*: the radio determines its own location and the location of the other devices, which are working in the same spectrum, to optimize the transmission parameters in order to improve the spectrum re-use;
- *Negotiate Use*: the CR can use algorithms to share the spectrum in terms of agreements among licensed parts and third parts or on ad-hoc/real-time basis.

According to these characteristic, the WLAN can be seen like a CR: the IEEE 802.11 devices use a listen-before-talk access, dynamically change the frequencies using DFS and adapt the transmission power using TCP.

The definition of the Cognitive Radio from Haykin is the following:

"*Cognitive Radio is an intelligent wireless communication system that is aware of its surroundings environment (i.e, outside world), and uses the methodology of understanding-by-building to learn from the environment and adapt its internal states to statistical variations in the incoming radio frequency stimuli by making corresponding changes in certain operating parameters (e.g. transmit power; carrier-frequency and modulation strategy) in real time, with two primary objectives in mind: (i) highly reliable communication whenever and wherever needed and (ii) efficient utilization of the radio spectrum.* " ([18.])

Hence using an intelligent radio is possible to observe the spectrum, to find which frequencies are free and then to implement the best communication shape, in this way the CR selects the frequency band, the modulation and the power levels that are most suitable to the condition and application, while guaranteeing that the interference is maintained at the minimum possible and allowed.

The CR is also used in environment in which there is the inter-network spectrum sharing, with the aim to provide opportunistic access to the licensed spectrum using unlicensed users ([1.]). In this kind of scenario the systems can deploy in overlapping locations and spectrum (Figure 9).

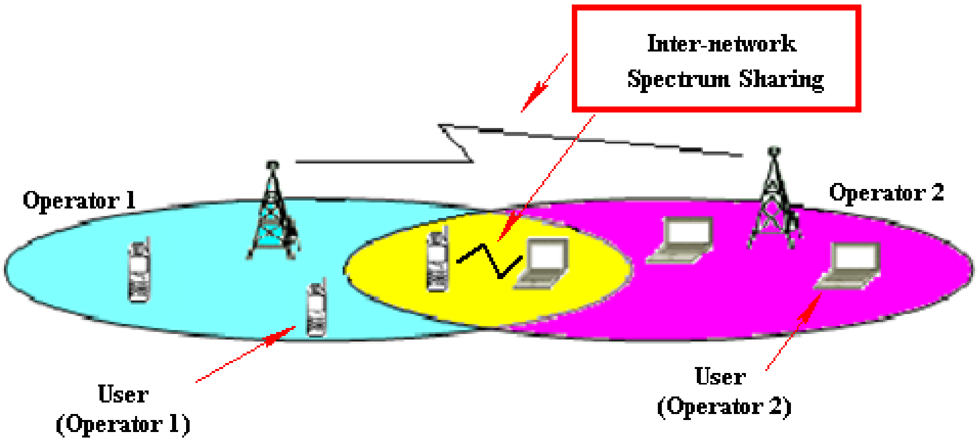


Figure 9 Inter-Network Spectrum Sharing for CRs

The inter-network spectrum sharing is regulated through static frequency assignment between different systems or centralized allocations between different systems.

In the *Centralized inter-network spectrum sharing,* each node is equipped with a cognitive radio and a low bit-rate, narrow-band control radio. The coexistence is possible maintaining the coordination among these nodes with each other through broadcasting *Common Spectrum Coordination Channel* (CSCC) messages.

Each user determines the channel it can use for data transmission such that interference is avoided. Also the power adaptation is required.

In the *Distributed inter-network spectrum sharing* the providers share the same spectrum and a distributed Qos based dynamic channel reservation scheme is used. A base station (BS) competes with its interferer BSs according to the QoS requirements of its users to allocate a portion of the spectrum. The control and data channels are separated. The competition BSs are performed according to the priority of each BS depending on a BSs data volume and QoS requirement.

Chapter 3

Description of the Project

3.1 Scenario

The inefficiency problem in the spectrum use calls for a new paradigm. Currently the Spectrum Sharing (SpS) is gaining attention and different strategies are studied to allow different operators to share the spectrum in opportunistic way and at the same time aiming at higher spectrum efficiency.

The control strategies can have different approaches:

- **Centralized Approach**, in which a centralized entity controls the spectrum allocation and the access procedures and also it provides a distributed sensing procedure such that each device forwards their measurements about the spectrum allocation to the central entity and this entity construct a spectrum allocation map ([7.]).
- **Decentralized Approach**, in which the network devices take individually the decision about the spectrum. The decentralized strategies can be classified in:
    - *Fully autonomous and distributed*, in which the devices sense the spectrum and identify the transmission opportunities on the suitable spectrum avoiding the interference. The challenges of this strategy are the identification of transmission opportunity that will be obtained through the detection or broadcast, and the coexistence and cooperation among the devices with the target to promote a fair and efficient utilization among the devices.
    - *Collaborative Distributed Approach*, in which a group of devices cooperates with other groups to identify the transmission opportunities and coexisting possibility. This approach can be with or without control, in the first case there is a central entity that checks the spectrum access while in the second case the communication are coordinated by the group.

In this work a decentralized environment is considered, in which there is not a central entity and the devices allocations are observed and predicted by the other devices.
In this scenario will be present two operators, each with the same number of users (i.e. number of users equal 5), therefore the cells can be drawn as following (Figure 10):

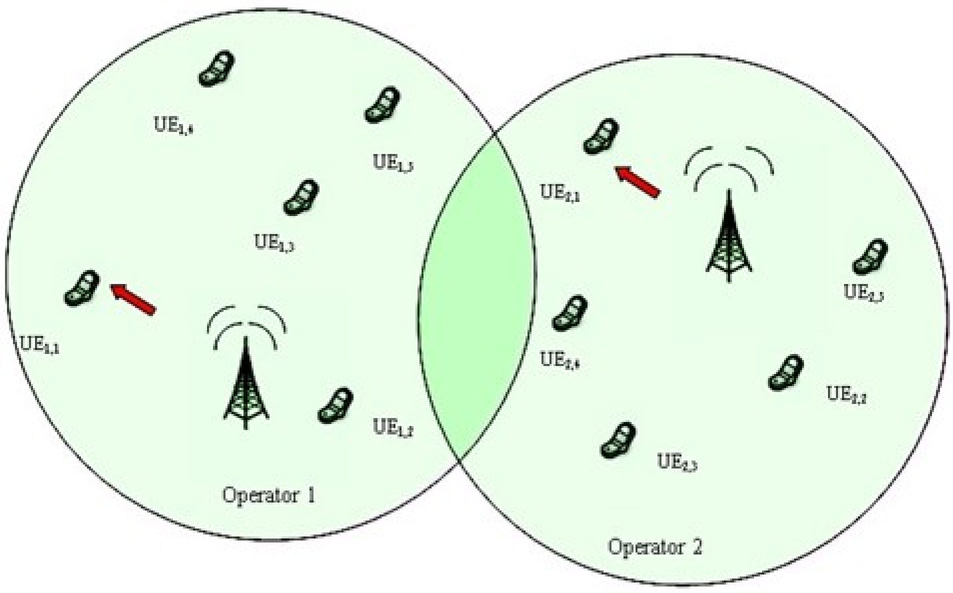


Figure 10 Reference Scenario

In reference to used simulator the scenario chosen is an Indoor corporate (office) with uncoordinated deployment of HeNB by the operators, the layout is flexible because the placements of rooms, walls, corridors, users (UEs) can be modified (Figure 11).

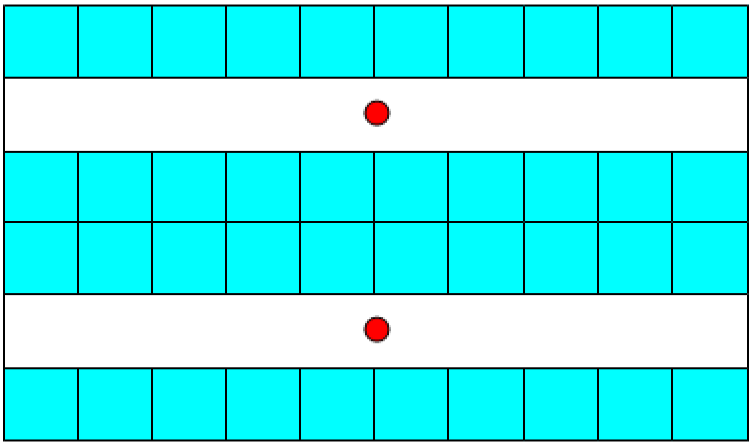


Figure 11 Corporate LA deployment scenario model with HeNB locations

Moreover one considered:

- Downlink transmission;
- Access scheme: OFDMA;
- Duplexing Scheme: TDD;
- Frequency reuse among cells;
- Perfect synchronization between HeNB and its serving UEs.

Regarding the frames these will be composed by 10 time slots and in each time slot there are 125 PRBs (= number of carrier/PRBs size), hence the frequency frame can be drawn as follows (Figure 12):

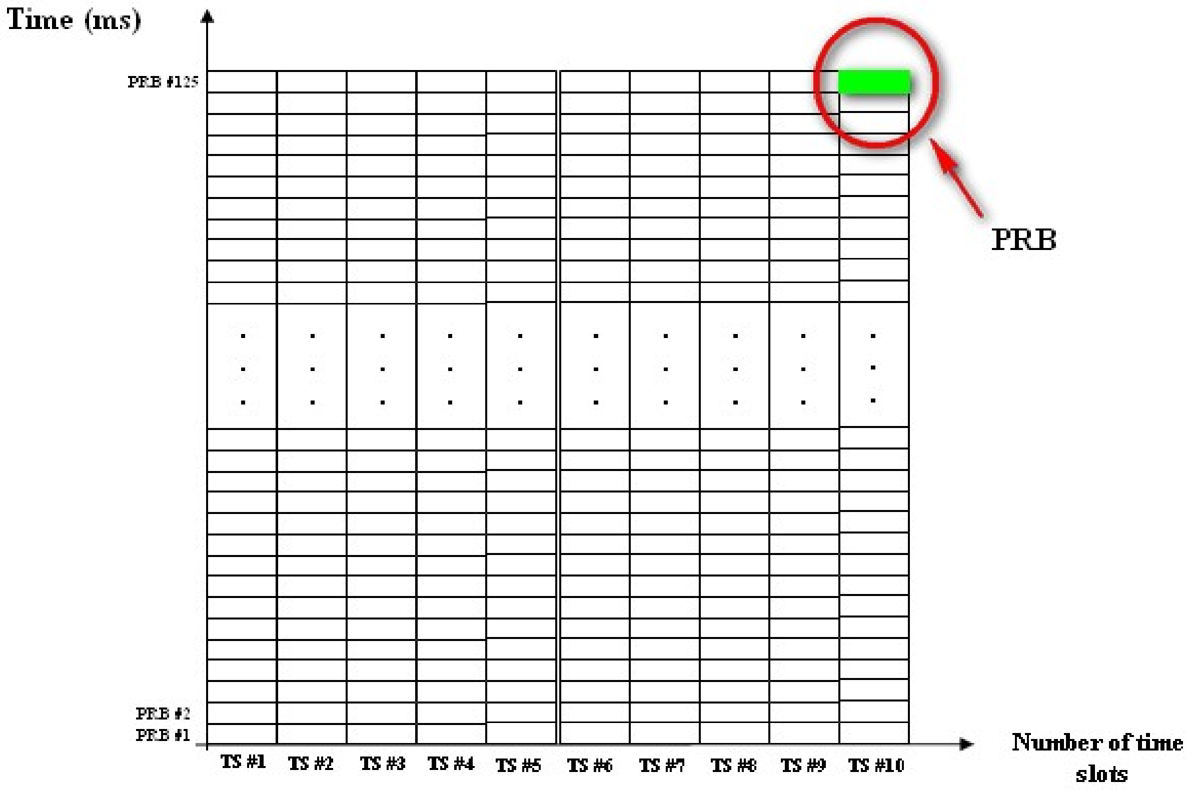


Figure 12 Frame structure

The behaviour of the operators will depend on the considered algorithm:

- **Spectrum Load Balancing Algorithm**: a minimum collaboration among the operators HeNB, that are co-located in the scenario is assumed, because if there was not the operators could interfere between them. This collaboration is reached through the resource reservation by one of HeNB for the allocation;
- **FSU Algorithm based on SINR and Interference Threshold**: two operators run simultaneously the algorithm and they can select also the same PRBs, since we allow an overlapping allocation of the spectrum. To obtain a fair distribution of the resources, appropriate thresholds for SINR and interference must be selected.

3.2 Spectrum Load Balancing

The reduction of the destructive, mutual interference in order to allow the "peaceful" coexistence of different operators and to support of the Quality of Service in the wireless network, can be obtained with the application of the Spectrum Load

Balancing (SLB) that enables a decentralized coordinated and opportunistic use of the spectrum ([19.]).

The purpose of SLB is an equally-smoothed allocation of the spectrum by redistributing, in respect of their individual QoS requirements, HeNB's spectrum allocations.

The SLB enables an optimized use of the available spectrum, in fact it allows to detect the unused spectrum, which was initially licensed, and to release it if it is needed again.

The basic principle, that characterized the SLB, is a radio resource allocation that is decentralized and uniform over the available shared radio spectrum.

SLB can be applied by all devices sharing a set of channels. The transmission of incumbent, legacy or non-SLB using devices is seen as fixed allocations and the SLB devices distribute, if possible, their allocations around them.

In Figure 13 there is the outcome from SLB in TDMA/FDMA system, in which the different time slots are on the x-axis, the frequency is on the y-axis and the fraction of an allocation in a certain time-frequency slot is on the z-axis. The dark grey allocations are the result of the SLB while the light gray allocations represent the fixed allocations that belong to an incumbent communication system ([20.]).

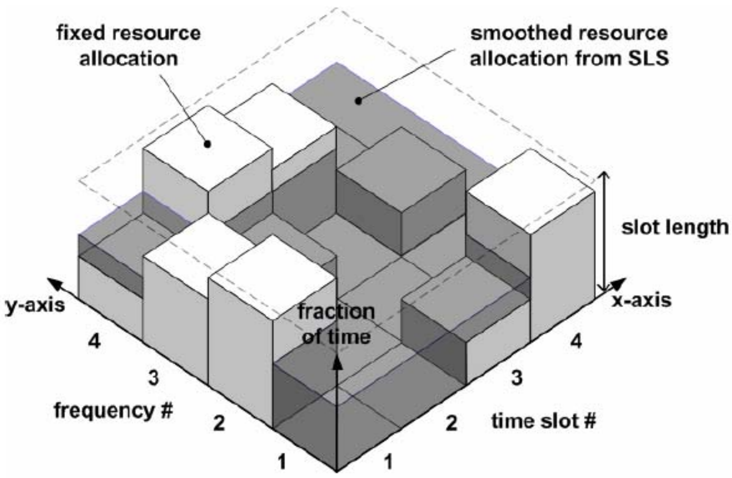


Figure 13 SLB in the time and frequency domain of a TDMA/FDMA system ([19.])

In the case of predictable allocations of a medium, the interaction of a device with the other devices may be seen as a contribution to cooperation. All devices can observe and predict the period resource allocations of a device and they can adapt their allocations, with the purpose of partially or completely preventing mutual interference on the shared medium.

The cooperation enables:

- Interference reduction or avoidance;
- An increased chance for other devices to reduce the delay for their data packet;
- A reduced block probability and access time for new devices.

3.2.1 Spectrum Load Balancing Algorithm

The SLB can be distinguished between ([19.]):

- SLB improved through reservation;
- SLB based on the observation of the past frame (without reservation).

In the first case, the SLB observe the allocations of the past frame actualized through the reservation for the actual frame that is notified through a dedicated *coordination period*, located at the beginning of the frame and within this coordination the devices use the SLB and broadcast their reservation successively ([20.]). The SLB considers the already received reservation from the other devices if available or considers the allocations of the last frame ([19.]).

In the second case, the SLB is done simultaneously at beginning/end of a frame and to enable a mutual interaction the SLB is done step wise frame after frame in redistributing a limited amount of allocations from the previous frame.

In the Spectrum Load Balancing a fixed frame structure and a fixed single frequency is considered and the Spectrum Load Balancing is done by one device per frame.

The frame is constituted by four slots, which have the same length and represent an interval in which the multiple accesses are done.

The goal of this iterative algorithm is to redistribute the allocations and obtain an equalized overall utilization of the slots.

In the figures (Figure 14, Figure 15), the iterative determination of the Smoothed Load Level is shown:

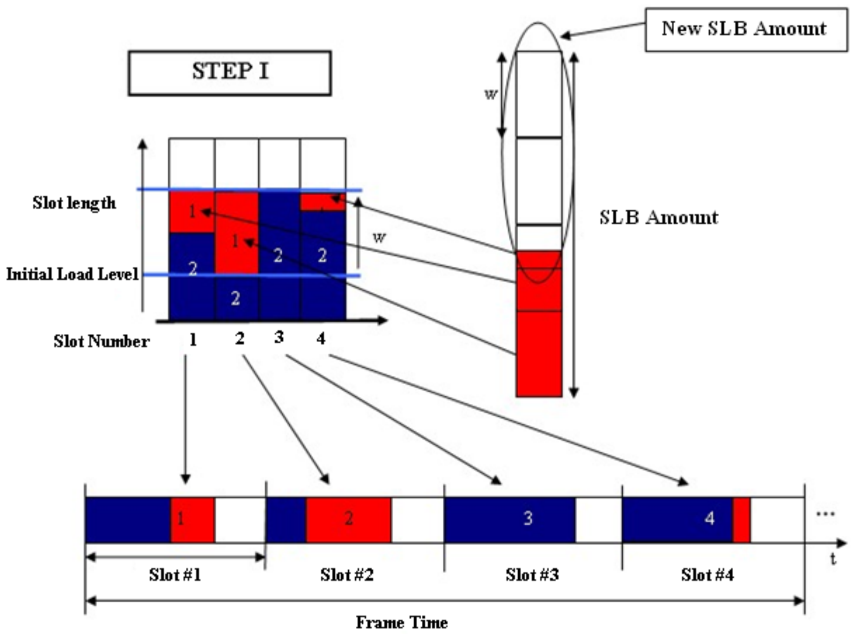


Figure 14 Step I of iterative SLB algorithm

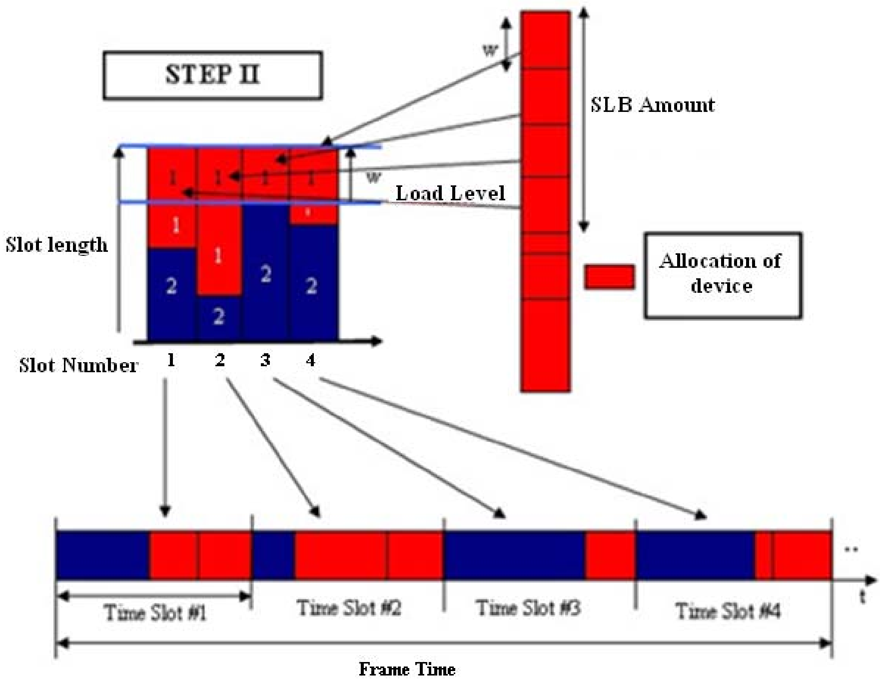


Figure 15 Step II of iterative SLB Algorithm

In this case the other device is considered as interferer (i.e. device 2), hence the Spectrum Load Balancing Amount is calculated as the sum of the transmission times per slot that are available, hence as the sum of the differences among the Maximum Load Level (MLL) and the occupancy of each slot C_i :

$$SLB\_A = \sum_{i=1}^{4} (MLL - C_i)$$

Where the MLL is the threshold of the maximum slot usage and it can be equal to slot length when this is completely used.

At the first step, the slot less utilized is considered and the Initial Load Level of the device 1 goes up of the Step Size:

$$w = \frac{SLB\_Amount}{Number\_of\_Slots}$$

Hence the value of SLB Amount is update:

$$SLB\_A = SLB\_A - w$$

If the new Load Level (LL) is above the occupancy of the other slots, so the parts, that remain free, are filled with the allocation of device 1. Hence these allocations are subtracted from the amount, which has still to be distributed. The new value of SLB Amount in this case will be:

$$SLB\_A = SLB\_A_{old} - \sum_{i=1}^{4} (LL - C_i^{New})$$

Where:

- SLB_A_{old} is the non-updated value of SLB_A;
- C_i^{New} is the new occupancy vector after the allocation of the step size.

Thus iteration after iteration, SLB_Amount and Step Size decrease until the MLL is reached, hence the MLL is used as value that gives the condition for ending this iterative algorithm.

Another approach to Spectrum Load Balancing is an algorithm which uses the inverse reasoning for the resource allocation. It is the case of the **Reverse Water-filling Algorithm**, in which the allocations that have to be distributed using SLB, are determined in reverse way with respect to the direct version of the SLB Algorithm.

Also in this algorithm, the frame structure is fixed and it consists of four slots of equal length that is respected by all devices. The slot represents the interval during which the multiple access occurs. In the figure, the iterative determination of allocations is represented (Figure 16, Figure 17):

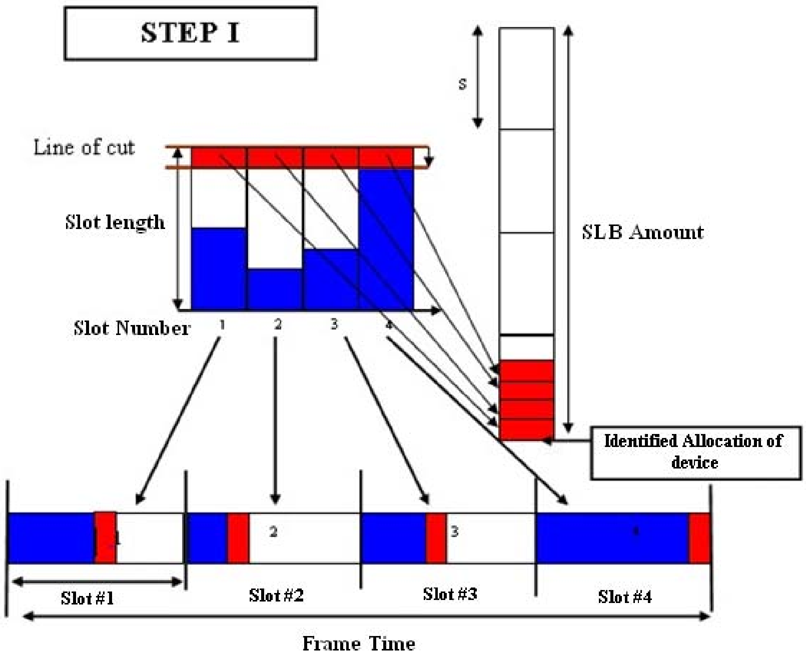


Figure 16 Step I Reverse SLB Algorithm

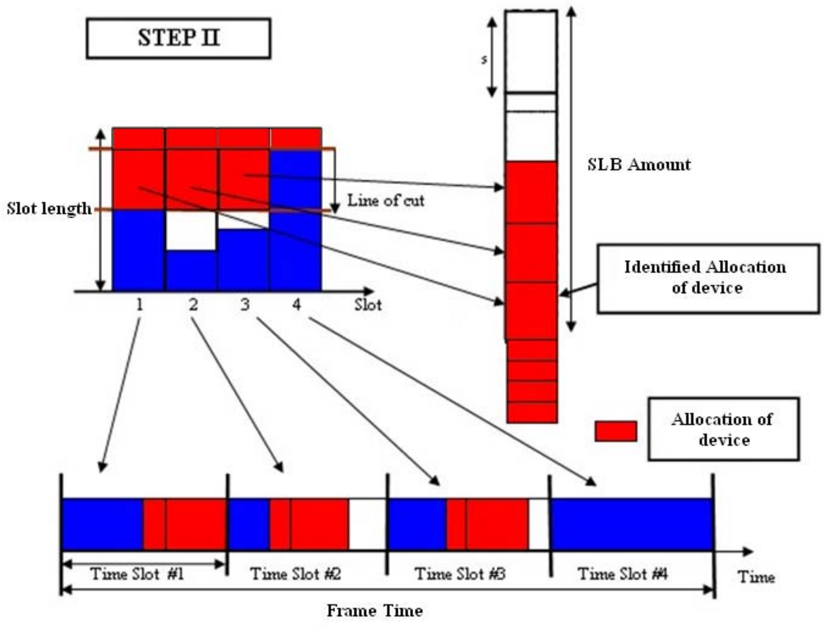


Figure 17 Step II Reverse SLB Algorithm

A virtual line of cut iteratively goes down from the most utilized slot and the parts, that are cut, are used for redistribution. The line of cut is moved down with a step size *s*, which is given by the following quotient:

$$s = \frac{Left\_amount\_of\_allocations\_to\_be\_cut\_for\_SLB}{Number\_of\_slots}$$

The allocations identified for redistribution are summed up and are subtracted from the amount of allocation. The next step size *s* is defined by the remaining quantity.

The initial value of the variable *SLB_Amount* is calculated as the sum of the differences among the Maximum Load Level (*MLL*) and the occupancy of each slot:

$$SLB\_A = \sum_{i=1}^{4}(MLL - C_i)$$

Once the initial SLB Amount is found, the initial step size *s* is calculated.

The constant *MLL* is the threshold that the slots must respect; therefore it is used as value that gives the condition for ending this iterative algorithm.

3.2.2 Spectrum Load Balancing Algorithm in the Simulator

The algorithm described above is adapted to a system level simulator, hence the frames that initially were considered composed of 4 slots, are modified and each frame is considered composed by 4 frames of the simulator, that will be indicated like sub-frames; in this manner the duration of one frame is equal to 20 ms. The frequency frame can be drawn as follow (Figure 198):

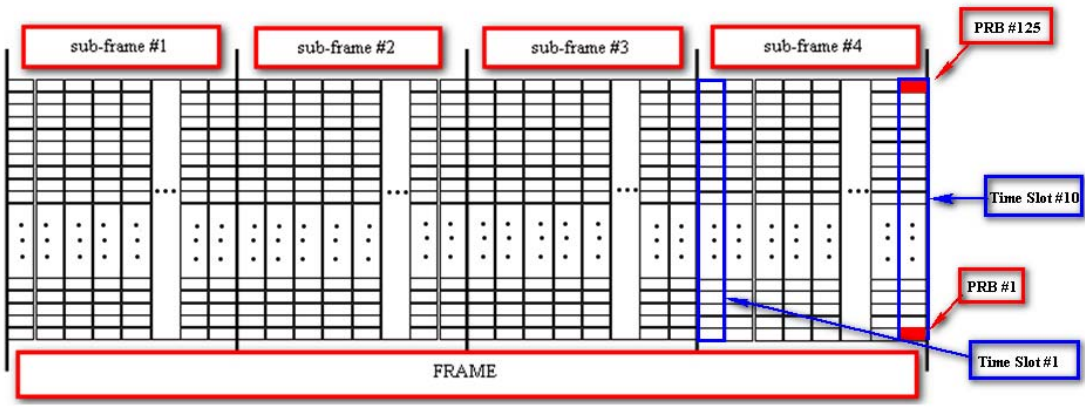


Figure 18 Frequency Frame

The allocations of the users in each time slot are fixed; hence the frame structure can be simplified as following (Figure 19):

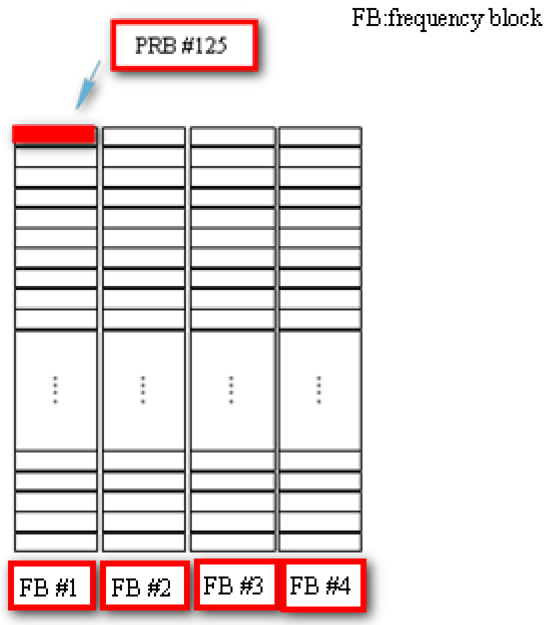


Figure 19 Semplified Frequency Frame

Among the operators there is cooperation, hence each operator knows the number of PRBs already occupied by the other HeNB, in this way an orthogonal allocation among the operators is done and the possible collision and reduced spectrum utilization are avoided.

For example if the operator 1 is the first to transmit, so for the first cell will be know:

- The number of allocated PRB in the current cell: it is the number of PRBs, that can be used in the cell from the operator;
- The vector of occupancy of the current frequency frame: it is the vector, that contains the number of PRBs used from the operator in each frequency block;
- The used allocated PRBs in each frequency block: they are the effective PRBs used from the operator.

From these information the operator 2 can calculate the SLB Amount in the current frequency frame and can start its allocation without selecting the same PRBs of the operator 1.

In each frequency frame we will have a fair allocation of PRBs and an increase of the overall throughput for the coexisting operators that lead to a high probability of a successful access to the shared spectrum.

3.2.3 FSU Algorithm based on SINR and Interference

Also for this algorithm the same scenario of the SLB Algorithm is considered, hence there are 2 operators that have the same number of users.

These operators have the same number of used PRBs, hence they have the same spectrum load and since the operators run the algorithm simultaneously e without coordination they will contend for the spectrum allocation and they will potentially interfere each other.

So a way to allocate the spectrum in a manner that the interference is minimized obtaining an opportunistic spectrum allocation is needed.

To obtain a fair shared spectrum in this algorithm same thresholds are determined with the target to select the appropriated PRBs by each operator.

The first threshold that is considered, concerns the SINR. One will be selected all PRBs that have the SINR greater than the SINR threshold and these PRBs will be candidate for the allocation of the operators, these are called PRB_{good}. The lower threshold will be the higher the number of PRBs that will be allocated.

But considering only SINR-threshold leads to a problem,as in the simulator the calculus of SINR in downlink is measured at UE on the scheduled PRBs to the UE, hence if the selection of PRBs, that are candidate for the allocation, is based only on the SINR, step by step the PRBs will be decreased drastically until the point when there will not be more PRBs for the allocation.

To avoid this problem another threshold is considered and concerns the Interference. The interference is associated to each PRB and depends on the position of the users with respect to interferer operator.

In this case the higher the threshold, the higher the number of PRBs allocated. The PRBs that will have the interference value lower then the threshold, will be chosen as suitable PRBs for the allocation because their interference in not harmful; they are called PRB_{free}.

The PRB_{free} selected for each cell will be shared among the operators, but before there is the check to verify how operator is less favourite. Hence the number of PRB_{good} of each cell is matched, and if an operator has a number of PRB_{good} lower then the other operator it will be less favourite for this reason after the calculus of the mean of PRB_{free} for each operator a bigger number of $PRBs_{free}$ will be assigned to the less favourite operator.

If both operators have the same number of PRB_{good} so each operator will allocate its own PRB_{free}.

In this manner a fair and balanced allocation should be obtained among the operators.

Chapter 4

Numerical Results

4.1 Simulator

The target of the project is found a fair and efficient algorithm for the spectrum sharing. For this purpose the algorithm discussed and proposed above were inserted in a simulator develop at Aalborg University.

This simulator is characterized by on indoor corporate (office) and indoor residential deployment scenarios with uncoordinated deployment of the HeNB (Home eNodeB).

In particular for this work it is considered an office scenario, in which the corridor is not necessarily the boundary of the cell, the walls are considered as light walls and the HeNB has a limited coverage. In particular only two HeNB are considered hence the cells will have 10x2 rooms and each cell may have from 5 to 10 users (UEs), (in Figure 20 five users for cell are considered).

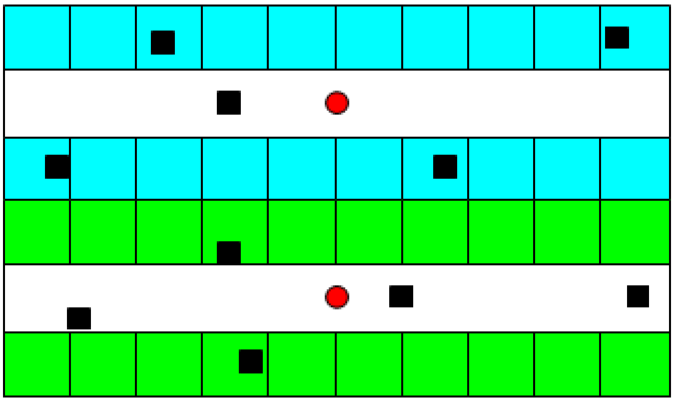


Figure 20 Office scenario topography with two operators

The layout that characterizes the scenario is flexible indeed the number and the position of walls, HeNBs and UEs can be changed. Once the basic layout is generated, HeNBs and UEs will be placed and the path loss will be calculated. The UEs will be randomly placed within the cell coverage and will change their position after the number of frames that was selected, while the HeNBs can be generated at any pre-defined locations or any random locations.

The HeNBs have the following characteristic:

- Transmission power: from 27 dBm to 30 dBm;
- Antenna omni- directional, 3 dBi gain;

While the UEs characteristic are:

- Transmission power: Min:-30 dBm Max:24 dBm;
- Antenna: Omni-directional, 0 dBi gain

Moreover the path loss and the shadow fading correlation are calculated in the following way:

- **Path-Loss**: in the simulator both LOS (corridor-to-corridor) and N-LOS (corridor-to-room) are considered. In the N-LOS case, a basic path-loss calculus for the users in the rooms adjacent to the corridor, in which the HeNB is located, is done, while for the users, that are placed in the further rooms also the wall penetration losses is considered:
  - **LOS:** $PL = 18.7\log_{10}(d[m]) + 46.8 + 20\log_{10}\left(f_c[GHz]/5\right)$;
  - **NLOS:**

    $PL = 36.8\log_{10}(d[m]) + 43.8 + 20\log_{10}\left(f_c[GHz]/5\right)$;
  - **NLOS with wall penetration factor:**

    $PL = 20\log_{10}(d[m]) + 46.4 + 20\log_{10}\left(f_c[GHz]/5\right) + n_w \times L_w$.

- **Shadow Fading Correlation** is applied a log-normal model with standard deviation of 3 for LOS case, 4 or 6 for N-LOS case depending on the number of walls among users and HeNB.

So in this work one considers the following parameters:

- Scenario: indoor office;
- Number of operators:2;
- Rooms per cell: 10x2;
- Cell coverage: 100mx25m;
- Number of users per cell: the minimum number is 5, the maximum number is 10, in this work the number of the users per cell considered is equal to 5 for both HeNBs ;
- Frequency re-use factor: 1 , all cells use the same frequency band;
- Synchronization: perfect;

- Traffic load: fractional;
- Signal Bandwidth: 100 MHz;
- Frequency: 3.5 GHz;
- Layout: 40 for FSU Algorithm based on SINR and Interference Threshold and 20 for Spectrum Load Balancing Algorithm;
- Selects: this parameter indicates how many times the number and the position of UEs changes; its duration is equal the number of frames. In this work it is considered equal to 40 for FSU Algorithm based on SINR and Interference Threshold and 20 for Spectrum Load Balancing Algorithm;
- Frames: 20 for FSU Algorithm based on SINR and Interference Threshold and 40 for Spectrum Load Balancing Algorithm.

4.1.1 Performance Metrics and Reference Case

For the evaluation of the results different performance metrics are considered:

- **Average Achieved cell Load**: represents the actual number of PRBs utilized by the HeNBs, i.e. it is the percentage of used PRBs over the total number of PRBs. It is important to measure the fairness;
- **Mean Cell Throughput**: represent the total throughput achieved by the HeNB during one frame after the FSU is stabilized;
- **User Outage Throughput**: it is the 5^{th} percentile of CDF of user throughput. This gives the minimum throughput achieved by the 95 % of the users.

The reference case is the blind random scheduling in frequency domain, called No-FSU in which there is the frequency reuse equal to 1 and the full load mode is considered.

4.2 Results for the SLB Algorithm

- Before to insert the SLB algorithm in the simulator, its correctness was verified and from the results is verified that both SLB Amount (Figure 21) and Step Size (Figure 22) decreases until they reach 0 that means that all resources are allocated (Figure 23).

  In the Matlab code, a single frame that consists of four slots and two devices, of which one is an interferer, are considered.

  At the beginning, the following parameters are used:

  - Slot Duration Ts=5 ms;
  - Slots Number Ns=4;
  - A Maximum Load Level, that is the maximum available time for transmission (i.e. MLL=5 ms);
  - Duration Frame Tf=Ns*Ts=20 ms;
  - A vector that contains the initial occupancy of each slot (i.e. C=[2.5 4 0.25 1.5]);
  - A variable SLB_Amount that contains the amount of allocation to be distributed.

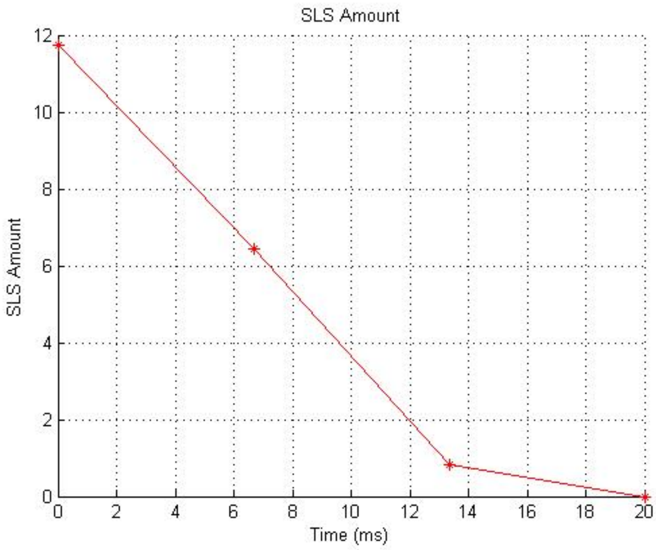


Figure 21 SLB Amount behaviour

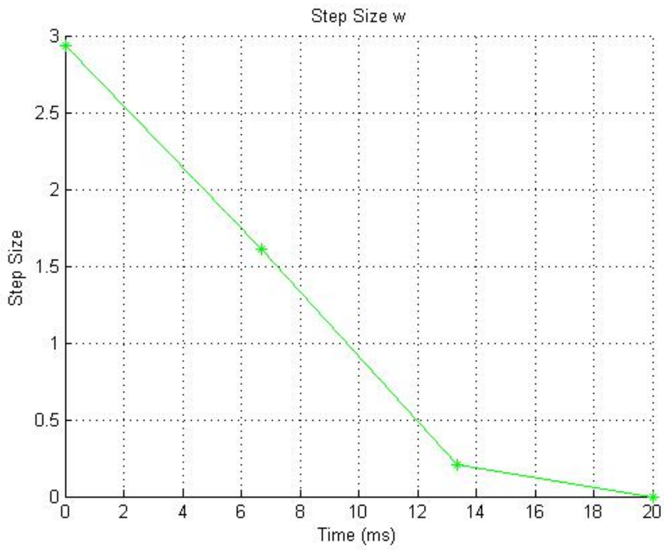


Figure 22 Step Size behaviour

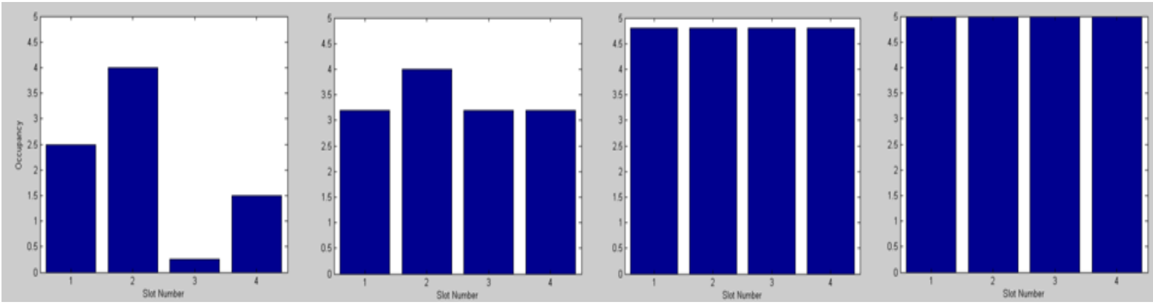


Figure 23 Iterative SLB Algorithm

Once the correct functioning of the algorithm is verified, the algorithm was adapted to the simulator and the results from the simulations are the following:

- **Average cell load**:

  The SLB algorithm (Case 5) is compared with the reference case (Case 0) in which all the spectrum is exploited by both operators HeNBs.

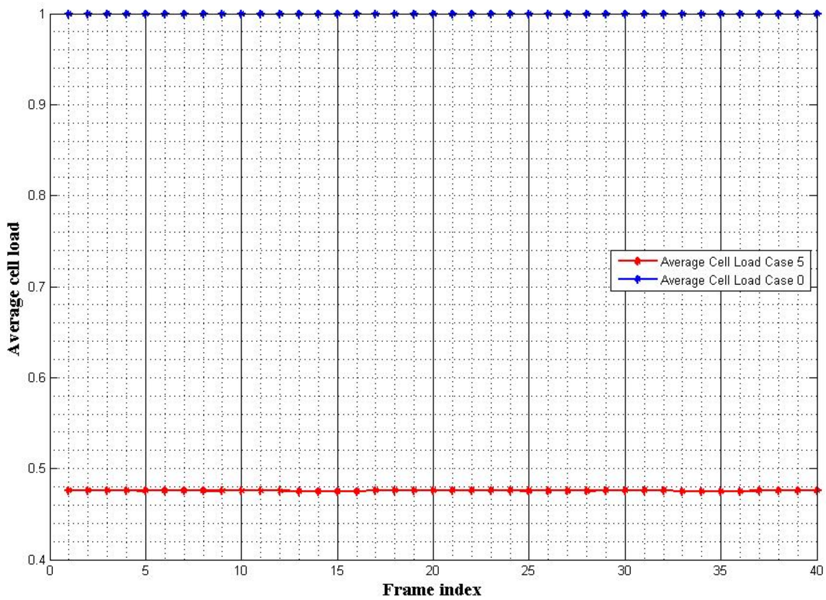


Figure 24 Average cell load: match among reference case and SLB Algorithm

From the result it is possible to see that with the introduction of the SLB algorithm (Case 5) the spectrum used is less then the spectrum used in reference case (Case 0), this is about 50% of the total spectrum, hence a fair spectrum sharing is reached (Figure 24).

- **User Outage Throughput:**
  In this figure one represents the minimum throughput achieved by 95% of the users in the reference case (Case 0) and in the case in which the SLB Algorithm (Case 5) is applied. With the application of SLB Algorithm the outage users throughput is increased respect the reference case (Figure 25).

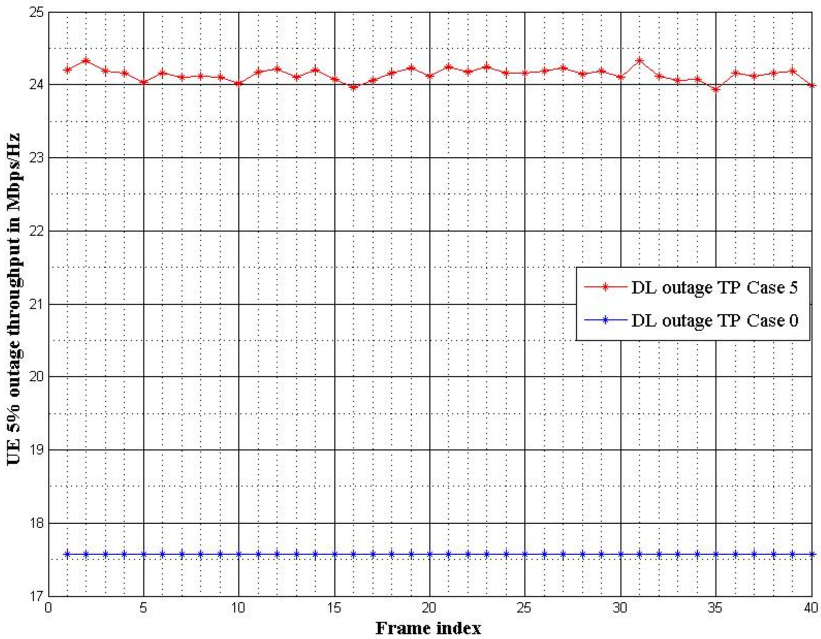


Figure 25 Outage comparison between reference case and SLB Algorithm

- **Mean Cell Throughput:**

  The decrease of spectrum utilization obtained can be see also from the comparison of the mean cell throughput among the reference case (Case 0) and the SLB Algorithm (Case 5), in fact the mean cell throughput is reduced because less PRBs are utilized (Figure 26).

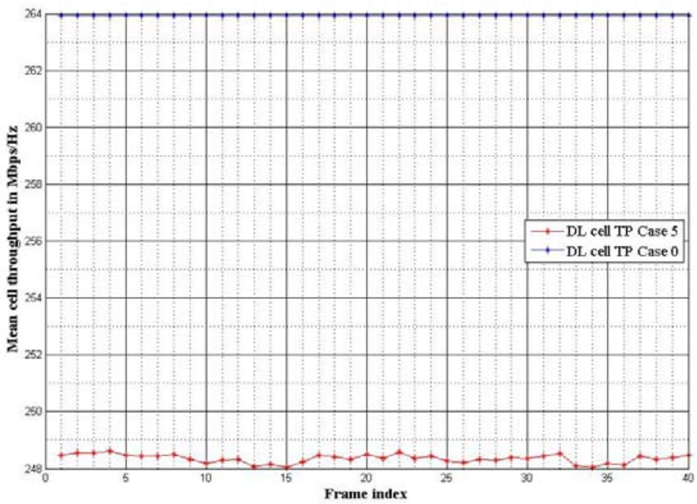


Figure 26 Mean throughput comparison between reference case and SLB Algorithm

- **CDF of cell throughput**:

  Figure 27 shows as at the start in the reference case the cell throughput is better, but above the 200 Mbps the cell throughput is better in the case of SLB Algorithm (Figure 27).

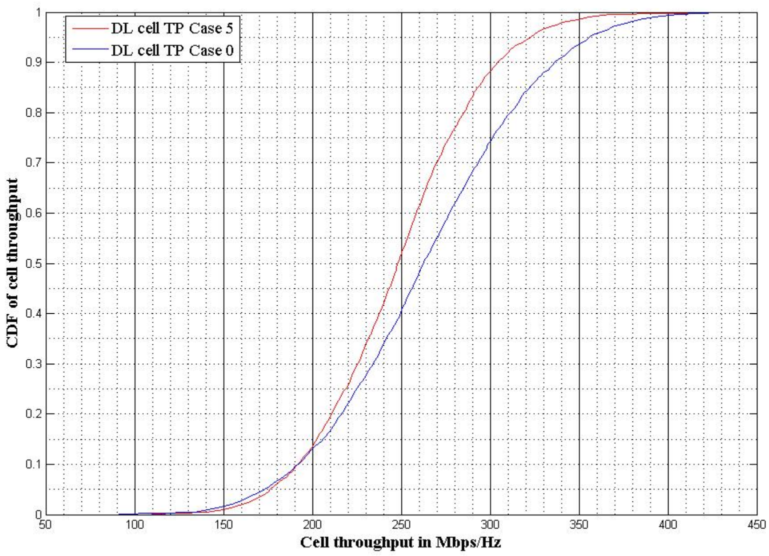


Figure 27 CDF of cell throughput comparison among reference case and SLB Algorithm

4.3 Results for the FSU algorithm based on SINR and Interference thresholds

In this simulation a key role is assumed by the choice of the threshold of interference because from these choice depends the allocation of more or less PRBs. In this case a threshold equal to 10e-15 is selected, in fact from the Figure 28 it can be seen that the average cell load decreases choosing the lower threshold values.

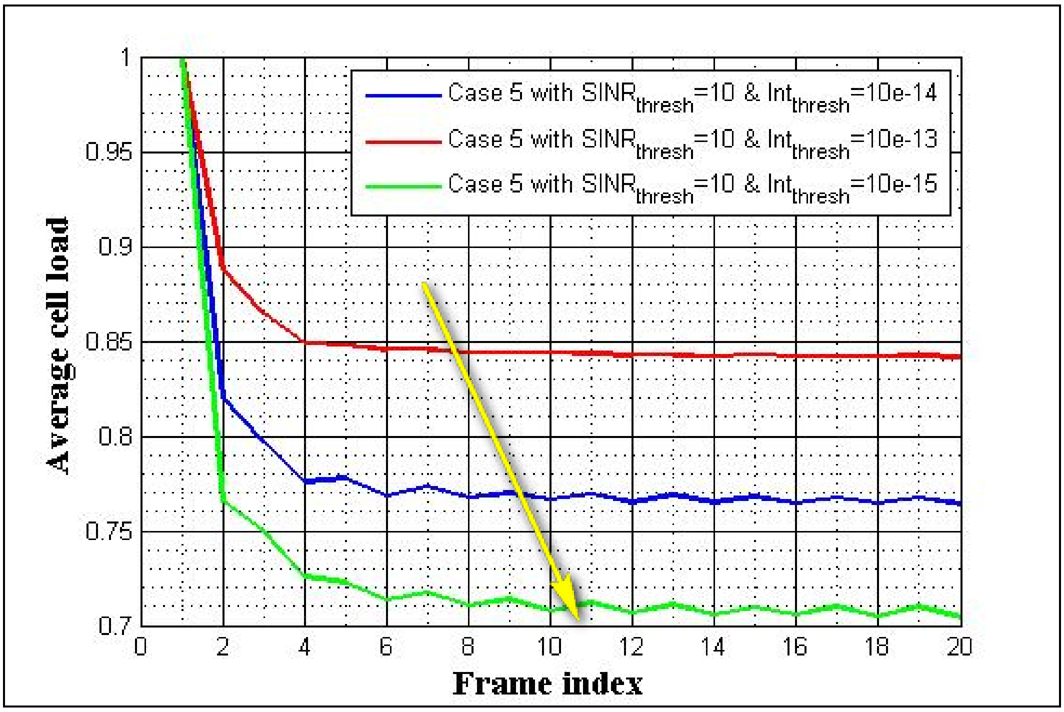


Figure 28 Choice of the interference threshold

After the selection of the threshold the result was compared with the reference case (Case 0) and the case of the FSU Algorithm based on SINR (Case 1), in which all HeNB run the algorithm simultaneously to select PRBs based on specified FSU target SINR threshold and the PRBs above the threshold are candidate for share selection, , while out of the all candidate PRBs the HeNB will only select the required number of PRBs. The SINR threshold is the same for both cases and it is equal to 10 dB.

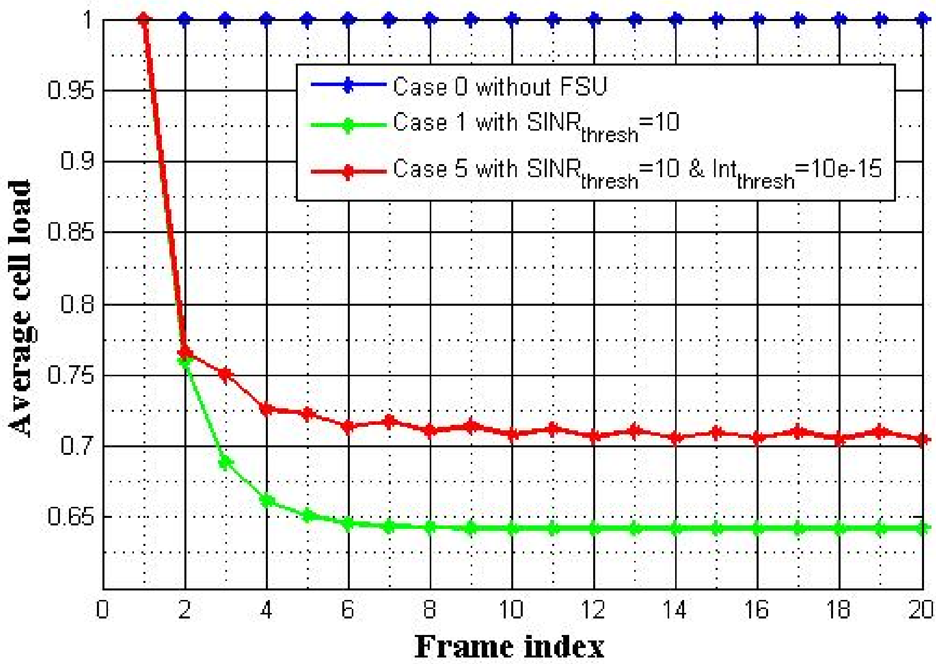


Figure 29 Average cell load comparison among reference case, FSU based SINR case and FSU based on SINR and Interference case

From Figure 29 it can be seen that the average cell load for the proposed algorithm (Case 5) is higher than the reference case (Case 0) but it is worst then the FSU Algorithm based SINR case (Case 1). This happens because introducing also the interference threshold the PRBs selected for the allocation will be more respect to the case in which only the SINR threshold is considered.

4.4 Improvement of the FSU Algorithm based on SINR and Interference Threshold and results

To obtain an improvement of the FSU Algorithm based on SINR and Interference Threshold, other than the two considered thresholds above (SINR threshold and Interference) it is also calculated the average number of PRBs required for an even distribution among the HeNBs and it is checked if the allocation of any HeNB is above this average number of PRBs and this is done until any HeNB has the number of PRBs below the average level.

The Interference threshold is selected equal to 1^{-15} because in this manner we will have an average cell load lower and hence a best spectrum allocation.

For the SINR threshold, the higher value will be selected; in this case it is equal to 30 dB, because in this manner we will have:

- An **Average cell load** (Figure 30) lower, hence the spectrum allocated is better;

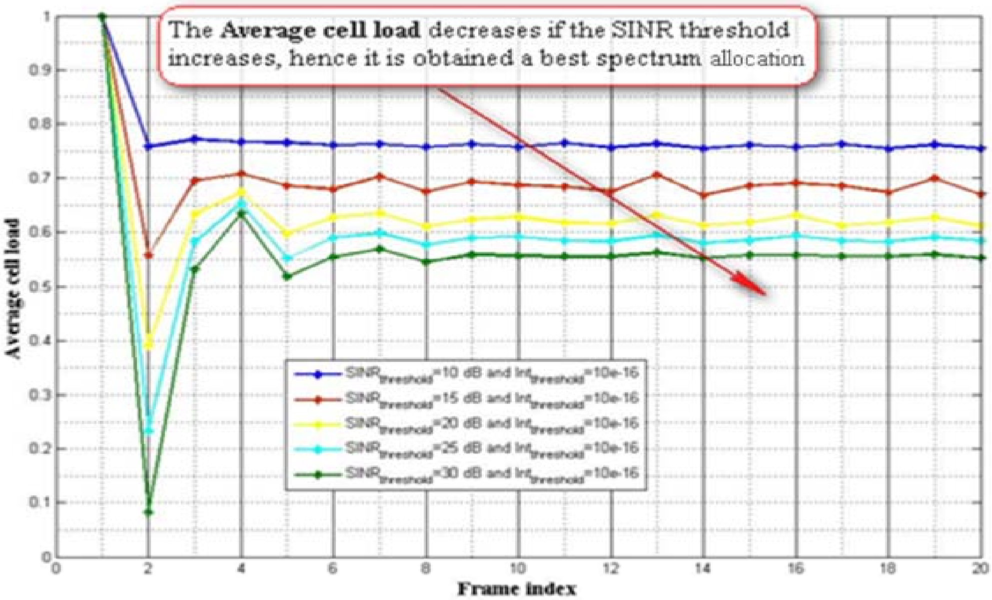


Figure 30 Average cell load: comparison among the different SINR thresholds

- **Mean cell throughput (Error! Reference source not found.**31) decreases, because less PRBs are used;

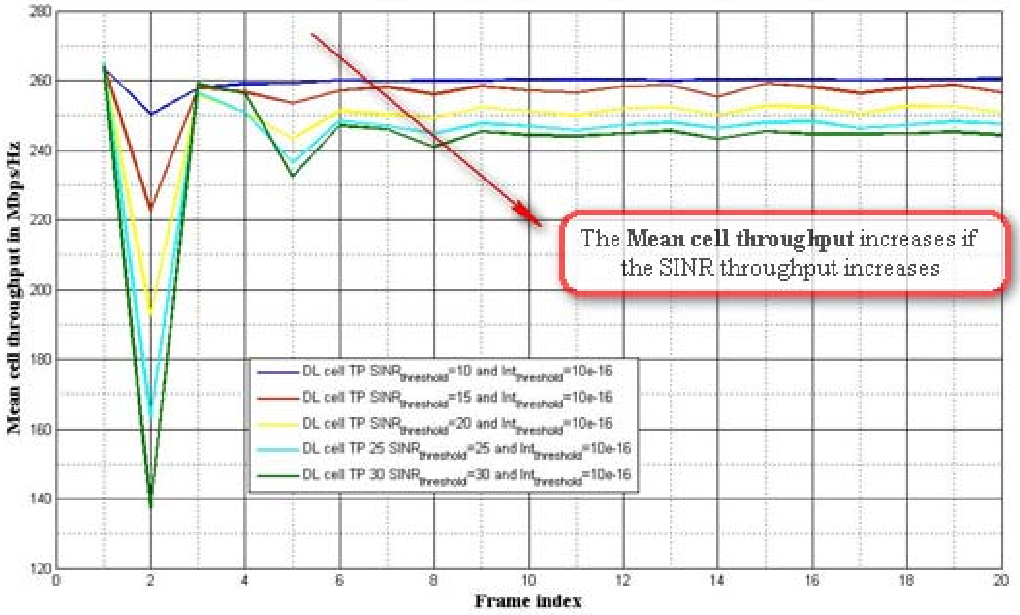


Figure 31 Mean cell throughput: comparison among different SINR thresholds

- **UE 5% outage throughput** (Figure 2) is better, indeed the minimum throughput achieved by 95% of the users, if the SINR threshold is equal to 30 dB, is about 22 Mbps.

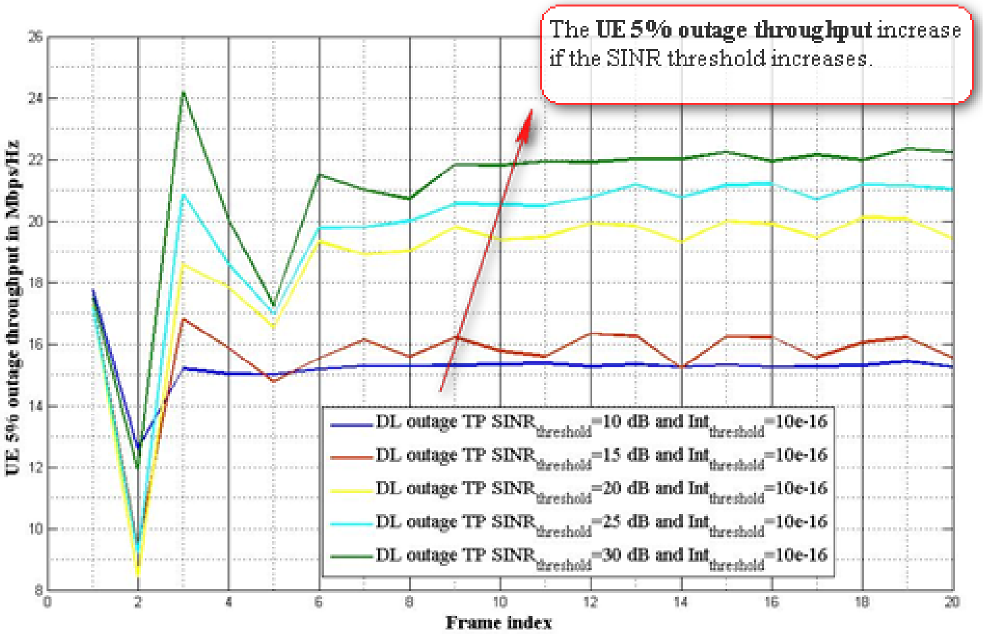


Figure 32 UE 5% outage throughput: comparison among different SINR thresholds

- **CDF of cell throughput** (**Error! Reference source not found.**33), CDF is getting steeper, which means less variations in the throughput. This comes from higher 'reliability' of the spectrum allocated, with higher SINR thresholds.

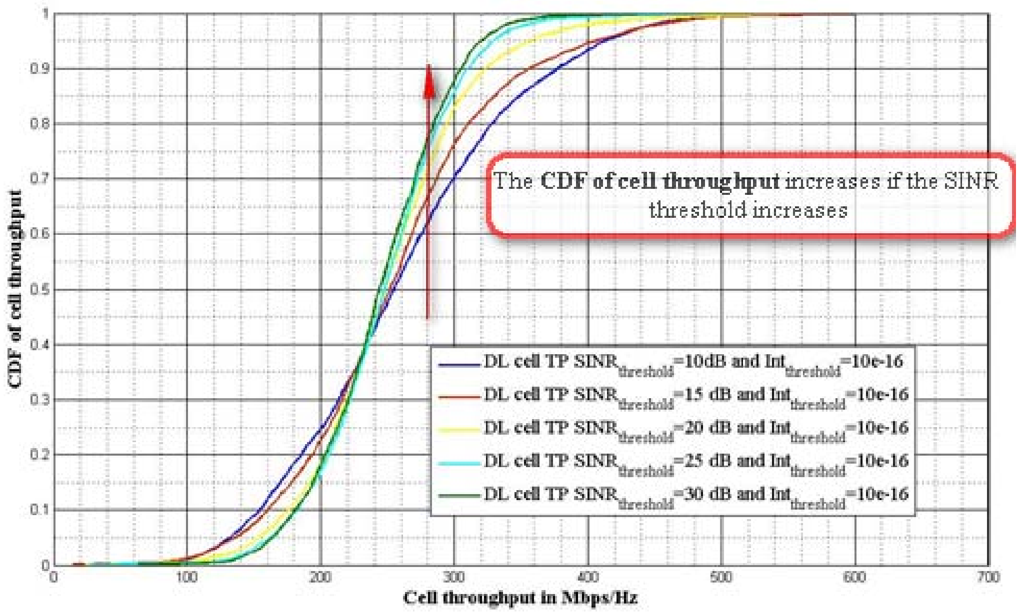


Figure 33 CDF of cell throughput: comparison among different SINR thresholds

- **CDF of user throughput** (**Error! Reference source not found.**34) is better above about 50 Mbps.

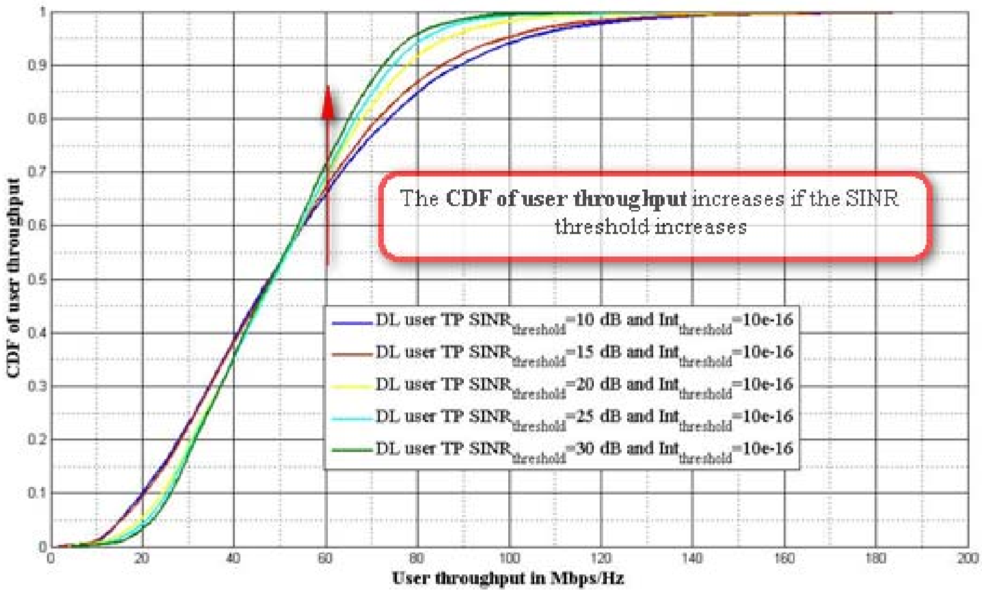


Figure 34 CDF of user throughput: comparison among different SINR thresholds

After the selection of the suitable thresholds of SINR and Interference, the results obtained for $SINR_{threshold}$=30 dB and $Interference_{threshold}$=10e-16 are compared with the reference case (case 0) and the case of FSU Algorithm based on SINR (case 1), in which the SINR threshold is considered equal to 30 dB.

We will have:

- **Average cell load (Error! Reference source not found.**35**):**
  It can be see that the average cell load for the proposed algorithm is lower than the reference case (case 0) but it is higher than the FSU based on SINR algorithm (case 1). This happens because introducing also the Interference threshold the selected PRBs for the allocation, hence the used spectrum, will be more respect case 1, but less respect to case 0.

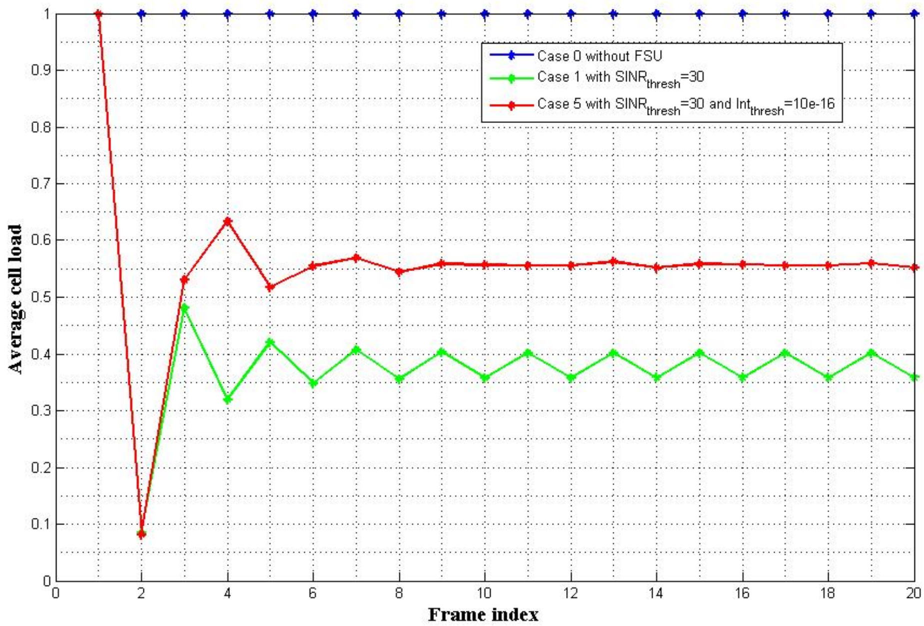


Figure 35 Average cell load comparison among reference case (case 0), FSU based SINR case (case 1) and FSU based on SINR and Interference threshold case (case 5)

- **Mean cell throughput** (**Error! Reference source not found.**36):
  From this comparison the less spectrum utilization in the case 5 is confirmed respect to the reference case and it is also confirmed the greater spectrum utilization in the case 5 respect to the FSU based on SINR case.

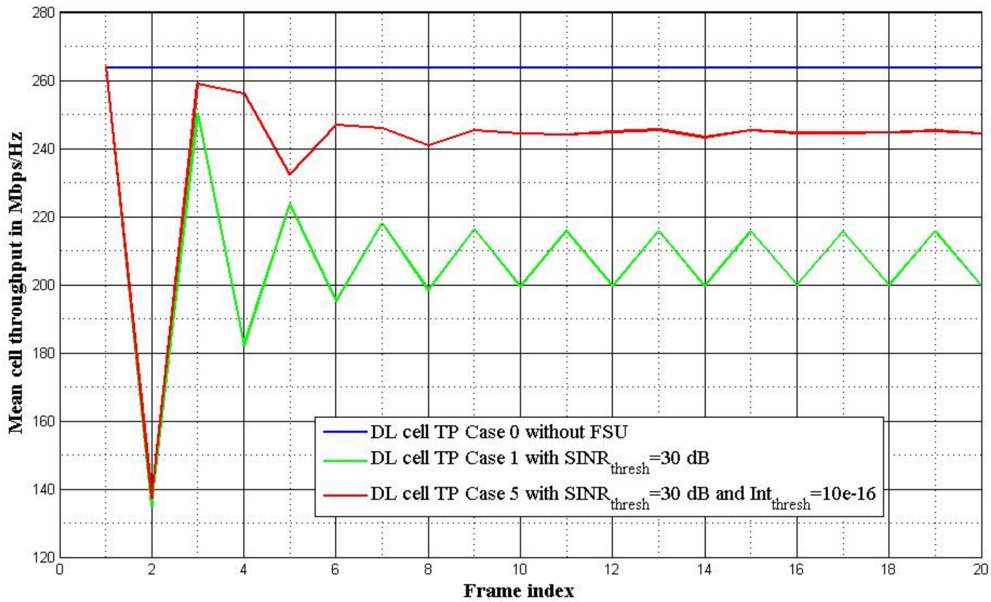


Figure 36 Mean cell throughput comparison amon the reference case (case 0), FSU based SINR case (case 1) and FSU based on SINR and Interference threshold case (case 5)

- **CDF of cell throughput** (**Error! Reference source not found.**37):

  In the FSU based on SINR case (case 1) the CDF of cell throughput is always better than the other case, but however the our case (case 5) above about 130 Mbps is better than the reference case (case 0).

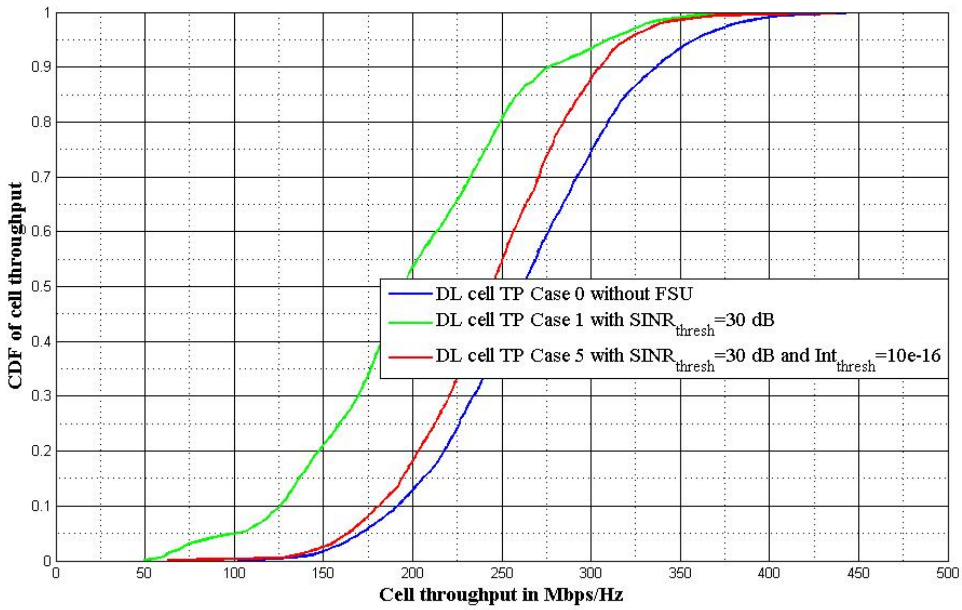


Figure 37 CDF of cell throughput comparison among the reference case (case 0), FSU based on SINR case (case 1) and FSU based on SINR and Interference threshold case (case 5)

Chapter 5

Conclusion and future work

In this work two algorithms are considered: SLB Algorithm and FSU Algorithm based on SINR and Interference, both with the target to realize an efficient and fair sharing of the spectrum.

An office scenario is considered in which two operators were placed, each with the same number of users. Moreover a decentralized approach is considered.

In the SLB Algorithm the two operators cooperate between them, hence each operator knows the number of PRBs already occupied by the other HeNB; in this way the orthogonality is maintained and the possible collision and reduced spectrum utilization are avoided. From the comparison of the results for the SLB algorithm with the reference case, in which all spectrum is allocated, an improvement for the outage throughput is obtained.

In the FSU Algorithm based on SINR and Interference still two operators are considered, but in this case without cooperation between them, indeed both transmit simultaneously and can select the same PRBs. To obtain a fair distribution of the resource, two thresholds are introduced, one based on SINR and another one based on the interference.
From the comparisons with the reference case and the case of the FSU Algorithm based on SINR, it is seen that the introduction of a new threshold the FSU

Algorithm based on SINR and Interference allow allocating more spectrum respect to the FSU Algorithm based on SINR, but it leads to a fair allocation respect the reference case.

In this work for the FSU Algorithm based on SINR and Interference the two operators are considered equal, indeed the same threshold are considered, but as an extension it would be interesting to study what happens by introducing different thresholds for the different operators, moving thus from an horizontal to a vertical spectrum sharing paradigm.

Appendix A

OFDMA ***[from Wikipedia]***

A **Orthogonal Frequency-Division Multiple Access ([21.])** (OFDMA) is a multi-user version of the popular Orthogonal frequency-division multiplexing (OFDM) digital modulation scheme. Multiple access is achieved in OFDMA by assigning subsets of subcarriers to individual users as shown in the figure below. This allows simultaneous low data rate transmission from several users.

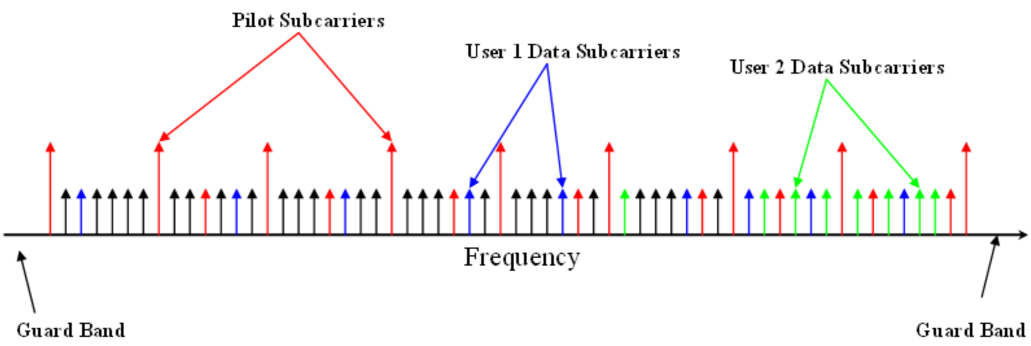
Based on feedback information about the channel conditions, adaptive user-to-subcarriers-to-users assignment can be achieved. If the assignment is done sufficiently fast, this further improves the OFDM robustness to fast fading and narrow-band cochannel interference, and makes it possible to achieve even better system spectral efficiency.

Different number of sub-carriers can be assigned to different users, in view to support differentiated Quality of Service (QoS), i.e. to control the data rate and error probability individually for each user.

OFDMA resembles code division multiple access (CDMA) spread spectrum, where users can achieve different data rates by assigning a different code spreading factor or a different number of spreading codes to each user.

OFDMA can also be seen as an alternative to combining OFDM with time division multiple access (TDMA) or time-domain statistical multiplexing, i.e. packet mode communication. Low data rate users can send continuously with low transmission power instead of using a "pulsed" high-power carrier. Constant delay, and shorter delay, can be achieved.

However, OFDMA can also be described as a combination of frequency domain and time domain multiple access, where the resources are partitioned in the time-frequency space, and slots are assigned along the OFDM symbol index as well as OFDM sub-carrier index.



List of figures

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