TITLE: Frequency Scheduling Algorithms for 3G-LTE Networks

MASTER DEGREE: Master in Science in Telecommunication Engineering & Management

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Overview

Long Term Evolution (LTE) represents the next step of the actual mobile communications standards, such as UMTS and GSM. Its main goal is to improve uplink and downlink throughput values up to 50 Mbps and 100 Mbps respectively. Another important point of this new standard is that uses scalable bandwidth from 1.25 to 20 MHz that suits the needs of the different network operators that have different bandwidth allocations. It is also expected to improve spectral efficiency in 3G networks, allowing carriers to provide more data and voice services over a given bandwidth.

The limited resources to transmit are an important fact to consider when the desire is to improve the speed of the transmissions. What this thesis proposes is different ways of sharing the available resources efficiently and also trying to not interfere in high manner the other transmissions.

Since the scheduling algorithms are not fixed in any 3GPP standard the main goal of this thesis is to analyze and compare different algorithms to extract the one or the several methods that improve the allocation in terms of throughput. To compare the different algorithms a simulator following the 3GPP LTE standard has been programmed and tried under two different scenarios: one static, considering full data buffers during all the simulation and another dynamic, taking into account real traffic in the way that is possible.

The thesis is divided in four different chapters. Firstly are defined some facts of the path that must be considered as well as some characteristics of the LTE standard. In the second chapter are detailed the different scheduling algorithms that will be compared. Finally chapter three and chapter four detail the results obtained with the static and the dynamic simulations respectively.

Is important to consider that the results related to the static scenario are very extensive so almost all of them can be founded in the annex of this thesis.
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>3G</td>
<td>Third Generation</td>
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<tr>
<td>3GPP</td>
<td>Third Generation Partnership Project</td>
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<tr>
<td>ACM</td>
<td>Adaptive Coding and Modulation</td>
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<td>ARQ</td>
<td>Automatic Repeat Request</td>
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<tr>
<td>CDF</td>
<td>Cumulative Distribution Function</td>
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<td>CP</td>
<td>Cyclic Prefix</td>
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<tr>
<td>eNB</td>
<td>enhanced Node B</td>
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<td>EPA</td>
<td>Extended Pedestrian A</td>
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<td>EUL</td>
<td>Enhanced Uplink</td>
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<tr>
<td>E-UTRA</td>
<td>evolved UTRA</td>
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<tr>
<td>FDD</td>
<td>Frequency Division Duplex</td>
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<tr>
<td>FFT</td>
<td>Fast Fourier Transform</td>
</tr>
<tr>
<td>H-ARQ</td>
<td>Hybrid ARQ</td>
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<tr>
<td>HSDPA</td>
<td>High Speed Downlink Packet Access</td>
</tr>
<tr>
<td>IP</td>
<td>Internet Protocol</td>
</tr>
<tr>
<td>ISI</td>
<td>Intersymbol Interference</td>
</tr>
<tr>
<td>LOS</td>
<td>Line of Sight</td>
</tr>
<tr>
<td>LTE</td>
<td>Long Term Evolution</td>
</tr>
<tr>
<td>MAC</td>
<td>Medium Access Control</td>
</tr>
<tr>
<td>MIMO</td>
<td>Multiple Input Multiple Output</td>
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<tr>
<td>OFDM</td>
<td>Orthogonal Frequency Division Multiplexing</td>
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<td>OFDMA</td>
<td>Orthogonal Frequency Division Multiple Access</td>
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<tr>
<td>PAPR</td>
<td>Peak to Average Power Ratio</td>
</tr>
<tr>
<td>PF</td>
<td>Proportional Fair</td>
</tr>
<tr>
<td>PHY</td>
<td>Physical (it usually refers to physical layer)</td>
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<tr>
<td>PRB</td>
<td>Physical Resource Block</td>
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<tr>
<td>QAM</td>
<td>Quadrature Amplitude Modulation</td>
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<tr>
<td>QPSK</td>
<td>Quadrature Phase Shift Keying</td>
</tr>
<tr>
<td>RGB</td>
<td>Resource Group Block</td>
</tr>
<tr>
<td>RLC</td>
<td>Radio Link Protocol</td>
</tr>
<tr>
<td>RR</td>
<td>Round Robin</td>
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<tr>
<td>RTP</td>
<td>Real-time Transport Protocol</td>
</tr>
<tr>
<td>SC-FDMA</td>
<td>Single Carrier – Frequency Domain Multiple Access</td>
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<tr>
<td>SINR</td>
<td>Signal to Interference Noise Ratio</td>
</tr>
<tr>
<td>SISO</td>
<td>Single Input Single Output</td>
</tr>
<tr>
<td>TCP</td>
<td>Transmission Control Protocol</td>
</tr>
<tr>
<td>TDD</td>
<td>Time Division Duplex</td>
</tr>
<tr>
<td>TTI</td>
<td>Transmission Time Interval</td>
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<tr>
<td>UDP</td>
<td>User Datagram Protocol</td>
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<td>UE</td>
<td>User Equipment</td>
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**NOTATION**

<table>
<thead>
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<th>Description</th>
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<tr>
<td>$\alpha$</td>
<td>ratio of reduced power level to full power level in soft frequency reuse</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Ratio of reduced power level to full power level in reuse partitioning</td>
</tr>
<tr>
<td>$b$</td>
<td>percentage of reduced power subband in reuse partitioning</td>
</tr>
<tr>
<td>$B_n$</td>
<td>bandwidth of one PRB</td>
</tr>
<tr>
<td>$P_{max}$</td>
<td>maximum power on a PRB</td>
</tr>
<tr>
<td>$P_{tot}$</td>
<td>total power in a cell</td>
</tr>
<tr>
<td>$U$</td>
<td>spectrum utility factor</td>
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INTRODUCTION

Long Term Evolution (LTE) is the next step in cellular 3G services, which represents basically an evolution of the actual mobile communications standards, such as UMTS and GSM. It is a 3GPP standard that provides throughputs up to 50 Mbps in uplink and up to 100 Mbps in downlink. It uses scalable bandwidth from 1.25 to 20 MHz that suits the needs of the different network operators that have different bandwidth allocations. LTE is also expected to improve spectral efficiency in 3G networks, allowing carriers to provide more data and voice services over a given bandwidth.

LTE uses OFDMA in the downlink for its ability to fight against intersymbol interference (ISI) and its robustness against frequency-selective fading and SC-FDMA in the uplink to mainly improve power consumption.

The limited resources to transmit are an important point when the desire is to improve the speed of the transmissions. What this thesis proposes is defining and analyzing in detail different ways of sharing the available resources efficiently while trying also to keep a reduced interference level over the other transmissions.

Since the scheduling algorithms are not fixed in any 3GPP standard the main goal of this thesis is the definition, simulation and comparison of different algorithms to extract the one or the several methods that improve the allocation in terms of throughput. To do this it has been programmed a simulator under the 3GPP LTE characteristics where the different eNB apply the proposed scheduling methods in a certain scenario.

The thesis is organized in four different chapters where firstly are defined some basic concepts of wireless communication systems and some LTE characteristics are briefly explained. In a second chapter the different scheduling algorithms that are going to be studied are defined in detail as well as the points that they have in common. To continue, a static scenario is initially used as test platform, where all the users have full traffic buffers during all the simulation, and the results of the different scheduling algorithms are deeply analyzed. To finish, the last chapter shows the results of the different algorithms in the case of a dynamic scenario where the users are divided in web and VoIP clients.
CHAPTER 1. THEORETICAL BASIS

This chapter summarizes different features of a wireless communication system that must be considered when designing a system level simulation platform as well as some important characteristics of the 3GPP Long-Term Evolution.

1.1. Wireless Communication Systems

The principal responsible for the communication impairments is the wireless channel due to the mobility of the transmitter/receiver as well as surrounding objects (buildings, cars, people, etc.), usually in a Non Line of Sight environment (buildings, hills etc. can obstruct the direct path) where multiple copies of the transmitted signal (multipath due to reflection and diffraction) can cause deep fadings and distortion.

All this is compounded by the fact that more communications will be occurring simultaneously so the consideration of the propagation characteristics, the cellular networks and the signal multiplexing is very important to mitigate interferences.

1.1.1. Propagation characteristics

As it has been indicated, the wireless signal propagates through the air so it can suffer reflection, absorption, scattering, diffraction and refraction what causes the attenuation of the signal.

It is conventional to group all these facts in three types of fading:

- Path loss.
- Shadowing (or slow fading).
- Fast fading (or multipath fading).

An example of the different types of fading can be seen in Figure 1.1, which shows a simulated signal received.

Each of these variations will be briefly defined in the following subsections.
This attenuation or loss $l$ can be defined as the ratio of the transmitted signal power $P_{tx}$ to the received signal power $P_{rx}$. The result is always higher than 1.

$$l = \frac{P_{tx}}{P_{rx}} \quad (1.1)$$

From this it can be also extracted the gain $g$ that is the inverse of (1.1). In this case, the result will be always lower than 1.

$$g = \frac{P_{rx}}{P_{tx}} \quad (1.2)$$
1.1.1.1. Distance path loss

In this thesis the attenuation caused by the distance is defined as follows.

\[ l_{path\ loss} = \beta \cdot R^\alpha \]  

(1.3)

And as before, the gain is

\[ g_{path\ loss} = \frac{1}{\beta \cdot R^\alpha} \]  

(1.4)

Where the parameter \( \beta \) depends on the transmission characteristics such as the transmission frequency, the antenna heights and other factors; \( \alpha \) depends on the environment and \( R \) is the transmission distance. Sample values for \( \alpha \) are 2 for free space propagation, 2.7-3.5 in urban microcells and 3.7-6.5 in urban macrocells [2]. Figure 1.2 shows \( g_{path\ loss} \) for \( \beta = 33.9 \) and \( \alpha = 3.76 \) which are the values used for the simulations.

![Distance path gain](image)

**Fig. 1.2** Distance path gain

1.1.1.2. Shadowing

The predicted path loss, as it had been indicated before, only depends on parameters such as the environment, the distance and the antenna heights.
These values will be always constant in a particular environment for a given distance. In practice, the objects blocking the line-of-sight (LOS) as buildings, mountains, trees and other objects will change these values making that in certain scenario and at the same distance, the path loss will be different. This phenomenon is known as *shadowing* or *slow fading*. It is very important to consider its effects to predict the reliability of the system’s coverage.

Its attenuation is usually modeled as a lognormal distribution which has mean $\mu$ and standard deviation $\sigma$, usually given in decibels as $\mu_{dB}$ and $\sigma_{dB}$. The standard deviation is in the range 5–12 dB and mean value is usually 0 dB [1].

As it depends on the obstacles between transmitter and receiver antennas it is spatially correlated, being the decorrelation distance the distance at which the normalized autocorrelation of the shadowing falls to 0.37 ($e^{-1}$) [1] and varies between 50 and 100 meters in typical outdoor environments.

Figure 1.3 shows the combined effect of path gain and shadowing.

![Figure 1.3 Distance path gain and distance path gain combined with shadowing](image)

**Fig. 1.3** Distance path gain and distance path gain combined with shadowing

[3]

1.1.1.3. *Fast Fading*

Additionally to path loss and shadowing there is also a significant variation in the received signal when the path distance is lower than the shadowing correlation distance. This phenomenon is called *multipath* or *fast fading*. What
happens is that the wave suffers reflections due to the obstacles, taking different paths, and at the receiver several waves arrive with different phases. The result is that the signal received is a sum of copies of the transmitted signal with different path loss, shadowing and delay.

In Figure 1.4 can be observed the previous results and the one showed in the Figure 1.3 also combined with fast fading.

![Distance path gain, distance path gain combined with shadowing and combination of path gain, shadowing and fast fading](image)

**Fig. 1.4** Distance path gain, distance path gain combined with shadowing and combination of path gain, shadowing and fast fading [3]. Note that fast fading effect is only plotted for distances between 100 and 300 m.

1.1.1.4. **Antenna gain**

Another fact that affects the propagation of the signal is the radiation characteristic of the antenna used. To not waste resources the most appropriate is to use a directional antenna. These antennas have the same total transmission power as an isotropic antenna but they concentrate the transmission in a small angle. The antenna gain for the deployment is given by

$$G_{\text{ant}}(\theta) = -\min \left[ 12 \left( \frac{\theta}{\theta_{3dB}} \right)^2, A_m \right] \text{dB}$$

$$\theta_{3dB} = 64^\circ, A_m = 25$$

(1.5)
Where $A_m$ corresponds to the minimum antenna gain relative to the maximum value. The antenna’s maximum gain is 18dBi and in Figure 1.5 and 1.6 can be observed the resulting horizontal and vertical, respectively, antenna diagram.

**Fig. 1.5** Horizontal antenna diagram

**Fig. 1.6** Vertical antenna diagram
1.2. LTE Basic Concepts

3GPP is a standardization committee that has produced several specification documents for LTE. In [4] can be found the different targets of LTE being some of them the following:

- **Peak Data Rates:** E-UTRA should support significantly increased instantaneous peak data rates. Note that peak data rates may depend on the number of transmit and receive antennas at the UE. The targets for downlink and uplink peak data rates are specified in terms of a reference UE configuration comprising: (a) Downlink capability $\rightarrow$ 2 receiver antennas at UE and (b) Uplink capability $\rightarrow$ 1 transmit antenna at UE. For this baseline configuration, the system should support an instantaneous downlink peak data rate of 100 Mb/s within a 20 MHz downlink spectrum allocation and an instantaneous uplink peak data rate of 50 Mb/s within a 20 MHz uplink spectrum allocation.

- **Latency:** A user plane latency of less than 5 ms one-way and a control plane transition time of less than 50 ms from dormant to active mode and less than 100 ms from idle to active mode.

- **User throughput:** 2-3 times higher downlink throughput than HSDPA Release 6 at the 5% point of the CDF. 3-4 times higher average downlink throughput than HSDPA Release 6. 2-3 times higher uplink than Release 6 EUL at the 5% point of the CDF. 2-3 times higher average uplink than Release 6 EUL.

- **Spectrum efficiency:** 3-4 times higher spectrum efficiency (in bits/s/Hz/site) in downlink and 2-3 times higher in uplink, compared to Release 6 HSDPA and EUL respectively.

- **Mobility:** Shall support mobility across the cellular network and should be optimized for 0 to 15 km/h. Furthermore, should support also higher performance at 15 and 120 km/h. Connection shall be maintained at speeds from 120 km/h to 350 km/h (or even up to 500 km/h depending on the frequency band).

- **Coverage:** Cell ranges up to 5 km support the above targets; up to 30 km will suffer some degradation in throughput and spectrum efficiency and up to 100 km will have overall performance degradation.

- **Spectrum flexibility:** Should support several different spectrum allocation sizes as: 1.25 MHz, 1.6 MHz, 2.5 MHz, 5 MHz, 10 MHz, 15 MHz and 20 MHz with both TDD and FDD modes. Shall also enable the flexibility to modify the radio resource allocation for broadcast transmission according to specific demand or operator’s policy.
1.2.1. Technologies involved

LTE employs different technologies such as OFDM, OFDMA, MIMO and SC-FDMA. These methods are briefly described in the following subsections.

1.2.1.1. OFDM

OFDM is a digital multi-carrier modulation scheme that distributes the data over a large number of carriers closely spaced. This spacing, in that case 15 kHz, provides the orthogonal property which prevents from interference.

The two main characteristics are that each subcarrier is modulated using varying levels of QAM modulation and each OFDM symbol is preceded by a cyclic prefix (CP) used to effectively eliminate ISI.

OFDM has several advantages such as can easily adapt to severe channel conditions, is robust against ISI and fading caused by multipath and give high spectral efficiency. But it also has disadvantages as is sensitive to Doppler shift, defined as the change in frequency of a wave for an observer moving relative to the source of the waves. It is also sensitive to frequency synchronization problems and has a high peak-to-average-power ratio (PAPR).

1.2.1.2. OFDMA

Orthogonal Frequency Division Multiple Access (OFDMA) is a multi-user version of OFDM. Multiple access is achieved by assigning different OFDM sub-channels to different users.

Among the advantages of OFDMA, can be emphasized that improves OFDM robustness to fading and interference. It also averages the interferences within the cells using allocation with cyclic permutation and offers frequency diversity by spreading the carriers all over the used spectrum. On the other hand, is higher sensible to frequency offsets and phase noise and the resistance to the frequency-selective fading may partly be lost if very few sub-carriers are assigned to each user and if the same carrier is used in every OFDM symbol.

OFDMA is used as the multiplexing scheme in the LTE downlink and its basic parameters are defined in [5].
1.2.1.3. **MIMO**

MIMO technology offers significant increases in data throughput and link range without additional bandwidth or transmitted power. There are multiple transceivers at both the base station and UE in order to enhance link robustness and increase data rates for the LTE downlink.

1.2.1.4. **SC-FDMA**

LTE requirements in uplink differ in several aspects from downlink. The main fact is the transmission scheme used. Power consumption is a key consideration for UE terminals and for this; the high PAPR and related loss of efficiency associated to OFDM signaling are major concerns. As a result, an alternative to OFDM was sought for use in the LTE uplink.

The solution is Single Carrier – Frequency Domain Multiple Access (SC-FDMA) that suits very well with the LTE uplink requirements. The basic transmitter and receiver architecture is very similar (nearly identical) to OFDMA, and it offers the same degree of multipath protection.

Since the goal of the thesis is only the downlink transmission no more characteristics of the uplink will be defined. More information can be founded in [5].
CHAPTER 2. SIMULATION BASIS

This chapter describes the different scheduling scenarios that will be evaluated. The main goal is increasing the throughput reducing the inter-cell interference levels. After the definition of the different methods in this section, the results will be deeply evaluated in Chapter 3 and Chapter 4.

2.1. Theoretical analysis

For each cell, a base station scheduler assigns the resource blocks (PRBs) to the UEs. LTE uses adaptive coding and modulation (ACM) per resource block, so the scheduler determines also the modulation type and coding.

It is considered a regular cell deployment with a determined number of eNBs. Each eNB has available \( N \) PRBs to transmit. There are a total \( M \) users distributed along the whole scenario (\( B \) eNBs) so the number of users served by each \( b \) eNB is \( M_b \).

\( \sigma^2 \) is the UE receiving thermal noise at PRB \( n \), \( i \) is the serving eNB for user \( i \), \( L_{ib} \) is the path loss (including shadowing fading) between eNB \( b \) and user \( i \) and \( P_{bn} \) is the transmitted power by eNB \( b \) in PRB \( n \).

With these considerations, the SINR measured by user \( i \) on PRB \( n \) is calculated as:

\[
SINR_{in} = \frac{P_{in}/L_{ii}}{\sigma^2 + \sum_{b=1}^{B} \left( \sum_{m=1}^{M_b} u_{mn} \cdot P_{bn}/L_{ib} \right)}
\tag{2.1}
\]

Where \( u_{mn} \) is 1 if the PRB \( n \) is assigned to the user \( m \) and 0 if not.

Associated to the SINR value, the UE will obtain a given combination of modulation and coding, and therefore a given capacity (expressed in bits/s). Two different strategies, for different situations, have been used in the project:

- Using Shannon’s capacity formula (2.2) which gives an upper bound on the capacity values. Used to calculate the real capacity.
- Using SINR values to relate them with the capacity like in [6]. This strategy is used at the beginning to calculate the worst case.
From the SINR, the upper bound on achievable capacity can be calculated on a PRB $n$ using the Shannon’s capacity formula:

$$C = B_n \cdot \log_2(1 + \text{SINR})$$

(2.2)

Where $B_n$ is the bandwidth of the PRB $n$.

Assuming all these it can be considered three different values for the SINR$_{in}$:

- The realistic value with real interference level (SINR$_{in,real}$).
- The ideal value with no interference (SINR$_{in,ideal}$).
- The worst value assuming that all the eNBs use all the resources simultaneously (SINR$_{in,worst}$).

All these values have their corresponding capacities $C_{in,real}$, $C_{in,ideal}$ and $C_{in,worst}$ respectively. The best scheduling algorithm will be the one that guarantees a minimum value for the capacity loss, expressed as follows:

$$C_{in,loss} = C_{in,ideal} - C_{in,real}$$

(2.3)

In terms of a scenario with different cells, the best scheduling for cell $b$ is the one that achieves the maximum possible capacity for the maximum number of UEs in the cell, while simultaneously minimizes the capacity loss over the rest of cells.

The study of this project is done considering several UEs per cell randomly distributed. The scheduling done follows some rules detailed below:

- The SINR$_{in,worst}$ is obtained for all the UEs as detailed before. According to the value obtained the UEs are classified as internal and cell edge UEs (in one algorithm will be also necessary classify users as intermediate).
- For each cell, start assigning one PRB per UE, starting with the one with highest SINR. After each assignment the SINR$_{in,real}$ of the UE is recalculated and also the SINR$_{in,real}$ of the UEs that have also assigned the same PRB.
- If after assigning one PRB to each UE, there are still free PRBs, there are two different assignment procedures to check:
o RR assignment: The free PRBs start being assigned in the same way; first to the UEs with higher $\text{SINR}_{\text{in,worst}}$.
o PF assignment: The free PRBs start being assigned to the UEs with worst values of $\text{SINR}_{\text{in,worst}}$.

- Proceed with the second cell following the same steps.
- After finishing store the parameters that are important in terms of statistics (UEs throughput in bits/s, cell efficiency in bits/s/Hz, SINR values, etc.) and start again with a new distribution of UEs in the scenario.

The scheduling strategies analyzed in this project can be implemented in a complete distributed system, with no coordination, because it has been decided previously which are the bands and the power levels associated to each cell and subband. So the eNB only have to choose which is the best PRB (and the number of PRBs) for a given UE based on its quality indicators (in this case on its SINR).

### 2.2. Fixed Reuse

Reuse 1 and reuse 3 consider fixed power per PRB ($P_{\text{max}}$). The main issue of reuse 1 is the interference due to the absence of frequency planning. In this method all the cells have available the whole subbands with the same power level. This makes reuse 1 suitable for scenarios with low traffic because in high traffic scenarios the interference will be very high. Figure 2.1 shows the reuse 1 method.

On the other hand, reuse 3 makes available $1/3$ of the subbands for every three cells. In this manner, the interference is reduced, what improves the situation of
cell edge users although the global results of the cell are worse. This method is better in high load scenarios due to its frequency planning that can be observed in Figure 2.2.

![Reuse 3](image1.png)

**Fig. 2.2** Reuse 3

### 2.3. Mixed Scenario

Using this scheduling technique means two things: the first is cell edge users are allocated using reuse 3 and the second is that central users get resources following reuse 1 method.

In Figure 2.3 can be observe the scheduling method.

![Mixed Scenario](image2.png)

**Fig. 2.3** Mixed Scenario
As happens with the fixed reuse, the power level is also $P_{max}$. In this case the eNB starts assigning resources to the central users, but using different subbands that those “reserved” for cell edge users. If the subbands are not enough it starts assigning those initially “reserved” for the cell edge users. This means that if there are not cell edge users, the central ones can use the whole band. On the other hand, cell edge users cannot use more than the subbands that have “reserved” and if there are no central users 2/3 of the subbands will not be used.

2.4. 3 type of users

Figure 2.4 shows the method of the 3 types of users.

In this method all the subbands are divided initially in three groups, each of them with a different power level associated. The algorithm starts assigning resources to the central users (those with a higher SINR) that will be the ones that will have the lowest power level associated. If there are not enough subbands the eNB will assign those “reserved” to middle users but using also the lowest power level. The same will be done with the middle users and finally if still are enough free PRBs they will be assigned to the cell edge users.

2.5. Soft Frequency Reuse

This scheduling technique priory 1/3 of the band in each cell and also adds a power difference between prioritized and nonprioritized resources. Each eNB have available the whole band to assign PRBs to the users.
In Figure 2.5 can be seen that the prioritized PRBs have a power level equal to $P_{\text{max}}$ while the rest have a value of $\alpha P_{\text{max}}$ with $\alpha$ lower than 1.

The variable $\alpha$ determines the ratio of the reduced power level with the full power level. If this is not considered as a fixed value it is useful to better adapt the different load conditions while controlling the interference levels. For low traffic it can be used with a value close to one being the results close to the ones obtained with reuse 1 and for high traffic loads if $\alpha$ is close to 0 it will performs as reuse 3.

As before, the cell is divided considering central users and cell edge users regarding its SINR value. The subbands reserved for central users are those with a power level equal to $\alpha P_{\text{max}}$ while the subbands related to a power level of $P_{\text{max}}$ are for the cell edge users. In this method if there are free subbands in a certain type user the others cannot use these subbands.

### 2.6. Reuse Partitioning

This method is similar to the soft frequency reuse since it also divides the band in two parts: low and high power subbands. In this case, the parameter that governs the ratio between low and full power is $\beta$, which must be also lower than 1. Another parameter that appears in this method is $b$ that indicates the percentage of low power subbands in relation with the total number of subbands.

Low power subbands are those assigned to the central users, with a power level equal to $\beta P_{\text{max}}$ and where reuse 1 is used. On the other hand, the subbands with a power level of $P_{\text{max}}$ are the assigned to cell edge users and where reuse 3 is implemented.
In Figure 2.6 can be observed the way that this method uses the resources.

\[ U = \frac{1}{N_{PRB} \cdot P_{max}} \cdot \sum_{i \in N_{PRB}} P_i = \frac{P_{tot}}{N_{PRB} \cdot P_{max}} = \frac{P_{tot}}{P_{tot, max}} \] (2.4)

Where \( N_{PRB} \) is the total number of subbands, \( P_{max} \) is the maximum power used on a subband and \( P_i \) is the power used in the subband \( i \).

In the fixed reuse methods, reuse 1 have a utility factor equal to 1 while reuse 3 gets 1/3. In soft frequency reuse one third of the band takes a power level of \( P_{max} \) and the rest have a level of \( \alpha P_{max} \), what means:

\[ U = \frac{1}{N_{PRB} \cdot P_{max}} \cdot \left[ \frac{N_{PRB}}{3} \cdot P_{max} + \frac{2 \cdot N_{PRB}}{3} \cdot \alpha P_{max} \right] = \frac{1+2\alpha}{3} \] (2.5)

In reuse partitioning method, \( bN_{PRB} \) of the subbands use a power equal to \( \beta P_{max} \) while the rest of the subbands use \( P_{max} \). This means that the utility factor is equal to:

\[ U = \frac{1}{N_{PRB} \cdot P_{max}} \cdot \left[ \frac{bN_{PRB}}{3} \cdot \beta P_{max} + \frac{2 \cdot N_{PRB}}{3} \cdot P_{max} \right] = \frac{1+2\alpha}{3} \] (2.5)
\[ U = \frac{1}{N_{PRB} \cdot P_{max}} \cdot \left[ b \cdot N_{PRB} \cdot \beta P_{max} + \frac{1-b}{3} \cdot N_{PRB} \cdot P_{max} \right] = \frac{3b\beta + 1-b}{3} \] (2.6)

With (2.5) and (2.6) the value of the different parameters to compare properly both methods can be obtained.
CHAPTER 3. STATIC SIMULATIONS

In this chapter the performance and results of the simulations with a static scenario are explained in detail. Firstly, the scenario’s parameters are defined. Then fixed Reuse 1 and Reuse 3 strategies are compared while in the next sections other scheduling schemes are explained being always compared with Reuse 1 and 3 strategies. To finish a comparison between all the scheduling strategies is briefly explained.

3.1. Simulation parameters

The main parameters of the scenario are defined in Tables 3.1 and 3.2, being most of them extracted from the 3GPP’s specifications for evolved UTRA [7].

A static network has been considered with 21 sites and three cells per site. The number of users has been established in 900 and they are assigned randomly to the different cells having, in average, 15 users in each cell. The maximum allowed power $P_{tot} = 49$ dBm ($\approx 80$ W) is the maximum power for each cell and per subband, the transmitted power is $P_{max} = 80/108$ W since there are 108 subbands to transmit in each cell.

Table 3.1 Scenario parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier frequency</td>
<td>2 GHz</td>
</tr>
<tr>
<td>Transmission bandwidth</td>
<td>20 MHz</td>
</tr>
<tr>
<td>Sub-carrier spacing</td>
<td>15 KHz</td>
</tr>
<tr>
<td>OFDM PHY parameters</td>
<td>CP of 4.69 $\mu$s 7 modulation symbols/sub-frame (2 for control)</td>
</tr>
<tr>
<td>FFT size</td>
<td>2048</td>
</tr>
<tr>
<td>Number of useful sub-carriers</td>
<td>1200</td>
</tr>
<tr>
<td>OFDM symbol duration</td>
<td>71.43 $\mu$s</td>
</tr>
<tr>
<td>Number of sub-carriers per PRB</td>
<td>12</td>
</tr>
<tr>
<td>Number of PRBs/RBGs</td>
<td>108/27</td>
</tr>
<tr>
<td>Sub-frame duration</td>
<td>0.5 ms</td>
</tr>
<tr>
<td>Number of PRBs/RBGs</td>
<td>4</td>
</tr>
<tr>
<td>TTI length</td>
<td>1 ms</td>
</tr>
<tr>
<td>Number of OFDM symbols per TTI</td>
<td>14 (4 for control)</td>
</tr>
<tr>
<td>Frame duration</td>
<td>10 ms</td>
</tr>
<tr>
<td>Superframe duration</td>
<td>600 ms</td>
</tr>
<tr>
<td>Transmission model</td>
<td>Localized</td>
</tr>
<tr>
<td>---------------------------------</td>
<td>-------------------------------</td>
</tr>
<tr>
<td>Power delay profile</td>
<td>EPA channel model Pedestrian speed 3 km/h</td>
</tr>
</tbody>
</table>

### Table 3.2 Link level parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel Coding</td>
<td>Turbo code basic rate 1/3</td>
</tr>
<tr>
<td>Code block sizes</td>
<td>40-120 bits</td>
</tr>
<tr>
<td>Rate Matching and H-ARQ</td>
<td>According to [8] (release 8). Max 4 IR transmissions</td>
</tr>
<tr>
<td>AMC formats</td>
<td>QPSK: 1/3, 1/2, 2/3, 4/5 16QAM: 1/2, 2/3, 4/5 64QAM: 2/3, 4/5</td>
</tr>
<tr>
<td>Channel estimation</td>
<td>Ideal</td>
</tr>
<tr>
<td>Antenna scheme</td>
<td>SISO/MIMO</td>
</tr>
<tr>
<td>Cell radius</td>
<td>500 m</td>
</tr>
<tr>
<td>Path loss expression</td>
<td>$L_{\text{path loss}} = \beta \cdot R^\alpha$ with $\beta=33.9$ and $\alpha=3.76$</td>
</tr>
<tr>
<td>Shadow fading</td>
<td>standard deviation 8 dB decorrelation distance of 50 m</td>
</tr>
<tr>
<td>Number of active UEs per cell (infinite buffer per user)</td>
<td>15 (in average) and 900 UEs in the scenario</td>
</tr>
<tr>
<td>Number of cells</td>
<td>21 trisectorial cells</td>
</tr>
<tr>
<td>Maximum transmitted power</td>
<td>49 dBm</td>
</tr>
<tr>
<td>Mobile noise figure</td>
<td>9 dB</td>
</tr>
<tr>
<td>Antenna gain</td>
<td>18 dBi</td>
</tr>
</tbody>
</table>

### 3.2. Simulation results

The parameters analyzed and compared for the different strategies are the SINR, the average cell throughput (histograms and CDF) and the users’ throughput, in some cases separating them by user’s type (closer or far from the eNB or what is equivalent with high or slow SINR).

SINR and capacity statistics have been obtained by averaging only the results from the central cells (those surrounded completely by other cells). As indicated before, the network has 900 randomly allocated users (around 15 users per cell) and the statistics are the result of averaging 100 snapshots. In this case traffic models have not yet been considered, so in this analysis users have infinite buffers.
With all these considerations, all the scheduling strategies defined in Chapter 2 will be analyzed and compared in detail. Both assignment algorithms have been simulated but almost all the results are very similar so only in the cases that the differences can be observed the graphics will appear.

### 3.2.1. Reuse 1 and Reuse 3

Figure 3.1 represents the Cell SINR CDF for reuse 1 and reuse 3, henceforth R1 and R3 respectively, strategies. As expected, R3 achieve higher SINR values (there is approximately 10 dB difference from the 60\textsuperscript{th} percentile to the 95\textsuperscript{th} percentile). This improvement in SINR, and consequently in the PRB’s throughput, only compensates the reduction in cell’s bandwidth (from B to B/3) being the cell’s capacity a while worse than for R1. This can be observed in Figure 3.2 where is represented the CDF of the cell throughput (in bits/s/Hz).

![Cell SINR CDF](image-url)
To see the reason why in terms of capacity R3 is worse than R1 it can be observed Figure 3.3 that represents the histogram of the cell throughput.

The figure above (Figure 3.3) represents the number of cells that have a certain throughput. As happens in the Figure 3.2 it can be seen that in R3 most of the cells have throughputs below 1.25 bits/s/Hz while in R1 are more distributed. The reason is that in R3 only 1/3 of the bandwidth is used and the graphic considers the average throughput of each cell. This means that users with high throughput are compensated by users with a lower value while in R1, that all the bandwidth is used; this compensation affects less to the results. To know the
real throughput of the users in each system Figure 3.4 (the numbers of users are considered between two values of the x axis) detail this fact where can be seen that there are users with high values that in R3 case are compensated by users with lower values. This means that R3 system performs better for users that want to transmit at lower rates.

![Users throughput histogram](image)

**Fig. 3.4** Histogram of User throughput in a reuse 1 and reuse 3 system

It can be also considered the CDF of the values of Figure 3.4 where can be observed that from the 0th percentile to the 35th percentile the difference between throughputs is around 180 Kbits/s. As expected looking the previous graphics, in R1 system users achieve higher throughput values due to the fact that they could have more PRBs available to transmit than in R3.

![Users throughput CDF](image)

**Fig. 3.5** CDF of User throughput in a reuse 1 and reuse 3 system
Another point of view is representing the SINR and the throughput values depending on the type of user: central or cell edge. As we can see in Figure 3.6 R3 achieve better SINR values in both types of users as happens in Figure 3.1. In like manner, this only compensates the reduction in user's throughput. In Figure 3.7 it can be observed that users under R1 scheduling achieve better throughput rates due principally to the fact that in this system there are more PRBs assigned to each user.

In this case there is a difference in results if we use one type of assignment or the other. Figure 3.7(a) represents the results using the RR assignment while Figure 3.7(b) represents the case of using the PF assignment. It can be seen that with PF assignment the number of users with higher throughput is reduced because this assignment prioritize the PRBs allocation to the user with lower SINR values. This election provokes that the users with higher SINR receives less PRBs than the ones with lower values so the results is that with PF assignment the number of users with lower throughput is higher than with RR assignment.

![Users SINR CDF](image)

**Fig. 3.6** CDF of User SINR in a reuse 1 and reuse 3 system
3.2.2. Mixed Scenario

From now on and for each of the rest scheduling algorithms there will be only represented the results of the cell SINR CDF and the cell throughput. In Annex A can be found the other graphs represented and compared.

Figure 3.8 represents the Cell SINR CDF for the mixed scenario compared with R1 and R3 strategies. As can be observed, the results of the mixed scenario are closer to R1 than to R3. The result is logical since the mixed scenario uses R3 only for the cell edge users, but if there are free bands it can be used by the
central ones. So, in most of the cases the system works like R1 but improving the cell’s SINR.

![Figure 3.8 CDF of SINR in a mixed system](image)

In Figure 3.9 it can be observed that mixed scenario obtains better throughput values than R1 and R3. The reason is that almost all the PRBs are reserved for central users that have less interference and consequently they achieve higher rates contributing in higher values of cell throughput. This fact can be seen in Figure 3.10 where most of the cells have better rates than R1 and R3 systems.

![Figure 3.9 CDF of Cell throughput in a mixed system](image)
3.2.3. 3 type of users

Figure 3.10 represents the Cell SINR CDF for the 3 type of users scenario compared with R1 and R3 strategies. As can be observed, the results are closer to R1 than to R3. From the 0th percentile to the 50th percentile this system improves the SINR but for the other values R1 works better.

Regarding to the cell throughput Figure 3.11 shows that the response of the system is very close to R1. This happens because as in R1 all the users have approximately the same number of PRB’s to transmit. The reason why they are not identically is that in R1 all the PRBs transmit at the same power while in the 3 type of users system each user transmit at a certain power depending on which type of user is.

![Cell SINR CDF](image1)

**Fig. 3.10** CDF of SINR in a 3 type of users system

![Cell throughput CDF](image2)

**Fig. 3.11** CDF of Cell throughput in a 3 type of users system
3.2.4. Soft Frequency Reuse

Figure 3.12 represents the Cell SINR CDF for different soft frequency reuse schemes, henceforth SR, with different utility factors (this is with different $\alpha$ values). The different schemes are also compared with R1 and R3 strategies and it can be observed that all the results are between both figures being closer to R1. This is due to the fact that as the central users transmit at $\alpha P_{\text{max}}$ they have lower SINR values and consequently lower throughput. As lower is the utility, worse are the results except if the utility factor is 1/3 ($\alpha=0$) that the results are closer to R3. The explanation is that if $U=1/3$ this means that is like R3 but the values are not the same because the reuse 3 is only done to the cell edge users that have worse SINR values than the central ones. Furthermore, if $U=0.4$ what means $\alpha=0.1$ the results are quasi identical to R1 and it can also be observed that if the utility factor is 1 (what means $\alpha=1$) the results are exactly the same as the mixed scenario. It is important to notice that SR is a technique not oriented to improve the SINR, but only to improve the throughput of the cell edge UEs.

As is expected, in Figure 3.13 the throughput if $U=1/3$ is the worst because as it had been indicated in this case only the cell edge users are transmitting in one third of the total subbands. As in the Figure 3.12 if $U=0.4$ the results are the same as R1.

![Cell SINR CDF](image)

**Fig. 3.12** CDF of SINR in a soft frequency reuse system

3.2.5. Reuse Partitioning

Figure 3.14 represents the Cell SINR CDF for different reuse partitioning schemes, henceforth RP, with different utility factors (this is with different $\beta$ values) and with different number of PRBs for the central users (called $b$). The different schemes are also compared with R1 and R3 strategies and it can be observed that all the results are between both figures.

In figure 3.14(a) can be seen that the utility factor does not affect to the result because all the results are the same. With this system low SINR values disappear and the CDF obtained is narrower (the variation is between 3 and 20 dB) while in the R1 the variation is between -8 and 15 dB. Till nearly the 20\textsuperscript{th} percentile the SINR values are also better than for R3 case, being the 9/27 division the worst (that is the closer to R3 behavior).

Regarding Figure 3.14 (b) and (c) the results are the same except in the case of (b) that the SINR values are always between R1 and R3 responses and the graph is a bit closer to R3.
(a) Cell SINR with different utility factors and different $b$ values

(b) Cell SINR with $\beta=0$ and different $b$ values

(c) Cell SINR with $\beta=1$ and different $b$ values

Fig. 3.14 CDF of SINR in a reuse partitioning system
If the different facts are compared it can be observed in Figure 3.15(a) that again the transmitted power level does not affects to the results but this scheduling scheme is clearly better than R1 and R3. Only if $b=9/27$, what means that 1/3 of the band is for central users with reuse 1 and the others 2/3 are for cell edge users under reuse 3 scheme, the results are closer to R1.

$\beta=0$ (Figure 3.15(b)) means that the power level of the subbands “reserved” ($\beta P_{\text{max}}$) to the central users is also 0 so they do not contribute to the results but the cell edge users can only use their assigned PRBs. As $b$ increases, the number of free PRBs for the cell edge users decreases so is logical that RP with $b=9/27$ obtains higher throughput than with $b=21/27$. The results are worse than R3 due to the fact that the number of PRBs per cell is lower and there are not central users which use to have better rates.

In Figure 3.15(c) the situation is the same explained in the (a) case.
3.3. Conclusions

The main goal of studying different scheduling methods is the improvement of the throughput. After having all the results, some conclusions can be extracted.

Regarding to the cell throughput what can be seen is that the RP method with $b=21/27$ is the one that obtains better rates. For example, in the 60th percentile achieves 360 Kbits/s. The problem with this system could be the fact that cell edge users have “reserved” less than 1/3 of the subbands but if this does not suppose a problem this is the method that provides better values of throughput. On the other hand, if this supposes a problem, there are other systems that also provide high values. Mixed scenario in the 60th percentile achieves 290 Kbits/s, and in the same way, SR with $U=1$ or even with $U=0.9$.

If now what is observed is the users’ throughput divided in central and cell edge users, what can be seen is that there is a problem to find a method that improves the throughput of both type of users. The one that fits both conditions is SR method with $U=0.4$, where the results are good for both. Cell edge users have better rates than R1 and R3, achieving in the 60th percentile 1.44 Mbits/s. On the other hand, central users’ rates do not exceed the R1 and R3 results but it has a difference with R3 around 180 Kbits/s, obtaining in the 40th percentile rates of nearly 2 Mbits/s. But if what is desired is to improve one of the two types of users mixed scenario, for example achieve very high values for central users while the cell edge obtain low values. Depending on what users will be improved there are several solutions but almost all at the expenses of reducing the throughput of the other users.
CHAPTER 4. DYNAMIC SIMULATIONS

This chapter considers the simulations with a more realistic load. Since in the static simulations have been assumed full buffers, in this case the users have certain load depending on what type of information want.

In a first part the characteristics of the scenario are defined being almost all the same than in the static scenario. The traffic model in the different cases is also defined and to finish, the performance of the different scheduling algorithms explained in Chapter 2 are compared.

4.1. Simulation parameters

The main parameters of the scenario are the same than the defined in Tables 3.1 and 3.2. As before the network has 21 sites and three cells per site and the maximum allowed power is $P_{tot}=49$ dBm.

There are some different parameters with the static scenario that can be observed in Table 4.1.

Table 4.1 Scenario parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load</td>
<td>Average of 1, 4, 7, 10, 30 and 50 users per cell</td>
</tr>
<tr>
<td>Simulation time</td>
<td>1000 TTIs (1 TTI last 1 ms)</td>
</tr>
<tr>
<td>Web traffic</td>
<td>200 kB object size</td>
</tr>
<tr>
<td>VoIP traffic</td>
<td>32 B packet size</td>
</tr>
<tr>
<td></td>
<td>1 packet every 20 ms</td>
</tr>
</tbody>
</table>

Another important difference is the handover. As the implementation is a dynamic scenario, the users will change its position. For this reason, what has been considered is hard handover where when the user is going to change its cell link, the simulator firstly breaks the connection with the cell where the user is before connecting to the new.
4.1.1. Scenario characteristics

There are several considerations in the dynamic scenario such as the number of users, the simulation time and the traffic models. All the considerations that has been taken into account for the scenario simulation are the following explained.

4.1.1.1. Users

The different scheduling methods are simulated for an average of 1, 4, 7, 10, 30 and 50 users per cell. The users are removed when they have finished their web downloads. If there are 1, 4, 7 or 10 users per cell after two web downloads are removed; if there are 30 users per cell, they are removed after four web downloads and finally if the number of users per cell are 50, they are removed after five downloads.

When a user is removed, a new user is created at a random position in the scenario to keep constant the average number of users. The users are removed when they reach their web downloads’ limit but if a user never arrive to their limit it last for the entire simulation.

4.1.1.2. Simulations

Depending on the users the number of simulations varies. If the number of users per cell is 1 or 4 the simulation runs four times; if there are 7 users per cell, three times; two times for 10 users per cell and only one if there are 30 or 50 users per cell. When a simulation finishes to start a new one the users are redistributed along the scenario and the resources are allocated from the beginning again. Each simulation runs for 1000 TTIs what means 1 second.

4.1.1.3. Traffic models

In each simulation and randomly, each user is defined as VoIP or web user. The traffic parameters [3] used in the simulator for every case are defined below.

Figure 4.1 shows the users’ plane protocol stack.
VoIP traffic  Web traffic

<table>
<thead>
<tr>
<th></th>
<th>UDP</th>
<th>TCP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IP</td>
<td></td>
</tr>
<tr>
<td></td>
<td>RLC</td>
<td></td>
</tr>
<tr>
<td></td>
<td>MAC</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PHY</td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 4.1 User plane protocol stack**

Each protocol adds a header to the information that is necessary to consider for the simulations. For this reason, the headers considered in each case are the following defined:

**Web traffic model**
- **TCP header**: 24 bytes.
- **IP header**: 20 bytes.
- **RLC header**: 16 bytes.
- **MAC header**: 14 bytes.
- **PHY**: All web pages are 200 Kbytes each one.

**VoIP traffic model**
- **UDP header**: 24 bytes.
- **IP header**: 20 bytes.
- **RLC header**: 16 bytes.
- **MAC header**: 14 bytes.
- **PHY**: Each user generate packets of 32 bytes every 20 ms. The packet consist of a RTP header of 12 bytes and two 10 ms frames of 8 Kbits/s coded speech (ITU-T standard G.729).

### 4.2. Simulation results

The parameters analyzed in the dynamic scenario are the number of used subbands and the cell throughput, both for each scheduling algorithm detailed in Chapter 2.

In this case the number of users varies in each simulation and the results obtained are compared in terms of cell throughput and used subbands. As before, the scenario has 63 cells and the users are equally distributed.
4.2.1. Reuse 1 and Reuse 3

Figure 4.2 represents the number of used subbands for R1 scheme. As is logical when there is only one user per cell in the 70 percent of the cells only one or as much two or three subbands will be used. The reason is, as it has been explained, when a user finishes its download changes its position and this can make that more than one user stays at the same cell. In the same way this means that there will be some cells without users and this is the reason why the 20 percent of the cells do not use any subband.

In the other cases, all the subbands are used because although the users change their position, the probability of having a cell without users is very low.

If the cell throughput is observed, Figure 4.3 shows that in the 1-user case the cell throughput achieved is very low. Is a logical result because although the interference between users is small, if one user is far away from the base the throughput is also lower.

If the number of users increase this implies that the interference will be also higher so the cell throughput will decrease. As can be observed the situation that improves the cell throughput is that where the number of users per cell is equal to four.
Regarding to R3 algorithm the results can be observed in Figure 4.4 and 4.5.

As explained before, in R3 each cell has available only one third of the subbands and that is what can be observed in the Figure 4.4. In all the cases, the maximum number of subbands used is 36 and the only difference between them is the percentage of cells without users that can be in the scenario. As before, the 20 percent of the cells with initially one user in certain moment of the simulation do not have any user to serve and in the case of 4 users there are less than a 10 percent of the cells without users.

In the case of the cell throughput, as in all the user cases the cells only have 36 subbands available the values obtained are very similar and do not depend in a
high manner of the number of users per cell. Only in the case of having one user the throughput achieved by the cell is lower than the other situations. In Figure 4.5 can be observed the results obtained.

![Cell throughput CDF in R3](image)

**Fig. 4.5** Cell throughput CDF in reuse 3 scheme

### 4.2.2. Mixed Scenario

The mixed scenario algorithm joins R3 and R1 as has been detailed. In Figure 4.6 can be observed the number of subbands used when applying this scheme.

![Used subbands in Mixed scenario](image)

**Fig. 4.6** Subband utilization CDF in a mixed scheme
As happens in R3 algorithm, 36 subbands is an important point of the result. This is because if all the users in a certain cell are cell edge they can only use these 36 subbands so it can be observed that except the case of 50 users per cell, in all the cases there is a certain probability of having only cell edge users or as much VoIP central users, which only need one subband per TTI. In the case of having 50 users per cell do not exist the possibility of having only cell edge users so the whole subbands are always assigned.

In the Figure 4.7 is shown that between the 0th percentile and the 30th percentile the scenario with 50 users per cell improves the cell throughput due to the fact that all the subbands are used what increase the values. From this point on, the case of having 30 users achieve better values and basically is because the interference, that is higher in the 50-user case, limits the throughput.

![Cell throughput CDF in Mixed scenario](image.png)

**Fig. 4.7** Cell throughput CDF in a mixed scheme

### 4.2.3. 3 type of users

The case of the three different types of users can be observed in Figure 4.8. If the number of users per cell is higher than four all the subband are used in each TTI. If each cell initially only has 1 user, in a certain moment some cells could not have users to serve so there is a probability of the 20 percent of not using any subband. Furthermore, the probability of using only one or two subbands is around the 70 percent what means that the users served by the cell are VoIP users because in the case of being web users, all the subbands are used.

In the case of having 4 users per cell the situation is the same but in this case, a cell always have users to serve and the minimum number of used subbands is around four.
Regarding the cell throughput what is shown in Figure 4.9 can be observed that from the 0\textsuperscript{th} percentile to the 90\textsuperscript{th} percentile as higher is the number of users per cell, better are the throughput values achieved. The reason is that when there are several users they can be of different types so although the cell edge can reduce the cell throughput, the central ones compensate the values.

From the 90\textsuperscript{th} percentile on the best situation is having only one user. If this user is central, what can be possible because there is few interference, and also is a web user it will have all the subbands available and it will achieve higher throughput what directly can be seen in the cell throughput.
4.2.4. Soft Frequency Reuse

Fig. 4.10 Subband utilization CDF in a soft frequency reuse scheme
What can be observed in Figure 4.10 is that if $\alpha$ is higher than 0.1 the results obtained are nearly the same (the differences in probabilities are due to the different users' distribution used in each case). There are two main points to emphasize. The first one is 36 subbands that if there are only cell edge users this is the maximum number of subbands that can be assigned and the other point is 72 subbands that if in the other hand all the users are central, is the maximum number of subbands that can be allocated. When $\alpha$ is 1 the results are not the same as in R1 because each type of user (central or cell edge) has a certain number of subband available while in R1 all the users can use any subband.

If $\alpha$ is equal to 0 the response related to the number of subbands used is the same as in R3 because two thirds of the subbands have a transmitted power assigned of 0 W.

If the cell throughput is analyzed, Figure 4.11 shows that if $\alpha$ is 0 the cell throughput behavior is the same as in R3 but with lower values due to the fact that in this case only the cell edge users will be using the subbands what means lower users' throughput and consequently lower cell throughput.

For higher $\alpha$ values, between the 0th percentile and the 60th percentile the 50-user case is the one that achieve better rates because, as before, as there are more users there can be more central users too that improve the results. From the 60th percentile this case gets worse due to the high interference that limits the throughput values and scenarios with fewer users per cell achieve better rates.
Fig. 4.11 Cell throughput CDF in a soft frequency reuse scheme

4.2.5. Reuse Partitioning

In the reuse partitioning algorithm can be compared several points. The two main points to compare are the results with different utility factor values ($U$ or $\beta$) and the results with different percentage of reduced power subbands ($b$).

Figure 4.12 shows the results obtained with two different utility factors. As can be observed the results are nearly the same, as is logical. The differences, as happens in the SR algorithm, are due to the fact that the initial users’ distribution is not the same for the algorithms.
Fig. 4.12 Subband utilization CDF in a reuse partitioning scheme with different utility factors

As happens with the number of subbands used, the cell throughput shown in Figure 4.13 has the same behavior and does not depend on the value of the utility factor. As has been detailed in section 3.2.4, the transmitted power does not affect to the cell throughput and the differences that can be observed are due to the differences in the scenario, as before.
Another point to compare is the number of subbands used with different values of $b$. The results are shown in Figure 4.14.

The main fact to emphasize in this situation is that the 108 subbands are never used in a same cell. This is because $b$ indicates the subbands available to the central users and the rest are divided by three so a cell never has the whole band to allocate resources.

If $b=9/27$ the maximum number of subbands that a cell can use is 60, if $b=15/27$ the maximum is 76 and if $b=21/27$ the maximum is 92. These maximum values can be observed in the figures below.
So, as higher is the number of subbands “reserved” for central users higher is the total available subbands in a cell. In the same way, if a cell has more subbands allocated its throughput will be also higher. This fact can be seen in
Figure 4.15 where higher values of $b$ improve the cell throughput because the central users always achieve better rates than the cell edge ones.

This situation is quite different than the detailed in the static scenario due to the fact that in this case there are users that only need one subband to transmit.

**Fig. 4.15** Cell throughput CDF in a reuse partitioning scheme with different $b$ values.
As it has been indicated, different utility factor values does not affect to the cell throughput but what can be compared is what happens if there are considered the two ends: $\beta=0$ and $\beta=1$.

If $\beta=0$ the situation will be the opposite than the detailed in Figure 4.14 and 4.15. In this case, as there are only available subbands for the cell edge users, as higher in $b$ lower in the number of subbands to use in a cell.

If $b=9/27$ the maximum number of subbands that a cell can use is 24, if $b=15/27$ the maximum is 16 and if $b=21/27$ the maximum is 8. This is shown in Figure 4.16.

In the same manner, as higher is $b$ lower are the cell throughput values achieved. This is due to the fact that when increasing $b$, cell edge users has
fewer subbands available per cell and what is also important is that these users achieve lower rates. Figure 4.16 shows this behavior.

![Cell throughput CDF in RP with $\beta=0$ and $b=9/27$](image1)

![Cell throughput CDF in RP with $\beta=0$ and $b=15/27$](image2)

![Cell throughput CDF in RP with $\beta=0$ and $b=21/27$](image3)

**Fig. 4.17** Cell throughput CDF in a reuse partitioning scheme with $\beta=0$ and different $b$ values

To finish with this algorithm, the results related to the number of used subbands obtained considering $\beta=1$ are the same than the ones observed in Figure 4.14. Regarding the cell throughput, as happens in Figure 4.13, the different values of the utility factor (or $\beta$) do not affect in a high manner to the results so the ones obtained without considering different power levels($\beta=1$) are nearly the same than the showed in Figure 4.15.
CONCLUSIONS

3GPP LTE standard does not specify a particular scheduling algorithm to be used so the goal of this master thesis has been the definition, software implementation and comparison of different algorithms and strategies to find which can fit better.

This thesis has investigated four possible choices: mixed scenario, 3 types of fixed reuse schemes, reuse partitioning and soft frequency reuse; always comparing them with the traditional algorithms reuse 1 and reuse 3. All these algorithms have been evaluated in two different scenarios: static and dynamic. The static scenario considers full data buffers in all the cases while the dynamic scenario divides the users in VoIP or web users with fixed data to download in the web case or a minimum throughput to achieve for the VoIP users.

In the static case the comparison has been done based on several quality indicators as the SINR and throughput, given per cell, per user and also for the different type of users. The main objective of the scheduling algorithms is to improve the cell throughput while accomplishing user service requirements. Regarding to the cell throughput what can be seen is that reuse partitioning with $b=21/27$ is the method that obtain better rates but it also has a problem because with 108 subbands only 8 are “reserved” for cell edge users. Furthermore, mixed scenario or soft frequency reuse with a utility factor around 1 are also good options if the desire is to improve the cell throughput.

If the goal is the users’ throughput there is not a specific method that improves in high manner both cell edge and central users’ throughput. The best option in this case could be soft frequency reuse with a utility factor of 0.4 which is the method that fits better.

Talking about the dynamic scenario, the goal in this case has been comparing the number of used subbands and the cell throughput achieved. As has been indicated the objective of the scheduling algorithms detailed is to improve the throughput so in this case and considering high traffic load the best option is, as happens in the static scenario, reuse partitioning with $b=21/27$ or even soft frequency reuse with $\alpha=0.85$. These are the two options that achieve better cell throughput values but also with other values of $b$ or $\alpha$ and depending on the operators’ requirements other options could be also a good choice.

Although all these algorithms have been designed with the objective of reducing inter-cell interferences, a next step in this way could be considering the study of adaptive power masks which could help to reduce even more the interference and consequently to improve the throughput values.
ANNEXES
ANNEX A

In this annex are detailed the results obtained for the different scheduling algorithms explained in Chapter 2 except for reuse 1 and reuse 3 that all the results appear in Chapter 3.

All the results are for the static scenario.

A.1. Mixed Scenario

As in Figure 3.9 can be observed mixed scenario obtains better throughput values than R1 and R3. The reason is that almost all the PRBs are reserved for central users that have less interference and consequently they achieve higher rates contributing in higher values of cell throughput. This fact can be seen in Figure A.1 where most of the cells have better rates than R1 and R3 systems.

![Fig. A.1 Histogram of Cell throughput in a mixed system](image)

The higher rates in the cell throughput (Figure A.1) obtained with the mixed scenario indicates that the users have better throughput values but if Figure A.2 is analyzed this is not showed and what can be observed is that with mixed scenario there are more users with lower rates that makes no sense with the results of Figure A.1. The fact is that with mixed scenario due to its scheduling system there are users with very high throughputs. In Figure A.3 is detailed the comparison between systems to check that the results are coherent.
As it can be seen in the Figure A.3, in the mixed scenario there are more users with very high throughput values than in R1 and R3 systems. These users compensate the ones with low values. This is why with this system the cell throughput is improved.

It can be also considered the CDF (Figure A.4) of the values of Figure A.2 and A.3 where can be observed that due to the high number of users with low
throughput in the mixed scenario, users under R1 and R3 systems achieve higher values.

![Users throughput CDF](image1)

**Fig. A.4** CDF of User throughput in a mixed system

To see how this system affects depending the type of user it is interesting to see the results of the SINR and the throughput values divided in central and cell edge users. In terms of SINR (Figure A.5) the mixed scenario works as R1 system. The main reason is that the entire band is used with the same power as R1 and the only difference is that in the mixed scenario cell edge users have given parts to transmit what does not affect in this result.

![User SINR CDF](image2)

**Fig. A.5** CDF of User SINR in a mixed system
Regarding to the users throughput (Figure A.6) is important to see how mixed scenario improves the rates for the central users while the cell edge have worse values. Is logical to have more central users with better values than in R3, basically because with mixed scenario these users have two thirds (or more) of the total number of subbands while in R3 they can only use one third and they have to share them with cell edge users. If it is compared with R1, this improve is due mainly to the fact that in mixed scenario cell edge users have delimited subbands to transmit and they cannot use the others although they do not have enough. Furthermore, this is the reason why cell edge users have worse throughput values than R1 and R3 systems.

![Users throughput CDF](image)

**Fig. A.6** CDF of User throughput in a mixed system

### A.2. 3 type of users

The figure below (Figure A.7) shows the number of cells with a certain throughput. As is observed in the Figure 3.11, most of the cells take throughput values between R1 and R3. Almost all the cells achieve values between 180 Kbits/s and 270 Kbits/s apparently due to the fact that the throughput of the central users and the cell edge ones compensates each other. To check this is necessary to observe the users throughput that can give more information.
The reason why the cell throughput in the 3 types of users system is between the values of R1 and R3 systems can be defined with the Figure A.8. Most of the users achieve higher values than with R1 and R3 systems being almost all above 1.08 Mbits/s and as it can be checked lower rates compensate the higher ones. In Figure A.9 the same fact can be observed. The 25 percent of the users achieve at most 1.08 Mbits/s and till the 50th percentile the response is better. Between the 50th percentile and the 65th percentile, 3 types of users system responds worse than R1 and nearly in the same way that R3. From here on both R1 and R3 are a bit better. From the 65th (1.44 Mbits/s) the response of the 3 types of users starts getting worsen. This can also be observed in the Figure A.8 where from this point the difference in users between systems starts to decrease.
As done before, the graphics can be detailed depending on the type of users. In this case, as its name indicates, there are three different types: central, middle and cell edge. Figure A.10 shows the SINR regarding the type of user. In R3, both central and cell edge users, achieve better SINR values mainly due to the fact that using a reuse 3 the interference are less. They are also worse than central users in R1. This is logical too because although the interference are high due to the fact every cell uses the same subbands than the others the transmission power of the central users in R1 is much higher than in the 3 types of users system.
Very useful is also to see the throughput that each of the users achieve. As expected as before, in Figure A.11 can be seen that central R1 users achieve better rates than central “3Users” mainly because with R1 central users can use more PRBs than in this system that they have to be divided between three types. R3 central users are also better because although they have less than one third of the PRBs to be used, they have less interference and their transmission power us higher. After, as is logical, the results are central, medium and cell edge users of the 3 type of users system, and the worse are the cell edge users in R1 and R3. The cell edge users of this system have a better response due to the fact that they transmit at maximum allowed power, they have more PRBs than R3 to transmit and they have less interference than R1.

![Users throughput CDF](image)

**Fig. A.11** CDF of User throughput in a 3 type of users system

### A.3. Soft Frequency Reuse

In the following Figure A.12 it can be seen the effect of the different utility values. Almost all the cells with U=1/3 have very low values while the others, like U=0.65 and U=0.9, have cells with different and higher throughput values. To see the effect that the utility factor (or $\alpha$) has in the users is more convenient to see the following graphs that are related to the users facts.
In Figure A.13 can be seen more clearly the case of U=1/3. It can be seen that the users are very distributed along all the values. The problem with the cell throughput is that as these values are only for one third of the subbands, the others are free and they do not contribute to the cells throughput. It can also be noted that the number of users for each throughput value in U=0.4 and R1 are very similar, and the same happens with U=0.9 and U=1.

It is important to notice that SR is a technique oriented to improve the throughput of the cell edge users and not to improve the SINR values. This can
be checked in Figure A.14 where although the case of U=1/3 has only cell edge users that supposedly have poor values the result is that together with R1 and U=0.4 schemes obtain the best rates. Compared with R3 the difference in values never exceeds the 180 Kbits/s.

SR with U=0.9 (α=0.85) obtain values very close to U=1, that as indicated before is the same as mixed scenario.

Is also useful to divide the results regarding if they are central or cell edge users. In the Figure A.15 is detailed the SINR for each case. As U=1/3 do not have central users this graph does not appears.

Cell edge users in R1, U=0.9 and U=1 schemes achieve the same SINR values as well as the central users that in these three configurations are also equal. As the utility factor decreases the results are closer to R3 values that are also the same that in U=1/3.

As is logical, central users with U=0.4 have worse SINR values than U=0.65 and as U increases the values get closer to the R3 scheme, due to the transmitted power that is lower in central users as lowest is the utility factor what makes the subbands more susceptible to interference.

**Fig. A.14 CDF of User throughput in a soft frequency reuse system**
As was expected the users that achieve higher throughput are the central ones under the SR with $U=1$ and $U=0.9$. As happens in the mixed scenario the central users achieve very high rates because they dispose of several PRBs for each user. In this case, the results of R1 and SR with $U=0.4$ are not the same. The central users achieve better rates with R1 due to the transmission power but the cell edge are worse (in the 80th percentile the difference is around 360 Kbits/s) due to the interference level related to the power transmission in R1 that is $P_{\text{max}}$. As indicated, SR improves the cell edge throughput and can be seen that with utility factors equal to 0.4 or 1/3 the values are better than for R1 or R3 systems. This is shown in the Figure A.16.
A.4. Reuse Partitioning

As in the previous algorithms the cell throughput histogram (Figure A.17) shows the same aspects. In figure A.17 (a) and (c) can be observed that changing the power level of the central users does not affect to the results. Furthermore in Figure A.17(c) with $\beta=0$, what can be seen is that as higher is $b$ lower are the throughput values that the cells achieve.

(a) Cell throughput histogram with different utility factors and different $b$ values

(b) Cell throughput histogram with $\beta=0$ and different $b$ values
Regarding to the throughput that the users achieve, in Figure A.18(a) can be observed that as happens before different power levels does not vary the results so the explanation made in (a) will be the same for (c). If $b=9/27$ the number of users with high rates is lower than the ones with low rates, this is logical since the cell edge users can transmit in $2/3$ of the subbands. In the case of $b=15/27$ cell edge users have the 45% of the bands to transmit so there are more or less the same number of users with high throughput than with low. To finish, if $b=21/27$ most of the subbands are “reserved” for the central users so is logical that the number of users with high throughput is larger. If $\beta=0$ there are no users with high throughput due to the fact that the subbands assigned to them have a power level equal to 0.
(a) Users’ throughput histogram with different utility factors and different $b$ values

(b) Users’ throughput histogram with $\beta=0$ and different $b$ values
(c) Users’ throughput histogram with $\beta=1$ and different $b$ values

Fig. A.18 Histogram of User throughput in a reuse partitioning system

Figure A.19 shows the CDF of the users’ throughput. In (a) case if $b=9/27$ from the $0^{th}$ percentile to the $30^{th}$ percentile the results are the same as R3 and from the $60^{th}$ to forward the response is closer to R1. If $b=15/27$ the response is worse till the $65^{th}$ percentile when the throughput improves. The fact is there are nearly the same PRBs for central users than for cell edge so is logic that the $60\%$ of the users achieve as much 1.62 Mbits/s. The case of $b=21/27$ is the worst. Cell edge user only have available a low number of PRBs so the rates that achieve are very low. That makes that although the central users could achieve high values the CDF seems worse because the cell edge users affect the results. This could be checked with the Figure (b) that does not have central users. The main difference observed is that in (a) due to the effect of the central users from the $65^{th}$ percentile the values exceed all the ones corresponding to the other cases while in (b) this not happens.
In Figure A.19(b) all the results are worse than R1 and R2 because the cell edge users have lower throughput values and they do not have the contribution of central users’ throughput.

Figure A.19(c) responds exactly the same than (a).

(a) Users’ throughput with different utility factors and different $b$ values

(b) Users’ throughput with $\beta=0$ and different $b$ values
If the results are divided regarding the type of users (central or cell edge) the results in terms of SINR can be observed in Figure A.20. The results are exactly the same in all the cases because as it has been indicated, the power level of the central users does not affect to the results.

The only difference between graphics is that in (b), as before, there are no central users so they do not appear in the results.

Central users, if there are, get the same values that the central ones in R1 while the cell edge users achieve the same SINR values that the ones under R3 scheme.
(a) CDF of User SINR with different utility factors and different $b$ values

(b) CDF of User SINR with $\beta=1$ and different utility factors and different $b$ values
(c) CDF of User SINR with $\beta=1$ and different utility factors and different $b$ values

**Fig. A.20** CDF of User SINR in a reuse partitioning system

As expected (Figure A.21) the users that achieve higher throughput are the central ones under the RP with $b=21/27$ and $b=15/27$. This is a logical result because in these cases the central users have several PRBs to transmit. The scheme that achieve lower throughput is RP with $b=9/27$ due to the fact that the central users only have $1/3$ of the PRBs to transmit. On the other hand, the cell edge users under this scheme are the ones that achieve better rates.

As happens before the cell edge users of the schemes $b=21/27$ and $b=15/27$ are the ones that achieve worse rates. They have less PRBs to transmit so it is normal that these users do not get good values of throughput.

It can also be observed that the results of RP with $b=9/27$ are quasi identical to the ones achieves by cell edge users in R3. Is very logical because in R3 each cell has $1/3$ of the subbands that has to distribute between central and cell edge users while, in RP with $b=9/27$ although the cell edge users only dispose of $2/3$ of the band and each cell has $1/3$ of this part, this is only for the cell edge users so it can be checked that with different schemes the results are nearly the same.
(a) CDF of User throughput with different utility factors and different $b$ values

(b) CDF of User throughput with $\beta=0$ and different utility factors and different $b$ values
(c) CDF of User throughput with $\beta=1$ and different utility factors and different $b$ values

Fig. A.21 CDF of User throughput in a reuse partitioning system

In the reuse partitioning scheme it can be also checked how the average throughput of the cells could change in function of $b$ and $\beta$. To do this it has been elected three different traffic situations:

- 13 central users and 2 cell edge users, what means the 13.3% of cell edge users.
- 7 central users and 8 cell edge users, what means the 53.3% of cell edge users.
- 2 central users and 13 cell edge users, what means the 86.6% of cell edge users.

In the following figures can be observed the results obtained. These graphs are needed to choose the optimum $b$ and $\beta$ in each situation.
(a) Average cell throughput according to the number of low power subbands

(b) Average cell throughput according to $\beta$ values

Fig. A.22 Average cell throughput according to the number of low power subbands and $\beta$ values in a scenario with 13 central users and 2 cell edge users
Annex A

53.3% cell-edge users

(a) Average cell throughput according to the number of low power subbands

(b) Average cell throughput according to $\beta$ values

Fig. A.23 Average cell throughput according to the number of low power subbands and $\beta$ values in a scenario with 7 central users and 8 cell edge users
**86.6% cell-edge users**

(a) Average cell throughput according to the number of low power subbands

(b) Average cell throughput according to $\beta$ values

**Fig. A.24** Average cell throughput according to the number of low power subbands and $\beta$ values in a scenario with 2 central users and 13 cell edge users

Observing the Figures A.22, A.23 and A.24 it can be defined the intervals of optimum $b$ and $\beta$.

- **Case 13.3% cell edge users:**
  - Optimum $b$: Between 20% and 80%.
  - Optimum $\beta$: Between 0.1 and 1.

- **Case 53.3% cell edge users:**
  - Optimum $b$: Between 20% and 60%.
  - Optimum $\beta$: Between 0.1 and 1.
• Case 86.6% cell edge users:
  o Optimum $b$: Between 20% and 60%.
  o Optimum $\beta$: Between 0.1 and 1.

It can be observed that the three situations have common interval values so the optimum values elected are:

• $b=30\%$
• $\beta=0.4$

With these values now what can be done is changing the traffic of the central cell for each case maintaining constant the rest of the cells.

The following figures show the CDF of the central cell throughput and the CDF of the rest of the cells, for each case.

(a) CDF of Cell throughput. 13 central users/2 cell edge users
In Figure A.25 (a) the results are extracted considering that the central cell has 13 central and 2 cell edge users. It can be seen that till the 95th percentile, the central cell achieve higher throughput than the rest of the cells. The reason could be that the central cell always has 13 central users that usually achieve higher rates while the other cells have a variable number of central users. Furthermore the number of cell edge users is very low so it will be more users with high throughput than with low.

Figure A.25 (b) shows the case with 7 central and 8 cell edge users. In this case the results are very similar mainly due that in average most of the rest of the cells will have more or less the same distribution of users. Only for very low throughputs the difference is higher than in the rest of the graph maybe caused
by the interference because if the rest of the cells have more cell edge users, it will be higher and consequently the throughput will decrease.

The last figure (Figure A.25(c)) reflects the situation with 2 central users and 13 cell edge users. In this case, like in (a) the central cell achieve higher rates. Although there are only 2 central users, RP system applies reuse 3 in the cell edge what helps to improve the cell throughput. Furthermore, the difference between results in (c) is smaller than in (a) due to the fact that the users that contribute with higher rates are the central ones.
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