



UNIVERSITAT POLITÈCNICA
DE CATALUNYA
BARCELONATECH



**Implementation of 5G broad-/multi-casting features to
support video broadcasting and cellular assisted
vehicular communications**

A Degree Thesis

**Submitted to the Faculty of the
Escola Tècnica d'Enginyeria de Telecomunicació de
Barcelona**

Universitat Politècnica de Catalunya

by

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**In partial fulfilment
of the requirements for the degree in
SYSTEM OF TELECOMMUNICATIONS ENGINEERING**

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Barcelona, June 2020

Abstract

This thesis conducts a study of scheduling methods for combined unicast and multicast traffic in the Vienna 5G system level simulator. In particular, the main purpose of the thesis is to extend this 5G simulator to support broadcasting and multicasting transmissions from a single base station. This requires some extensions of the schedulers that are already implemented in the software (Round Robin and Best CQI) such that it can serve a number of users in parallel with a transmission rate that is suitable for all users. Based on this, an investigation of the achievable rate compared to unicast transmission is carried out.

Resum

Aquesta tesis consisteix en un estudi dels mètodes de “scheduling” pels tràfics unicast i multicast combinats en el simulador “5G Vienna System Level Simulator”. En particular, l'objectiu principal d'aquesta tesis es extendre aquest simulador 5G per tal de poder suportar transmissions broadcasting i multicasting des d'una base station. Això requereix algunes modificacions dels “schedulers” ja implementats al software (Round Robin i Best CQI) per tal que puguin donar servei a un número d'usuaris en paral·lel amb una velocitat de transmissió adequada. Basat en això, es farà una investigació de les velocitats que es poden conseguir tant en el cas multicast com en l'unicast.

Resumen

Esta tesis consiste en un estudio de los métodos de “scheduling” para los tráficos unicast y multicast combinados en el simulador “5G Vienna System Simulator”. En particular, el objetivo principal de esta tesis es extender este simulador 5G para que pueda soportar transmisiones broadcasting y multicasting desde una estación base. Esto requiere algunas modificaciones de los “schedulers” ya implementados en el software (Round Robin y Best CQI) para que puedan proporcionar un servicio a un número de usuarios en paralelo con una velocidad de transmisión adecuada. Basado en esto, se hará una investigación de las velocidades que se pueden conseguir tanto en el caso multicast como en el unicast.

Dedication

Firstly, I would like to dedicate my work to my parents who have encouraged me to keep going and do not struggle with realisation of the thesis, to understand the entire situation of work I was under and being such comprehensive.

Secondly, to my friends. They, my way of scape. Who I appeal to when I am stressed and I want to disconnect. They provided me with the energy that cannot be learnt from any book.

And last, but not least, to UPC and all the group of teachers. If something good can be extracted from this thesis, is all thanks to the effort they put in teaching and making not only students, but encouraging learners.

Acknowledgements

This work started as a continuation of an existing software done by, amongst others, Martin Müller, Fjolla Ademaj, Agnes Fastenbauer, Thomas Dittrich, Blanca Ramos Elbal, Armand Nabavi, Lukas Nagel, Markus Rupp and Stefan Schwarz, my supervisor. Without their effort put in the simulator and the user manual, this thesis had not been possible to do.

I would also like to remark the assistance given by Stefan Schwarz, the supervisor. Given the difficulties that we have gone through the semester, he did not stop helping in any doubt I had, no matter how many those were. Thank you for your patience and dedication.

Finally, I would also like to emphasize the help that has been Ramon Ferrús, co-supervisor of the thesis in UPC. He has been always ready to help with useful advises and has been very attentive. Ramon, thank you.

Revision history and approval record

Revision	Date	Purpose
0	10/06/2020	Document creation
1	dd/mm/yyyy	Document revision

DOCUMENT DISTRIBUTION LIST

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1. Introduction

1.1. Context

Broadcasting/multicasting is a technology that is considered as very important for vehicular communications, since it allows to efficiently distribute the same information to many users at once. In the vehicular context this is especially important if some upcoming cars should be warned when they are heading to some traffic accident. It allows to achieve much smaller latency than, in contrast, unicast transmissions.

On the other hand, 5G will likely also be used in future TV broadcasting system as replacement for DVB-T2, which could give an idea about how important broadcasting will be in this technology.

The study conducted in this thesis is based on the “Vienna 5G System Level Simulator”. This software started off from a research group in 2009 with a freely-available LTE link-level simulator together with an LTE-system-level simulator.

Since that day, several modifications have been made, not only by the research group but also by some developers and some users via online thanks to its open-source nature. All these modifications were made with the intention of making it grow and adapted to new technologies that would be released eventually.

Therefore, the version of the software taken for this thesis is nothing else but the result of years of research by, amongst others, Stefan Schwarz who, in this case, is the supervisor of the thesis.

1.2. Statement of purpose

The main purpose of the thesis is to extend this 5G simulator to support broadcasting and multicasting transmissions from a single base station. This requires some extensions of the schedulers that are already implemented in the software (Round Robin and Best CQI) such that it can serve a number of users in parallel with a transmission rate that is suitable for all users. Based on this, there would be an investigation of the achievable rate compared to unicast transmission.

1.3. Requirements and specifications

Based on the previous statement, a brief list of requirements and specifications can be done.

Regarding the requirements:

- To implement broadcasting/multicasting features.
- To implement a Best CQI scheduling strategy for broadcast users.
- To investigate the splitting of broadcast users into multicasting and unicasting.
- Evaluate the performance of each scheduler in terms of transmission rate.
- Study the advantages and drawbacks of the broadcasting implementation.

Finally, regarding the specifications:

- To have the most possible efficient transmission.
- To have a reasonable rate for all multicast users related to the minimum CQI of all of them.

1.4. Methods and procedures

Since it is a completely functional 5G system level simulator, the first thing that was done is to understand how it works, i.e., understand how the code is written, which classes among all available were of my interest and to see which parts should be modified in order to fulfil the purpose of the project.

Once the user gets familiar with the software, the next thing to do was to start extending one scheduler in order to support broadcast features. The most doable was the Round Robin scheduler (RR) since this scheduler only “sees” which users are attached to the Base Station (BS). Hence, it assigns resource blocks following the order of the queue and given that in the code these variables were already defined, it seemed the easiest way to get ready with the project.

This method was not any different from any other programming project that could come to our minds: Creating new variables, modifying the values of the existing ones and debugging everything to check if everything was working properly.

In general terms, the procedure would be resumed as finishing one scheduler, getting the figures, starting another scheduler, getting its own figure and make a final comparison.

Theoretically, there were two schedulers to make (RR and best CQI) but as some deviations of the initial plan were appearing (as it will be explained later on in this section) it turned out to be three final different schedulers.

1.5. Workplan

Project: Understanding the simulator	WP ref: (WP1)	
Major constituent: Software	Sheet 1 of 6	
Short description: The first thing to do is to understand how the simulator is working.	Plan. start date: 19/02/2020 Plan. end date: 26/02/2020	
	Start event: 19/02/2020 End event: 26/02/2020	
Internal task T1: To read the Vienna 5G System Level simulator user's manual.	Deliverables:	Dates:
Internal task T2: To get familiar with the classes that are written in the simulator.		

Project: Implementing broadcast features to Round Robin scheduling algorithm.	WP ref: (WP2)	
Major constituent: software	Sheet 2 of 6	
Short description: To expand it to broadcast transmissions.	Plan. start date: 27/02/2020 Plan. end date: 17/04/2020	
	Start event: 27/02/2020 End event: 21/04/2020	
Internal task T1: To modify the user allocation resource block grid in order to assign the same number of resource blocks to multicast users. Internal task T2: given a resource block assigned to a multicast user, see if any of the multicast users has a zero-CQI. If that is the case, assign this RB to a unicast user. Internal task T3: Little modifications in the general scheduler class (Scheduler.m). This class is actually the one that assigns RBs. The ones regarding RR (current WP) and best CQI(next WP) are about how these RBs are assigned in Scheduler.m. Internal task T4: To split into two different plots the results obtained for both multicast and unicast users.	Deliverables:	Dates:

Project: Implementing broadcast features to best-CQI scheduling algorithm	WP ref: (WP3)	
Major constituent: software	Sheet 3 of 6	
Short description: Once the round robin scheduling algorithm is fully adapted to broadcast transmissions, it has to be done the same with the best-CQI algorithm.	Plan. start date: 17/04/2020 Plan. end date: 20/05/2020	
	Start event: 21/04/2020 End event: 07/05/2020	
Internal task T1: To take the estimated CQI per RB of all users to assign them the right one. Internal task T2: To allocate users in the resource block grid, specifically where they have the maximum CQI.	Deliverables:	Dates:

Before this, the minimum estimated CQI of all multicast users in every RB is set for all multicast users.		
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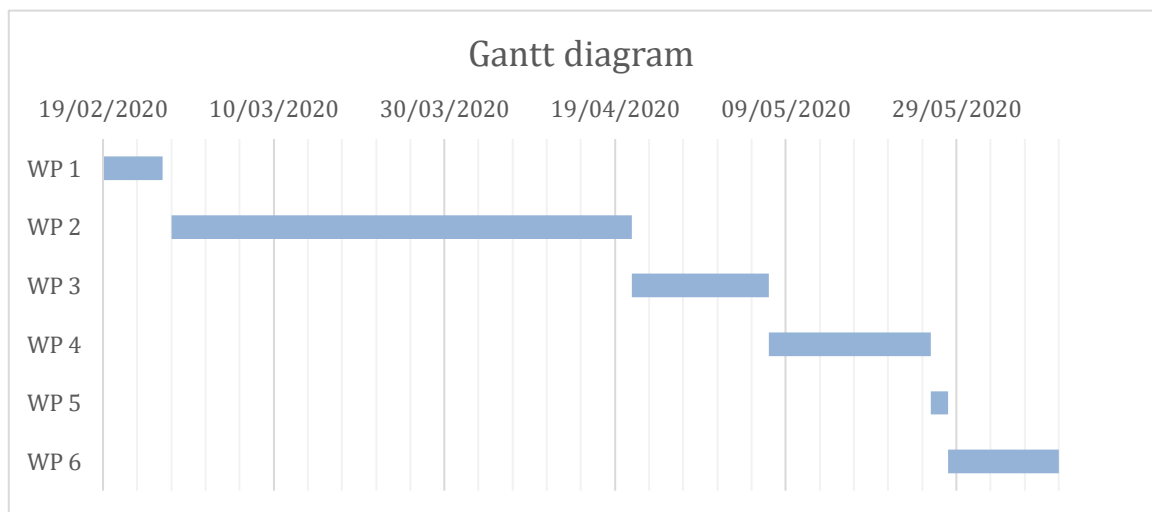
Project: Fixing best CQI implementation	WP ref: (WP4)	
Major constituent: software	Sheet 4 of 6	
Short description: The results of the previous WP were not convincing at all. Therefore, a few modifications were made to fix these errors.	Plan. start date: ~ Plan. end date: 15/05/2020	
	Start event: 07/05/2020 End event: 26/05/2020	
Internal task T1: To try to understand why the rate for multicast users were limited to a certain value. Internal task T2: To Modify several variables of different classes in order to see any change. Internal task T3: After checking through a lot of simulations that it was not still working as expected (figures were unintelligible) some modifications both in best CQI and RR were made.	Deliverables:	Dates:

Project: Implementation of the new scheduling decision	WP ref: (WP5)	
Major constituent: software	Sheet 5 of 6	
Short description: Before knowing what was going wrong with the previous simulations, a slightly new scheduling decision derived from best CQI was thought.	Plan. start date: ~ Plan. end date: 05/06/2020	
	Start event: 26/05/2020 End event: 26/05/2020	
Internal task T1: To implement the new scheduling decision.	Deliverables:	Dates:

Project: Final simulations and conclusions	WP ref: (WP6)	
Major constituent: software	Sheet 6 of 6	
Short description: Once the results seems to have sense, final simulations were made with different densities of users.	Plan. start date: ~ Plan. end date: 05/06/2020	
	Start event: 26/05/2020 End event: 10/06/2020	
Internal task T1: To make the final simulations of the three different schedulers and to take conclusions.	Deliverables:	Dates:

1.6. Gantt diagram

	Start date	Days	End date
WP 1	19/02/2020	7	26/02/2020
WP 2	27/02/2020	54	21/04/2020
WP 3	21/04/2020	16	07/05/2020
WP 4	07/05/2020	19	26/05/2020
WP 5	26/05/2020	2	28/05/2020
WP 6	28/05/2020	13	10/06/2020



1.7. Deviations and incidences

In this thesis in particular, incidences have been the cause of the deviation in terms of how schedulers have finally been implemented.

As it has been said in the WP 4, best CQI scheduler was not working correctly. When simulating for different density of users, the results did not match with the main principles of the comparison for both schedulers: higher rates in best CQI scheduler as it takes into account the CQI of users to allocate them into the resource block grid. And this improvement was not being observed in the figures. Also, some inconsistency on the best CQI performance appeared.

For those reasons, a slight different scheduling algorithm in both schedulers regarding the RBs assignment was made. And this supposed the first deviation of the project, since from these point on the project would be investigated under two modifications of best CQI and RR rather than the regular ones that are known which were the ones supposed to be worked with.

Moreover, an improved version based on best CQI scheduler was designed. A slightly different one. Hence, it turned out to be finishing the thesis with three different schedulers rather than the two firstly planned.

2. State of the art of the technology used or applied in this thesis:

2.1. Multicasting in Cellular Mobile Networks

Broadcast/multicast services have been earmarked as a potential area of growth in the future.

In the recent years, resource-efficient multicast for third-generation networks received significant attention in the research community. The goal behind introducing multicast capabilities is to save costs by transmitting the same data to multiple receivers on shared resource.

Specifically, a potential sector of use for multicast transmission is the dedicated public safety systems. These systems are based on standards like Terrestrial Trunked Radio (TETRA). In fact, in Release 13, 3GPP researched Single-Cell Point-to-Multipoint (SC-PTM) transmissions (the one used on the whole methodology of this thesis) as an option for group communications required by public services.

In relation to this, in PSN (Public Safe Networks) the multicasting is a present technology. It has been proven to be an efficient and important communication technology and has been standardized in 3GPP protocols in the form of evolved multimedia broadcast and multicast services (eMBMS).

Inside PSN, 5G nowadays supports PWS (Public Warning Services) in terms of delivering warning messages as specified in 3GPP TS 23.041. These warnings could consist in advise people about geological disasters, tsunamis and medical emergencies, between others.

2.2. Radio schedulers

Radio scheduling is one of the most important functions in mobile broadband networks. The design of a mobile network radio scheduler holds several objectives that need to be satisfied, for example: the scheduler needs to maximize the radio performance by efficiently distributing the limited radio resources, since the operator's revenue depends on it. Thus, the design of an effective scheduler is rather a complex task.

In order to provide the services, a scheduler works with an imaginary frequency vs time grid. This grid is used to assign RBs to a certain user and therefore its respective channel.

In this thesis, 5G scheduling is done at per subframe basis, i.e., every 1 ms.

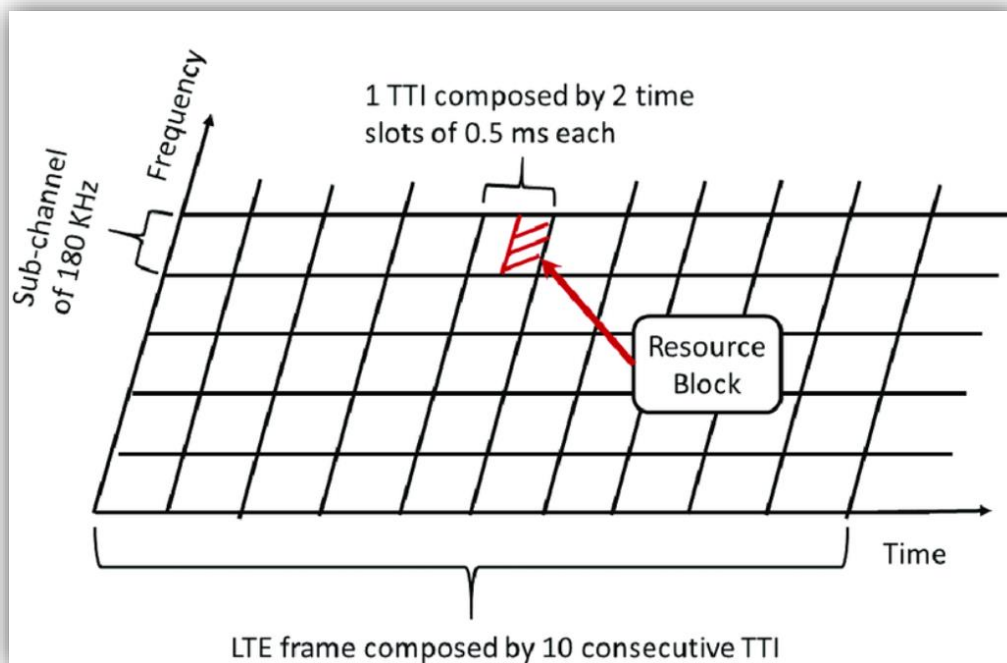


Figure 1. Resource grid example figure. Reference: https://www.researchgate.net/figure/Time-Frequency-radio-resource-grid_fig3_319855131

In this image it can be seen an example of a resource grid. It is done for LTE technology but in this thesis although it is based on 5G, the same grid is used. As it shows, each LTE frame is composed by 10 consecutive Transmission Time Interval (TTI), each one composed by 2 time slots of 0.5 ms each. In this thesis, it has been worked with 2 consecutive TTI.

In the frequency domain, this grid has a sub-channel formed by 12 carrier frequencies of 15 kHz each which gives a total of 180 kHz. Every Resource Block given to a user has the duration of a time slot, i.e., 0.5 ms.

The BW used by the scheduler would be basically the number of sub-channels used multiplied by the BW of each sub-channel.

2.3. 5G Vienna System Level Simulator

The Vienna 5G SL Simulator is written in MATLAB code and is utilizing OOP. Individual parts of the simulator are separated into different packages and, e.g., network elements, such as BS, are defined in classes. In general, the simulator is written in a modular fashion, such that new functions can be added easily, without the need to alter other parts of the code.

The simulator structure is defined by four major parts as it is displayed:

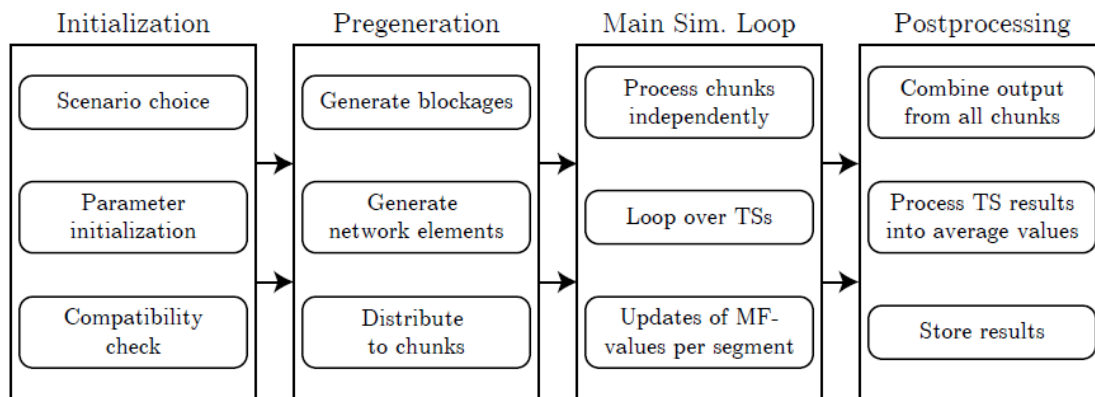


Figure 2. Overview of the 4 main parts of the simulator: Initialization, Pregeneration, Main Simulation Loop and Postprocessing. Reference: User Manual, “The Vienna 5G System Level Simulator”. Institute of Telecommunications, TU WIEN.

Each simulation begins with running the desired simulator launcher file. This already fixes the parameter set which is going to be used for this particular simulation. In the file **simulation.m** it is found the line:

```
%create simulation object
localSimulation = simulation.LocalSimulation(params);
```

Figure 3. Create Simulation Object line in the Simulator.

Where the simulation object is created and the predefined parameters are attached to this object.

Next, the simulation time line is generated, as well as the network element objects (BS and users, per example). Additionally, the fast fading traces are pregenerated, if necessary. This is done in:

```
%setup simulation and generate network elements
localSimulation.setup();
```

Figure 4. Setup Simulation and generation of network elements in the simulator

Now that the pregeneration is done, the actual simulation is carried out.

The following line contains the main simulation loop (over chunks and TSs):

```
%main simulation loop
localSimulation.run();
```

Figure 5. Main Simulation Loop line in the simulator.

Here, random samples in time (represented by channel realizations and scheduling decisions) and in space (represented by the geometry of the network elements) are simulated and the individual results of each TS are stored.

The postprocessing steps follows in:

```

% get results
simulationResults = localSimulation.simulationResult;
  
```

Figure 6. Extraction and storage of the individual results of the simulation

This results are actually calculated and stored also has to be specified in the simulator parameters. After processing and storing the results, selected results are plotted, which is integrated in the simulator launcher.

Regarding the simulation time line, this is divided into three different units, namely the time slots (TS), mentioned in the previous section. The TS is the shortest unit and also corresponds to the scheduler granularity. Thus it corresponds to one iteration of the inner simulation loop. It has a constant length, e.g., 1 ms to represent an LTE-A subframe, but can otherwise be specified freely.

A segment consists of various chunks and corresponds to the time in which the macroscopic fading (MF) is assumed to be constant.

A chunk consists of a fixed number of TS and on one or more segments (depending on the maximum user speed).

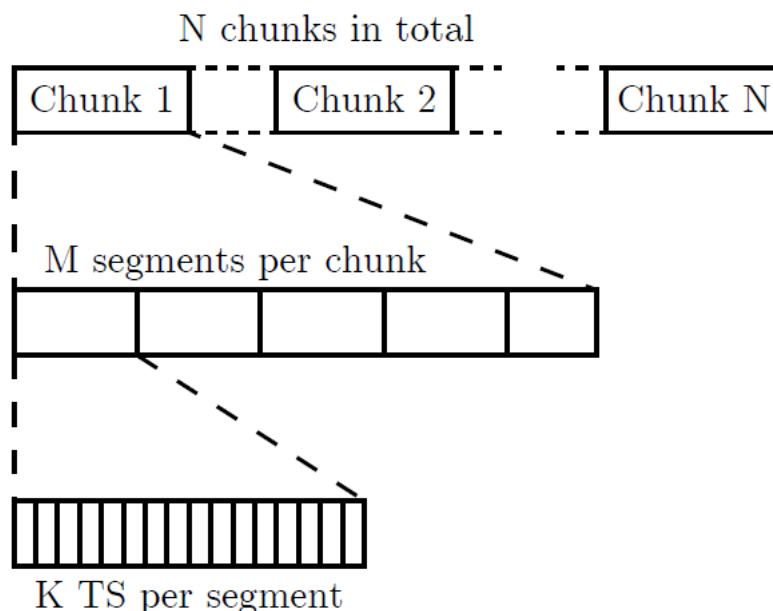


Figure 7. The different time units utilized in the simulator. Reference: User Manual, "The Vienna 5G System Level Simulator". Institute of Telecommunications, TU WIEN.

For creating the user trajectory, a consecutive generation is assumed, but also a considerably long distance between chunks, which leads to uncorrelated user positions among chunks.

3. Methodology / project development:

In order to approach the thesis requirements, the first mandatory thing to do was to see how the variables of the code were created, to know what these were for and eventually see the results of the simulator for unicast transmissions since it is supposed that, once the basis is known and understood, the new multicast features would be easier to do.

All of this together with the reading of the user manual provided by the supervisor. In this, a clear view was taken about how the Time Line of the simulator works, The Main Simulation Loop and how classes were distributed and what were those used for.

Once this study was done, the idea of how to expand the current schedulers was clearer. Basically, the goals had to be accomplished by modifying both Round Robin and Best CQI schedulers the way RBs were assigned by each BS.

So far, for unicast transmissions those schedulers worked as it is known: Regarding RR, RBs will be assigned in the grid following the order of the queue and each channel assigned will only be used for the chosen user. Regarding Best CQI the scheduling algorithm is different as it takes into account the CQI of the users to assign a channel but as RR, this channel will only be used for the assigned user.

What shall be done here is to expand it to multicast transmissions, modifying the scheduler process so that all multicast channels assigned can be used for all multicast users attached to a certain BS. And this is done by modifying the way schedulers assign RBs as just mentioned.

Regarding the scenario distribution, BS were spread following an hexagonal grid by 17 BS in total with a distance of 100 meters between each all along the region of interest (ROI).

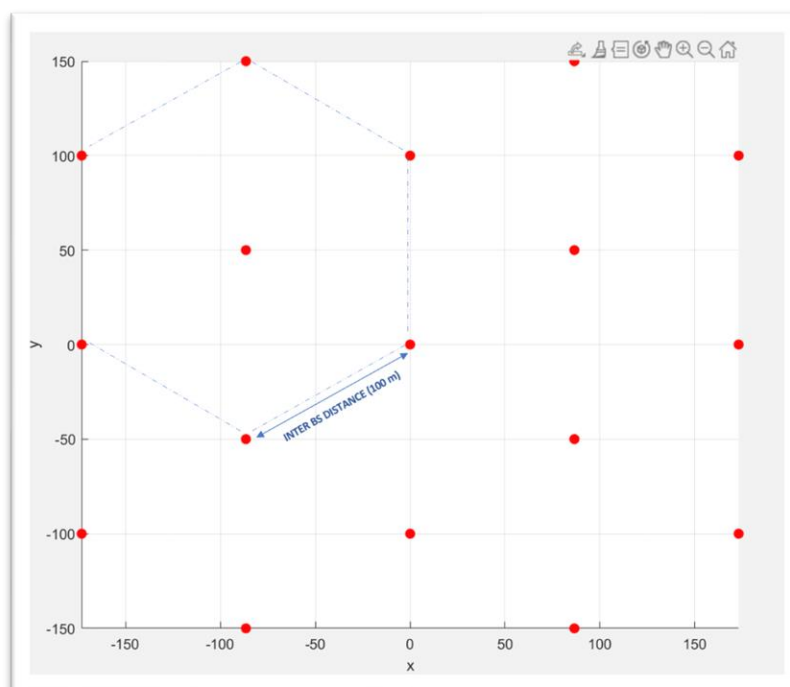


Figure 8. All BS (red) spread all along the ROI (XY plane) separated by INTER BS DISTANCE

First of all, let's explain some of the concepts taken into account in order to modify the schedulers:

- For all the users generated in each simulation there were some of them who had to receive the same packet given a single carrier frequency (from now on, this users will be named as subscribers/multicast users).
- All multicast users attached to a BS should have the same minimum CQI. This is, if there are three multicast users the scheduler should be able to pick the user with the minimum CQI and set it to all multicast users. The idea of this is since this packet had to be correctly received for every subscriber, if the subscriber with the worst channel conditions, i.e., CQI, receives the data correctly, the rest would do it as well. Therefore, the process is thought to be done correctly for the worst CQI case.
- All multicast users should achieve the same throughput. Here, throughput was considered as a function of CQI and the RBs assigned. Therefore, besides having the same minimum CQI, all multicast users should also have the same RBs assigned.

So far, for unicast transmissions the RBs assignment was done following the RB grid allocation created in the simulator. The scheduler looks at each RB and assigns the channel to the user which identification number is in it. With this, each user would have his own channel to receive the information.

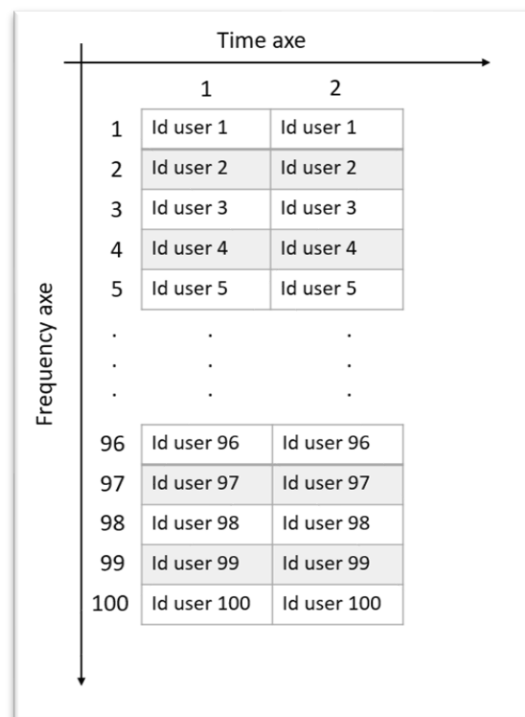


Figure 9. RB grid allocation for the standard version of the simulator. It can be seen that it consists of 100 vertical frequency slots and 2 horizontal time slots.

Nevertheless, this is something that had to be changed if it is wanted to make all multicast users use all multicast channels assigns, no matter to which user was assigned

at first. The idea that I came up with was to, instead of allocating the user identifier which is different for each user, set a common arbitrary number for those RBs which were assigned to multicast users. With this, the scheduler will associate this number to multicasting.

In figure 9 it is shown how for every slots there is the identifier of each user, all of them unicast users. The following picture displays the multicasting modification for RR scheduler:

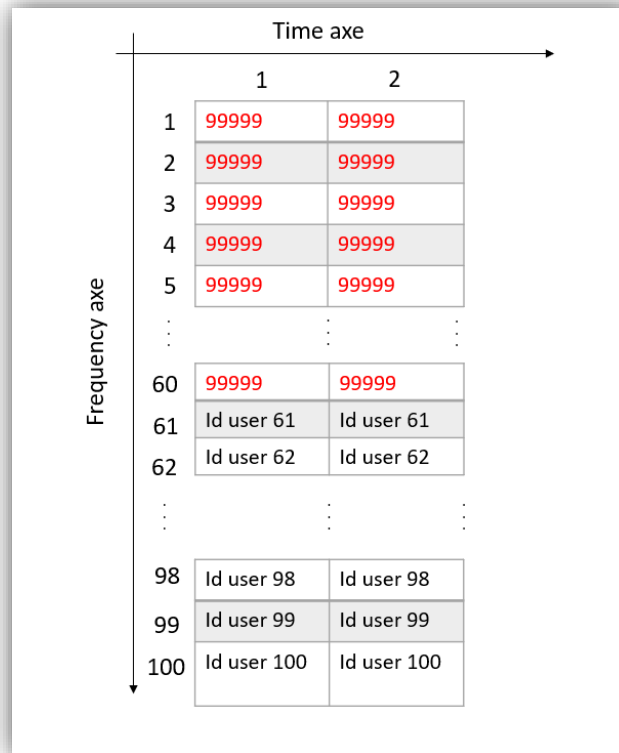


Figure 10. Modified grid allocation for RR scheduler. In red, it can be seen the common arbitrary number chosen ('99999') to make the scheduler know that those will be assigned to multicasting, in this case as an example, 60 RBs assigned to multicasting and 40 to unicast.

In the previous picture can be seen that the first 60 RBs are assigned to multicasting for RR scheduler as the first 60 users of the queue are multicast users, but they do not have to be.

Since some problems appeared regarding the number of RBs assigned during the first approach to extend the standard unicast scheduler, the one used for the results in fact works a bit different. Instead of assigning RBs in the order users are in the queue, a pre-calculated values of the number RBs to be assigned for multicast and unicast were done. This way, the scheduler is being forced to assign a certain value of RBs to both unicast and multicast users rather than assign them according to the queue. And this is what it has been seen in figure 10.

This number of RBs depends on the proportion of multicast and unicast users over all users, respectively, as it follows:

Equation 1:

$$nRBs_{multicast} = \frac{Nm}{Nm + Nu} \cdot TOTALRBs$$

Where: Nm is the number of multicast users in the queue.
Nu is the number of unicast users in the queue.
TOTALRBs is the total number of RBs from the grid in the frequency axe

Equation 2:

$$nRBs_{unicast} = \frac{Nu}{Nm + Nu} \cdot TOTALRBs$$

The idea here was to assign the first RBs from the grid to multicast users equally and then to unicast users according to their position in the queue.

For unicast case, the same assigning resource algorithm that RR uses for unicast users is implemented with the only difference that now the number of RBs to be assigned is fixed (Eq.2).

Regarding best CQI scheduler, the algorithm implemented in the thesis is quite different from the regular one. Instead of assigning a single RB to the user with the best CQI, what it is done here, first of all, is to considerate multicast case.

What this scheduler does is to study the matrix of CQI of all multicast users. This matrix, different for each user, has the same size and dimension of the RB grid allocation. In this matrix, for each slot it is allocated the CQI that would have a certain user in the grid allocation. The next step that this scheduler does is to make the minimum CQI matrix of all multicast users. This is, for each slot of the matrix the scheduler compares it to the same slot for all multicast CQI matrix and picks the minimum.

Once the matrix of minimum CQI is done, $nRBs_{multicast}$ is calculated. Then, the scheduler picks the first $nRBs_{multicast}$ slots where the maximum of those minimum CQI are allocated and assigns this slots in the grid allocation to multicasting.

Once all multicast users are assigned, unicast users are assigned $nRBs_{unicast}$ RBs following the regular algorithm: for every RB (in this case, the remaining ones after the multicasts assignment) study which user has the maximum CQI and assign this RB to the user.

In order to have a clearer view of how it works, here is an example:

Let's suppose there are 4 users in the queue: two multicasts and two unicasts and 4 RBs in the grid to assign. If both equation 1 and equation 2 are applied, it is obtained that $nRBs_{multicast} = 2$ and $nRBs_{unicast} = 2$. The CQIs of the multicast users are:

$$CQI_m1 = [4,5,6,7] \quad CQI_m2 = [7,6,5,4].$$

Thus, the minCQI is: $CQI_min = [4,5,5,4]$.

Now, the scheduler assigns the 2 RBs with largest minCQI to multicast users, i.e., RB 2 and 3. The others RBs 1 and 4 will be assigned to the unicast user with the largest CQI on it.

Finally, a new scheduler named 'Heuristic' based on Best CQI was designed. This modification only affected to multicast users and it does the following:

Rather than selecting the RB with the maximum minimum CQI amongst all multicast users as best CQI does, it should be attempted to maximize the minimum average CQI of the users over all assigned RBs. What this will imply as it will be seen in Results section is a lower percentage of multicast users with null rate.

4. Results

This should include your data analysis and findings

When it came to see the results, it had to be chosen the density of users to consider. Depending on this, it would be obtained different results. Basically, the larger the number of users attached to a BS is, the lower the throughput in order to receive the data correctly. In this thesis it have been considered three different densities: 0.0008, 0.05 and 0.01 (121, 828 and 1700 average users, respectively). Users who are spread among all 17 BS.

Before seeing the figures, it is shown some of the simulation parameters in order to understand better where the results come from.

To begin with, some parameters regarding the BS:

BS	
Channels used	100 sub-channels of 180 kHz each.
Pathloss model	Free Space ($\alpha = 2$)
Type of antenna	Omnidirectional, SISO
Height	15 meters
Tx Power	40 W
Distribution	Hexagonal grid

Table 1. Parameters set in BS class.

Users	
Antenna	SISO
Distribution	Randomly distributed (Poisson distribution)

Table 2. Parameters set in User class

Time configuration	
Number of chunks	2
Duration TS	1 ms
Slots/chunk	10
Time between chunks	50 TS = 50 ms

Table 3. Time configuration parameters set.

In the next sections it will be compared the performance of the three different schedulers implemented in terms of throughput in downlink situation. This comparison will be studied along the three densities chosen to see how these behave while the number of users increase. Since every simulation it is ran randomly following a Poisson distribution of users, a several number of averaged simulation for each scheduler in every density was done to get smoother curves and more reliable conclusions.

Regarding the figures, what it is really obtained is the empirical distribution function (e.c.d.f) of it, i.e., the cumulative probability of existing this value of the throughput or below amongst all multicast and unicast users, respectively.

4.1. Density = 0.0008

For this density it has been averaged 30 simulations of 2 minutes each per scheduler, obtaining the following figures:

4.1.1. RR

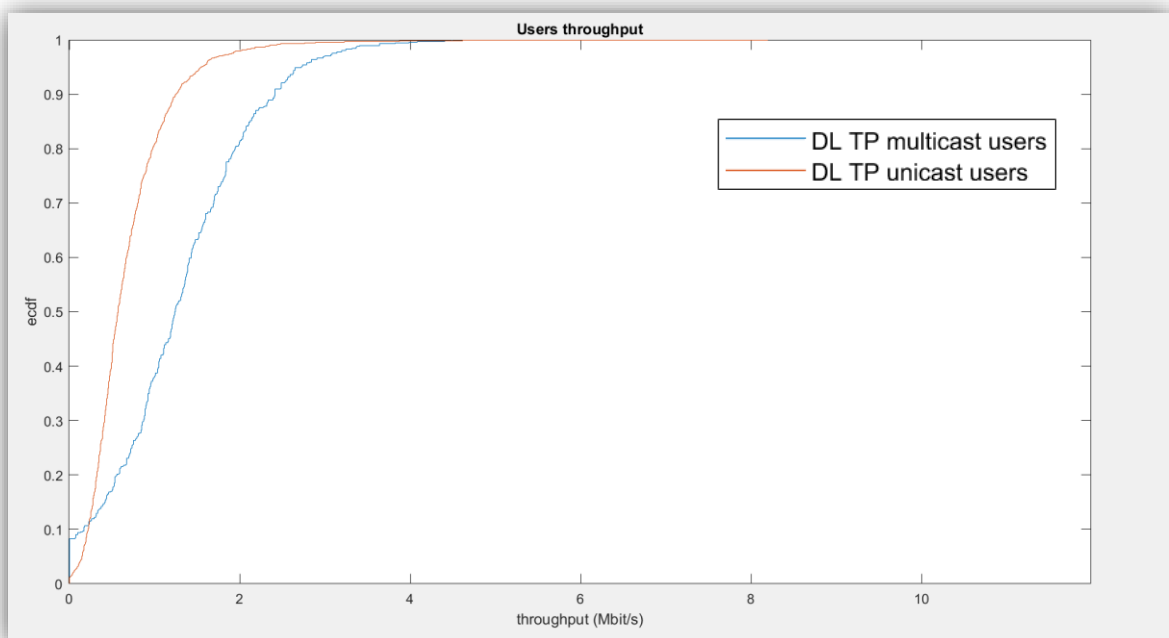


Figure 11. Throughput figure of RR scheduler with density = 0.0008 for both multicast (blue) and unicast (orange) users.

From the previous figure it can be seen that for multicast users we obtain the following information:

1. There is a 8.2% of users that are not having any rate at all. It supposes about 163 users out of 1993. The cause of this is subscribers with null CQI (therefore, null rate). They are being prejudicial to the rest of multicast users since the same minimum CQI is set to all of them.
2. The minimum non-zero rate achieved is 66.14 kb/s.
3. The maximum rate achieved is 4.49 Mb/s.

For unicast users:

1. Every user is achieving rate.
2. The maximum rate achieved is 8.19 Mb/s.

From this results, what it can be seen is that for multicast users, apart from letting some multicast users without receiving information due to the subscribers with null CQI, it is also achieved a lower maximum rate which seems normal due to the restriction that supposes setting the minimum CQI to all multicast users. This way, several CQIs of multicast users will be lower than unicast users and consequently their rate.

4.1.2. Best CQI

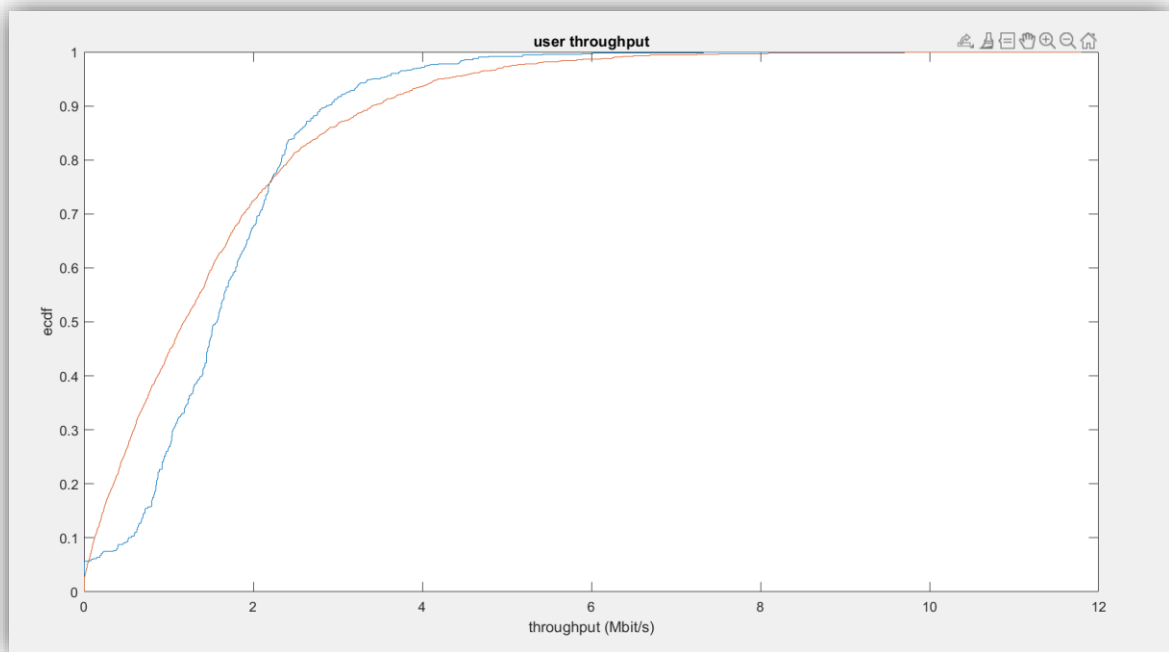


Figure 12. Throughput figure of Best CQI scheduler with density = 0.0008 for both multicast (blue) and unicast (orange) users.

Multicast users:

1. 5.6% of users with null rate.
2. The minimum non-zero rate achieved is 35.11 kb/s.
3. The maximum rate is 9.7 Mb/s.

Unicast users:

1. Again, all users are achieving rate.

2. The maximum rate is 11.8 Mb/s.

In this case, higher rates are achieved than in RR case since this scheduler takes into account the CQI when it comes to assign RBs. The better the CQIs, the more probably a user would be transmitting. Consequently, a lower percentage in the multicast case are not having any rate.

However, there is still a percentage of multicast users that are not being able to establish the connection to the BS.

4.1.3. Heuristic

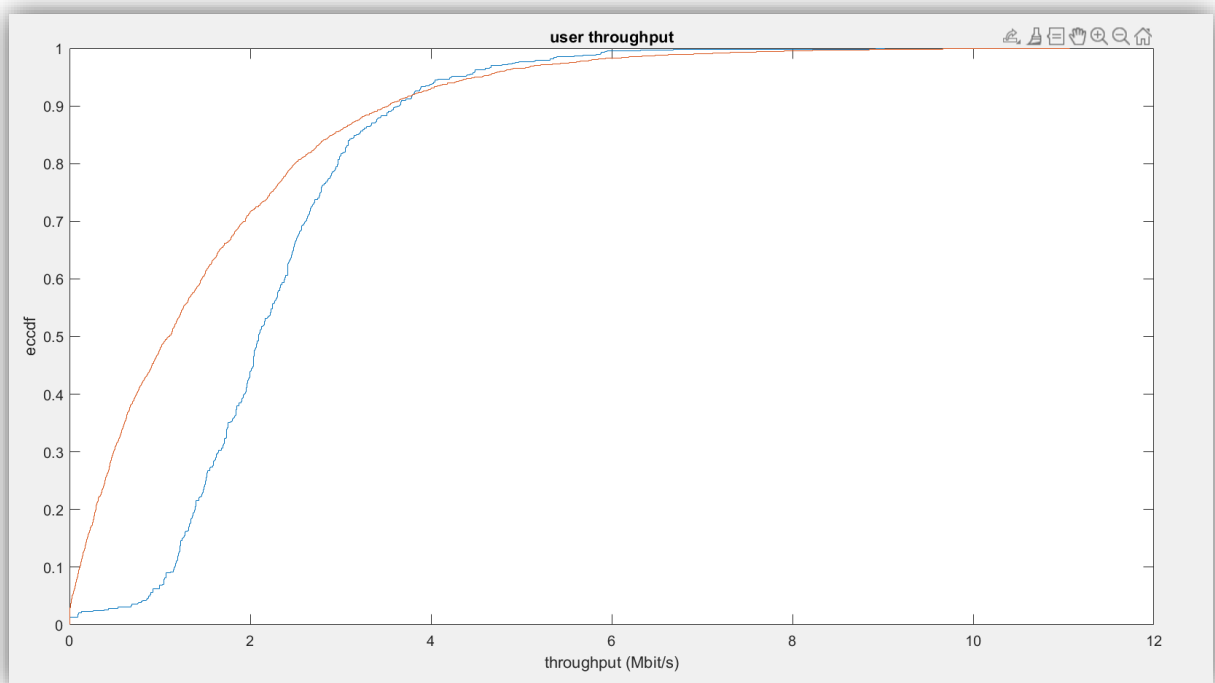


Figure 13. Throughput figure of Heuristic scheduler with density = 0.0008 for both multicast (blue) and unicast (orange) users.

Multicast users:

1. 1.34% of users with null rate.
2. The minimum non-zero rate achieved is 9.46 kb/s.
3. The maximum rate achieved is 9.66 Mb/s

Unicast users:

1. 1.8% of users with null rate.

2. The minimum non-zero rate achieved is 77 bits/s
3. The maximum rate achieved is 11.07 Mb/s

4.2. Density = 0.005

For this density it has been averaged 20 simulations of 10 minutes each per scheduler.

4.2.1. RR

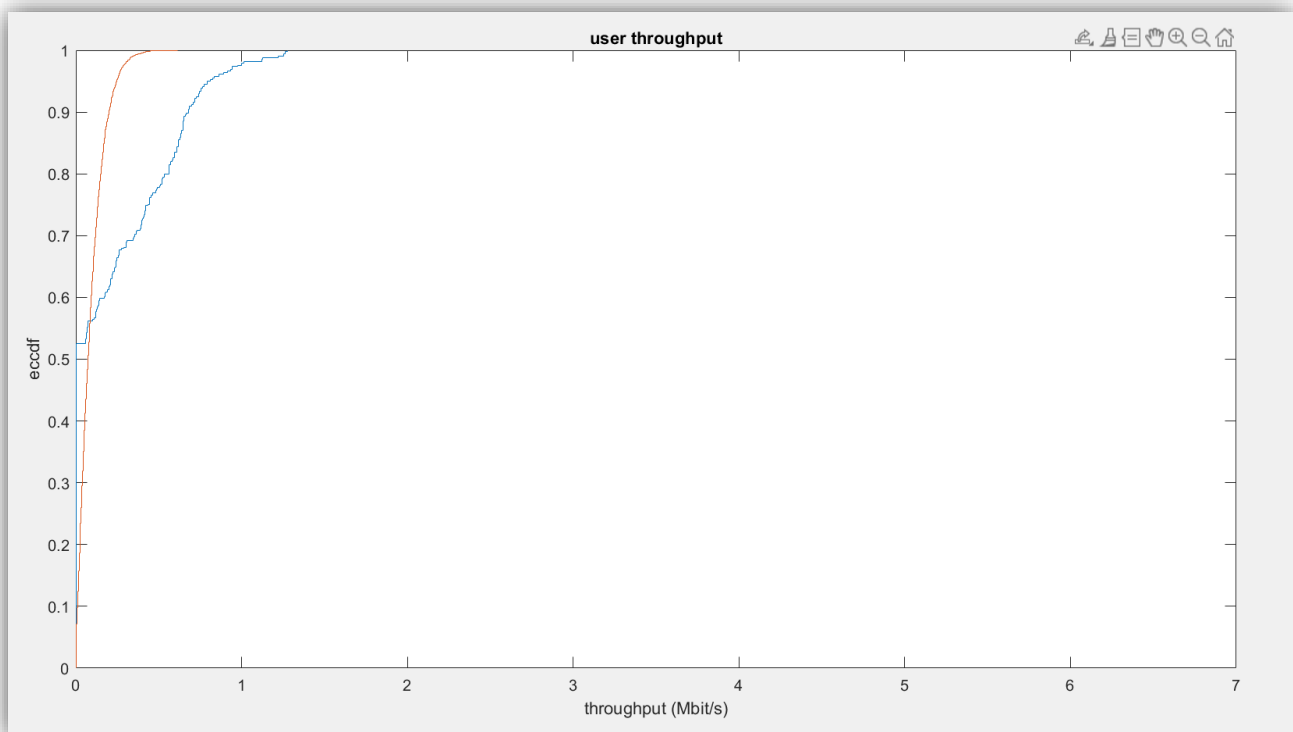


Figure 14. Throughput figure of RR scheduler with density = 0.05 for both multicast (blue) and unicast (orange) users.

Multicast users:

1. 52.6% of users with null rate.
2. The minimum non-zero rate achieved is 58.22 kb/s
3. The maximum rate achieved is 1.28 Mb/s.

Unicast users:

1. All users achieve rates.
2. The maximum rate achieved is 611.7 kb/s.

4.2.2. BEST CQI

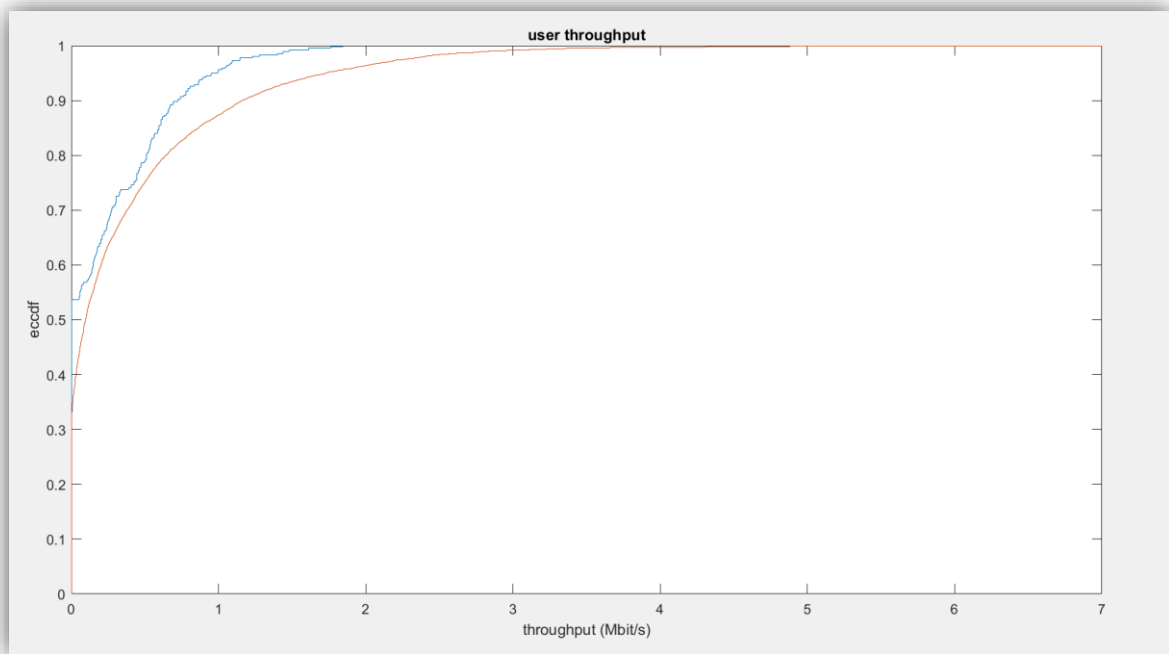


Figure 15. Throughput figure of best CQI scheduler with density = 0.05 for both multicast (blue) and unicast (orange) users.

Multicast users:

1. 53.72% of users with null-rate.
2. The minimum rate achieved is 49.11 kb/s.
3. The maximum rate achieved is 1.85 Mb/s.

Unicast users:

1. 30.3% of users with null-rate.
2. The minimum rate achieved is 11.4 kb/s.
3. The maximum rate achieved is 7 Mb/s.

4.2.3. HEURISTIC

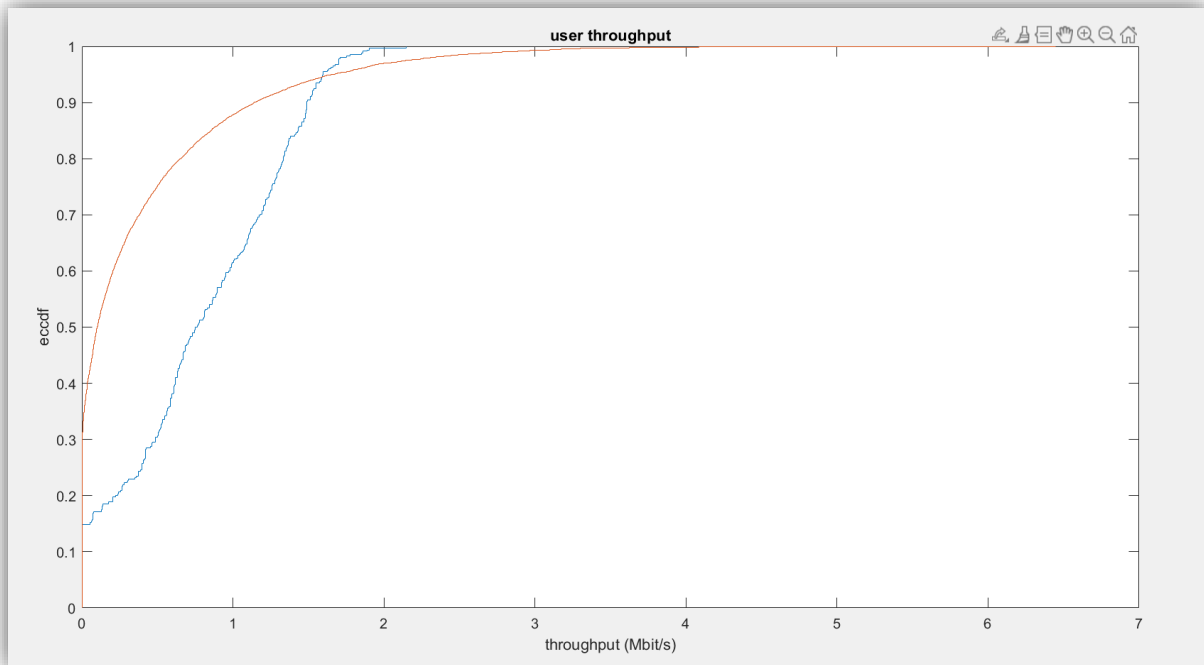


Figure 16. Throughput figure in Heuristic scheduler with density = 0.05 for both multicast (blue) and unicast (orange) users.

Multicast users:

1. 15% of users with null rate.
2. The minimum rate achieved is 54.21 kb/s.
3. The maximum rate achieved is 2.15 Mb/s.

Unicast users:

1. 28.6% of users with null rate.
2. The minimum rate achieved is 44 b/s.
3. The maximum rate achieved is 6.45 Mb/s.

4.3. Density = 0.01

For this density it has been averaged 10 simulations of 20 minutes each per scheduler.

4.3.1. RR

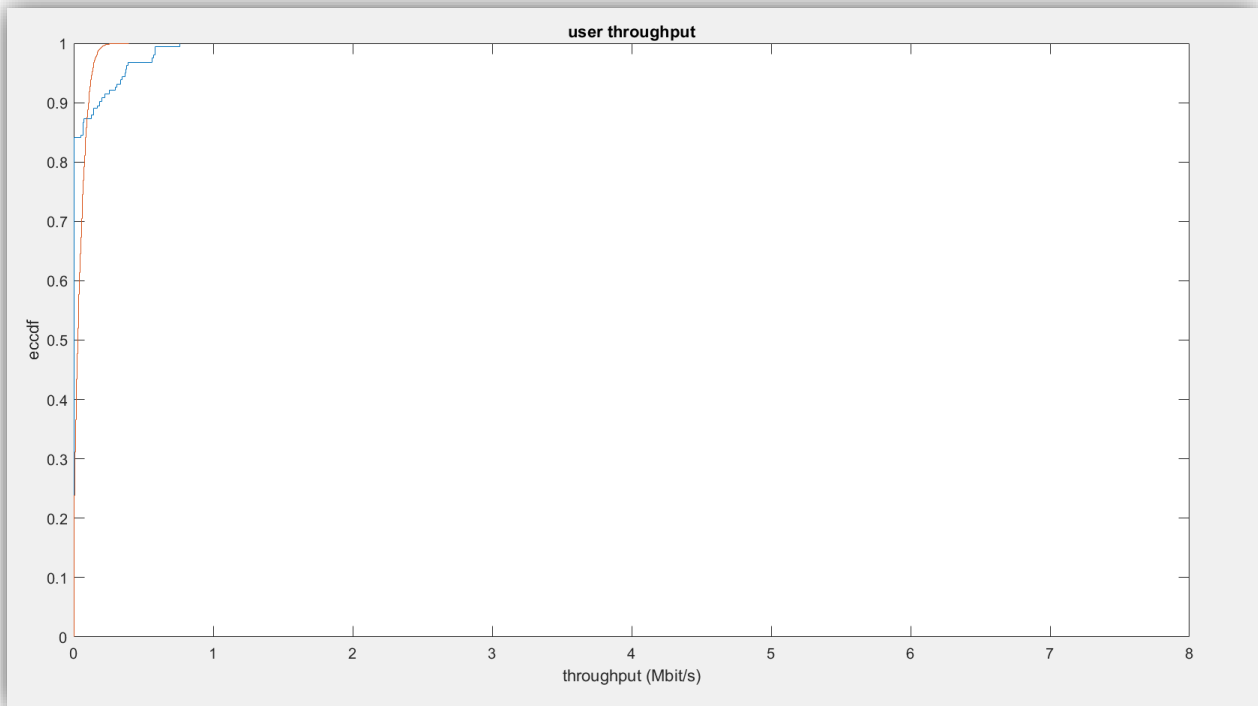


Figure 17. Throughput figure in Round Robin scheduler with density = 0.01 for both multicast (blue) and unicast (orange) users.

Multicast users:

1. 84.13% of users with null rate.
2. The minimum rate achieved is 52.71 kb/s.
3. The maximum rate achieved is 758.67 kb/s.

Unicast users:

1. 14.41% of users with null rate.
2. The minimum rate achieved is 234.6 bits/s.
3. The maximum rate achieved is 394.67 kb/s.

4.3.2. BEST CQI

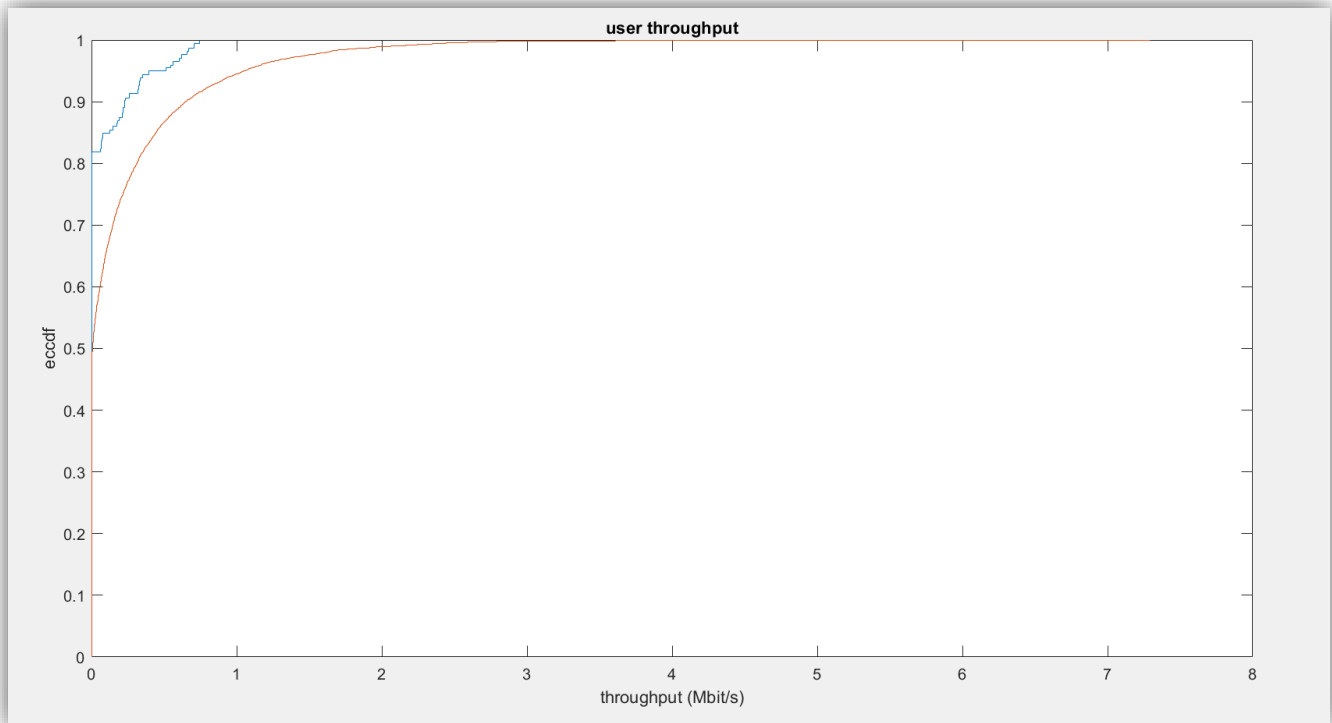


Figure 18. Throughput figure in best CQI scheduler with density = 0.01 for both multicast (blue) and unicast (orange) users.

Multicast users:

1. 81.82% of users with null rate.
2. The minimum rate achieved is 63.51 kb/s.
3. The maximum rate is 745.33 kb/s.

Unicast users:

1. 46.53% of users with null rate.
2. The minimum rate achieved is 40.2 bits/s.
3. The maximum rate is 7.29 Mb/s.

4.3.3. HEURISTIC

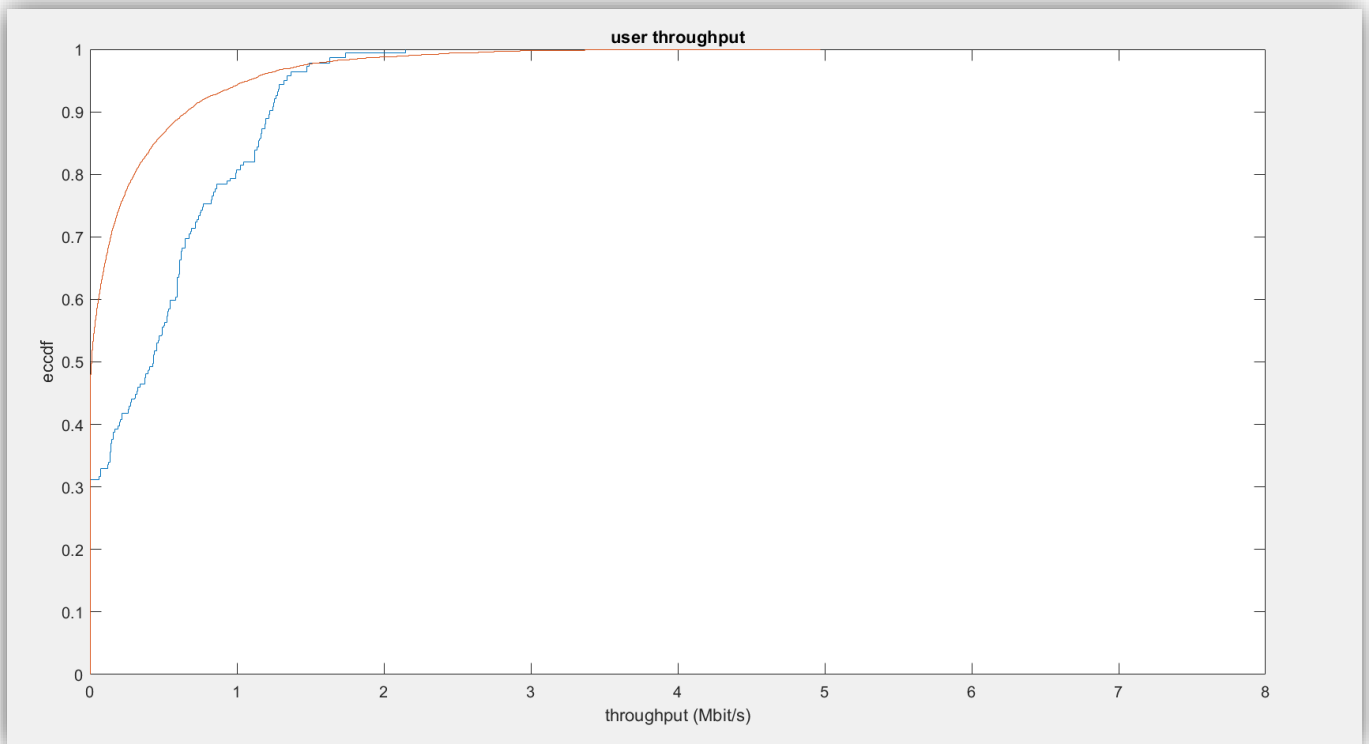


Figure 19. Throughput figure in heuristic scheduler with density = 0.01 for both multicast (blue) and unicast (orange) users.

Multicast case:

1. 31.13% of users with null rate.
2. The minimum rate achieved is 62.23 kb/s.
3. The maximum rate achieved is 2.15 Mb/s.

Unicast case:

1. 45.4% of users with null rate.
2. The minimum rate achieved is 30 bits/s.
3. The maximum rate achieved is 4.97 Mb/s.

4.4. Throughput table comparison

THROUGHPUT		DENSITY = 0.0008		
		% null rate	Min rate	Max rate
RR	M	8.2	66.14 kb/s	4.49 Mb/s
	U	0	-	8.19 Mb/s
Best CQI	M	5.6	35.11 kb/s	9.7 Mb/s
	U	0	-	11.8 Mb/s
Heuristic	M	1.34	9.46 kb/s	9.66 Mb/s
	U	1.8	77 bits/s	11.07 Mb/s

Table 4. Performance of the schedulers in terms of percentage of users with null rate (left) and bit rate (mid and right) of both multicast (M) and unicast (U) users for a density = 0.0008.

THROUGHPUT		DENSITY = 0.005		
		% null rate	Min rate	Max rate
RR	M	52.6	58.22 kb/s	1.28 Mb/s
	U	0	-	611.7 kb/s
Best CQI	M	53.72	49.11 kb/s	1.85 Mb/s
	U	30.3	11.4 kb/s	7 Mb/s
Heuristic	M	15	54.21 kb/s	2.15 Mb/s
	U	28.6	44 bits/s	6.45 Mb/s

Table 5. Performance of the schedulers in terms of percentage of users with null rate (left) and bit rate (mid and right) of both multicast (M) and unicast (U) users for a density = 0.005.

THROUGHPUT		DENSITY = 0.01		
		% null rate	Min rate	Max rate
RR	M	84.13	52.71 kb/s	758.67 kb/s
	U	14.41	234.6 bits/s	394.67 kb/s
Best CQI	M	81.82	63.51 kb/s	745.33 kb/s
	U	46.53	40.2 b/s	7.29 Mb/s
Heuristic	M	31.13	62.23 kb/s	2.15 Mb/s
	U	45.4	30 bits/s	4.97 Mb/s

Table 6. Performance of the schedulers in terms of percentage of users with null rate (left) and bit rate (mid and right) of both multicast (M) and unicast (U) users for a density = 0.01.

Before seeing the conclusions, it should be said that the parameter regarding the minimum rate achieved is put in this thesis as an extra information of the figure. It is thought that this parameter should mean something regarding the scheduler performance. But since in this thesis it has not been figured out in what way, nothing is commented in this regard.

To make the conclusions regarding the table values, it would be interesting to divide multicast case from unicast case. Regarding multicast users:

- As it could be thought “a priori”, the performance of the scheduler get worse as the density increase. Due to the limitation of the grid allocation, the more users there are (especially when the number of users is higher than the number of RBs to assign) the higher the % of null rates since there would be more users without being assigned to any channel. In the multicast case it is affected the most since them, moreover, are affected to their CQI limitation. This is, the more users there are attached to a certain BS the more likely it would be for one of them to have a null CQI and, therefore, every multicast users would have it as well.
- RR is the only scheduler that provides better conditions for multicast users than to unicast users as it can be seen in terms of throughput.
- It can be seen how RR and Best CQI provides the same conditions in terms of percentage of null rate and throughput achieved since regardless the scheduler algorithm, all multicast users have the same minimum CQI and while the density increases so it does the probability to have one of them null CQI, and therefore, all multicast users. Then, both RR and Best CQI schedulers in multicast case does give the user any difference as the density grows.
- Heuristic has the most balanced performance in terms of percentage of null rate as density grows up and provides the best values on the percentage of users with null rates by far.

In the unicast case, we can see that the usual comparison of RR and Best CQI takes place. This is, better rates in Best CQI but higher % of users with null rate (as it is the less fair due to the CQI of the users). When comparing Best CQI to Heuristic:

- Heuristic does not provide any important improvement in terms of % of null rate.
- Best CQI provides better rates than Heuristic in terms of bit rate.

5. Budget

Depending on the thesis scope this document should include:

- Components list with approximate costs (prototype)
- Design and prototyping costs separate by main tasks (hours person x cost)
- Economic and/or financial viability analysis

If the object of the thesis is not a prototype at least you should include in this section an estimation of the number of hours you have dedicated to the thesis, evaluated at cost of junior engineer.

If you have used a specific software you should also include the license and amortization costs.

Since it has been worked with Matlab student version (free) the budget consists of the estimation of the number of hours dedicated to the thesis as a junior engineer.

Task	€/hour	Hours	Cost (€)
Literature review	8,5	21,6	183,6
Round Robin modification	8,5	126	1071
Best CQI modification	8,5	50,4	428,4
Fixing Best CQI modification	8,5	46,8	397,8
Implementation of new scheduling decision	8,5	3,6	30,6
Final simulations and conclusions	8,5	39,6	336,6
FULL COST (€)			2448

6. Conclusions and future development:

In this thesis, it has been seen that while one scheduler might be a good choice for multicasting, may be it is not such a good option for unicasting and reverse. In this regard, a possible option may lead in changing the scheduler depending on the percentage of multicast/unicast users considered.

Although it is true than the more multicast users there are, Heuristic scheduler might be the best one as it provides the best conditions for both multicast and unciast users.

If, on the other hand, there are significantly more unicast users, RR or best CQI might be chosen following the same reason that it is done nowadays.

Regarding the broadcast features implemented, it seems that unicast transmissions seems to be faster and more reliable than multicast ones as multicast have CQI limitations. Nevertheless, multicast transmissions are a better way to minimize network traffic and optimize bandwidth as all multicast resources block assigned are possible to use for any multicast user.

As a future development, it would be interesting to extend to single-frequency networks features (SFN). SFN allows to broadcast/multicast the same information from many base stations in parallel, which is required specially for TV broadcasting.

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Glossary

CQI – Channel Quality Indicator

UPC – Universitat Politècnica de Catalunya

LTE – Long Term Evolution

RR – Round Robin

BS – Base Station

RB – Resource Block

WP – Work package

TETRA – Terrestrial trunked radio

SC-PTM – Single Cell-Point to Multipoint

PSN – Public Safe Networks

3GPP – 3rd Generation Partnership Project

eMBMS – evolved Multimedia Broadcast and Multicast Services

PWS – Public Warning Services

TTI – Transmission Time Interval

BW – Bandwidth

OOP – Object-Oriented Programming

TS – Time Slot

LTE-A – Long Term Evolution Advanced

MF – Macroscopic Fading

ROI – Region Of Interest

SISO – Single Input Single Output

ECDF – Empirical Cumulative Distributive Function

SFN – Single Frequency Network.