LTE-Advanced cell-specific reference signals in dependence of power allocation

A Degree Thesis

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Escola Tècnica d'Enginyeria de Telecomunicació de Barcelona -

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and

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by

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of the requirements for the degree in

TELECOMMUNICATIONS SYSTEMS ENGINEERING

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Abstract

The main objective of this thesis is to study the channel estimation subject in LTE (Long Term Evolution). LTE uses coherent detection and, with the purpose of obtaining information about the channel, pilot signals are used. The main axis of this study is how the reference signals according to the 3GPP standard (3th generation partnership project) are generated.

In this project it is expected to understand the differences between different channel estimators using a 5G simulator developed at the Technische Universität Wien. The advantages of some pilot sequences and allocation in the signal will be studied.

It is also an objective of the thesis to study the advantages from the estimator point of view in using more than one antenna in each base station with their corresponding reference signals.

Resum

En aquest projecte s'estudia el problema de l'estimació de canal en LTE (Long Term Evolution). LTE fa servir detecció coherent i per tal de conèixer el canal es proporcionen seqüències de referència. L'estudi es realitzarà sobre com es construeixen aquestes senyals pilot a partir del 3GPP standard (3th generation partnership project).

Aquest projecte té com a principal objectiu estudiar les diferències entre diferents estimadors de canal a partir de l'ús d'un simulador de 5G desenvolupat a la Technische Universität Wien. Es comparan quins avantatges té fer servir diferents seqüències pilot i la seva posició.

També es pretén estudiar els avantatges d'utilitzar més d'una antena per estació base amb les seves respectives senyals pilot a nivell del estimador de canal.

Resumen

En este proyecto se pretende estudiar el problema de la estimación de canal en LTE (Long Term Evolution). LTE utiliza detección coherente y con el objetivo de conocer el canal se proporcionan secuencias de referencia. El estudio se realiza en cómo se generan estas señales piloto a partir del 3GPP standard (3th generation partnership project).

Este proyecto tiene como principal objetivo entender las diferencias entre diferentes estimadores a partir del uso de un simulador de 5G desarrollado en la Technische Universität Wien. Se comparan qué ventajas tiene usar determinadas secuencias piloto y su posición.

También se pretende estudiar qué ventajas tiene utilizar más de una antena por estación base con sus respectivas señales de referencia a nivel del estimador de canal.

Acknowledgements

I would first like to thank my supervisor, professor Stefan Schwartz from the TU, and Stefan Pratschner, PhD student at the TU, for proposing this project and being always available to meet and resolve my doubts. I would like to thank professor Markus Rupp for giving me the opportunity to work with his group.

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1. Introduction

1.1. Statement of purpose (objectives)

The purpose of this project is to implement 3GPP LTE/NR compliant reference signals and, based on these, to evaluate the performance of different channel estimation strategies.

This project consists on modifying the Matlab-based 5G link level cellular communications simulator by adding the 3GPP LTE/NR compliant reference signals. The objective is to be able to work with the random reference signals already implemented but also allow the user of the simulator to choose the 3GPP standard reference signals implemented.

The project main goals are:

1.- Generate the reference signal for the LTE using the 3GPP standard.

2.- Modificate the least squares channel estimator in order for it to support cell specific-reference signal.

3.- Simulate different scenarios and tests with different configurations and different pillot allocations and sequences. Extract conclusions using the simulator results.

1.2. Requirements and specifications

The simulator is already able to estimate the channel but we want to add a new way to do it in order to improve the channel estimation of the simulator when using the LTE scenario. We will add to the simulator a new function to generate and map the Pilot Signal matrix containing cell-specific reference signals. This reference signal generation and mapping is based on one time subframe of 1 ms according to the 3GPP standard.

This new reference signal will allow the simulator to estimate the channel more accurately and therefore, to obtain a better quality signal at the end of the communication system.

The objective of my thesis is to study the performance of the system using this new cell-specific reference signal channel estimator in dependance of the power allocation.

1.3. Methods and procedures

The project is carried out at **Technische Universität Wien.**

The initial idea of the thesis was provided by Stefan Schwarz, a professor of the TU working with a team of students that have developed a 5G simulator implemented in Matlab.

The research group of the TU has a long and successful history of developing and sharing open-source cellular communications simulators, in total three reliable simulators. Over the years, many simulator versions, including new features according to the LTE standard were released. Today the Vienna LTE Simulators count more than 50.000 downloads in total. This historical development shows the need for a standard compliant reliable simulation tool for performance evaluation and comparison. Therefore the TU research group has extended their simulator suite and evolved to the next generation of mobile communication by introducing new 5G simulators.

Through the simulators, it is intend to offer a unifying platform for performance evaluation as well as co-existence investigation of candidate 5G physical layer schemes. Since there exists no concrete specification yet, it provide great flexibility by supporting a broad range of simulation parameters. Thus, many different combinations of physical layer settings are comparable by the 5G link level simulator.

My thesis is performed in the framework of a group project. So, the project does not start from scratch and continues the project of implementing and adding functionalities to the simulator. My part project consists in adding a new feature to the 5G simulator already implemented.

1.4. Work plan with tasks, milestones and a Gantt diagram.

1) Background investigation.
2) Become familiar with the 5G simulator.
3) Implementation of the cell-specific reference signals (CS-RS).
4) Extend LS channel estimator to support CS-RS.

5) Test the new functionality of the simulator.

6) Performance evaluation in dependence of Power allocation.

7) Thesis reports

Work Packages:

Background investigation and project definition	WP ref: 1
Major constituent: information and documentation	
Short description: - Background information - Goals definition - Project proposal	Planned start date: 05/03/18 Planned end date: 22/03/18 Start event: 09/03/18 End event: 30/03/18
	Table 1: Work package 1

5G simulator familiarization	WP ref: 2
Major constituent: SW	
Short description: Learn how the simulator works and understand the different options and features.	Planned start date: 15/03/18 Planned end date: 02/04/18 Start event: 15/03/18 End event: 04/04/18
	Table 2: Work package 2

Implementation of the cell-specific reference signals (CS-RS)	WP ref: 3
Major constituent: SW	
Short description: Implement the function to generate the reference signal for the LTE using the 3GPP standard. Add the function to the "PilotSymbolAidedChannelEstimation" class.	Planned start date: 04/04/18 Planned end date: 17/04/18
	Table 3: Work package 3

Extend LS channel estimator to support CS-RS	WP ref: 4
Major constituent: SW	
Short description: Modificate the least squares channel estimator in order for it to support cell specific-reference signal.	Planned start date: 20/04/18 Planned end date: 10/05/18
	Table 4: Work package 4

Test the new functionality of the simulator	WP ref: 5
Major constituent: SW	
Short description: Verify that the simulator works properly with the new functionality and test different scenarios and parameters.	Planned start date: 10/05/18 Planned end date: 15/05/18
	Table 5: Work package 5

Performance evaluation in dependence of Power allocation	WP ref: 6
Major constituent: SW	
Short description: Simulate different scenarios and tests with different configurations and different power allocations. Extract conclusions using the simulator results.	Planned start date: 16/05/18 Planned end date: 14/06/18
	Table 6: Work package 6

Thesis reports	WP ref: 7
Major constituent: SW	
Short description: - Project proposal and workplan - Critical review - Final Report	Planned start date: 06/03/18 Planned end date: 29/06/18
	Table 7: Work package 7

Gantt diagram:

	Thesis	16.8 w	6 Mar 2018...	29 Jun 2018...
1	Background investigation and project definition	3.08 w?	9 Mar 2018...	30 Mar 2018...
2	5G simulator familiarization	2.5 w?	15 Mar 2018...	2 Apr 2018 at...
3	Implementation of CS-RS	9.44 d?	4 Apr 2018 a...	17 Apr 2018 a...
4	Extend LS channel stimator to support CS-RS	13.26 d?	20 Apr 2018...	10 May 2018...
5	Test funcionality	3.63 d?	10 May 2018...	15 May 2018...
6	Performance avaluation in dependence of Pow...	21.47 d?	16 May 2018...	14 Jun 2018...
7	Thesis reports	84 d?	6 Mar 2018...	29 Jun 2018...

Table 8: Gantt diagram plan

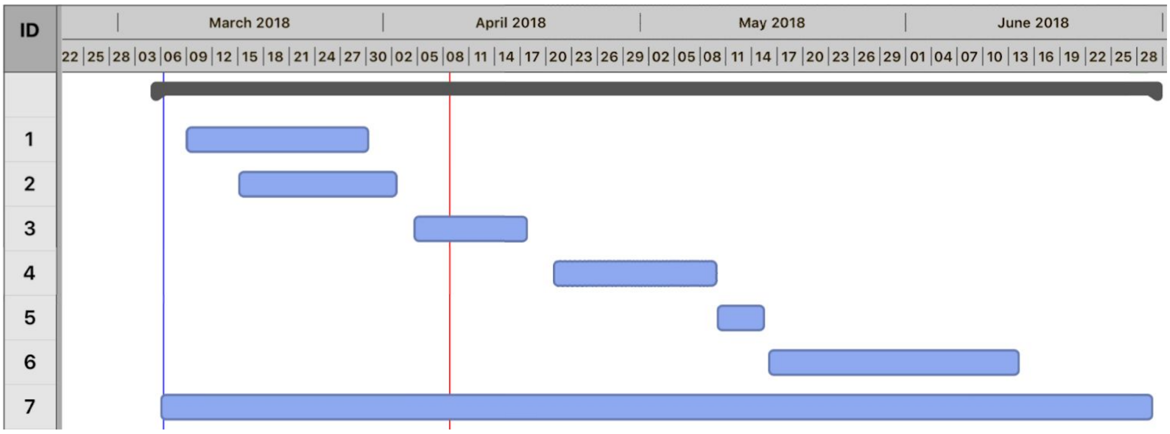


Figure 1: Gantt diagram

There has not been any major incidence. The only thing that has gotten us behind the planned schedule is that the third work-package took longer than what we planned.

When generating the complete orthogonal sequence, the simulator performance was not as expected. This was due that the simulator had problems with the symbols that were 0 and it took us a while to realise what the problem was. Once the problem was identified, fixing it was very simple: two orthogonal sequences without zeros were used.

We also decided to generate a new class, that was not in the initial plan, in order to make sure that all the Pilot matrix generated (pattern + symbols) were orthogonal. And if they were not, to see which cell IDs were the most suitable, meaning, the ones that produced the dot product between signals lower.

So, the only significant change on the previous work plan is that the work package three has took 2 more weeks than planned.

At the end of the project, there was some time left and the implementation for the pilot signal for more than one antenna was added to the simulator.

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

2.1. 5G Simulator

In general the purpose of link level simulations of communication systems is to evaluate the average performance of the physical layer transceiver architecture. Correspondingly, the focus of the 5G link level simulator is on point-to-point simulations. However, there is neither a physical cell size nor a distance to the user being considered; the path-loss to a user is rather specified as an input parameter, leading to an average signal to noise ratio. The concept of a cell can be thought of a group of nodes, that is, one base station and several users are grouped within a cell.

As a result of the system performance the simulator can calculate the throughput, the Bit Error Ratio (BER) or the Frame Error Ratio (FER) among others.

The 5G link level simulator supports both, up- and downlink simulations. The simulator includes parameter settings for Long Term Evolution-Advanced (LTE-A) compliant simulations and additionally further user defined settings for the simulation of future 5G cellular communications systems which will be detailed in section 3.1.1. (Simulation set up). While currently up- and downlink are implemented for Frequency Division Duplex (FDD) mode only, the simulator structure allows for future implementation of Device-to-Device (D2D) communications as well as a Time Division Duplex (TDD) frame structure. Further, for simulation of 5G communications systems, it offers high flexibility in choosing desired physical layer methods. Not only simulation parameters such as channel model, bandwidth or receiver type, but also very basic parameters, such as sampling rate and frame duration, are adjustable in our simulator.

To enable investigation of 5G physical layer candidate methods, it support features such as new PHY waveforms like Iterated or windowed Orthogonal Frequency Division Multiplexing (OFDM), Filter Bank Multicarrier (FBMC) or Universal Filtered Multicarrier (UFMC), and different channel codes like Turbo coding, Low Density Parity Check (LDPC) coding or Polar coding. All of these schemes support any combination of channel coding rate and Quadrature Amplitude Modulation (QAM) alphabet size, which results in many different Modulation and Coding Scheme (MCS). In addition, the employed physical layer schemes can be different for users of different cells such that their co-existence can be simulated.

The following table presents a summary of the principal characteristics of the simulator.

General Functionality

The Vienna 5G Link Level Simulator evaluates the average PHY layer performance by means of Monte Carlo simulations.

- no network geometry, no path loss model
- average user SINR is an input parameter
- simulate almost any multicarrier system
- choose parameters individually for each node

Channels and Links

Currently a FDD fame structure is implemented.

- Uplink data channel
- Downlink data channel

Channel Coding

Different channel coding schemes may be chosen for different cells to investigate their co-existence.

Supported channel codes are:

- Turbo coding (LTE-A)
- TB convolutional coding
- Polar coding
- LDPC coding

Transmission Modes

- receive diversity
- spatial multiplexing with arbitrary MIMO configurations

Modulation

Different modulation schemes and waveforms may be chosen for different cells to investigate their co-existence.

Supported PHY waveforms are:

- OFDM
- f-OFDM
- WOLA
- FBMC
- UFMC

Table 9: Simulator characteristics

2.2. LTE

2.2.1. Introduction to LTE

The LTE downlink is based on Orthogonal Frequency Division Multiplexing (OFDM), which is an attractive downlink transmission scheme due to its robustness against frequency selective channels. LTE supports the use of multiple transmit and receive antennas , and uses different modulation alphabets and channel codes according to the signalized channel quality. Furthermore, the time-frequency resources are dynamically shared between users. Adaptive modulation and coding, support of Multiple Input Multiple Output (MIMO) and Hybrid Automated Repeat Request (H-ARQ) are the prime keystones of the LTE downlink.

At the highest level, the LTE signal in the time domain consists of frames of duration $T_{frame} = 10\ ms$, which themselves consists of ten equally long subframes with $T_{subframe} = 1\ ms$. Each subframe comprises two equally long slots of duration $T_{slot} = 0,5\ ms$. Each slot consists of a number of OFDM symbols (six or seven) with cyclic prefix. LTE defines two different cyclic prefix length, normal and extended. In Figure 2, the signal structure for normal cyclic prefix length is depicted. According to the used bandwidth, each OFDM symbol consists of a number of subcarriers. Subcarriers are grouped into resource blocks, where each resource block consists of 12 adjacent subcarriers, with 15 kHz spacing between two consecutive subcarriers. LTE allows to use any number of resource blocks from 6 up to 100, which corresponds to bandwidth from 1.4MHz up to 20 MHz.

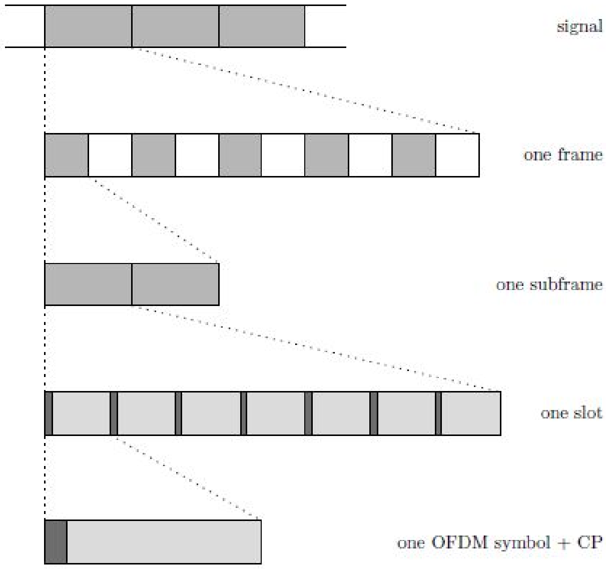


Figure 2: OFDM signal structure

2.2.2. System model

The relevant components of the considered system are depicted in Figure 3. In the following mathematical description just one subframe is considered and for sake of simplicity the subframe index will be omitted.

At the transmitter, the data bits of one subframe are generated (in the complete system these data bits are scrambled and encoded, but from channel estimation point of view this is of minor importance). Before serial-to-parallel conversion, the symbols are modulated according to [3] and pilot symbols are inserted. After Inverse Fast Fourier Transform (IFFT) and parallel-to-serial conversion, the cyclic prex is inserted and the transmit signal is generated by a Digital-to-analog converter.

At the receiver, the cyclic prex is removed. Using Fast Fourier Transform (FFT), the signal is converted into the frequency domain. Using the channel estimation and equalization, the data estimates are obtained.

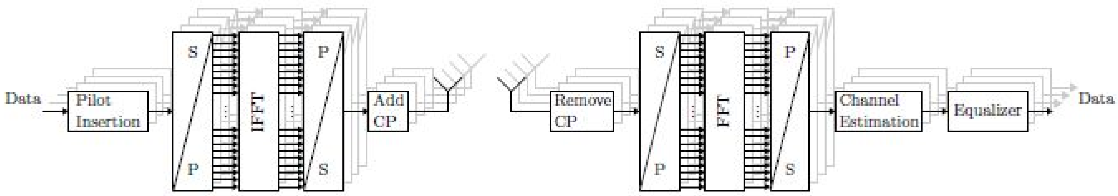


Figure 3: System model

2.2.3. Structure of Pilot Symbols

To enable coherent demodulation, channel estimation is required. A simple way to enable channel estimation in an OFDM system is to insert known pilot symbols into the time-frequency grid of the transmit signal. The position of the pilot symbols depends on the number of transmit antenna ports.

Whenever, there is a pilot symbol located within the time-frequency grid at one transmit antenna port, the symbols at same position at the remaining transmit antenna ports are 0. In figure 4 the structure of the pilot symbols for 4 transmit antenna ports is shown. The colored squares correspond to the pilot symbols at a particular antenna port and crosses corresponds to positions within time-frequency grid, which are 0. Within each resource block at 1st and 2nd transmit antenna port, there are 4 pilot symbols, and at the 3rd and 4th transmit antenna port just 2. It is obvious, that with increasing number of antennas, the number of pilot symbols and symbols, which are 0, is increasing.

This fact results in decreasing spectral efficiency with increasing number of transmit antenna ports (e.g. in case of 4 transmit antenna ports, 14:3% of all symbols is used just for channel estimation). At the 3rd and 4th transmit antenna ports, less pilot symbols than at the 1st and 2nd transmit antenna ports are located. Therefore, in general the quality of the channel estimates from 3rd and 4th transmit antenna ports will be poorer, than the quality of channel estimate from 1st and 2nd transmit antenna port. Consequently, the use of 4 transmit antenna ports should be restricted to scenarios, in which the channel is not changing rapidly.

The complex value of the pilot symbols will vary between different pilot symbol positions and also between different cells. Thus, the reference signal can be seen as two dimensional cell identifier sequence

The complex value of pilot symbols is cell dependent. The frequency domain position of the pilot symbols may vary between consecutive subframes. The relative position of the pilot symbols is always the same, as depicted in Figure 4. The frequency hopping can be described as adding frequency offset to the basis pilot symbols position structure.

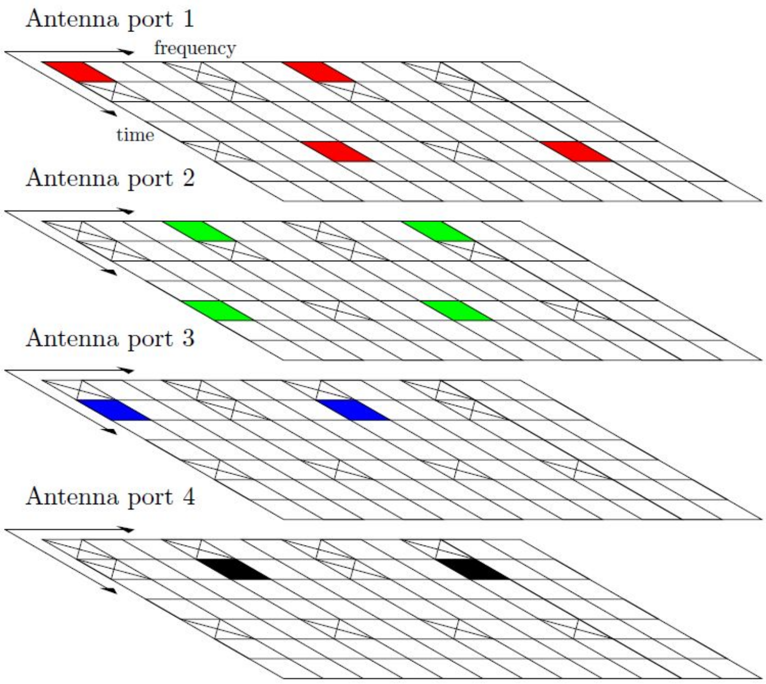


Figure 4: Pilot positions in the time-frequency grid

In section 2.3 is explained with more detail how this sequence of pilot symbols and their allocation is calculated.

2.3. Reference Signals in the 3GPP standard

There are six types of downlink reference signals are defined:

- Cell-specific Reference Signal (CRS)

- MBSFN reference signal
- UE-specific Reference Signal (DM-RS) associated with PDSCH
- DeModulation Reference Signal (DM-RS) associated with EPDCCH or MPDCCH
- Positioning Reference Signal (PRS)
- CSI Reference Signal (CSI-RS)

The project focuses on the study of the Cell-specific Reference Signal (CRS). Cell-specific reference signals are transmitted on one or several antenna ports of 0 to 3. Cell-specific reference signals are transmitted in subframes where f 15 kHz only.

2.3.1. Sequence of Pilot Symbols

According to the GPP standard the sequence generation is defined by:

$$r_{l,n_s}(m) = \frac{1}{\sqrt{2}}(1-2\cdot c(2m)) + j\frac{1}{\sqrt{2}}(1-2\cdot c(2m+1)), \quad m = 0, 1, ..., 2N_{RB}^{max,DL} - 1$$

where n_s is the slot number within a radio frame and l is the OFDM symbol number within the slot.

The pseudorandom sequence $c(n)$ is defined as:

$$c(n) = (x_1(n+N_c) + (x_2(n+N_c))\ mod\ 2$$

where:

$$x_1(n+31) = (x_1(n+3) + x_1(n))\ mod\ 2$$

$$x_2(n+31) = (x_2(n+3) + x_2(n+2) + x_2(n+1) + x_2(n))\ mod\ 2$$

and it has to be initialized with:

$$c_{init} = 2^{10}\cdot(7\cdot(n'_s+1) + l + 1)\cdot(2\cdot N_{ID}^{cell} + 1) + 2\cdot N_{ID}^{cell} + N_{CP}$$

where:

$N_{CP} = 1$ for normal CP and $N_{CP} = 0$ for extended CP

$n'_s = 10\lfloor n_s/10 \rfloor + n_s \ mod\ 2$ for frame structure type 3 when the CRS is part of a DRS and $n'_s = n_s$ otherwise

In section 3.2.2. the sequence generated used in the channel estimator is detailed.

2.3.2. Allocation of Pilot Symbols

The reference signal generated as described on the previous apartment have to be mapped to complex-valued modulation symbols $a_{k,l}^{(p)}$ used as reference symbols for each antenna port p in slot n_s. This mapping is done according to the expresion:

$$a_{k,l}^{(p)} = r_{l,n_s}(m')$$

where:

$k = 6m + (v + v_{shift})\ mod\ 6$

$l = 0,\ N_{symb}^{DL} - 3$ if $p \in \{0,\ 1\}$ and $l = 1$ if $p \in \{2,\ 3\}$

$m = 0,\ 1, ...,\ 2 \cdot N_{RB}^{DL} - 1$

$m' = m + N_{RB}^{max,DL} - N_{RB}^{DL}$

v and v_{shift} define the position in the frequency domain for the different pilot signals used.

v is given different values depending on p (the antenna port) and l. This values are:

0 if $p = 0$ and $l = 0$

3 if $p = 0$ and $l \neq 0$

3 if $p = 1$ and $l = 0$

0 if $p = 1$ and $l \neq 0$

$3(n_s\ mod\ 2)$ if $p = 2$

$3 + 3(n_s\ mod\ 2)$ if $p = 3$

v_{shift} is the cell-specific shift and it is given by:

$$v_{shift} = N_{ID}^{cell} \ mod\ 6$$

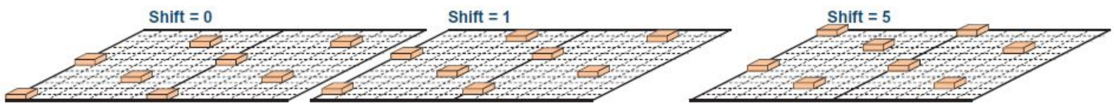


Figure 5: Different reference-signal frequency shifts

Resource elements $(k,\ l)$ used for the cell-specific reference signals on any of the antenna ports in a slot can not be used for any transmission on any other antenna port in the same slot and have to be set to zero.

For example, if two antenna ports are used:

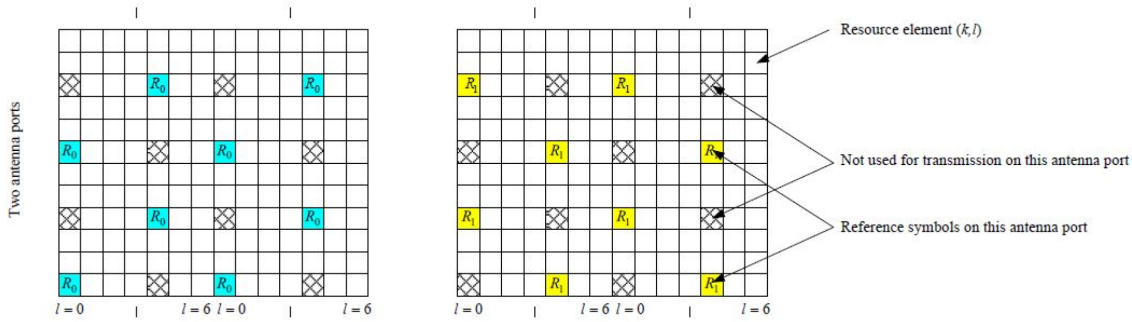


Figure 6: Mapping of downlink reference signals (normal cyclic prefix)

2.4. Channel Estimation

Considering a scenario with two base stations where each one is connected to a user, it exists an interference between BS2 and UE1. The scenario is shown in the figure 7.

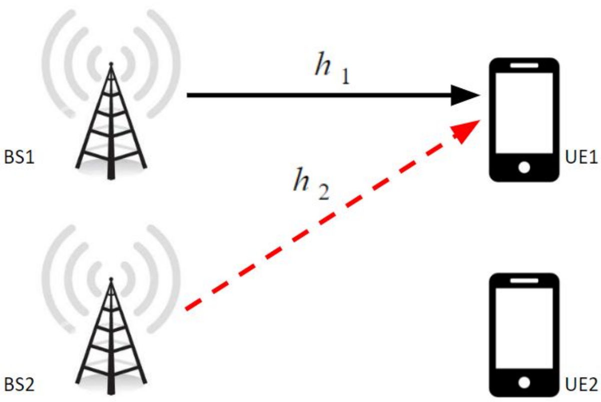


Figure 7: Proposed scenario

The received reference signal in UE1 is equal to:

$$y = h_1 \cdot x_1 + h_2 \cdot x_2 + v$$

where:

$x_i \equiv$ pilot signal of the signal transmitted by the base station i

$h_i \equiv$ is the channel of the link connecting the base station i with the UE1

$v \equiv added\ noise$

To estimate h_1, the dot product between the received pilot signal and the pilot signal sended by the base station 1 is calculated and then it is divided by the norm of the pilot signal

$$\widehat{h}_1 = \frac{y^H \cdot x_1}{x_1^H \cdot x_1} = h_1^* \cdot \frac{x_1 \cdot x_1}{x_1^H \cdot x_1} + h_2^* \cdot \frac{x_1^* \cdot x_2}{x_1^H \cdot x_1} + v \cdot \frac{x_1^*}{x_1^H \cdot x_1} = h_1 + h_2 \cdot e + \widehat{v}$$

If the the pilot signal 1 and the pilot signal 2 were orthogonal, the dot product between them would be zero. Consequently, the parameter e also would be zero and the term with the second channel would disappear. This situation would be ideal, but if the reference signals are not completely orthogonal an error term will always appear.

$$\widehat{h}_1 = h_1 + h_2 \cdot e + \widehat{v}$$

The resulting error of the channel will be defined as:

$$MSE = \tfrac{1}{N} \Sigma \left| h_1 - h_1 - h_2 \cdot e - \widehat{v} \right|^2 = \tfrac{1}{N} \Sigma \left| - h_2 \cdot e - \widehat{v} \right|^2$$

3. Methodology / project development:

The development of this project is divided in:

1) Understanding how the simulator works
2) Generating the pilot signal
3) Implementing the new channel estimator

3.1. Simulator performance description

The simulator, which is implemented in Matlab, has many different classes and functions.

3.1.1. Set up

Fist of all, a scenario where the parameters are declared is needed. In this file the parameters declared are:

- Topology: elements (base stations and users) and the links between them (the desired and the interference ones). Also the attenuation between the interferencing links is declared here.
- Simulation parameters: the type of link (downlink or uplink) and the cellID array. The plot options and the sweep parameter desired is defined here. The number of frames of the simulation is also included in this section.
- Physical transmission parameters: center frequency, transmitted power, number of antennas, user velocity and the pathloss between links are defined here.
- Channel parameters: among other parameters, the power delay profile model is chosen here (AWGN, Flat, PedestrianA, ...).
- Channel estimation and equalization: in this section the channel estimation method and the pilot pattern used as well as the equalizer type are declared.
- MIMO parameters: the layer mapping and the MIMO mode are established here.

- Feedback parameters: the feedback is enabled here as well as the the options offered by this function. If the feedback is disabled, the number of spatial streams and the precoding matrix are needed.
- Modulation parameters: it consists in choosing the waveform, number of subcarriers per subband, total number of subcarriers, its spacing and the number of symbols per frame among others.
- Channel coding parameters: including the channel code per link, the decoding algorithm and the number of decoding iterations needed.
- Schedule: here the static schedule per base station (using uplink or downlink) is defined.

For the simulations runned for this project, some of this parameters remain statics and some others will be changed depending on the objective of the simulation. The parameters used in each simulation will be detailed with their corresponding results in section 4.

3.1.2. Simulation

The first task that the main class of the simulator does, loads the parameters declared in the scenario described previously and generates the network topology and the links between them, it also initialize the result variables. Then, the simulation loop is started over the sweep value.

Based on the updated sweep parameter, regenerates the network and saves the average frame duration. Another loop based on the number of frames used on the simulation is started. What needs to be done first is update all the links including both, the primary and the interference type.

Now the rest of the simulations depends on it is downlink or uplink. Just the downlink case will be detailed given that will be the only one useful for the simulations that we are interested in.

Once it is in the downlink case every base station declared in the scenario generates the transmit signal for the frame of the loop. The transmit functions are implemented on the BaseStation class, which is one of the ones that have been modified for this project. First of all, the total transmit signal is generated using a loop through all the scheduled users. The input bits are generated using a random function are an encoded using the channel coder of the link used for the user in the current iteration. The signal generated is modulated and repeated depending on the number of transmitters used on the simulation /number of base stations). At this point we have the sequences of data symbols precoded that will be transmitted.

Now the Pilot signal needs to be added to the data symbols to obtain the total signal that will be transmitted. Depending on the channel estimation method the pilot signal is generated and merged with the one containing the data. Now, the complete signal is generated and ready to be transmitted.

Back to the main class, a new loop is started where each user receives the signal. The signal received is modified applying the pathloss ot the attenuation depending on the link that the base station and the current user conforms, if it is primary or interference. Each user collect signals from all the Base stations. To this total signal collected for each user, the noise is added and the total signal is processed. This means that the signal is demodulated and decoded. The demodulation is done for each receive antenna.

In the demodulation process we can estimate the noise power or not, but the focus of this thesis is the channel estimation. The first step is to calculate the perfect channel using the transfer function of the channel object. Then, to estimate the channel, the simulator gives different options. The one used in for this project is Pilot Aided estimation method, which has been previously explained and detailed in section 2.4. The last step is to calculate the channel estimation error defined as:

$$channelEstimationMSE = \frac{1}{Received\ Power} \cdot mean\,|Estimated\ Channel - Perfect\ Channel|$$

Then we can equalizate the symbols and calculate the LLR (Log-likelihood ratio). This last part is not included in the objectives of this project so it will not be further explained.

3.1.3. Results

The simulation results are collected and stored in each primary link. After the simulation is finished, the results are processed. In this post processing function the coded bit error ratio, the uncoded bit error ratio, the frame error ratio and the throughput per user among others are calculated and plotted.

3.2. Pilot signal

According to the 3GPP standard, and as it is explained on the previous section 2.3.2. the allocation of the reference signals depends on the cellID because the parameter v_{shift}. This is also shown in Figure 5.

In most of the simulations runned in this project the parameter cellID is fixed to 1 in the matrix allocation of the pilot symbols. There is just only one example that uses different allocation matrix for both base stations. If the standard is followed, we realise that the pilot symbols sended by the first base station get mixed with the data symbols sended by the second base stations in the same positions. That is why we just make a single test using the shifted allocation in order to see the effect (Figure 21).

Shifted allocation: Non-shifted allocation:

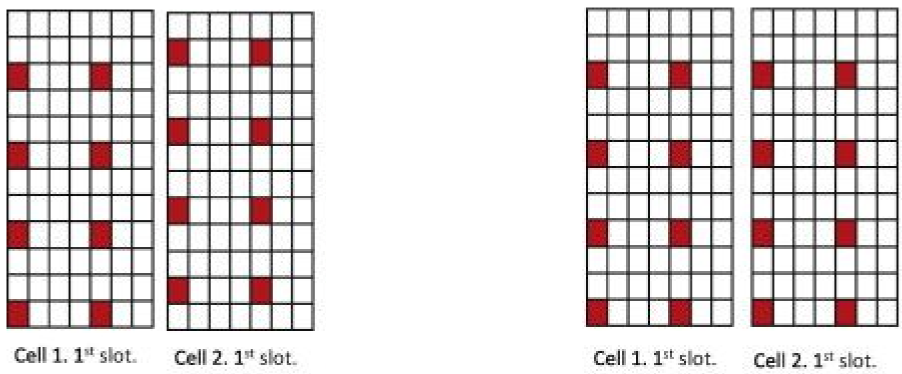


Figure 8: Pilot symbols allocation

3.2.1 Orthogonality between the pilot signals.

A new function to study the orthogonality of the different pilot signals has been implemented. It generates a table where all the dot products between the pilot signals are calculated. The one with a lower value is the product between the more orthogonal reference signals.

The input parameters of this function are the number of base stations, the number of antennas per base station and the array of cell IDs. It is also possible to decide between the shifted and the non-shifted allocation.

If the shifted allocation is chosen, it is shown that the maximum number of base stations with completely orthogonal signals is six having one antenna in each base station.

On the other hand, if we choose the non-shifted allocation and consider six different base stations with one antenna each, the following matrix is obtained:

48.0000	7.0711	7.0711	12.0830	3.1623	2.8284
7.0711	48.0000	10.1980	6.0000	4.0000	3.1623
7.0711	10.1980	48.0000	8.9443	4.0000	3.1623
12.0830	6.0000	8.9443	48.0000	7.2111	5.0990
3.1623	4.0000	4.0000	7.2111	48.0000	1.4142
2.8284	3.1623	3.1623	5.0990	1.4142	48.0000

Figure 9: orthogonality between sequences

This means that the dot product between the cell with $cellID = 5$ and the one with $cellID = 6$ is the lower. This means that this IDs are the more suitable ones for obtaining the better estimation and will be used in the simulations for the results.

3.2.2. Pilot signal generation

The pilot signal is generated by two parts, the first part is the pilot matrix allocation. To get the non-shifted allocation the cell ID parameter is fixed to 1, and the matrix obtained is a matrix 72x14 (number of subcarriers x number of OFDM symbols in one subframe) with repeating the following matrix with dimensions 6x14 (number of resource blocks x number of OFDM symbols in one subframe):

0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	1	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	1	0	0	0	0	0	0	1	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 10: Allocation of pilot symbols (cellID=1)

The resultant matrix is used for all the base stations if we are not interested in the shifted allocation. On the other side, if we want to use the shifted one, the matrix that needs to be repeated on the second base station is:

0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	1	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	1	0	0	0	0	0	0	1	0	0

Figure 11: Allocation of pilot symbols (cellID=2)

If we considered two different antennas per base station, the allocation of the symbols for the first antenna would be Figure 10 and for the second antenna would be the one:

0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	1	0	0	0	0	0	0	1	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	1	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 12: Allocation of pilot symbols for the second antenna of the base station

We can see that the allocation of the symbols is different for the two antennas in the same base station. This means that all the pilot matrices between antennas will be orthogonal independently of the sequence of symbols.

To generate the sequence of reference symbols, the cell ID has to be always taken into account.

In section 3.2.1. is explained why this cell IDs had been used. In all the antennas of the first base station (cellID=5), for the first frame, the sequence will be:

```
-0.7071 + 0.7071i  -0.7071 - 0.7071i   0.7071 + 0.7071i   0.7071 + 0.7071i
-0.7071 - 0.7071i  -0.7071 + 0.7071i  -0.7071 + 0.7071i  -0.7071 + 0.7071i
 0.7071 + 0.7071i  -0.7071 - 0.7071i  -0.7071 + 0.7071i   0.7071 + 0.7071i
 0.7071 - 0.7071i  -0.7071 + 0.7071i  -0.7071 - 0.7071i  -0.7071 + 0.7071i
 0.7071 + 0.7071i   0.7071 + 0.7071i   0.7071 - 0.7071i   0.7071 + 0.7071i
-0.7071 - 0.7071i  -0.7071 + 0.7071i   0.7071 - 0.7071i  -0.7071 + 0.7071i
-0.7071 + 0.7071i   0.7071 - 0.7071i   0.7071 + 0.7071i  -0.7071 - 0.7071i
 0.7071 - 0.7071i  -0.7071 - 0.7071i  -0.7071 - 0.7071i  -0.7071 - 0.7071i
-0.7071 + 0.7071i   0.7071 - 0.7071i  -0.7071 - 0.7071i   0.7071 - 0.7071i
-0.7071 - 0.7071i  -0.7071 - 0.7071i   0.7071 - 0.7071i   0.7071 - 0.7071i
 0.7071 - 0.7071i   0.7071 - 0.7071i   0.7071 - 0.7071i   0.7071 + 0.7071i
 0.7071 - 0.7071i  -0.7071 - 0.7071i   0.7071 - 0.7071i   0.7071 - 0.7071i
```

Figure 13: Sequence of pilot symbols (cellID=5)

And for the second base station (cellID=6):

```
-0.7071 + 0.7071i   0.7071 + 0.7071i  -0.7071 + 0.7071i  -0.7071 + 0.7071i
-0.7071 + 0.7071i  -0.7071 + 0.7071i   0.7071 - 0.7071i   0.7071 - 0.7071i
-0.7071 + 0.7071i  -0.7071 + 0.7071i  -0.7071 - 0.7071i   0.7071 - 0.7071i
-0.7071 + 0.7071i  -0.7071 + 0.7071i  -0.7071 - 0.7071i  -0.7071 + 0.7071i
 0.7071 - 0.7071i   0.7071 + 0.7071i  -0.7071 + 0.7071i   0.7071 - 0.7071i
 0.7071 + 0.7071i   0.7071 + 0.7071i  -0.7071 + 0.7071i   0.7071 + 0.7071i
-0.7071 + 0.7071i   0.7071 + 0.7071i  -0.7071 - 0.7071i   0.7071 - 0.7071i
 0.7071 - 0.7071i  -0.7071 - 0.7071i   0.7071 + 0.7071i   0.7071 + 0.7071i
-0.7071 + 0.7071i  -0.7071 + 0.7071i  -0.7071 + 0.7071i   0.7071 + 0.7071i
 0.7071 - 0.7071i   0.7071 + 0.7071i   0.7071 - 0.7071i  -0.7071 + 0.7071i
-0.7071 - 0.7071i   0.7071 - 0.7071i  -0.7071 - 0.7071i  -0.7071 - 0.7071i
 0.7071 + 0.7071i  -0.7071 - 0.7071i   0.7071 - 0.7071i  -0.7071 + 0.7071i
```

Figure 14: Sequence of pilot symbols (cellID=6)

4. Results

The simulations shown below have been done using the following parameters:

- central frequency = 2,5GHz
- pathloss = 100dB
- LTE as a layer mapping mode
- OFDM
- 12 subcarriers per subband
- 72 carriers used per base station
- 15kHz of subcarrier spacing
- 15 symbols as the total number of time-symbols per frame per base station
- 1 symbol as a cyclic prefix in OFDM
- Automatic sampling rate
- Turbo coding
- Linear-Log-MAP decoding

These parameters are common in all the simulations. The difference between them are:

- Attenuation: the used values are 400 if the interference is not considered, or 100 if the same power is wanted between the desired signal and the interfering one.
- Estimator model
- Pilot sequences
- Pilot allocation matrices

The calculation of the estimation error is done sweeping over the transmitted power, which would be the same as sweeping over the SNR.

Previous estimator

When using the estimator already implemented in the simulator the following graphs were obtained:

attenuation=400 (no interference)

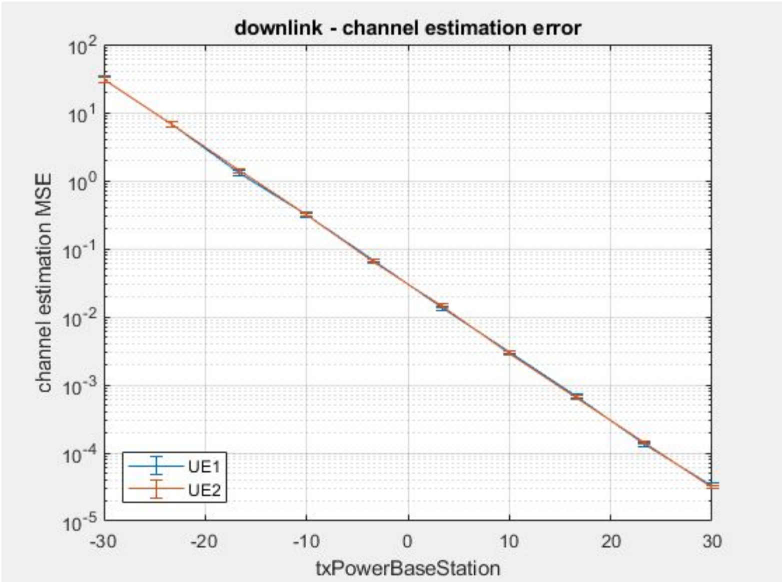


Figure 15: Simulation 1

attenuation=100

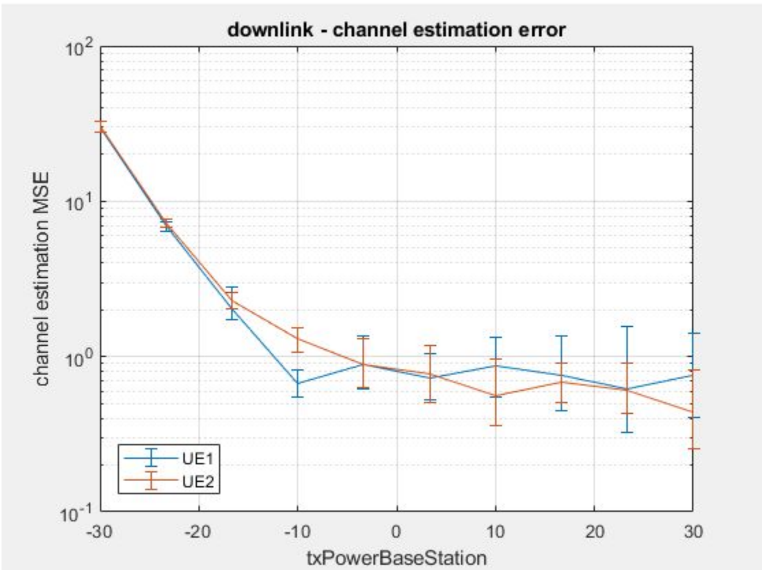


Figure 16: Simulation 2

If the attenuation on the interference link is high enough, the estimator works properly, but if the interference signal arrives at the user with the same power as the desired one the estimation is not accurate and the error is too high.

New estimator with completely orthogonal Pilot sequences

If the new implementation of the estimator is used with two sequences completely orthogonal, which make the pilot signals also completely orthogonal the following estimator error is obtained:

attenuation=400

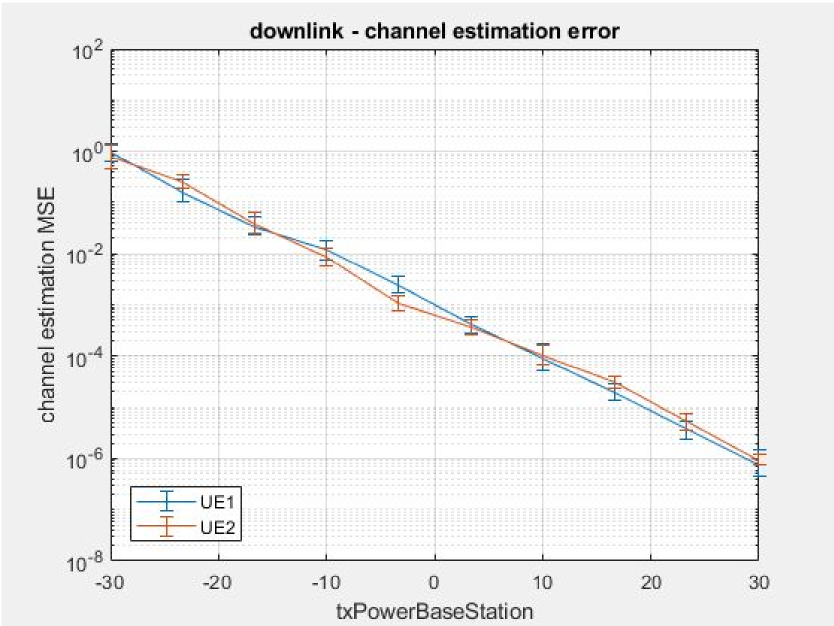


Figure 17: Simulation 3

attenuation=100

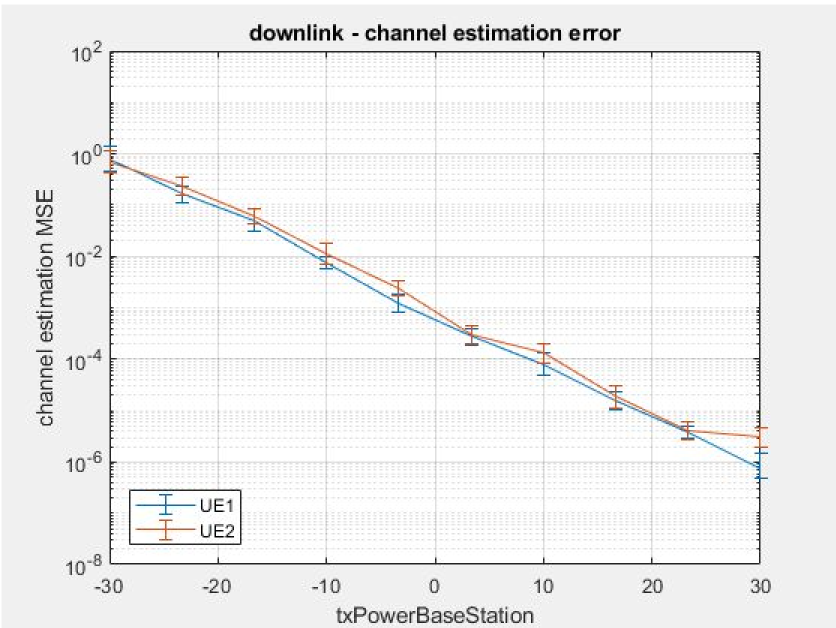


Figure 18: SImulation 4

The performance of the estimator is almost perfect as expected. The error of the simulation having interference gets as low as the one without.

New estimator with standard sequences:

In this section the new estimator is used and the completely orthogonal sequences used before, are now replaced with the ones generated with the standard criteria explained in section 2.3.2. and shown in figure 13 and 14.

attenuation=400

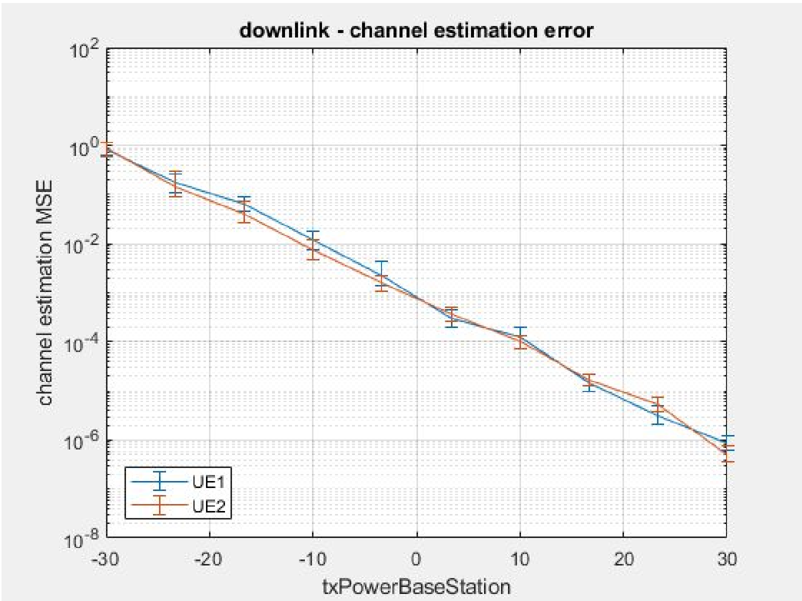


Figure 19: SImulation 5

attenuation=100

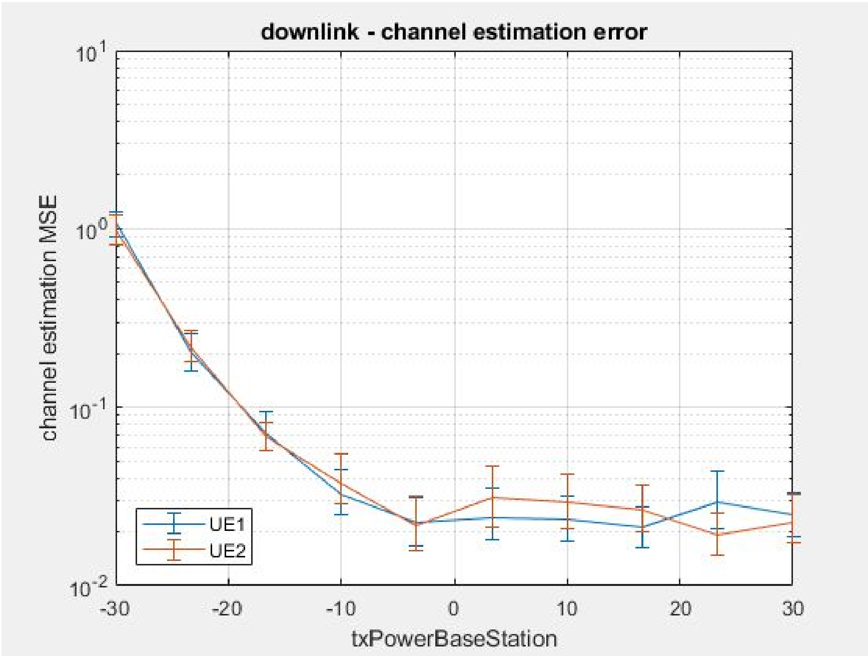


Figure 20: SImulation 6

A significant improvement is shown in the figure 20 in comparison with the previous estimator shown in figure 16.

Using different allocation for the pilot signal

In this simulation the sequences of the pilot signals are the standard ones, same as the previous simulation. The only difference is that in this case, the shifted allocation for the pilot signals in dependence of the cell ID, is used.

Attenuation=100

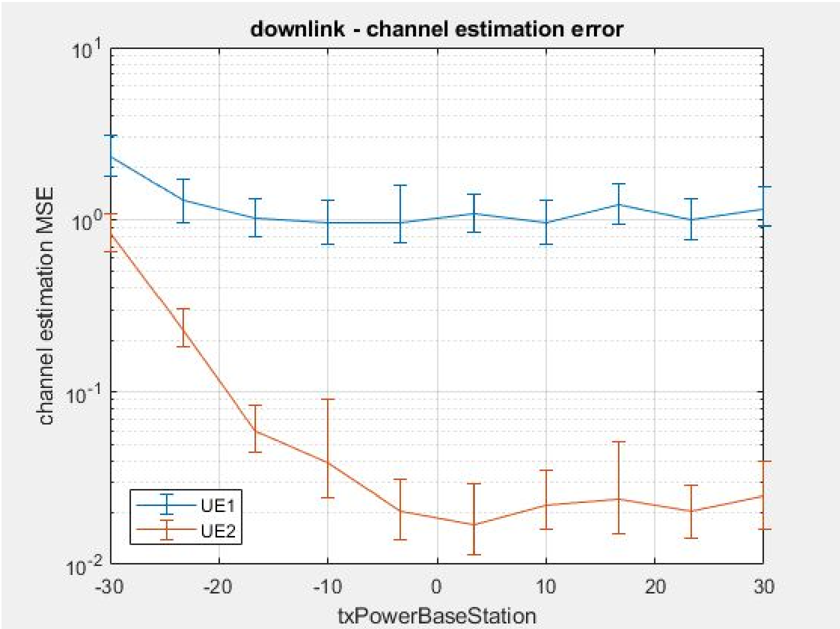


Figure 21: SImulation 7

This graph demonstrates that the shifted matrix allocation for the reference symbols does not work in this particular case because of the reason explained in section 3.2.

More than one antenna per Base station (2 transmitters):

Using the standard sequences on both antennas of the same base station, shown in figure 13.

Using different allocation for the two antennas on the same base station. Figure 10 i the first antenna and figure 12 in the second.

Attenuation = 100

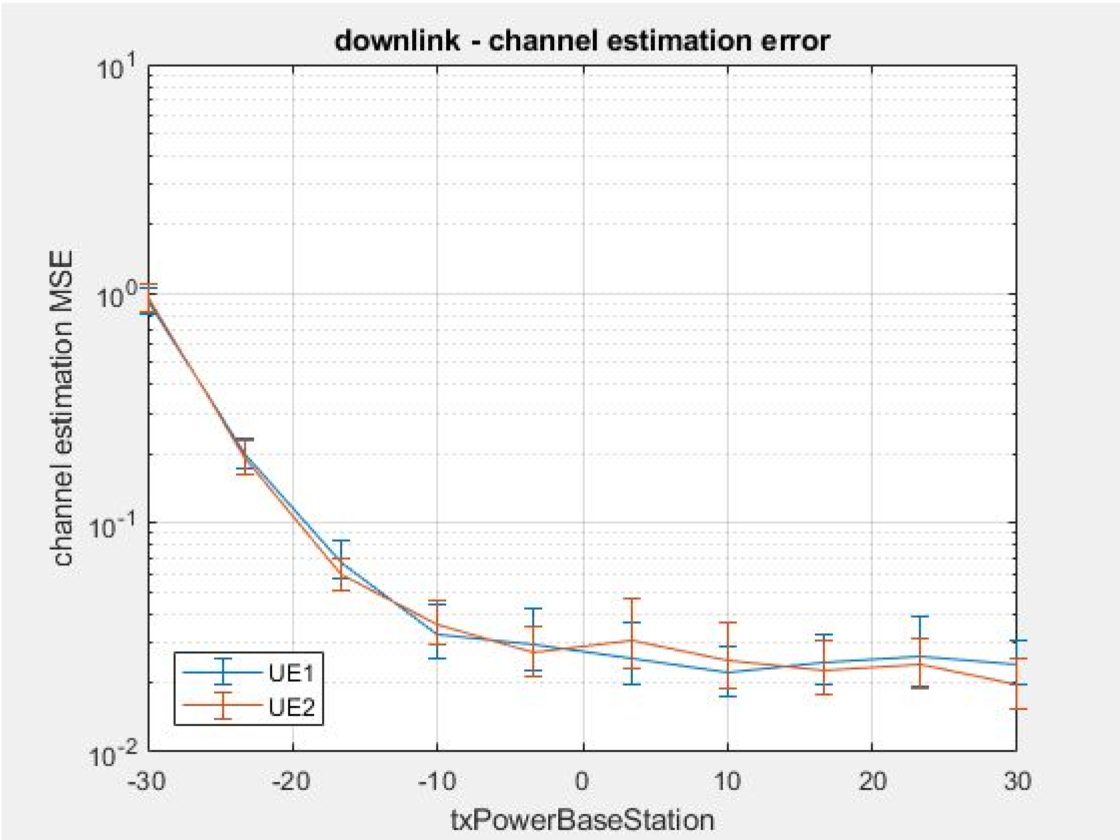


Figure 22: Simulation 8

This graph demonstrates that the estimation is a bit better with more than one antenna because if it is compared to figure 20, this one is a bit shifted to the right. This means that we get the same error with less transmitted power.

5. Budget

Software

- Matlab license: free for students, 500€ for educational institutions as UPC.

Design and prototyping costs

Task	Subtask	Time	Cost/hour	Cost
Laboratory work	Simulator	306 hours (17 weeks, 18h/week)	8 €/h.	2.448 €
	Meetings	24 hours (2 weeks, 18h/week)	8 €/h.	192 €
Deliverables	Project Proposal and Work Plan	25 hours	8 €/h.	200 €
	Critical Review	10 hours	8 €/h.	80 €
	Degree Thesis	80 hours	8 €/h.	640 €
Total				

Table 10: Budget

6. Conclusions and future development:

6.1. Conclusions

The expected conclusions have been drawn from this simulations. The more orthogonal, the pilots signals from the different base stations are, the better the obtained estimation will be.

The shifted pilot allocation does not work in this case because the pilot signals get mixed with data from other base stations.

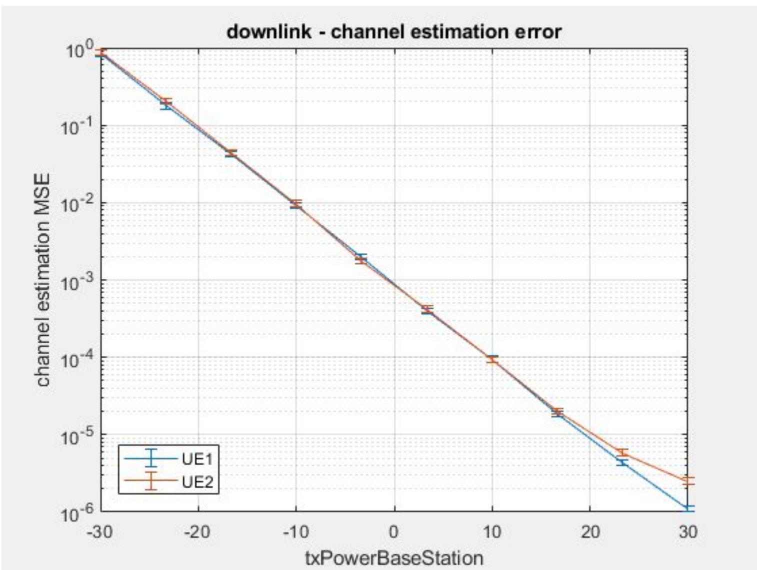
It gets a better estimation if there is more than one antenna per base station.

6.2. Future development

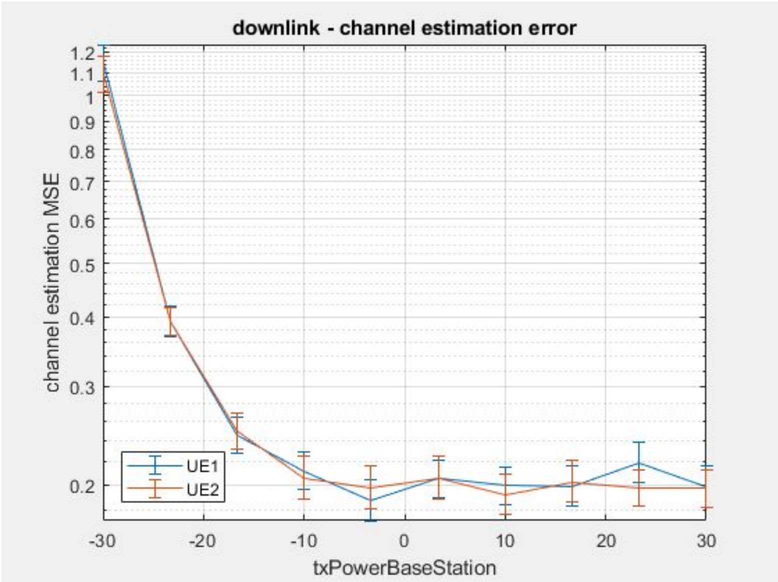
The same study could be done for up-link.

also, the code developed for this new estimation is also useful to run more simulations and study the effect of the delay profile model on the channel estimation. Some simulations have been runned changing it. For this simulations the new estimator has been used with completely orthogonal sequences. An attenuation of 100 dB has been defined. The only parameter that has been changed on the tests has been the power delay profile model.

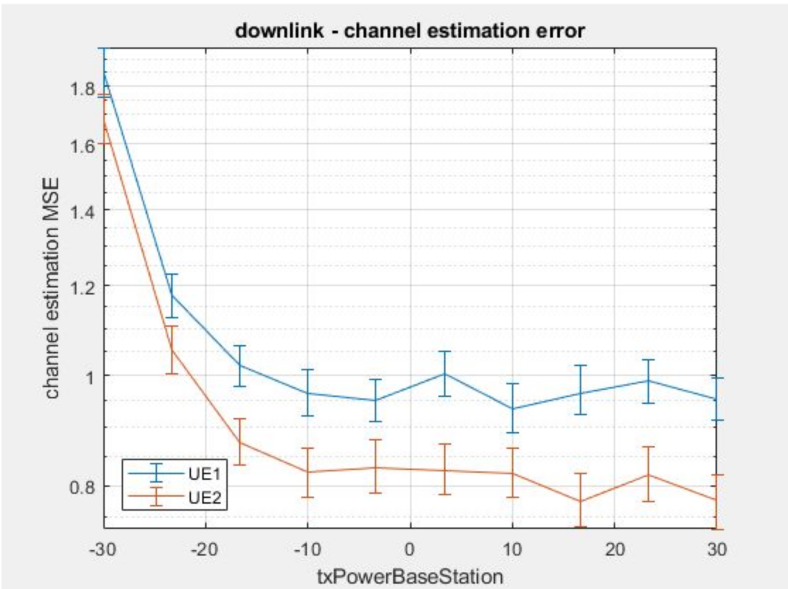
Flat



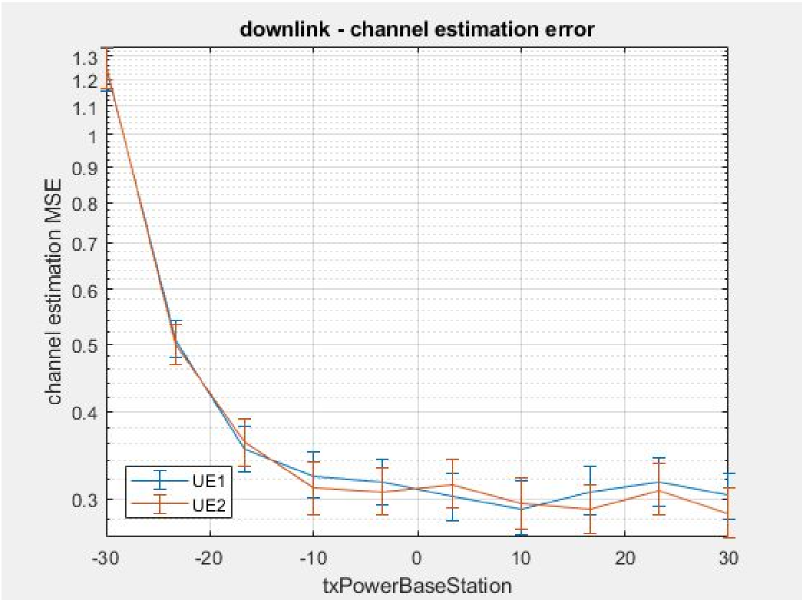
PedestrianA



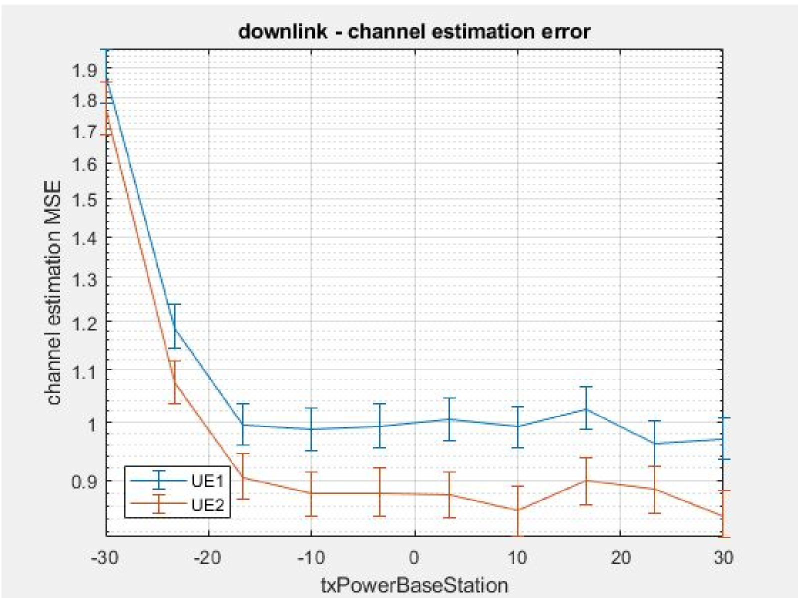
VehicularA



TDL-A_50ns



TDL-A_400ns



In the graphs is shown than the error is really high when using a model other than the flat.

The problem is that with the current implementation a single channel estimation value for the whole bandwidth is obtained. The two proposed ways to fix this problem are:

1) Decrease the scheduled bandwidth of the user (to 12 subcarriers for example)
2) Split the channel estimation into parts. So, for example, split the pilots according to frequency and consider groups of pilots that lie within 12 subcarriers. Then perform the inner product on them. In terms of interpolation, this estimation value should have to be repeated this only for 12 subcarriers an not over the whole bandwidth.

So, the channel could be estimated the current way (with the inner product) but on a resource block basis, to get one channel estimate per resource block. This way a way better frequency granularity would be obtained and if the channels is slightly frequency selective (f. e. PedestrianA) low error should be given.

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