Performance of LTE Applying Transmit Antenna Selection Algorithms

Author: Xavier Bernat Serret

Supervisors:
Stefan Schwarz
Martin Taranetz
Markus Rupp
Jordi Casademont

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Declaration of Authorship

I, Xavier Bernat Serret, declare that this thesis titled, ‘Performance of LTE Applying Transmit Antenna Selection Algorithms’ and the work presented in it are my own. I confirm that:

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- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

Signed: 

Date:
“The real progress is the one that put technology available for everyone”

Henry Ford
Antenna selection can reduce the number of the RF chains as well as the complexity of the system. This article explains the aim of antenna selection in a Multiple-Input Multiple-Output (MIMO) system but applied in an LTE environment.

However, these systems carry bad consequences such as the number of RF chains associated with multiple antennas, which are costly in terms of size, power and hardware.

In this report, an introduction to a MIMO system is given, specifying the case of a Distributed Antenna System (DAS).

The antenna selection algorithms applied at the transmitter side of an LTE system are the transmission rate based algorithm, the path loss based algorithm, the total norm based algorithm and the norm based algorithm.

The results shown in this paper are obtained through simulations executed on a MATLAB-based system level simulator from the Vienna University of Technology.

The results show that a DAS system can achieve better performance than a system where the transmit antennas are collocated in the base station. Furthermore, any of the antenna selection algorithms improves the throughput, both cell and user throughput, compared to the same system without antenna selection.
Agraïments

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### Abbreviations

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<td>LTE</td>
<td>Long Term Evolution</td>
</tr>
<tr>
<td>OFDMA</td>
<td>Orthogonal Frequency Division Multiple Access</td>
</tr>
<tr>
<td>SC-FDMA</td>
<td>Single Carrier Frequency Division Multiple Access</td>
</tr>
<tr>
<td>CP</td>
<td>Cyclic Prefix</td>
</tr>
<tr>
<td>MBSFN</td>
<td>Multicast-Broadcast Single Frequency Network</td>
</tr>
<tr>
<td>RB</td>
<td>Resource Block</td>
</tr>
<tr>
<td>RE</td>
<td>Resource Element</td>
</tr>
<tr>
<td>MIMO</td>
<td>Multiple Input Multiple Output</td>
</tr>
<tr>
<td>SIMO</td>
<td>Single Input Multiple Output</td>
</tr>
<tr>
<td>MISO</td>
<td>Multiple Input Single Output</td>
</tr>
<tr>
<td>WLAN</td>
<td>Wireless Local Area Network</td>
</tr>
<tr>
<td>WiMAX</td>
<td>Worldwide interoperability for Microwave Access</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal to Noise Ratio</td>
</tr>
<tr>
<td>SM</td>
<td>Spatial Multiplexing</td>
</tr>
<tr>
<td>OLSM</td>
<td>Open Loop Spatial Multiplexing</td>
</tr>
<tr>
<td>CLSM</td>
<td>Closed Loop Spatial Multiplexing</td>
</tr>
<tr>
<td>PMI</td>
<td>Precoding Matrix Indicator</td>
</tr>
<tr>
<td>ZF</td>
<td>Zero Forcing</td>
</tr>
<tr>
<td>MMSE</td>
<td>Minimum Mean Squared Error</td>
</tr>
<tr>
<td>DAS</td>
<td>Distributed Antenna System</td>
</tr>
<tr>
<td>BS</td>
<td>Base Station</td>
</tr>
<tr>
<td>RRU</td>
<td>Remote Radio Unit</td>
</tr>
<tr>
<td>RRH</td>
<td>Remote Radio Head</td>
</tr>
<tr>
<td>UE</td>
<td>User Equipment</td>
</tr>
<tr>
<td>AS</td>
<td>Antenna Selection</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>AWGN</td>
<td>Additive White Gaussian Noise</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>-------------</td>
</tr>
<tr>
<td>MI</td>
<td>Mutual Information</td>
</tr>
<tr>
<td>SINR</td>
<td>Signal to Interference plus Noise Ratio</td>
</tr>
<tr>
<td>BLER</td>
<td>Block Error Rate</td>
</tr>
<tr>
<td>ROI</td>
<td>Region Of Interest</td>
</tr>
<tr>
<td>TTI</td>
<td>Transmission Time Interval</td>
</tr>
<tr>
<td>CQI</td>
<td>Channel Quality Indicator</td>
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<tr>
<td>RI</td>
<td>Rank Indicator</td>
</tr>
<tr>
<td>MCS</td>
<td>Modulation and Coding Scheme</td>
</tr>
<tr>
<td>TU</td>
<td>Typical Urban</td>
</tr>
<tr>
<td>AMC</td>
<td>Adaptive Modulation and Coding</td>
</tr>
<tr>
<td>QPSK</td>
<td>Quadrature Phase-Shift Keying</td>
</tr>
<tr>
<td>QAM</td>
<td>Quadrature Amplitude Modulation</td>
</tr>
<tr>
<td>RS</td>
<td>Reference Signals</td>
</tr>
<tr>
<td>PUSCH</td>
<td>Physical Uplink Shared CHannel</td>
</tr>
<tr>
<td>RR</td>
<td>Round Robin</td>
</tr>
</tbody>
</table>
Chapter 1

Preliminary ties

1.1 Used Notation

In this first chapter the following notation has been used: vectors are introduced as $\mathbf{v}$, bold uppercase $\mathbf{H}$ denotes a matrix and non-bold letters $M$ denote scalars.

1.2 LTE Basics

In this section the most relevant aspects of Long Term Evolution (LTE) will be introduced [1].

LTE multiple access schemes:
LTE uses Orthogonal Frequency Division Multiple Access (OFDMA) with a Cyclic Prefix (CP) in the downlink and Single Carrier Frequency Division Multiple Access (SC-FDMA) with a CP in the uplink.

In LTE, 12 consecutive OFDM subcarriers with a spacing of 15 kHz each are grouped in a Resource Block (RB). Therefore, the bandwidth of one RB is $12 \cdot 15$ kHz = 180 kHz.

For Multicast-Broadcast Single Frequency Network (MBSFN) transmission, the spacing is 7.5 kHz.

LTE downlink frequencies:
LTE enables spectrum flexibility, i.e. the transmission bandwidth can vary between 1.4 MHz and 20 MHz, as summarized in Table 1.1. According to this table, in LTE, 6 bandwidth profiles are available.
The transmission bandwidth (Tx Bandwidth) takes into account only the RBs that are available for data transmission. The channel bandwidth takes into account all the possible RB plus the guard band, introduced at both ends of the spectrum to ensure negligible out-of-band emission.

Frame Structure:
The LTE frame structure is shown in Figure 1.1.

An LTE frame consists of 20 slots with 0.5 ms each. Thus, the total frame length is 10 ms. A subframe is defined as two consecutive slots (1 ms). Each slot allocates 1 RB.

Each one of the RBs is defined as 7 OFDM symbols (if normal cycling prefix is used) with a cyclic prefix between each symbol in the time domain. In the frequency domain there are 12 subcarriers. Therefore, one RB consist on 84 (12 subcarriers x 7 symbols) Resource Elements (RE), which are the smallest unit for data allocation.

The LTE resource grid is visualized in Figure 1.2.
Figure 1.2: LTE physical layer structure [2].
1.3 Antenna Selection

1.3.1 MIMO Systems

1.3.1.1 Overview

MIMO was first used in wireless systems such as WLAN or WiMAX. Due to its multiple advantages was also considered in the LTE standard.

MIMO systems standard deploy multiple antennas both at the transmitter and at the receiver [3].

There are defined other types of systems related to the general one: SIMO (Single-Input Multiple-Output) and MISO (Multiple-Input Single-Output) systems. Exploiting the spatial dimension (takes advantage of multi-path fading, use of multiple antennas to transmit multiple parallel signals) can improve the wireless system capacity, the range and also the reliability of the transmission, and it can also provide lower delays and support for multiple users [4] [5] [6].

Multi-path propagation occurs when the signals sent from different antennas arrive at the receiver at different times, due to propagation delay difference as well as reflections and scattering in the environment.

MIMO systems can be employed in different ways to exploit multi-path propagation:

- Antenna Diversity: The same information is sent on all transmitter antennas. Due to spatial diversity and multipath, this method improves the Signal to Noise Ratio (SNR).

From [7], the generalized SNR formula is given as:

$$SNR = SNR \cdot L \left( 1 + \sum_{k=L+1}^{M} \frac{1}{k} \right)$$

where $SNR$ is the average path SNR, $L$ is the number of Radio Frequency (RF) chains to select, which have the largest SNR, and $M$ is the total number of antennas.

- Spatial Multiplexing: Each transmit antenna sends an independent stream of data exploiting multi-path. The maximum spatial multiplexing order is $min(M, N)$
(where $M$ denotes the number of transmit antennas and $N$ denotes the number of receive antennas). This means that $\min(M, N)$ independent data streams can be transmitted in parallel. This method has the aim of improving the achievable rate without requiring more spectrum.

The capacity formula, as given in [8] [9], formulates as:

$$C = \log_2 \left( \det \left( I_N + \frac{\text{SNR}}{M} HH^H \right) \right)$$

(1.2)

where $I_N$ is the $N \times N$ identity matrix, $\text{SNR}$ is the mean SNR for receiver branch, $M$ is the number of transmit antennas, $H$ is the channel matrix and $H^H$ is the Hermitian transpose of the channel matrix.

Spatial multiplexing can use 2 modes of operation in LTE: Open-Loop Spatial Multiplexing (OLSM) and Closed-Loop Spatial Multiplexing (CLSM). The latter one is explained in further detail in section 1.4.4.

- Beamforming: It can be divided into transmit and receive beamforming. The transmit beamforming uses multiple antennas to manage the direction of a wavefront by weighting the magnitude and phase of single antenna. It is used to provide better coverage to a specific area. The receive beamforming determines the direction that the wavefront will arrive [10].

Figure 1.3: MIMO system versus SIMO and MISO systems [11].
In Figure 1.3 the channel capacity curve of a MIMO system as well as the capacity curve of SIMO and MISO systems are shown.

As shown in Figure 1.3, if the number of the antennas is increased in the transmitter and/or the receiver, the capacity of the system is also increased. However, for the case of SIMO/MISO systems this capacity increases following a logarithmic curve, and for the case of MIMO the capacity increases following a linear curve.

1.3.1.2 Distributed Antenna System (DAS)

MIMO systems can be exploited in different ways depending on the geographic distribution of the antennas. They can be collocated (C-MIMO) or distributed inside the cell. In this work, DAS are mainly used.

In the receiver, the antennas are collocated on the User Equipment (UE). Moreover, the transmitter can be thought as multiple antennas collocated on a single base station, or multiple spatially distributed antennas in the large of a cell, which are connected to the central node by a high-bandwidth low-latency connection [12].

For instance, we can have a $4 \times 4$ MIMO system with all 4 transmit antennas at the BS or, 1 transmit antenna at the central node and 3 Remote Radio Units (RRUs), which are distributed in the cell. Both cases yield a $4 \times 4$ system effectively.

DAS systems configuration are typically deployed in environments like indoor scenario, urban (outdoor) scenario or high-speed railway scenario [13]. However, only the urban environment is considered in this paper. The principal characteristics of this scenario are the small cell radius, the severe inter-cell interference that user experiences or the frequent handover if moving with high speed.

The most notable benefits of DAS are that it achieves better indoor [14] and outdoor coverage [15] since it reduces the large scale shadowing [16] (even when the UE is at the cell edge, scenario where the C-MIMO does not work well), the macroscopic diversity since the antennas can be distributed in a large area or that it improves system capacity [17] and reliability due to the elimination of the correlation between transmit antennas [18].

Other benefits are the lower transmit power since the antennas can be closer to the UE compared to the central node and improves battery life of mobile since transmit powers can be lower.
1.3.2 Antenna Selection Motivation

Although MIMO can enhance the capacity and reliability of the system, this gain comes
with certain trade-off, like the usage of more Radio Frequency (RF) chains. A system
with $M$ transmit antennas and $N$ receive antennas requires $M$ complete RF chains in the
transmitter and $N$ complete RF chains in the receiver, apart from low-noise amplifiers,
down-converters, and analog-to-digital converters.

Therefore, the cost of the system increases. Further the correspondingly larger number of
channel state parameters increases complexity, e.g., for channel estimation and feedback
calculation.

However, the antennas connecting these RF chains are less expensive. The aim of
antenna selection is to implement more antennas than RF chains and use only a subset of
them, but maintaining the advantages of MIMO. In this point, using Antenna Selection
(AS) algorithms has become of great interest \[7\] \[19\]. Antenna selection can be applied
both in the transmitter and in the receiver. The best $L_t$ out of $M$ antennas (in the
case of applying antenna selection at the transmitter) or the best $L_r$ out of $N$ antennas
(in the case of antenna selection applied at the receiver) are selected. This reduces the
number of RF chains from $M$ (or $N$) to $L_t$ (or $L_r$) and correspondingly, the complexity
of the system.

Apart from that, antenna selection requires only a small fraction of the full channel
state information. As explained in \[7\], only on the order of $L_t \log M$ bits of feedback
information is necessary for transmit antenna selection.

1.3.3 Antenna Selection Block Diagram

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{as_system.png}
\caption{Block diagram of AS system \[7\].}
\end{figure}

Figure 1.4 shows the generic structure considered in this paper for an antenna selection
system. A stream of bits is sent to the signal processing and encoder module. The
encoder converts the stream into $L_t$ parallel complex symbol streams. In the case of transmit diversity, these streams can all carry the same data. In the case of Spatial Multiplexing they all bear independent data. Then, the RF switch module, assigns the modulated signals to the best $L_t$ out of $M$ antennas, taking into account the feedback as received from the UE.

The signal experiences a flat-fading channel ($H$) which can be represented by an $N \times M$ matrix. Its output is additionally affected by Additive White Gaussian Noise (AWGN), which is assumed to be independent for each receive antenna. At the receiver, the best $L_r$ out of $N$ antenna elements are selected by the RF switch taking into account the information received by the signal processing and decoding module. With the antenna selection, both in the transmitter and in the receiver, the number of RF chains is reduced.

In the next formula, the input-output relationship in the already explained system is formulated:

$$\vec{y} = H \cdot \vec{x} + \vec{n} \quad (1.3)$$

where $\vec{y} = [y_0, \ldots, y_{N-1}]^T$ and $y_n$ is the complex symbol from the received signal, $H$ ($N \times M$) is the channel matrix, $\vec{x} = [x_0, \ldots, x_{M-1}]^T$ and $x_m$ is the modulation symbol from the transmit signal and $\vec{n} = [n_0, \ldots, n_{N-1}]^T$ is the noise vector.
1.3.4 Transmit - Receive Antenna Selection

The main difference between AS at the transmitter and at the receiver is the usage of feedback.

In the case of transmit antenna selection, as shown in Figure 1.5, there are $M$ antennas and $L_t$ RF chains with $L_t \leq M$.

In the case of receive antenna selection, as depicted in Figure 1.6, there are $N$ antennas and $L_r$ RF chains with $L_r \leq N$.

In the transmitter case, there is a feedback path from the receiver to the transmitter.
1.3.5 Different Antenna Selection Schemes in MIMO systems

To apply antenna selection, a lower number of antennas from all the available antennas has to be selected, that is to select some columns from the channel matrix (in the case of transmit antenna selection) or select some rows from the channel matrix (in the case of receive antenna selection).

The methods as presented in the following equivalently apply to both transmit and receive antenna selection and are typically employed with spatial multiplexing.

1. Optimal Solution:
   This method maximizes the Mutual Information (MI) by performing an exhaustive search over all possible channel matrix subsets. Therefore, it yields the highest achievable performance. First, the receiver calculates the MI for all the possible submatrices. For example, a possible submatrix can be the first and the second column or the three first columns of the channel matrix. The number of combinations depends on the number of transmit antennas.

   Then, the submatrix that gives the highest MI is selected and the corresponding column indices are sent to the transmitter. Then, equation 1.2 formulates as [20]:

   \[ C = \max_{S(\tilde{H})} \left[ \log_2 \det \left( I_N - \frac{SNR}{M} \tilde{H} \tilde{H}^H \right) \right] \]  

   (1.4)

   where \( \tilde{H} \) is generated by deleting \( M - L \) columns from \( H \) and \( S(\tilde{H}) \) denotes the subset of all possible \( \tilde{H} \).

   The number of possibilities, in a system where \( M \) is the total number of transmit antennas and \( L \) is the number of antennas in the submatrix, is calculated as [21]:

   \[ \sum_{L=1}^{M} \binom{M}{L} \]  

   (1.5)

   E.g., a 4 × 4 MIMO system yields 15 possible combinations in each front-end. Thus, while this method gives best results in terms of MI it is also the most time-consuming and complex one.

   This is quite prohibitive expecting that the number of antennas will grow remarkably in future wireless systems.
Thus, we aim at finding less complex methods where the number of antennas that are going to be selected is pre-defined before applying the algorithm (except for the path loss based algorithm).

2. Total Norm Based AS:

In this algorithm, the equation 1.2 is expressed as [7]:

\[
C = \log_2 \det \left( I_N + \left( \frac{\overline{SNR}}{L_t} \right) \tilde{H} \tilde{H}^H \right) \tag{1.6}
\]

Where \( I_N \) is the \( N \times N \) identity matrix, \( \overline{SNR} \) is the mean SNR, \( L_t \) is the pre-selected number of columns, \( \tilde{H} \) is the submatrix formed by the \( L_t \) number of columns and \( \tilde{H}^H \) is the Hermitian of \( \tilde{H} \).

Applying the Taylor expansion of \( \log(\cdot) \) in the expression above, as in [7], and assuming low SNR, the MI is proportional to \( |\tilde{H}|^2 \).

This algorithm selects the group of columns which give the highest Euclidean norm of the reduced channel matrix. The size of the group of columns can be 1 or 2, depending on the pre-selection done.

This algorithm is frequently used because of its low complexity and well-known statistics [22][23].

3. Norm Based AS [24]:

This algorithm is even simpler than the total norm based algorithm mentioned above with some similarities and some differences.

This method calculates the Euclidean norm of all columns of the channel matrix \( \tilde{H} \) and then selects the antenna or antennas, which obtain the highest norm, depending on the pre-selection done.

The resulting sub-channel matrix would contain \( L_t \) out of \( M \) columns of the channel matrix.

4. Decremental Selection or Successive Elimination [19] [25]:

Starting with the full channel matrix, this algorithm discards those columns in each step, which yields a minimum loss of MI.

Define \( \tilde{H}_p \) as the p-th column of \( H \) (channel matrix), \( \tilde{H} \) as the matrix made by the remaining \( M - 1 \) columns of \( H \) after deleting the p-th column.
From Shannon’s achievable rate formula in [25]:

\[ C(H) = \log_2 \det \left( I_N + \left( \frac{E_s}{N_0} \right) H H^H \right) \]  

(1.7)

where \( E_s \) is the average signal energy and the energy of the AWGN is \( \frac{N_0}{2} \).

If some algebra is applied to the equation above:

\[ C(H_p) = C(H) + \log_2 \left( 1 - \frac{E_s}{N_0} \bar{H}_p^H \left[ I_N + \frac{E_s}{N_0} H H^H \right]^{-1} \bar{H}_p \right) \]  

(1.8)

Removing the \( p \)-th column results in a loss of the MI, which is reflected by the second term in the right-hand side of the expression above.

Then, to minimize this loss of MI, the \( p \)-th antenna is removed according to:

\[ p = \arg \max_p \{ \bar{H}_p^H \left[ I_N + \frac{E_s}{N_0} H H^H \right]^{-1} \bar{H}_p \} \]  

(1.9)

This step is repeated \( M - L_t \) times. In every iteration, the channel matrix \( H \) has to be changed for its submatrix with the already removed column.

5. Incremental Solution or Successive Selection [7]:

Start with the column that has the highest norm, in every iteration, project each one of the remaining column vector on the orthogonal complement of the span of the already chosen columns, and choose the column that has the projection with the largest magnitude. This has to be repeated until the desired number of antennas (\( L_t \) in this case) is achieved.

In Figure 1.7 the capacity curve for the case of full CSI at the transmitter, the MI curves for the optimal solution, the total norm based solution and the successive selection solution as well as the ergodic capacity curve for the case of having no CSI at the transmitter are compared.

This realization were carried out with \( 8 \times 2 \) system and the number of the selected transmit and receive antennas was fixed to 2. In the figure, successive selection is superposed to the optimal solution.

6. Receive-Power Selection [19]:

This method selects the desired transmit antennas based on the power of the received signals. The first step is to calculate the power of each column and then select the columns with the highest power. The number of antennas or columns selected corresponds to the pre-selection done.
An alternative of this method as suggested in [20] can be the following: if there are two identical columns in the channel matrix, any one of these two columns can be discarded without losing information. However, this case is very unlikely. In the case there are not 2 identical columns, the 2 most correlated columns are found and the one with less power is discarded. Using this method yields a channel submatrix with minimum correlation among its columns.

7. Path-Loss based AS [26]:
In comparison to previous methods, path loss based selection is a large-scale scheme. It takes into account the macroscopic path loss from the UE to each of the antennas of the cell to find the best subset of antennas.

Let $S$ be the subset of antennas selected for each user and $L_i$ the large-scale fading from one user to the antenna $i$ ($i = 0, 1, \ldots, M - 1$). Then:

$$S = \{ i | L_i < 10 \cdot \min(L_0, L_1, \ldots, L_i, \ldots, L_{(M-1)}) \}$$  \hspace{1cm} (1.10)
For each UE, one antenna is selected if the path loss between this UE and this antenna is lower than 10 times the minimum path loss between this UE and each one of the antennas.

For these algorithms it is assumed that the not selected antennas should be powered off for the user in consideration, but not for the other users in the system.

Since most of the presented methods assume a large number of antennas, simulations made in an LTE environment, where the number of antennas is restricted to 1, 2 and 4, might yield considerable deviations.
1.4 System Level Simulator

1.4.1 Simulator Structure

A simplified structure of the Vienna LTE System Level Simulator (SLS) is shown in Figure 1.8.

The crucial modules are the link quality and the link performance model.

The quality model carries out the calculation of the post-equalization Signal to Interference and Noise Ratio (SINR), using a Zero Forcing (ZF) receiver model.

The performance model uses the output of the link quality model as input of its module to evaluate the throughput of the system and its Block Error Ratio (BLER).

A general workflow is described below:

In the initial phase of the simulation, the network is generated. A Region Of Interest (ROI) is defined and the eNodeBs and UEs are placed in this ROI. The ROI is depicted in Figure 1.9 and shows an environment with 19 sites with 3 cells per site. In this case, each site employs 1 transmit antenna and 3 RRHs.

Then, the simulator enters the main simulation loop. At each TTI, first the users are moved according to a pre-selected walking model (e.g., straight-line, random walk, etc.). However, if any UE leaves the ROI it is relocated randomly inside the ROI.
Next, the eNodeBs receive the UE feedback with a given delay (in this work, the delay is specified to 1 TTI). Then, the UEs are scheduled.

In the link quality model, the channel matrix and the interfering matrix are created for each UE taking into account the geometry of the network. Further the precoding matrices are generated. With this information the SINR is calculated.

Then, the obtained SINR, in addition to the selected Modulation and Coding Schemes (MCS), are provided to the link performance model to calculate the BLER.

The last step is to calculate the UE’s feedback and send it through an idealistic delaying, but error-free feedback channel.

![Network structure in the SLS: cell and user positions.](image1)

**Figure 1.9:** Network structure in the SLS: cell and user positions.

In Figure 1.10 there is a more detailed view of a single site with a central BS, three RRHs per cell and some UEs.

![Detailed view of a single site](image2)

**Figure 1.10:** Detailed view of a single site
1.4.2 Channel Matrix Structure

The channel matrix is constructed as follows:

\[
H = \begin{bmatrix}
    h_{1,1} & h_{1,2} & \ldots & h_{1,m} \\
    h_{2,1} & h_{2,2} & \ldots & h_{2,m} \\
    \vdots & \vdots & \ddots & \vdots \\
    h_{n,1} & h_{n,2} & \ldots & h_{N,M}
\end{bmatrix}
\]

The elements of the channel matrix, \( h_{n,m} \), denote the complex-valued channel between the transmit antenna \( m \) and the receive antenna \( n \). Figure 1.11 shows a MIMO system with multiple antennas both at the transmitter and at the receiver with the different \( h_{n,m} \) values.

![MIMO channel overview](image-url)

**Figure 1.11:** MIMO channel overview.
1.4.3 Schedulers

The scheduler takes care of the allocation of shared time-frequency resources among users at each time instant. The scheduler is placed at the base station and is assigned downlink resources with certain objectives such as:

- Required QoS.
- Optimized spectral efficiency.
- Fairness.
- Limiting the impact of interference.

The scheduler determines to which user the shared resources for each TTI should be allocated for reception of DL-SCH transmission.

In this work, a Round Robin (RR) scheduler is employed.

In RR scheduling strategy, the terminals are assigned the shared resources one after another and cyclically, handling all users without priority.

The principal advantage of RR scheduling is the guaranty of fairness for all users in terms of the number of assigned RBs. Further, the RR scheduler is easy to implement, which is the reason why it is usually used by many systems. Since RR does not take the channel quality information into account, it does not achieve a multi-user diversity gain. A flowchart of the RR scheduling is shown in Figure 1.12.

1.4.4 Closed-Loop Spatial Multiplexing

CLSM is also referred to as mode 4 of the LTE standard [28]. This mode supports up to 4 layers that are multiplexed to up to four antennas, respectively, in order to achieve higher data rates.

To permit channel estimation at the receiver, the BS transmits Reference Signals (RSs), distributed over various REs and over various timeslots. Then, the UE sends a response regarding the channel situation. This response, the feedback, consists of Rank Indicator (RI), Precoding Matrix Indicator (PMI) and Channel Quality Indicator (CQI) in the case of CLSM.
The PMI refers to the index of the precoding matrix in a predefined codebook, known by both front-ends, which is selected by the RI. Table 1.2 [1] lists possible precoding matrices for 2 antennas and for 1 or 2 layers.

<table>
<thead>
<tr>
<th>Codebook index</th>
<th>Number of layers</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>0</td>
<td>( \frac{1}{\sqrt{2}} ) [ \begin{matrix} 1 \ 1 \end{matrix} ]</td>
</tr>
<tr>
<td>1</td>
<td>( \frac{1}{\sqrt{2}} ) [ \begin{matrix} 1 \ -1 \end{matrix} ]</td>
</tr>
<tr>
<td>2</td>
<td>( \frac{1}{\sqrt{2}} ) [ \begin{matrix} 1 \ j \end{matrix} ]</td>
</tr>
<tr>
<td>3</td>
<td>( \frac{1}{\sqrt{2}} ) [ \begin{matrix} 1 \ -j \end{matrix} ]</td>
</tr>
</tbody>
</table>

Table 1.2: Codebook for transmission with 2 antenna ports.

In Table 1.3 [1] a corresponding table for 4 antennas (and correspondingly with up to 4 layers) is defined.

Note that \( W_n^{(s)} \) is the matrix with a number of \( \{s\} \) columns as seen in the expression 1.11.

\[
W_n = I - \frac{2u_n u_n^H}{u_n^H u_n} \tag{1.11}
\]
Chapter 1. Preliminary ties

<table>
<thead>
<tr>
<th>Codebook index</th>
<th>( u_n )</th>
<th>Number of layers</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>( u_0 = [1 \ -1 \ -1 \ -1]^T )</td>
<td>( W_0^1 )</td>
</tr>
<tr>
<td>1</td>
<td>( u_1 = [1 \ -j \ 1 \ j]^T )</td>
<td>( W_1^1 )</td>
</tr>
<tr>
<td>2</td>
<td>( u_2 = [1 \ 1 \ -1 \ 1]^T )</td>
<td>( W_2^1 )</td>
</tr>
<tr>
<td>3</td>
<td>( u_3 = [1 \ j \ 1 \ -j]^T )</td>
<td>( W_3^1 )</td>
</tr>
<tr>
<td>4</td>
<td>( u_4 = [1 \ \frac{-1-j}{\sqrt{2}} \ -j \ \frac{1-j}{\sqrt{2}}]^T )</td>
<td>( W_4^1 )</td>
</tr>
<tr>
<td>5</td>
<td>( u_5 = [1 \ \frac{1-j}{\sqrt{2}} \ j \ \frac{-1-j}{\sqrt{2}}]^T )</td>
<td>( W_5^1 )</td>
</tr>
<tr>
<td>6</td>
<td>( u_6 = [1 \ \frac{1+j}{\sqrt{2}} \ -j \ \frac{-1+j}{\sqrt{2}}]^T )</td>
<td>( W_6^1 )</td>
</tr>
<tr>
<td>7</td>
<td>( u_7 = [1 \ \frac{-1+j}{\sqrt{2}} \ j \ \frac{1+j}{\sqrt{2}}]^T )</td>
<td>( W_7^1 )</td>
</tr>
<tr>
<td>8</td>
<td>( u_8 = [1 \ -1 \ 1 \ 1]^T )</td>
<td>( W_8^1 )</td>
</tr>
<tr>
<td>9</td>
<td>( u_9 = [1 \ -j \ -1 \ -j]^T )</td>
<td>( W_9^1 )</td>
</tr>
<tr>
<td>10</td>
<td>( u_{10} = [1 \ 1 \ 1 \ -1]^T )</td>
<td>( W_{10}^1 )</td>
</tr>
<tr>
<td>11</td>
<td>( u_{11} = [1 \ j \ -1 \ j]^T )</td>
<td>( W_{11}^1 )</td>
</tr>
<tr>
<td>12</td>
<td>( u_{12} = [1 \ -1 \ -1 \ 1]^T )</td>
<td>( W_{12}^1 )</td>
</tr>
<tr>
<td>13</td>
<td>( u_{13} = [1 \ -1 \ 1 \ -1]^T )</td>
<td>( W_{13}^1 )</td>
</tr>
<tr>
<td>14</td>
<td>( u_{14} = [1 \ 1 \ -1 \ -1]^T )</td>
<td>( W_{14}^1 )</td>
</tr>
<tr>
<td>15</td>
<td>( u_{15} = [1 \ 1 \ 1 \ 1]^T )</td>
<td>( W_{15}^1 )</td>
</tr>
</tbody>
</table>

Table 1.3: Codebook for transmission with 4 antenna ports.

1.4.5 Channel State Information Feedback

The time and frequency resources that can be used by the UE to report Channel State Information (CSI) which consists of CQI, PMI, and RI are controlled by the eNodeB.

1.4.5.1 Channel Quality Indicator

Channel Quality Indicator is based on an observation interval in time and frequency. The UE should determine the highest CQI index between 1 and 15 in Table 1.4 which satisfies the following condition, or CQI index 0 if CQI index 1 does not satisfy the following condition:

A single transport block with a combination of modulation scheme and transport block size corresponding to the CQI index could be received with a BLER probability not exceeding 0.1.
Table 1.4 provides an overview of the CQI indices and their interpretations.

<table>
<thead>
<tr>
<th>CQI index</th>
<th>Mod.</th>
<th>code rate x 1024</th>
<th>eff.(b/s/Hz)</th>
<th>SNR (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Out of Range</td>
<td></td>
<td>0.1523</td>
<td>-9.5</td>
</tr>
<tr>
<td>1</td>
<td>QPSK</td>
<td>79</td>
<td>0.2344</td>
<td>-7.5</td>
</tr>
<tr>
<td>2</td>
<td>QPSK</td>
<td>120</td>
<td>0.3770</td>
<td>-5.2</td>
</tr>
<tr>
<td>3</td>
<td>QPSK</td>
<td>193</td>
<td>0.6016</td>
<td>-2.9</td>
</tr>
<tr>
<td>4</td>
<td>QPSK</td>
<td>308</td>
<td>0.8770</td>
<td>-0.8</td>
</tr>
<tr>
<td>5</td>
<td>QPSK</td>
<td>449</td>
<td>1.1758</td>
<td>1.0</td>
</tr>
<tr>
<td>6</td>
<td>QPSK</td>
<td>602</td>
<td>1.4766</td>
<td>2.5</td>
</tr>
<tr>
<td>7</td>
<td>16QAM</td>
<td>378</td>
<td>1.9141</td>
<td>4.4</td>
</tr>
<tr>
<td>8</td>
<td>16QAM</td>
<td>490</td>
<td>2.4063</td>
<td>6.3</td>
</tr>
<tr>
<td>9</td>
<td>16QAM</td>
<td>616</td>
<td>2.7305</td>
<td>7.5</td>
</tr>
<tr>
<td>10</td>
<td>64QAM</td>
<td>466</td>
<td>3.3223</td>
<td>9.5</td>
</tr>
<tr>
<td>11</td>
<td>64QAM</td>
<td>567</td>
<td>3.9023</td>
<td>11.4</td>
</tr>
<tr>
<td>12</td>
<td>64QAM</td>
<td>666</td>
<td>4.5234</td>
<td>13.4</td>
</tr>
<tr>
<td>13</td>
<td>64QAM</td>
<td>772</td>
<td>5.1152</td>
<td>15.3</td>
</tr>
<tr>
<td>14</td>
<td>64QAM</td>
<td>873</td>
<td>5.5547</td>
<td>16.6</td>
</tr>
<tr>
<td>15</td>
<td>64QAM</td>
<td>948</td>
<td>6.0016</td>
<td>18.5</td>
</tr>
</tbody>
</table>

Table 1.4: Wide-band CQI table.

In Table 1.4 the efficiency can be found by using:

\[ e = CR \cdot \log_2 MOD \]  

(1.12)

Where \( e \) is the efficiency, \( CR \) is the code rate divided by 1024 and \( MOD \) is the modulation order (4, 16 or 64).

1.4.5.2 Rank Indicator

With the RI, the UE signals to its attached eNodeB the number of layers, i.e., the number of independent data streams that are transmitted simultaneously on the same time and frequency resources.
1.4.5.3 Precoding Matrix Indicator

In the system level simulator the PMI and the RI are chosen in a combined way such that highest sum MI can be achieved.

Each PMI and RI value is related to a codebook [1]. Depending on the number of layers, i.e., the RI value, a PMI value is chosen and it refers to a unique precoder.

In Table 1.2 the case for two transmit antenna ports and their corresponding precoders are shown. For 1 layer the PMI can be chosen from the 4 codebook indices shown in the table and for 2 layers it can be chosen from the codebook indices 1 and 2. For the CLSM transmission mode the codebook index 0 is not used.

In Table 1.3 the case for 4 transmit antenna ports and their corresponding precoders are shown. In this case it can be up to 4 layers and up to 16 codebook indices.

1.4.6 Implementation of Antenna Selection in the Simulator

To apply antenna selection, two new fields in the feedback information have been placed to inform the transmitter which antenna indices are the ones selected by the UE and which are the new number of antennas according to the number of selected indices.

The feedback is calculated in the UE class. There, a new function, where the different algorithms would be added, is placed with the name: "antenna selection feedback". To apply all the antenna selection schemes, information like the channel matrix, the macroscopic path loss or the Transport Block (TB) SINR, besides others, must be the input of the function. In this function, there is only one output with the feedback information related with the sub-matrix selected.

Then, the feedback is sent and it is received by the eNodeB in the next TTI.

With the feedback received and again in the UE class, two new functions are added. The first function called "precoding as channel" changes to zero the rows of the precoding matrix, related to the channel matrix, for the not selected antennas, taking into account the feedback information. The second function called "percoding as interfering" changes to zero the rows of the interfering precoding matrix following the same steps as the previous function and taking into account how the users are scheduled.

To make all the system work a new case in the codebook have to be added. In antenna selection it is possible to have a subset of selected antennas with only one antenna, but
the mode 4 (Closed-Loop Spatial Multiplexing mode) only contemplates the cases with 2 and 4 antenna ports, so the case for 1 antenna port is added and the precoding matrix for this case is specified.
1.5 Simulation

1.5.1 General Simulation Setup

In this chapter, the employed simulation setup is introduced.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier frequency</td>
<td>2.14 GHz</td>
</tr>
<tr>
<td>Channel bandwidth</td>
<td>3 MHz</td>
</tr>
<tr>
<td>Layout</td>
<td>Hexagonal grid, 3 cells/site</td>
</tr>
<tr>
<td>Inter-site distance</td>
<td>500 m</td>
</tr>
<tr>
<td>Transmission power</td>
<td>40 W (46 dBm)</td>
</tr>
<tr>
<td>Thermal noise density</td>
<td>-174 dBm/Hz</td>
</tr>
<tr>
<td>Number of eNodeB rings</td>
<td>2</td>
</tr>
<tr>
<td>Channel model</td>
<td>ITU-T Typical Urban (TU) [29]</td>
</tr>
<tr>
<td>Trace length</td>
<td>100 s</td>
</tr>
<tr>
<td>Transmit mode</td>
<td>CLSM</td>
</tr>
<tr>
<td>Scheduler</td>
<td>Round Robin</td>
</tr>
<tr>
<td>UEs/cell</td>
<td>5</td>
</tr>
<tr>
<td>Antenna configuration</td>
<td>1x4-3RRH / 2x4-2RRH / 4x4-0RRH</td>
</tr>
<tr>
<td>Feedback delay</td>
<td>1 TTI</td>
</tr>
<tr>
<td>User Speed</td>
<td>100 km/h</td>
</tr>
<tr>
<td>Antenna gain pattern</td>
<td>Katherin TS Antenna</td>
</tr>
</tbody>
</table>

Table 1.5: Simulation parameters.

From now on the following notation is used to refer to the antenna configuration:

\[
\text{Configuration} = m \times n - r \text{RRH}
\] (1.13)

Where \( m \) is the number of transmit antennas in the BS, \( n \) is the number of receive antennas and \( r \) is the number of RRH.

The term \( 1 \times 4 - 3\text{RRH} \) refers to a system with 1 transmit antenna in the Base Station (BS), 4 receive antennas in the User Equipment (UE) and there are also 3 Remote Radio Heads (RRHs) enabled per eNodeB with 1 transmit antenna per RRH.

If not mentioned otherwise, a 1x4-3RRH system and 5 users per cell are employed.

1.5.2 Implemented Schemes

In section 1.3.5, different algorithms to apply antenna selection in a MIMO system were introduced. However, not all these methods would yield significant results due to the LTE standard restriction of using only 1, 2 or 4 antennas [28].
Referring to section 1.3.5, the following schemes were implemented into the simulator:

1. Transmission Rate based antenna selection.
2. Path loss based antenna selection.
3. Total norm based antenna selection.
Chapter 2

Antenna Selection Algorithms

2.1 Transmission Rate Based Antenna Selection

2.1.1 Algorithm Description

This antenna selection algorithm is based on the first explained algorithm in section 1.3.5, the optimal solution.

The main difference between the optimal solution from section 1.3.5 and the algorithm presented in this section is that in this case, and to make easier to implement it in the LTE simulator, the element to be maximized is the Transmission Rate (TR), instead of maximize the mutual information.

Another difference between the optimal solution from section 1.3.5 and the algorithm presented in this section is the number of possible sub-matrix combinations. E.g., a $4 \times 4$ system yields 15 possible combinations, in each front-end, with the optimal solution algorithm applied in a MIMO system, whereas the same system yields 11 possible combinations, in each front-end, with this algorithm applied in an LTE environment. The difference comes from the restriction on using only 1, 2 or 4 antennas in LTE.

This algorithm performs an exhaustive search from all the possible set of sub-matrices from the channel matrix and selects the subset that gives the highest TR.

In Figure 2.1 an example of how the columns are selected can be seen. On the left there is the whole channel matrix ($4 \times 4$) and on the right, the sub-matrix with only the first and the second column selected ($4 \times 2$).
To apply this algorithm, the following equation is the one that has to be maximized:

\[ TR = (\text{rank}) \cdot (\text{modulation order}) \cdot (\text{coding rate}) \cdot (\text{symbol per RB}) \cdot (\text{number of RB}) \cdot 2^{24} \]  

(2.1)

In the equation above the modulation order and the coding rate are related to the Table 1.4. The 24 is the overhead for the Cyclic Redundancy Check (CRC) appended by LTE. The result of the expression is the number of bits that can be transmitted per TTI.

2.1.2 Simulation Results

In this section, the results obtained with the TR based antenna selection algorithm are shown. The results are obtained from 4 different antenna configurations, all of them with 4 transmit antennas.

The algorithm was first applied in a system with only one receive antenna in order to make easier the correct implementation of the scheme in the simulator. Since it has only one receive antenna, the rank would be 1 and, taking into account the methodology of the Matlab code, there would only be one result in the expression above for each sub-matrix.

Note that all the average cell and user throughput curves depicted in this work are shown in terms of Empirical Cumulative Distribution Function (ECDF).
Figure 2.2 shows the cell throughput obtained applying the TR algorithm in a $1 \times 1 - 3RRH$ system.

The solid line represents the cell throughput for the TR algorithm of antenna selection and the dashed line, the cell throughput without antenna selection, but with the same antenna configuration. Antenna selection improves the throughput considerably.

![Cell Throughput 1x1-3RRH](image)

**Figure 2.2:** Average cell throughput 1x1-3RRH.

Table 2.1 shows the average cell and user throughput as well as the percentage of users that have selected one or two antennas.

<table>
<thead>
<tr>
<th></th>
<th>Av. Cell Thr. (Mbit/s)</th>
<th>Av. User Thr. (Mbit/s)</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO AS</td>
<td>1.7626</td>
<td>0.3519</td>
<td>—</td>
</tr>
<tr>
<td>AS</td>
<td>2.6830</td>
<td>0.5356</td>
<td>92.66</td>
</tr>
<tr>
<td>Improvement</td>
<td>52.21%</td>
<td>52.2%</td>
<td>—</td>
</tr>
</tbody>
</table>

**Table 2.1:** 1x1-3RRH system, numerical results.

Apart from having improved the average throughput of the UE (almost 0.2 Mbit/s) and the average throughput of the cell (almost 1 Mbit/s), it can be seen, in the "Percentage" column of the table, that the number of the users that get better throughput by selecting less than 4 antennas represent the 92.66\% of the total users. Therefore, the number of used resources, such as RF chains, has been reduced significantly in the transmitter.
2.1.2.1 1x4-3RRH System

In Table 2.2 the numerical results from this simulation are shown.

The first thing to comment is that increasing the number of receive antennas implies an improvement on the throughput, both in cell and user throughput.

<table>
<thead>
<tr>
<th></th>
<th>Av. Cell Thr. (Mbit/s)</th>
<th>Av. User Thr. (Mbit/s)</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO AS</td>
<td>4.6370</td>
<td>0.9186</td>
<td>—</td>
</tr>
<tr>
<td>AS</td>
<td>5.9214</td>
<td>1.1729</td>
<td>72.12</td>
</tr>
<tr>
<td>Improvement</td>
<td>27.7%</td>
<td>27.7%</td>
<td>—</td>
</tr>
</tbody>
</table>

Table 2.2: 1x4-3RRH system, numerical results.

In this case, the improvement of throughput for the cell is 1.28 Mbit/s (higher than in the previous case) and for the user is 0.25 Mbit/s (again, higher than in the previous case). But this time the percentage of the users that have selected sub-matrices with a size of 1 or 2 antennas is less than in the other case (72%), but also in this case AS outperforms non-AS.

In Figure 2.3 the curves of the cell throughput obtained from the simulation with this system are shown.

In [21], results obtained through a link level simulator are given. One simulation is made with a DAS system formed by one central antenna array with two antennas, 3 distributed antenna arrays with 2 antennas each and comparing the cases with 1, 2 and 4 receive antennas per user. The system has 8 transmit antennas.
The simulation is made comparing a system that uses CLSM transmission mode and applies antenna subset selection with the same system without applying antenna subset selection. With eight transmit antennas, the throughput obtained is higher than the system used in this paper (only 4 transmit antennas). However, some conclusions can be taken.

The principal conclusion obtained comparing the results in this paper and the results from [21] is that applying antenna selection the performance of the system is improved. Another conclusion is that a system with more receive antennas obtains higher throughput.

2.1.2.2 Comparison with other Systems

In this section the performance of this algorithm based on the TR is compared in 3 antenna configurations.

In Figure 2.4 the average cell throughput of each system is shown. The 4x4-0RRH system is the dotted line, the 2x4-2RRH system is dashed line and the 1x4-3RRH system, the solid line. The thicker lines represent the throughput without taking into account antenna selection.

![Comparison of systems applying TR based AS. Average cell throughput.](image)

The two systems with RRHs have better performance. The throughput of these two systems is even better without antenna selection than the throughput of the non-RRH system with antenna selection.
To better compare and comment the curves shown in Figure 2.4, the numerical results for the three systems are listed in Table 2.3 and Table 2.4.

- No antenna selection:

<table>
<thead>
<tr>
<th></th>
<th>4x4-0RRH</th>
<th>2x4-2RRH</th>
<th>1x4-3RRH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Av. Cell Thr.</td>
<td>3.3444</td>
<td>4.4228</td>
<td>4.6370</td>
</tr>
<tr>
<td>Av. User Thr.</td>
<td>0.6636</td>
<td>0.8761</td>
<td>0.9186</td>
</tr>
</tbody>
</table>

**Table 2.3:** Average cell and user throughput without AS (Mbit/s)

- Antenna selection:

<table>
<thead>
<tr>
<th></th>
<th>4x4-0RRH</th>
<th>2x4-2RRH</th>
<th>1x4-3RRH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Av. Cell Thr.</td>
<td>4.2264</td>
<td>5.6750</td>
<td>5.9214</td>
</tr>
<tr>
<td>Av. User Thr.</td>
<td>0.8352</td>
<td>1.1235</td>
<td>1.1729</td>
</tr>
</tbody>
</table>

**Table 2.4:** Average cell and user throughput with AS (Mbit/s)

The first conclusion that can be obtained from the numerical results is that a system without remote radio heads obtains significantly less throughput than a system with remote radio heads, irrespective of whether antenna selection is applied or not.

As shown in Figure 2.4 as well as in Tables 2.3 and 2.4, the average cell throughput of a system without RRHs and applying antenna selection (4.2264 Mbit/s) is worse than the average cell throughput for the other two systems without applying antenna selection (4.4228 Mbit/s and 4.6370 Mbit/s).

Furthermore, from the tables above it can be seen that the system with 3 RRHs is the one that gets more difference on cell and user throughput between applying or not applying antenna selection. In Table 2.5 the difference between applying or not applying antenna selection in one system is shown.

<table>
<thead>
<tr>
<th></th>
<th>4x4-0RRH</th>
<th>2x4-2RRH</th>
<th>1x4-3RRH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Difference in cell throughput</td>
<td>0.882</td>
<td>1.2522</td>
<td>1.2844</td>
</tr>
<tr>
<td>Difference in user throughput</td>
<td>0.1716</td>
<td>0.2474</td>
<td>0.2543</td>
</tr>
</tbody>
</table>

**Table 2.5:** Difference between AS and non-AS

As it can be seen, the more RRHs in the system, the more difference in throughput between applying or not applying antenna selection. This means that antenna selection
works better in a DAS system. The reason of this behaviour might be the improved macro-diversity for having the antennas distributed inside the cell.

In this case, and to better see the improvement in terms of throughput obtained when working in a DAS system, Table 2.6 shows the percentage of improvement in the 50th percentile. The percentage is calculated between the median of the throughput of a system applying antenna selection and the median of the throughput for the same system without applying antenna selection (for both cell and user throughput).

- Median Cell/User improvement (50th percentile):

<table>
<thead>
<tr>
<th></th>
<th>4x4-0RRH</th>
<th>2x4-2RRH</th>
<th>1x4-3RRH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Median Cell improvement</td>
<td>24.12%</td>
<td>30.44%</td>
<td>34.18%</td>
</tr>
<tr>
<td>Median User improvement</td>
<td>50.65%</td>
<td>48.46%</td>
<td>54.23%</td>
</tr>
</tbody>
</table>

Table 2.6: Median cell and user improvement

The percentage of improvement is higher when more RRHs are used, further strengthening the use of DAS.
2.2 Path Loss Based Antenna Selection

2.2.1 Algorithm Description

This section presents results as obtained from the simulations using the path loss based antenna selection algorithm.

The algorithm is based on the one explained in the section 1.3.5 but taking into account the number of antennas it can be used in an LTE environment.

2.2.2 Simulation Results

In Figure 2.5 the average cell throughput obtained using the path loss algorithm (solid line) is shown and compared with the average cell throughput as obtained by the same system (1x4-3RRH) without antenna selection (dashed line).

Note that, although the path loss based optimization does not aim at maximizing throughput, it does still achieve a higher throughput than the system without antenna selection.

Numerical values for the throughput improvement are provided in Table 2.7. The same table structure as in section 2.1 has been followed.
Table 2.7: Results applying the path loss based antenna selection algorithm.

<table>
<thead>
<tr>
<th></th>
<th>Av. Cell Thr. (Mbit/s)</th>
<th>Av. User Thr. (Mbit/s)</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO AS</td>
<td>4.6370</td>
<td>0.9186</td>
<td>—</td>
</tr>
<tr>
<td>Path loss AS</td>
<td>5.8674</td>
<td>1.1622</td>
<td>65.7</td>
</tr>
</tbody>
</table>

The average cell throughput has improved by 1.23 Mbit/s compared to the system without antenna selection. Interestingly similar to the TR based algorithm (72.12%), 65.7% of the users get better results using less than 4 antennas.

2.2.2.1 Problems with Saturation and Proposed Solutions

In Figure 2.6 the average user throughput applying the path loss based algorithm is shown. The ECDF shows a step-like behaviour at 2.6 Mbit/s.

![Figure 2.6: Path loss based algorithm, average user throughput, first try.](image)

In order to obtain varying path loss values, a simulation where the users could change their positions each TTI following a straight line is done.

Note that the users have the same initial positions as the previous simulation as well as the same speed (100 km/h).

In Figure 2.7 the average user throughput curve obtained with this second system is depicted. In this simulation the users move in the order of 14 m over 500 TTI. However, the variation in the path loss values is not enough to see significant changes in the user throughput behaviour. Therefore, the users suffer the same step-like behaviour as before.
Then, two systems with different speed (100 and 200 km/h) with the mobility activated are simulated to see if changing the speed, a different behaviour can be seen.

However, the speed has minor to negligible impact. The users move in order of 14 m for the case with a speed of 100 km/h and 28 m for the case of with a speed of 200 km/h. With the path loss variation, 15% of the users, in the 100km/h case, change the selected antennas from the first TTI to the last one. For the 200 km/h case, this percentage is 26%.

In Figure 2.8 the average user throughput comparing the two simulations is shown. It can be seen that, despite some users have changed the antennas selected, the users still suffer the step-like behaviour. However, the number of users with deteriorated throughput for the case of 200 km/h is lower than in the case of 100 km/h. As a conclusion, the variation of the speed does not vary enough path loss values in order to see significant changes in the user throughput behaviour.

Then, the users that obtain an average throughput between 2.55 and 2.62 Mbit/s are checked.

14.4% of the users in one TTI for the first step and 10.5% of the users in one TTI for the second step are in that range of throughput. From the first and the second steps, there are 25 users in common and from these 25 users, 17 of them have exactly the same average throughput.
Interestingly, all these users have selected a subset of antennas with only one antenna. But this selection is not only made by the users with exactly the same throughput, but by all the users that had the throughput between 2.55 and 2.62 Mbit/s as well.

A reason of this behaviour is the throughput saturation in LTE [30].

The throughput saturation depends on the number of transmit antennas and the number of data streams or layers. If there are more transmit antennas used for the transmission, a higher number of pilot symbols are inserted in the OFDM frame. Thus, lower maximum throughput can be achieved.

Figure 2.9 shows the throughput curves in Mbit/s, starting from zero and going up to the maximum value of throughput (where the throughput saturates) of each CQI. Note that this throughput curves have been obtained with only one user and a bandwidth of 1.4 MHz.

In Figure 2.9 it can be seen that the CQI value of 15 saturates at the SNR value of 20 dB.

The users between the mentioned range (the ones that have selected only one antenna) have a CQI value of 15 in all the TTIs. Besides, they have an SNR over 20 dB.

However, the throughput in the simulations of this thesis saturates earlier (2.6 Mbit/s) than in Figure 2.9 (5 Mbit/s) for a CQI value of 15. The reason is that the simulations from this thesis are made with multiple users that share the 3 MHz bandwidth, whereas the simulations from Figure 2.9 are made with one user that gets full 1.4 MHz bandwidth.
To solve this problem, 2 solutions are presented.

- 1st Solution:

The first solution is to directly avoid having any subset of antennas with only one antenna selected.

All the users with one antenna selected following the formula for the path loss algorithm shown in section 1.3.5, are forced to chose two antennas. The first one is the already selected antenna. The other antenna is the one with the minimum path loss from the remaining antennas. With this methodology, all the users can only have 2 or 4 antennas in the antenna subset selection.

A drawback of this solution is that in case only one antenna has small path loss and all the other antennas have a large path loss, this solution will not provide useful results.

- 2nd Solution:

The second solution, taking into account the throughput saturation and the SNR value of 20 dB, where the saturation happened for a CQI of 15, is to force those users with only one antenna selected and with an SNR value over 20 dB to select 2 antennas.
To apply it in the Matlab code simulator, the mean of the Transport Block Signal to Interference plus Noise Ratio in dB (TB SINR dB) is used.

All the users for whom, again following the formula for the path loss algorithm, the best choice is to select only one antenna but, this time, those whose ”mean(TB SINR dB)” is over 20 dB, are forced to select a second antenna.

Again, the first antenna is the already selected one. The second antenna is the one with the minimum path loss from the remaining antennas.

### 2.2.2.2 Throughput Results

In this section the results applying each solution are shown. In the simulations made with the solutions, the users are initially placed in the same positions as in the first step and without the mobility activated too.

Figure 2.10 shows the average user throughput applying the path loss algorithm and taking into account the first (solid line) and the second (dashed line) solution explained above.

![](image)

**Figure 2.10:** Average user throughput applying path loss based AS, first solution (solid line) and second solution (dashed line).

As not expected, the users no longer suffer the deteriorated throughput and the step-like behaviour has disappeared. The assumption that the saturation of the throughput could be the problem was correct.

Table 2.8 shows the average user throughput as well as the percentage of users with one antenna selected obtained from all the simulations made in this section.
Despite the average user throughput is almost the same for all the cases, the interesting thing is to compare the percentage of users with one antenna selected.

For the first and the second simulations from section 2.2.2 (first without mobility and second with mobility), the number of users with one antenna is more or less the same (18.25% - 15.13%), although a bit lower for the second one due to the mobility of the users.

For the first solution, as expected, there are no users with only one antenna selected.

For the second solution, 9% of users select one antenna. Although this result is lower than for the first step (18.25%) and more resources are used (e.g., RF chains), the users do not suffer deteriorated throughput. Besides, it uses less resources than the first solution.

The percentage of users that have selected 1 and 2 antennas for the case where the second solution is applied is 68%.

<table>
<thead>
<tr>
<th>Av. User Throughput (Mbit/s)</th>
<th>Percentage 1 antenna (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st step</td>
<td>1.2593</td>
</tr>
<tr>
<td>2nd step</td>
<td>1.2442</td>
</tr>
<tr>
<td>1st solution</td>
<td>1.2564</td>
</tr>
<tr>
<td>2nd solution</td>
<td>1.2548</td>
</tr>
</tbody>
</table>

Table 2.8: Comparison on the results with the path loss algorithm.
2.2.3 Results in other System: 2x4-2RRH

In this case, this algorithm is applied on a 2x4-2RRH scheme.

Figure 2.11 shows the average user throughput applying the path loss algorithm.

As in the 1x4-3RRH system, the users suffer a step-like behaviour and their throughput is deteriorated. In this case, the users saturate at 2.48 Mbit/s instead of at 2.62 Mbit/s.

In this system 10.2% of the users in one TTI have the throughput between 2.45 and 2.55 Mbps and, 72.4% of these users have one antenna selected and a value of 15 in the CQI for all the TTIs. Therefore, the throughput for these users saturates.

In this case, only the second solution is applied, and the throughput obtained is shown in Figure 2.12.
The step-like behaviour has disappeared, and, as it happens with the 1x4-3RRH system, the average throughput is more or less the same with the solution and without it.

The numerical results are shown in Table 2.9.

<table>
<thead>
<tr>
<th></th>
<th>Av. Cell Thr. (Mbit/s)</th>
<th>Av. User Thr. (Mbit/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Path loss</td>
<td>5.8447</td>
<td>1.1667</td>
</tr>
<tr>
<td>Path loss 2nd solution</td>
<td>5.9964</td>
<td>1.1970</td>
</tr>
</tbody>
</table>

Table 2.9: Path loss algorithm performance, 2x4-2RRH system.
2.3 Total Norm Based Antenna Selection

2.3.1 Algorithm Description

In this chapter the Total Norm based antenna selection algorithm is presented as well as the results obtained by applying this scheme.

The Total norm based AS algorithm is based on the one explained in section 1.3.5 and extracted from [7].

In this algorithm the antennas have to be pre-selected. That is to pre-define the $L_t$ value.

2.3.2 Simulation Results

2.3.2.1 Two Antennas Pre-selection

In Figure 2.13 the average cell throughput obtained by applying total norm based antenna selection algorithm (solid line) and compared to the average cell throughput obtained with the same system (1x4-3RRH) but without applying antenna selection (dashed line) is shown.

![Figure 2.13: Average cell throughput, total norm based AS.](image)

The average cell throughput has been improved with the algorithm. Besides, the average user throughput has been improved too, as shown in Figure 2.14.
Table 2.10 shows the numerical results related to the average cell and user throughput.

<table>
<thead>
<tr>
<th></th>
<th>Av. Cell Thr. (Mbit/s)</th>
<th>Av. User Thr. (Mbit/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO AS</td>
<td>4.6370</td>
<td>0.9186</td>
</tr>
<tr>
<td>Total Norm Based</td>
<td>5.8905</td>
<td>1.1456</td>
</tr>
</tbody>
</table>

Table 2.10: Total norm based AS, throughput.

### 2.3.2.2 One Antenna Pre-selection

The results of pre-selecting only one antenna are shown. In Figure 2.15 the average cell throughput obtained in this case is shown and compared with the case of no antenna selection.

Table 2.11 shows the throughput improvement of this antenna selection algorithm related to the system without antenna selection.

<table>
<thead>
<tr>
<th></th>
<th>Av. Cell Throughput (Mbit/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO AS</td>
<td>4.6370</td>
</tr>
<tr>
<td>Total norm 1 antenna</td>
<td>5.9920</td>
</tr>
</tbody>
</table>

Table 2.11: Total norm based AS with 1 antenna pre-selection, throughput.

Note that the number of used resources in this case is lower than in the case with 2 antennas pre-selected.
Chapter 2. Antenna Selection Algorithms

Figure 2.15: Average cell throughput, total norm based AS with 1 antenna pre-selection.

As this case is based on the pre-selection of one antenna, all the users have selected only one antenna each TTI. This mandatory behaviour carries consequences as explained in the next section.

2.3.3 Problems with Saturation

As the algorithm explained in section 2.2, the path loss based AS algorithm, the continuous usage of just one antenna during all the TTIs leads to the saturation of the throughput of some users.

In Figure 2.16 the average user throughput from the total norm based AS (solid line) compared with the average user throughput without antenna selection (dashed line) is shown.

The user throughput of the total norm based AS scheme saturates like in the path loss AS case, but this time at the end of the throughput line.

This is because, in the case of the path loss AS algorithm, the users can also have 2 or 4 antennas in the selected subset, apart from one, with which the users can transmit over 2 or more spatial streams so that they can achieve higher throughput.

In this case, the users can only select subsets with one antenna each, so they can only transmit over one spatial stream and this limits the maximum throughput they can achieve.
Another interesting thing from Figure 2.16 is that in the case of the total norm based AS there are no users with zero throughput as it can be seen for low throughput in the solid line.

<table>
<thead>
<tr>
<th></th>
<th>Av. User Thr. (Mbit/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO AS</td>
<td>0.9186</td>
</tr>
<tr>
<td>Total norm based 1 antenna</td>
<td>1.1869</td>
</tr>
</tbody>
</table>

Table 2.12: Total norm based AS with 1 antenna, user throughput.

In Table 2.12 the numerical results for the average user throughput are shown comparing the case without antenna selection and the case applying the total norm based algorithm of AS.

### 2.3.4 Simulations with the Proposed Solutions

In this case, unlike in the path loss case, only the second solution (explained in section 2.2.2.1) is applied.

What is expected by applying this solution is to avoid the saturation, with the consequence of using more resources.

In Figure 2.17 the average user throughput applying this algorithm with the 2nd solution and compared with the same system without applying antenna selection is shown.
The step-like behaviour does not occur this time. Besides, for low throughput, the number of users with zero throughput is maintained to zero.

In Table 2.13 the results from all the cases shown in this section can be found.

Applying the 2nd solution carries a decrease on the average cell and user throughput and an increase of the used resources (RF chains) compared with the same system without the solution. Therefore, in this case is not optimal to get rid of the saturation.

In Table 2.13, the percentage in this case means the number of users that have changed the size of the selected subset from 1 to 2 antennas. That is, the users that have the "mean(TB SINR dB)" over 20 dB.

Figure 2.18 shows the comparison of the average cell throughput obtained with the cases of 2 antenna pre-selection and 1 antenna pre-selection without applying the solution.

The throughput obtained when 1 antenna is pre-selected is slightly higher than the case when 2 antennas are pre-selected.
2.4 Norm Based Antenna Selection

2.4.1 Algorithm Description

In this chapter the norm based antenna selection algorithm is presented and is based on the one explained in the section 1.3.5.

It also has the particularity of choosing the size of the subset that are going to be selected.

Note that this method has the same behaviour than the total norm based scheme for the one antenna pre-selection case and, thus, the results are the same in both cases. Therefore, in this section only the results for the case where two antennas have been pre-selected are shown.

2.4.2 Simulation Results

In this section the results obtained from the simulations with two antennas are shown.

Figure 2.19 shows the average cell throughput applying this antenna selection algorithm (solid line) compared with the same system without applying antenna selection (dashed line).

The throughput has been improved. For more detailed results, see Table 2.14.
Table 2.14: Norm based algorithm with 2 antennas pre-selection, throughput.

<table>
<thead>
<tr>
<th></th>
<th>Av. Cell Thr. (Mbit/s)</th>
<th>Av. User Thr. (Mbit/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO AS</td>
<td>4.6370</td>
<td>0.9186</td>
</tr>
<tr>
<td>Norm based 2 antennas</td>
<td>6.2449</td>
<td>1.2369</td>
</tr>
</tbody>
</table>

The percentage of users that have selected less than 4 antennas in the selected subset is not shown because it would always be 100% due to the pre-selection of the size of the subset.

The improvement on the cell throughput is almost 2 Mbit/s and there is also improvement on the user throughput (0.32 Mbit/s).

2.4.3 Comparison of Total Norm Based and Norm Based

In this section, the results of both algorithms when two antennas have been pre-selected are compared.

In Figure 3.1 the average cell throughput comparing the total norm based algorithm (solid line) and the norm based algorithm (dashed line) is shown. In both cases the pre-selection was made with two antennas.

The throughput for the norm based algorithm is slightly higher than in the total norm based. It can also be taken notice of this improvement in Table 2.15, where the numerical results comparing both algorithms are shown.
Figure 2.20: Average cell throughput comparison: total norm based - norm based, both with 2 antennas.

<table>
<thead>
<tr>
<th></th>
<th>Av. Cell Thr. (Mbit/s)</th>
<th>Av. User Thr. (Mbit/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Norm based</td>
<td>6.2449</td>
<td>1.2369</td>
</tr>
<tr>
<td>Total norm based</td>
<td>5.8905</td>
<td>1.1456</td>
</tr>
</tbody>
</table>

Table 2.15: Algorithms comparison, throughput.

The difference between the results obtained with the two methods might be that the total norm based algorithm works well only at low SNR [7], whereas the norm based algorithm works well at low and at high SNR [24].
Chapter 3

Comparison of the Schemes

In this chapter, the performance of each one of the antenna selection algorithms with the system 1x4-3RRH will be compared only taking into account the best results as found in the corresponding section.

3.1 Average Cell and User Throughput

In Figure 3.1 the average cell throughput comparison (image on the left) and the average user throughput comparison (image on the right) are shown. The algorithms compared are the following:

- Transmission rate based.
- Path loss based with the second solution.
- Total norm based with 2 antennas pre-selected.
- Total norm based with 1 antennas pre-selected.
- Norm based with 2 antennas pre-selected.

Due to the similar throughput obtained for all the cases it is difficult to distinguish the lines. Therefore, the average cell and user throughput are presented in Table 3.1, where the numerical results for each case as well as the percentage of the number of antenna subsets selected with a size lower than 4 are provided.
Comparison of the Schemes

Chapter 3

Figure 3.1: Left: average cell throughput comparison. Right: average user throughput comparison.

<table>
<thead>
<tr>
<th></th>
<th>Av. Cell Thr. (Mbit/s)</th>
<th>Av. User Thr. (Mbit/s)</th>
<th>(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TR based</td>
<td>5.9214</td>
<td>1.1729</td>
<td>72.12</td>
</tr>
<tr>
<td>Path loss based</td>
<td>6.2864</td>
<td>1.2548</td>
<td>68</td>
</tr>
<tr>
<td>Norm based 2 ant.</td>
<td>6.2449</td>
<td>1.2369</td>
<td>100</td>
</tr>
<tr>
<td>Total norm 1 ant.</td>
<td>5.9920</td>
<td>1.1869</td>
<td>100</td>
</tr>
<tr>
<td>Total norm 2 ant.</td>
<td>5.8905</td>
<td>1.1456</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 3.1: Numerical results: performance comparison.

3.2 Zero Throughput Users

Another important thing to compare is the users that receive zero throughput. To check it, a zoom in the user’s throughput figure has been made in the low throughput zone. The result is depicted in Figure 3.2.

Figure 3.2: Average user throughput comparison, zero throughput.
Chapter 3. Comparison of the Schemes

The total norm/norm based algorithm with one antenna pre-selected is the only one that serves all the users. The other antenna selection algorithms have users with throughput equal to zero. Table 3.2 shows the percentage of users that have zero throughput. In the table, the case without antenna selection in the same system (1x4-3RRH) has been added.

The reason of this behaviour is that the scheduler does not serve those users whose SINR is below a certain level.

If one user have a SINR value below that level in one of its RBs, the CQI mapper gives a value of zero to those RBs. Then, the scheduler filter the non-valid RBs which have a CQI value of zero.

<table>
<thead>
<tr>
<th>Zero throughput user percentage (%)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>NO AS</td>
<td>4.82</td>
</tr>
<tr>
<td>TR based</td>
<td>3.67</td>
</tr>
<tr>
<td>Path loss based</td>
<td>2.8</td>
</tr>
<tr>
<td>Norm based 2 ant.</td>
<td>1.65</td>
</tr>
<tr>
<td>Total norm 1 ant.</td>
<td>0</td>
</tr>
<tr>
<td>Total norm 2 ant.</td>
<td>1.88</td>
</tr>
</tbody>
</table>

Table 3.2: Percentage of users with zero throughput.

All the algorithms improve the performance in terms of users with zero throughput related with the case without antenna selection. The algorithms that has no users with this particularity are the total norm and norm based with one antenna pre-selected, and the second system that has less users with zero throughput is the norm based algorithm with two antennas pre-selected, really near to the total norm based with 2 antennas pre-selected.

3.3 Feedback Information

Another thing to check is the feedback trade-off for applying antenna selection. A qualitative look to it is be given.

All the systems need exactly the same feedback information to work: the indices of the selected antennas and the number of antennas in the selected set (1, 2 or 4), apart from the feedback already used without antenna selection.

However, the complexity to get this new feedback information is different in each case. The most complex algorithm to obtain this information, is the transmission rate based
algorithm, because it needs to check all the possible sub-matrix combinations, 11 possible combinations.

The second most complex algorithm is the total norm based with two antennas pre-selected, because it has to check all the sub-matrices with 2 antennas, 6 possible sub-matrices.

For the other methods, the complexity to obtain the feedback information is more or less the same.
Chapter 4

Conclusion and Future Work

In this thesis, the explanation of different algorithms to apply antenna selection as well as the results using this schemes in different systems, problems encountered and the solutions taken to solve these problems have been shown.

It was shown that a DAS system, having the antennas distributed inside the cell, can achieve higher throughput than the case of having the antennas collocated in the base station.

Further, the proposed solutions to avoid throughput saturation in the path loss based and the total norm/norm based algorithms have served their purpose. For all the cases, with the solutions applied, the step-like behaviour has disappeared.

Specially for the path loss based AS algorithm, the usage of any of the solutions has been beneficial. The average cell, but also the average user throughput, has been improved. Besides, it has improved the percentage of users that select a subset of antennas with a size of 1 or 2 antennas (from 65.7% to 68%) and it has also reduced the number of users with zero throughput (from 4.8% to 2.8%).

For the case of the total norm/norm based AS algorithm with one antenna pre-selected, the usage of the second solution has not been optimal. Although the users do not suffer the throughput deterioration, the solution has reduced the average cell and user throughput apart from using more resources than the case without the solution (almost 19% of users have changed the size of the selected subset from 1 to 2 antennas).

Comparing the throughput for all the algorithms, the first thing it can be said is that all the antenna selection schemes get higher throughput than the system without antenna selection. In addition, all the schemes use less resources than the non-AS system.
It is well known that the LTE precoders distribute the available transmit power uniformly over all antennas employed for transmission. When no antenna selection is applied, the different transmit antennas send the information with equal power. However, and taking into account the case of using a DAS system, if the path loss differences between the distributed antennas is significant, it is beneficial to concentrate the transmit power on those antennas that have good channel quality, i.e., to employ only a subset of antennas for transmission and thus, be able to achieve better performance.

Therefore, all the schemes meet the aim of antenna selection described at the beginning of the paper. The algorithm that gets the highest throughput is the path loss algorithm, both in cell and user throughput, with the second solution applied.

Comparing the resources used for the schemes, the two schemes that have the pre-selection of the size of the selected subsets of antennas (total norm and norm based) use less resources than the other schemes, because they, in no case, use any set with a large of 4 antennas.

The feedback information is essential to take into consideration. Because of the computational cost that the TR scheme has, it is the algorithm that has the hardest way to get this information compared with all the schemes, it has to check the transmission rate of 11 possible sub-matrices. The total norm based AS algorithm is the second most complex algorithm related to the obtaining of this information, it has to calculate the norm of 6 different sub-matrices.

In conclusion, the total norm/norm based AS algorithm, with one antenna pre-selection, would be the best option. Although it is not the algorithm that gets the best average throughput, it uses very few resources to obtain that performance.

Possible future work to continue with the labour started in this thesis are to apply the already commented algorithms in the receiver, to apply antenna selection both at the receiver and at the transmitter or the usage of coordination between base stations to apply antenna selection.
Bibliography


[29] 3GPP TS 05.05. "Radio transmission and reception, std".