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PERFORMANCE ANALYSES OF DIFFERENT MIMO MODES IN LTE RELEASE 8 NETWORKS

Master of Science Thesis

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ABSTRACT

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The multi-antenna techniques are the one of the key features in 3GPP LTE specifications. Thus, the understanding of different transmission modes behaviour, available in LTE, is very important for high quality and cost efficient LTE network deployment. Besides, the lack of available practical studies of this topic makes the problem even more attractive.

This master thesis work is focused on measurement based performance analyses of different special multiplexing (SM) modes available in LTE Release 8 networks using the same LTE base stations as used in this study. Field measurements have been carried out in different propagation environments. In analyses, user application throughput and MIMO utilization have been studied to demonstrate the efficiency of each mode.

The measurement results are different than the theoretical and simulation based studies. The results clearly show that the open-loop-dynamic SM is the best choice, independent of the environment, for SNR > -2 to -5 dB and can provide up to 3 Mbps or 11.7% advantage over closed loop SM. The open loop static SM is as good as open loop dynamic SM only for very good, SNR > 10 to 15 dB, channel conditions. And, for the bad channel conditions, SNR < -2 to -5 dB, the behaviour of all modes is the same that is transmit diversity and SM provide similar throughputs. The SNR threshold for MIMO utilization is found to be approximately -2 to -5 dB. And, another interesting conclusion is that no transmission percentage is going up from 5% up to 20% for SNR > 15 dB, which means, that there is a significant interference between parallel data streams. The bad performance of the closed loop is associated with low CQI reports for codeword 1 as the UE reduces the SNR for codeword 1 to mitigate the interference between parallel data streams.

The results can be generalized only for the studied equipment hardware, software and parameters as the other vendors can have slightly different implementation of some parts of LTE. But any way, the results show that knowledge of the different SM modes behaviour can help to increase the quality of the network.

PREFACE

This Master of Science thesis has been written for the completion of my M.Sc degree in Information Technology from the Tampere University of Technology. The thesis work has been carried out in the Department of Electronics and Communications Engineering at Tampere University of Technology during autumn and winter 2012-2013.

I would like to thank my examiners Tero Isotalo and Jarno Niemelä for their instructions and guidance during the whole duration of the thesis work. Their advices helped me not only to finish this study successfully, but also gave me invaluable experience that is a very strong base for further development as a professional wireless engineer.

Additionally, I am thankful from Nokia Siemens Networks for providing equipment for TUT LTE test bed, Anite Finland for providing Nemo software licenses, Elisa for the LTE data cards that I have been using for my measurements and Nokia for providing LTE network infrastructure.

I would like to separately thank to my dear wife Vanuhi, for her continuous support and love, for her encouragements which help me to be strong and do not give up even in very helpless situations that I have been facing.

In the end, I would like to devote this work for my whole family, my wife and parents. Without their constant support I would not be able to reach this stage and be proud of my path that I passed in my life.

Tampere, April 2013

Artur Brutyan

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TERMS AND ABBREVIATIONS

3GPP	3rd Generation Partnership Project
AMPS	Advanced Mobile Phone System
APP TP	Application Layer Throughput
BLER	Block Error Rate
CDD	Cyclic-Delay Diversity
CDF	Cumulative Distribution Function
CL-SM	Closed Loop Spatial Multiplexing
CP	Cyclic Prefix
CQI	Channel Quality Indicator
DC	Direct Current
DFT	Discrete Fourier Transform
DL-SCH	Downlink Shared Channel
E-UTRA	Evolved Universal Terrestrial Radio Access
FDD	Frequency Division Duplex
FFT	Fast Fourier Transform
FSTD	Frequency Shift Transmit Diversity
GSM	Global System for Mobile Communication
HSPA	High Speed Packet Access
HTTP	Hypertext Transfer Protocol
IDFT	Invers Discrete Fourier Transform
IFFT	Invers Fast Fourier Transform
IMT	International Mobile Communications
LOS	Line-of-sight
LTE	Long Term Evolution
MAC	Medium Access Control
MBSFN	Multicast broadcast Single Frequency Network
MCS	Modulation and Coding Scheme
MIMO	Multiple Input Multiple Output
MISO	Multiple Input Single Output
NLOS	Non Line-of-Sight
NMT	Nordic Mobile Telephony
NSN	Nokia Siemens Networks
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OL-D-SM	Closed Loop Dynamic Spatial Multiplexing
OL-SM	Open Loop Spatial Multiplexing
OL-S-SM	Closed Loop Static Spatial Multiplexing

PAPR	Pick to Average Power Ratio
PDF	Power Density Function
PMI	Pre-coding Matrix Indicator
PUCCH	Physical Uplink Control Channel
PUSCH	Physical Uplink Shared Channel
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
RAN	Radio Access Network
RAT	Radio Access Technology
RI	Rank Indicator
RLC	Radio Link Control
RRH	Remote Radio Head
RSRP	Reference Signal Received Power
RSRQ	Reference Signal Received Quality
RSSI	Received Signal Strength Indicator
Rx	Receiver
SAE	System Architecture Evolution
SC	Single Carrier
SC-FDMA	Single Carrier Frequency Division Multiple Access
SFBC	Space-Frequency Block Coding
SFTD	Space-Frequency Transmit Diversity
SIMO	Single Input Multiple Output
SISO	Single Input Single Output
SM	Spatial Multiplexing
SNR	Signal-to-Noise-Ratio
STBC	Space-Time Block Coding
TACS	Total Access Cellular System
TDD	Time Division Duplex
TTI	Transmit Time Intervals
TUT	Tampere University of Technology
Tx	Transmitter
UE	User Equipment
UMTS	Universal Mobile Telecommunication System
VLSI	Very-Large-Scale Integration
WCDMA	Wideband Code Division Multiple Access
WiMAX	Worldwide Interoperability for Microwave Access

1 INTRODUCTION

Wireless telecommunication networks are an important part of contemporary life. Even though, some parts of the world are not connected to fresh water supply, with adoption of Global System for Mobile Communication (GSM), mobile networks are available for more than 90% of population. The people that live in the smallest villages most probably have mobile phone coverage. Some statistics shows about extensive growth of number of mobile users since the introduction of the first wireless cellular systems, which can be counted by millions of new users per day [1].

Initially, the second generation mobile networks, like GSM, were originally designed for voice traffic and data capabilities were added later. Although, data traffic has increased in second generation networks, it was clearly dominated by voice traffic. The picture has changed by the dramatic progress in Very-Large-Scale Integration (VLSI), which has enabled small-area and low-power implementation of sophisticated signal processing algorithms and coding techniques. As a result, Wireless devices such as smartphones and most recently tablets are becoming more sophisticated every day. Besides, wireless internet both mobile and fixed and applications for playing online games or networking with other people, watching a video and listening a music, location based services and personal navigation are becoming part of daily life.

To meet the needs of the exponentially growing number of data users and to be able to provide more capacity and data rates, wireless mobile network operators have been investing a lot of resources to find out new efficient techniques and standards. Toward this aim is the development of 3rd Generation Partnership Project (3GPP) Long Term Evolution (LTE) standard, which is able to provide higher user data throughput, lower latency and higher spectral efficiency than the other legacy 3GPP mobile standards. To further improve all the above mentioned aspects, the utilization of multiple antenna technologies become an important and inherent part of the LTE specifications. Especially, spatial multiplexing (SM), also known as Multiple Input Multiple Output (MIMO) is very suitable for wireless communications, as it is able to double user peak data rates by utilizing parallel data streams without additional bandwidth. The details of multi antenna techniques are represented in Chapter 2.

In LTE there are several transmission modes, as explained in Section 4.4.4, which are designed to provide flexibility to cope with various wireless channel conditions and mobile terminal capabilities. And the study of those modes will help mobile operators to make correct parameterization of LTE network, according to different propagation environments and channel conditions. This in its turn will help to increase the reliability and efficiency of the whole network. On the other hand, MIMO also brings new challenge for network operators. The traditional methods that they have been using to provide the best service may be inefficient for the MIMO case. Thus, In order to achieve the best possible throughputs in LTE systems, operators must optimize their networks for MIMO. This optimization process requires accurate measurement in order to achieve the best performance for a given environment while avoiding the time and expense of guesswork.

There are several scientific publications representing different issues of the multi antenna techniques in LTE. In [2] different antenna configurations are studied in field measurements, representing the advantages of MIMO over single transmission mode. In [3] an algorithm for transmission mode selection and switching is proposed. But, the only paper, representing the comparison of the Closed Loop Spatial Multiplexing (CL-SM) and Open Loop Spatial Multiplexing (OL-SM) performance is [4]. In [4], which is based on simulations, the results clearly show the slight advantage of CL-SM over OL-SM, but this advantage is becoming even smaller when the reports of the mobile are considered to be erroneous.

The topic of this study is the performance evaluation of different SM modes (CL-SM vs. OL-SM) in LTE for different environments based on field measurements. Obviously, this is quite open topic, as there is no measurement based study and the only one is simulation based study.

The aim of this master thesis is to find out and to compere the behaviour of CL-SM and OL-SM in different channel conditions and environments, compare the available capacities for them and to determine the Signal-to-Noise-Ratio (SNR) threshold for MIMO utilizations. The comparison of the transmit diversity with SM is also possible to do, as the OL-SM has two options, Dynamic OL-SM (OL-D-SM), which dynamically switches between transmit diversity and SM and Static OL-SM (OL-S-SM), which always operates as SM. More details regarding to thesis topic are represented in Chapter 5.

To achieve the above mentioned aims, measurements have been conducted in indoor and outdoor (micro) environments. To do analyses and conclusions, user Application Layer Throughput (APP TP) and MIMO utilization are used. To support fair comparisons of different measurements cases, several link performance parameters like Signal to Noise Ratio (SNR), and Reference Signal Received Power (RSRP) and mobile reports like Channel Quality Indicator (CQI) and Rank Indicator (RI), are used.

2 RADIO NETWORK PLANNING OVERVIEW

To be able to plan and implement a cost efficient high quality cellular mobile wireless network, very careful radio network planning procedure must be done. Thus, the planning process carried out in phases and each phase is well documented. The radio network planning procedure requires good knowledge about the coverage area, propagation environment, traffic load and required services to be able to analyses the network and to decide the optimal radio network planning strategy. The fact, that all the above mentioned aspects are not constant and vary in time, makes the radio network planning a nonstop process, which requires continuous monitoring and optimization.

This chapter contains description of the overall radio network planning process, points out the importance of the radio propagation environment and the parameters which are used to characterized different type of environments and gives picture of curtain type of environments and planning techniques, which are used under the scope of this work. Besides, cellular concept is represented, as overall planning of mobile wireless networks is based on this concept.

2.1 Cellular Mobile Networks

First time in history, the concept of cellular networks was developed by AT&T/Bell laboratories in 1968 and the concept has been successfully implemented in several cellular systems over time and in different parts of the world [5].

Prior to cellular mobile networks, mobile telephony were limited systems designed only for voice communication and have been implemented with high towers to cover large areas with support of only a few simultaneous users in limited coverage area of the tower. No mobility was supported, so no hand over of calls between two towers, although the coverage area was so large and there were no much need of it. Besides, at that time, there were no portable mobile devices available. But, the technological advancements in many spheres, for example, a dramatic progress in VLSI, enables small-area and low-power implementation of sophisticated signal processing algorithms and coding techniques, make possible to build compact wireless devices which have been dramatically increased the popularity of mobile telephony. As a result, to be able to support the increasing depend on capacity, the idea of splitting network into smaller geographical areas and support for full mobility of the traffic between those areas, has born.

From this initial concept, several cellular networks were developed, first of these was an analog voice system with some data transmission modulated in voice channels to support mobility and power control. Some of the most well-known standards were/are Advanced Mobile Phone System (AMPS), which was launched in the Americas in 1978, in Israel in 1986, and Australia in 1987, Total Access Cellular System (TACS) first implemented in the UK, Nordic Mobile Telephony (NMT), the standard developed by the Scandinavian countries in 1981, and of course 3GPP legacy networks such GSM first time launched in 1991 Finland, than in other part of Europe and evolved to more or less a global standard, Universal Mobile Telecommunication System (UMTS), and LTE which is the technology used in this study and described in more details in Chapter 4 [5].

2.1.1 Cellular Concept

The initial success of the first mobile system, made it clear that there will be need for more capacity in future mobile telephony, so new methods were required to serve more users. And the solution was the cellular concept that is to divide the coverage area into small areas so called cells with continuous coverage and to introduce a handover functionality that could insure full mobility and uninterrupted services throughout the network, making it one big single network.

So, the main aim of the cell implementation is to increase the capacity of the network by as often as possible reuse of the radio resources. For example, in case of LTE those are carrier frequencies, in case of UMTS those are codes. The resources used in a cell can be reused in another cell located far enough to avoid inter cell interference. The sufficient distance between cells, utilizing the same resources, is defined by the resource reuse factor, which in case of the LTE is called frequency reused factor. The groups of the cells which are using different resources are called cluster. The logical cells in cluster cannot have the same radio resources so the minimum resource reuse factor is $1/N$, where N is the total number of cells, in a particular cluster. If there is N number of cells in a cluster that has a radius R then the minimum resource reuse distance D can be found by the formula $D = R\sqrt{3N}$ [6]. For example, in GSM frequency reuse factor 12 is usually used [7], on the other hand, in LTE flexible reuse factor can be used; for user located near base station the frequency reuse factor one can be used, but for users located near border, to avoid interference to/from neighbouring cells, frequency reuse factor bigger than one can be used. In LTE this is done by the radio resource scheduler, which takes into account the resource allocation in neighbouring cells. This procedure is called inter cell interference coordination.

Division of the coverage into cell, channel allocation to that cells and ability of power manipulation of base stations in each cell, give an opportunity of system flexible design. In areas with high traffic density, like in cities, the cell can be smaller which means that channel can be used more often. As a result higher traffic per unit area can be served. On the other hand, in rural areas the size of the cells are larger, power of base stations is higher, antennas are more often above surrounding constructions and small number of channels are allocated to each cell. So, the traffic intensity generated by users under certain geographical area has big influence on mobile system deployment.

2.1.2 Coverage, Capacity and Quality of Service

In addition, to the propagation environment, as described in Section 2.2, radio propagation heavily depends on the base station antenna array type and on its height with respect to the average height of the surrounding objects. In case of the highest possible position of the antenna, when it is above average rooftop levels, the best coverage will be provided. But this will not be an optimal solution for capacity and the system can easily be capacity limited, as the radio resources can be reused under the whole coverage area of the cell to avoid interference. Consequently, the radio propagation environment and antenna configuration used in base station defines the maximum resource reuse factor for the particular area. The maximum resource reuse factor in its turn determines the required minimum number of base station to meet capacity requirements.

Along with capacity requirements, the Quality of Service (QoS) requirements need to be determined to achieve high efficient performance. In commercial radio networks, the goal is not to achieve the maximum performance of the network throughout the whole coverage area of the network, which is impossible to provide, as the characteristics of the radio channel, the environment, the location and behaviour of the users, the weather, etc. are not constant. In commercial network the goal is to provide certain quality of the services with as high as possible probability. So, the QoS of a radio network can be described by the time and location probability. The location probability is the probability of the average received signal strength to be higher that the specified threshold, which is enough to provide a certain quality of services over a coverage area of the network. Time probability is the same just for different time periods, which is more difficult to predict. The location probability also depends on the antenna height, as the higher antenna position will provide higher location probability over the same coverage area.

2.1.3 Optimal Solution

It is very important to understand that an optimal solution for coverage is not usually an optimal solution for capacity and interference, and the same way, an optimal solution for capacity is not the best one for coverage. But, to be able to provide a cost efficient high quality services an optimal solution need to found, which could be an intelligent combination of the coverage, capacity and interference solutions.

In cellular networks planning process it is always required to maximize both coverage and capacity and minimize the interference. It is an optimization process, and like in any other optimization task the difficult part it to determine the point where to start. From the above discussions, it is clear that there is a link between base station antenna height and coverage and capacity. Antenna height has big effect on both coverage and capacity. Consequently this parameter should have priority on other parameter and the optimization of this parameter can be considering two be a starting point.

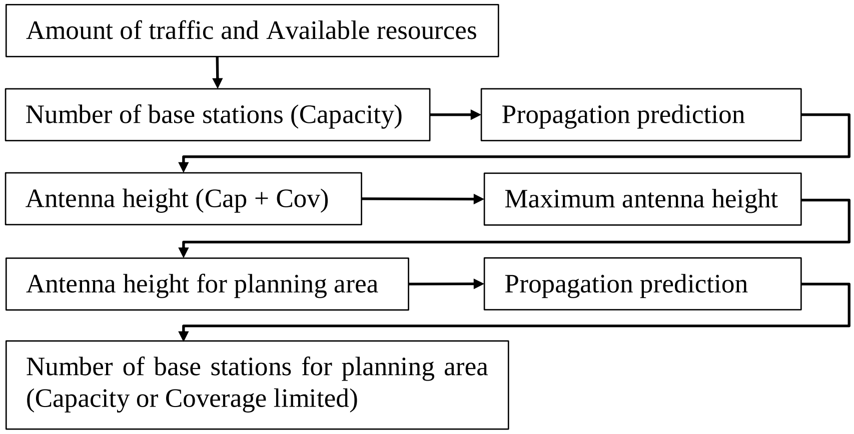


Figure 2.1 Antenna height definition process [7].

As illustrated in Figure 2.1, the antenna height determines the coverage area and the require number of base station, taking into account the traffic information, so the taking into account the capacity requirements. Consequently, the optimization of the antenna height will provide the result required by both coverage and capacity [7].

2.2 Radio Propagation Environment

As it was already mentioned in the beginning of this chapter, the radio propagation, consequently also the coverage and capacity, are heavily depend on radio propagation environment and this is true for any kind of wireless cellular systems including LTE. Thus, selection of the base station equipment and overall planning strategy is also environment specific. For this reason, there are various classifications of the environment to make possible the generalization of radio network planning processes. The classification of the environment can be done according to (Figure 2.2):

- *Mobile terminal location*, it can be outdoor or indoor. If the mobile terminal is located inside buildings the environment is called indoor, otherwise it is outdoor.
- *Antenna location*, above or below the average rooftop level. In case, when base station antenna array is above average height of the buildings, the environment is considered to be macro-cellular and, in case, when base station antenna array is below average height of the buildings, the environment is considered to be micro-cellular. There is even smaller type of the cells than macro and micro cells, so called pico-cells for which the antennas are located mainly in indoor environments.
- *Morphography type*, urban, suburban, rural. These area types are determined by the variation of size and density of both manmade and natural obstacles located in surroundings of User Equipment (UE) and base station sites. The micro-

cellular environment is usually available in urban areas, as there are buildings higher than trees and buildings having more than 4 floors. Besides, Micro base station is primarily intended for capacity purposes, as antennas are located below average rooftop level, which means that neighbouring buildings will block the signal and coverage will be reduced. Thus the radio resources may be used more frequently and the capacity will be increased.

Furthermore, the radio propagation characteristics are different for macro-cellular, micro-cellular and indoor environment. Consequently, the radio propagation need to be studied separately for different environments by the use of several parameters related to the radio propagation environment.

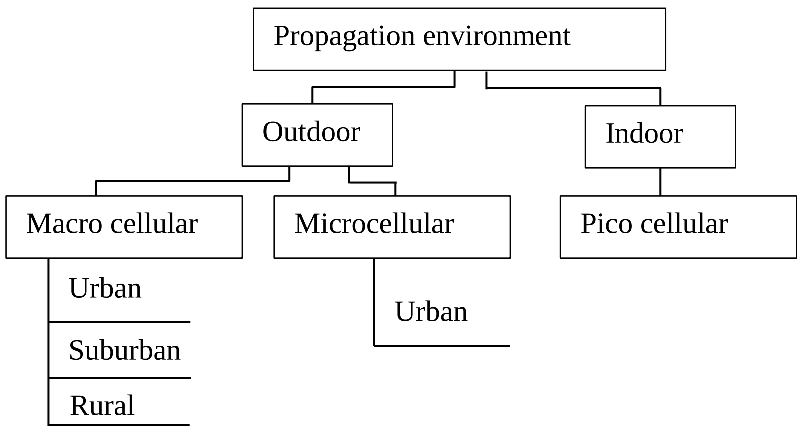


Figure 2.2 Radio propagation environments [7].

2.2.1 Radio Propagation Environment Parameters

The parameters used to specify the radio propagation in different environments, are acceptable for any wireless cellular mobile systems, so also for LTE. These parameters are shortly described below.

2.2.1.1 Angular Spread

This parameter defines variation of the signal incident angle. It can be calculated in both horizontal and vertical directions [8]. But the horizontal direction is in more interests, as multiple propagation paths are exists between bate station and mobile station in horizontal direction. The horizontal angular spread is different for different environments, in macro cells it is very narrow, while in micro cells and indoor environments it is very wide (typical values are represented in Table 2.1). This is important to know as the angular spread has direct impact on antenna installations in traditional space diversity reception; as wider the angular spread as closer can be located antennas for different diversity branches. The angular spread has effect also on additive antenna systems and it is more difficult to implement in macro cells than in micro cells.

2.2.1.2 Multipath propagation and delay spread

As a result of being reflected, diffracted and scattered form the different objects along signal propagation path from base station to mobile station, multiple copies of the same signal are arriving the receiver through different paths. This phenomenon is called multipath propagation. These multiple paths have different lengths, thus signals arrive at different time intervals. The variation of this time intervals is called delay spread. Usually, the delay spread S_r is calculated from the signal power-delay profile $P_r(r)$ [9]:

$$S_r = \sqrt{\frac{\int_0^\infty (r-\bar{r})^2 p_r(r)dr}{P_{r\_tot}}} \qquad 2.1$$

where $\bar{r}$ id the average delay and P_{r_tot} is the total received power.

The delay spread has bigger values for macro-cellular and relatively smaller values for micro-cellular ant indoor environments. The delay spread has significant impact on, for example, frequency hopping, because the coherence bandwidth Δf_c that is the bandwidth within which the channel frequency response is constant, defines the required frequency separation for frequency hopping and depend on delay spread [9]

$$\Delta f_c = \frac{1}{2\pi s_r} \qquad 2.2$$

As the delay spread is very small in indoor environment (typical values are represented in Table 2.1), consequently the coherence bandwidth is large and the frequency hopping will be impractical.

2.2.1.3 Fast fading and slow fading

As it was explained above, multiple replica of the same signal arrives via several paths to the receiver. Thus, the total received signal is a combination of all multipath components. Because different components arrive via different paths, the radio propagation mechanisms have different effect on them, as a results, they have different amplitudes and phases. Consequently, the summation of multipath components, which is based on super positioning principle, can be either constructive or destructive, depending on multipath components phases.

The change of the multipath components phase and amplitude is very fast, duo to the fact that even a small movement Δd over a distance of wavelength can cause up 360 degree change in phase $\Delta\phi$ which depends on the angle α between incoming signal and movement direction.

$$\Delta\phi = -\frac{2\pi\Delta d}{\lambda}\cos\alpha \qquad 2.3$$

As the result of the fast fluctuation in multipath components phases, the total signal also will have fast fluctuations. This phenomenon is called fast fading. Depending on the fact, whether the signal has line of side component or not the Power Density Function (PDF), used to describe the received signal, is different. In case, when signal has of line-of side component, the received signal is Rician distributed, in case of non-line-of side components, the received signal is Rayleigh distributed. So, this is clearly indicates that received signal distribution is different in different environments; for example in micro cell, the mobile station is usually closer to base station and there is always a strong signal component available.

Slow fading is nothing more than just a variation of the local mean value of the fast fading over a wide area [10]. The reason of the slow fading is that the environment is changes when a mobile moves. The variation of the fast fading mean value is log-normal distributed with mean value and standard deviation, for this reason, the slow fading also called log-normal distribution. Slow fading margin is used in planning process to take into account this phenomena, but the slow fading margin is usually used only for macro-cellular environments, as in micro cells the mobile terminal is usually in line-of side situation or at least close enough to the base station to have strong received signal level.

2.2.1.4 Propagation Slope

The attenuation of the signal due to the distance is called propagation slope. The propagation slope is different in different environments. For example, in free space it proportional to squire of the distance, in urban areas to the power of 4 of the distance. Usually dB/dec unit is used, which is $10\ n$ where n is the propagation exponent that is the variable to define the propagation slope for different environments. The usual values for propagation slope are 20-50 dB/dec [11], starting from free space ending with dense urban areas.

The propagation slope is following different laws at different distances. The distance, when the propagation slope changes, is called breakpoint distance. The breakpoint distance play very important role in radio network planning process, the mobile connected to a base station can have smaller propagation slope to the serving base station and higher propagation slope to the neighbouring base station. This will help to achieve better coverage and to reduce the interference.

2.2.2 Characteristics of Radio Propagation Environment

The parameters discussed in previous section determine the characteristics of radio propagation in different environments and also in different systems. These parameters have important effect on both coverage and capacity planning for all types of environments. These parameters are used to find an optimal solution for coverage and capacity in all environments. Each of these parameters has different values in different propagation environments, so different environments can be categorized based on these parameters. Table 2.1 contains typical values for these parameters in different environments.

Table 2.1 Characteristics for different radio propagation environments for 900 MHz frequency [7].

	Angular spread (deg)	**Delay spread (ms)**	**Fast fading**	**Slow fading standard deviation (dB)**	**Propagation slope (dB/dec)**
Macro-cellular					
Urban	5-10	0.5	NLOS	7-8	40
Suburban	5-10		NLOS	7-8	30
Rural	5	0.1	N(LOS)	7-8	25
Micro-cellular	40-90	<0.01	N(LOS)	6-10	20
Indoor	90-360	<0.01	N(LOS)	3-6	20

Table 2.1 gives a lot of information that need to be taken into account in planning process. For example, in indoor and micro-cellular environments, the fast fading distribution is varying, as there are many both Line-of-Sight (LOS) and Non LOS (NLOS) situations, the propagation slope is much bigger for macro cells and considered to be 20 for indoors. And, probably the most important parameters, angular spread and delay spread have very big influence on planning process, as they define the efficiency of the applications like frequency hopping, adaptive antenna system and diversity techniques in different environments [7].

2.3 Radio Network Planning Procedures

In the scope of this work, study of an optimal multi antenna mode in a LTE system for different channel conditions and environments is done. This process belongs to the so called parameter planning, which is a part of radio network planning for a LTE system. Thus, understanding of the radio network planning is necessary to have an overall picture of place and role of the parameter planning in general process. The planning processes represented below are common for any wireless cellular mobile systems.

The radio network planning is a process, which defines different steps, like measurements, planning, documentation, etc. that should be done in different phases to manage connections between coverage, capacity and interference. The coverage or capacity or QoS is not possible to maximize simultaneously, but all of them need to be optimized in order to implement a cost-efficient high quality radio network. To provide necessary coverage and, at the same time, optimize capacity and quality, the radio network panning can be divided in three main phases, illustrated in Figure 2.3. These phases can be used from initial deployment of the radio networks to their evolution and further development [7].

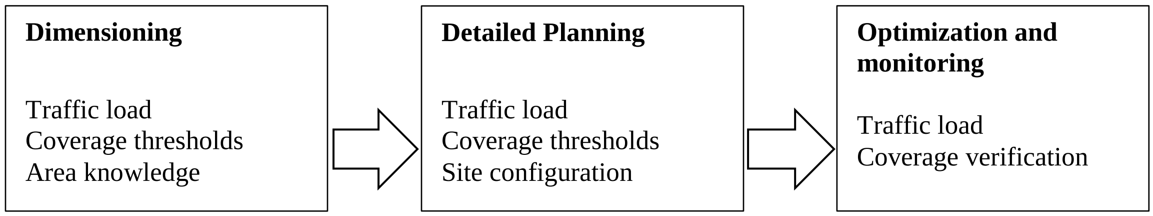


Figure 2.3 Radio system planning process phases and their key parameters [7].

Figure 2.3 represents the three main phases and their parameters. During the first phase, dimensioning, the planned network configuration is analysed and an appropriate radio network deployment strategy is defined. In second phase, detailed planning, the detailed design and actual implementation of the radio network is done. And in the third phases, optimization and monitoring, the monitoring of the network is done to optimize the network and to find out the evolution requirements.

Traffic load and coverage threshold are the parameters which are used in all three phases, because of their strong influence on the coverage, capacity and quality. Thus they are considered to be global parameters. The average base station antenna height also can be considered as global parameter, as it has strong influence on both coverage area and radio recourse reuse. So, these three parameters are considered throughout the whole evaluation path of the radio network.

2.3.1 Dimensioning

The main purpose of the first phase in radio network planning process is to make an initial radio network configuration and planning strategy, with other words, the main aim is to define important radio parameter values and technologies to deploy the network. The above mentioned three global parameters are also input for dimensioning phase. If dimensioning is going to be done for a new network, several scenarios need to be developed to exceed the coverage thresholds in case of different traffic loads. If dimensioning is going to be done to extend an existing network, so the existing traffic history must be used to predict traffic load for 1-3 years ahead. As accurate the traffic prediction as better the antenna height and capacity can be optimized for long period of time.

Figure 2.4 represents the summarized information that is required as input in dimensioning phase to study in more details the coverage and capacity requirements.

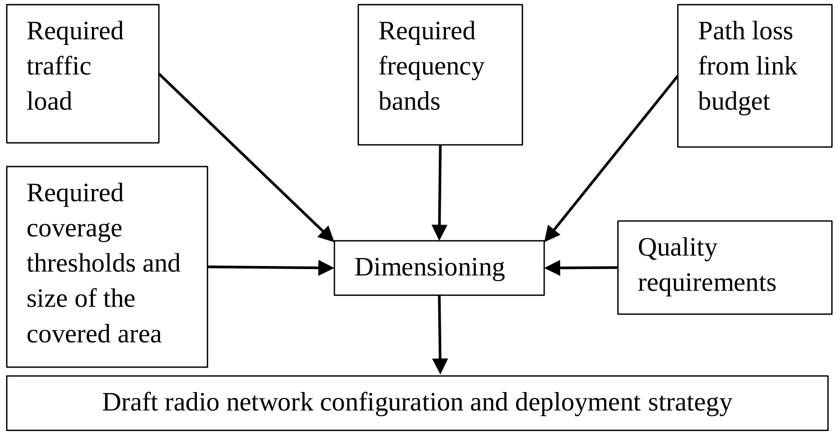


Figure 2.4 Dimensioning phases [7].

The estimation of the base station coverage area will be done with the help of the above mentioned coverage parameters, then the required number of the base station may be modified by changing base station antenna height to find an optimal number of base stations in accordance with traffic requirements. Of course, the traffic and coverage requirements are increasing continuously so the traffic and coverage predictions need to be done as accurate as possible to avoid further costly reconfiguration processes. The reconfiguration is not possible to avoid, as the network evolution is nonstop process, but it should be minimized.

2.3.2 Detailed Radio Planning

In the second phase of the radio network planning process, the results of the dimensioning phase, like the required base station antenna heights, are used to eventually design and implement the radio network. The detailed planning phase contains several planning steps, which are represented in Figure 2.5.

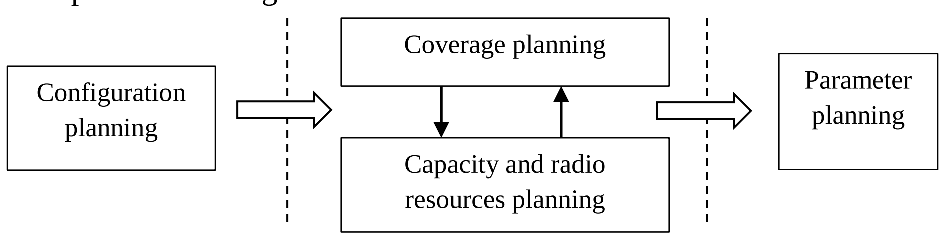


Figure 2.5 Detailed planning phases [7].

First step in detailed planning is the configuration planning, which need to be done prior to coverage and capacity planning to be able to analyses all available coverage and capacity related software and hardware features. The base station site configuration, which is different for different environments, need to be done based on both coverage and capacity requirements. Coverage specific requirements define coverage related base station elements and capacity requirements define capacity related base station elements. And finally, power budget can be calculated based on optimized base station parameters.

Eventually, the configuration planning will provide total base station site configuration for different places and environments.

The configuration planning is followed by coverage planning, the aim of which is to minimize the number of base station sites by utilizing output information of the dimensioning and configuration planning. An important role in configuration planning plays surveying which helps to find out potential propagation problems and suggest base station sites locations. After that, some measurements can be done to tune propagation models for the particular areas. The tuned propagation models will give the final locations for base stations, by taking as input base station configuration parameters as well as some information about environment. The final coverage prediction and base station locations are usually defined by the use of advance planning software

The next step is capacity planning which should be started as soon as the base station sides are selected. The capacity planning is done by the use of planning-tools, as the resource allocation mechanisms are already defined in dimensioning phase. The initial step is to define planning thresholds, after that, the main job will be done by planning-tools.

The last step in the detailed planning is parameter planning, which is done immediately before the launch of the network. This step is very important, as the wrong parameterization of a wireless cellular system like LTE, can cause serious degradation in term of QoS. For example, in LTE there are 7 transmission modes, as described later in Chapter 4, which are designed to increase the performance of a LTE network for different deployment scenarios. So, an appropriate transmission mode selection will increase the output the system. In this study, the performance evaluation of different MIMO modes, which are available in LTE, are done (the detailed objectives are represents in Chapter 1 and 5). In general, the parameter planning is usually very short step, because the values of the radio network parameters are based on the measurements of the other networks and they are fixed, although there are some differences for different environments.

2.3.3 Optimization and Monitoring

The radio network planning process could be finished after dimensioning, configuration, coverage and capacity phases, if the locations and number of the mobiles were constant after the deployment of the network. Unfortunately, both number and locations of the mobiles are not constant and it is impossible to get exact information prior to the network operation. So, accurate information will be available only after monitoring and gathering statistical data from up and running network. From this data it will be clear, whether there is a problem with overloading of the network or not. This data will be very valuable for the dimensioning phase in case of network extension.

The last phase of the continuous radio network planning cycle, the optimization and monitoring, at first tries to analyse whether the coverage is good or not, then tries to determine the traffic over a certain base station area to understand whether the base station is overloaded or not. Based on these analyses, a decision is made, whether to balance traffic between base stations, add radio resources or implement new base stations.

So, the optimization is a phase, where real life information about both coverage and traffic can initiate changes in radio network configuration, thus all radio network planning process are repeated in optimization phase. When new configuration is defined for the radio network, based on real time information, both coverage and capacity may be improved. Eventually, the radio network may become closer to optimal and may meet to the coverage and capacity current requirement.

It is important to note that the overall planning process can be managed and control only if all phases have been properly documented and there are accurate input and output documents. Moreover, the radio network configuration can be optimized and upgraded only if there are proper output documentations. The accurate and proper documentations are required to control the planning process, to guarantee cost efficient and high quality radio network system for long-term operation.

3 MULTI-ANTENNA TECHNIQUES

Multi-antenna techniques can be understood as general name for a set of techniques which are based on utilization of multiple antennas at receiver and/or transmitter side supported by some advance signal processing The improvement of the wireless communication system performance in terms of throughput, signal quality and availability, by utilizing different multi-antenna techniques, was discovered from very early times of wireless communications. Yet, the active scientific research process, toward determining the fundamental capabilities, real potential and different possible applications of multi-antenna techniques have been done in past 20 years [12, 13, 14]. Although, initial applications such as beam-forming were implemented 60 years ago, intensive utilization of multi-antenna techniques in commercial wireless networks started in the beginning of 21 century and play a key role in local, wide and metropolitan wireless networks technologies like Wi-Fi and WiMAX. Later, mobile cellular systems also begin to adopt multi-antenna techniques and a break point was with development of LTE which is the first global mobile cellular system designed to utilize different multi-antenna techniques as one of the most important parts of its specifications

In this chapter, different multi-antenna methods and the benefits of using them are represented along with most relevant applications which are important in the scope of this study, as the study is based on comparison of the different methods of the multi antenna techniques implemented in LTE systems.

3.1 Multi-Antenna Configurations

From engineering point of view there are several ways to make network devices equipped with multiple antennas. In all cellular mobile wireless networks, usually there are base stations and mobile stations which can have different number of antennas for transmission and reception. Depending on that, there are different multiple antenna configurations that can be used to implement certain type of applications. Those several configurations differ from each other by the number of antennas implemented on base station or UE side. All of them have their advantages and disadvantages and the right decision which format to use depend on application to be used.

So, those different formats of multi-antenna systems refer to single or multiple input and output streams and called as follows, Single Input Single Output (SISO), Single input Multiple Output (SIMO), Multiple Input Single Output (MISO) and Multiple Input Multiple Output (MIMO). Basic principle of each configuration is represented in Figure 3.1.

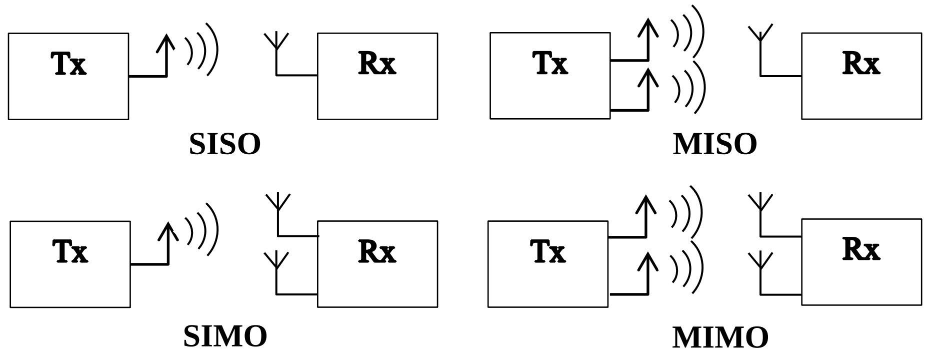


Figure 3.1 Different multi-antenna configurations.

3.1.1 Single Input Single Output

This is the traditional scenario, without any multi antenna implementation, that is a single transmission and a single reception antenna on both transmitter and receiver sides. This basic configuration is the most simple and called SISO. The advantage of this format is its simplicity. In comparison with other configurations, SISO has the worse robustness against interference and fading of the channel as no techniques like diversity transmission, explained later in this chapter, are implemented. Besides, the peak data rate is limited by Shannon's law [15]. This method is not specified in LTE and thus out of the scope of this study.

3.1.2 Single Input Multiple Output

Multi-antenna implementation could be done in several ways. One way is to implement more than one antenna at receiver side and only one antenna at transmitter side. This format is called SIMO. This configuration allows to implement receive diversity that is more than one uncorrelated replicas of the same signal is received by different antennas and combined together, using one of the several combining methods, to increased SNR and mitigate channel fading processes. In comparison with SISO it requires more processing capacity at the receiver side that is why the implementation is limited by the size, cost and battery life of a device. This method is also not specified in LTE and thus, the receiver diversity, which is one of the multi-antenna applications, is not described here, as it is out of the scope of this study

3.1.3 Multiple Input Single Output

The other way is to equip transmitter with more than one antenna and receiver with only one antenna. This configuration is called MISO, and actually corresponds to the transmit diversity that is transmission of the same data over several channels by utilizing multiple antennas at transmitter side. The receiver than will choose the better signal which will create redundancy against channel fading processes. This is more practical and easy to implement, in comparison with SIMO, as multiple antennas and complexity associated with additional processing are moved from receiver to transmitter. This can be considered as advantage for small devices like cell phones as the level of complexity will be significantly reduced. Consequently, the battery life could be increased, at the same time size and cost could be decreased.

3.1.4 Multiple Input Multiple Output

And finally the last configuration is the MIMO that is more than one antenna at both transmitter and receiver sides. This configuration can be used to increase both link throughput and channel robustness in expense of additional processing complexity in both receiver and transmitter side. In comparison with previous configurations, the information data need to be divided in different parts, according to the number of available antennas, and by using some pre-coding mechanisms channels will be separated from each other.

3.1.5 Applications for Multi-antenna Techniques

In this section, a few applications are presented for multi-antenna techniques, which play a key role in modern cellular mobile wireless networks especially those which are used in LTE that is described in Chapter 4. Having multiple antennas at receiver and/or transmitter side has several benefits, as it was already pointed out in above sections of this chapter, and can be utilized differently for different purposes:

- The implementation of multiple antennas at receiver and/or transmitter side allows mitigating fast fading of the wireless channel by utilizing diversity of channels. This technique is called receive/transmit diversity and has two main prerequisites. First of all, the fading processes must be uncorrelated on channels provided by different antennas, and secondly, the power of different channels needs to be equal. In LTE, only transmitter diversity is specified.
- The implementation of multiple antennas at receiver and/or transmitter side can be used for so called beam-forming that is to shape overall receive/transmit antenna radiation pattern. This will let to increase radiation intensity toward certain receiver/transmitter and/or decrease radiation intensity by creating nulls in radiation pattern toward high interference source. In LTE, only transmitter side beam forming is specified.
- The implementation of multiple antennas at receiver and transmitter side simultaneously can be used to dramatically increase data rates without degradation of the coverage and without increment of the bandwidth. This is done by implementing multiple parallel channels over the radio interface. This is referred as spatial multiplexing and it is also often referred to as MIMO.

3.2 Transmit Diversity

Having multiple antennas at transmitter side gives opportunity to implement transmit diversity or transmitter side beam-forming. But, to be able to implement beam-forming, some information about transmission channels of different antennas is required, otherwise multi antenna system cannot provide sufficient beam-forming at transmitter site. In this case, multiple transmit antennas can provide only diversity, for which the main prerequisite is low correlation between fading processes on the channels of the different antennas. The low correlation can be achieved, for example, by having multiple antennas separated in space (space diversity) or antennas which use different polarizations (polarization diversity) or antennas operating on different frequencies (frequency diversity), etc. Having any of the above mentioned antenna configurations, several methods can be applied to implement transmit diversity provided by the multiple transmit antennas.

3.2.1 Delay Diversity

Several replicas of the transmitted signal are arriving to the receiver via multiple independent fading paths, being reflected, diffracted or scattered from objects, located in the propagation path, with different time delays relative to each other. The multipath nature of the channel can be used as benefit if the multipath propagation is not very severe. The fading processes of different paths are mutually uncorrelated and there are mechanisms at the receiver side to eliminate effects caused by frequency selectivity of the channel, for instance, Orthogonal Frequency Division Multiplexing (OFDM) transmission or receiver equalization.

If the channel is not time dispersive, or frequency selective, the multiple antennas can be used to create artificial frequency selectivity, equivalently, artificial time dispersion. This is possible to do, by transmitting the same signal through different antennas, but with relative delays between each antenna. The relative delay T, illustrated in Figure 3.2 a), need to be selected in such a way to be able to achieve sufficient frequency selectivity [4].

From mobile terminal point of view, the delay diversity is understood as usual multipath propagation and time dispersion of the channel, that is why it is very easy to integrate to any mobile wireless systems as there is no need to bring changes in radio interface.

3.2.2 Cyclic-Delay Diversity

In comparison with delay diversity, Cyclic-Delay Diversity (CDD) [16] operates block wise, and instead of linear delays it applies cyclic shifts to different antennas. Due to its block-based operational nature, CDD is very convenient for OFDM and Single Carrier Frequency Division Multiple Access (SC-FDMA) multiplexing methods used in LTE as described in Chapter 4. This kind of time domain cyclic shift, in case of OFMD transmission, corresponds to phase shift in frequency domain before OFDM modulation, as represented in Figure 3.2 b) and c). Figure 3.2 contains example for the case of two antennas, but both delay diversity and CDD can be extended for more than two antenna case with different linear and cyclic shifts for each antenna.

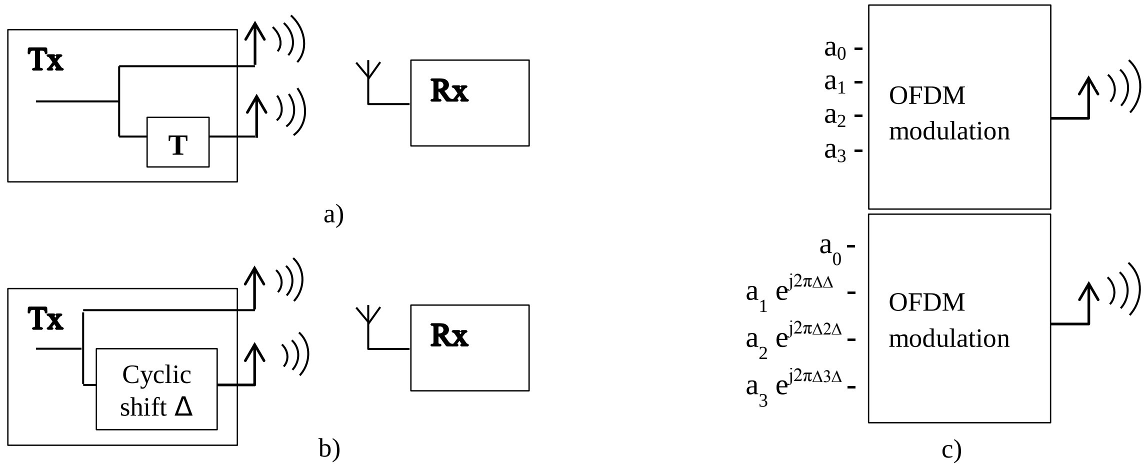


Figure 3.2 Two antenna transmit diversity a) delay diversity b) and c) CDD [17].

3.2.3 Diversity by Means of Space-Frequency Coding

Space-frequency term is used to specify multi-antenna transmission method where modulated symbols are mapped into two domains, space (different antennas) and frequency (in case of OFDM, subcarriers) to provide multi antenna diversity. In this method, so called Space-Frequency Block Coding (SFBC), special encoding is carried out in frequency/antenna domain. It is also possible to implement encoding in time/frequency domain that is Space-Time Block Coding (STBC), but this is not discussed further as only SFBC is chosen to be the transmit diversity scheme in LTE networks as described in Chapter 4. The SFBC is sometimes referred to as Space-Frequency Transmit Diversity (SFTD) and represented in Figure 3.3, and it is very well applicable for frequency domain multiplexing methods, like OFDM.

As can be seen from Figure 3.3, a block of consecutive symbols are directly mapped to the first antenna and the negative complex conjugated versions of the same modulated symbols, changed in order for a pair of symbols, are mapped on the same subcarriers of the other antenna. The obvious drawback of SFBC is that extension to more than two antennas will require data rate reduction.

In comparison with CDD, SFBC provides diversity on modulation symbol level, whereas CDD utilizes channel coding and frequency domain interleaving to make diversity possible.

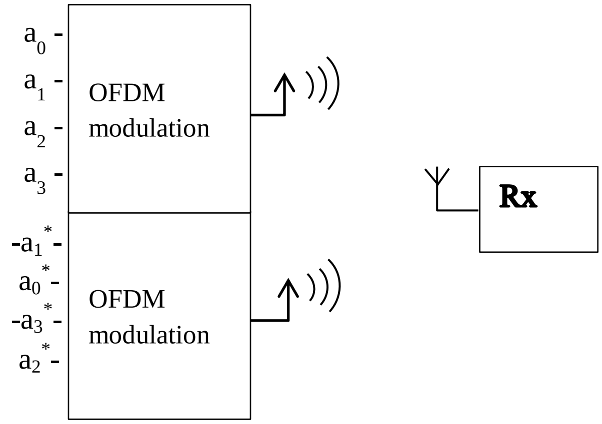


Figure 3.3 Space-Frequency Transmit Diversity for two antennas [17].

3.3 Spatial Multiplexing

In all cases discussed so far, there were multiple antennas at either receiver or transmitter side. But it is obvious, that simultaneous availability of multiple antennas at both sides will bring improvements in SNR and increase robustness against fast fading in comparison with only receive or transmit multiple antennas. On the other hand, having multiple antennas on both sides can be used to significantly increase data rates by implementing so called spatial multiplexing that is instead of transmitting/receiving the same data over multiple antennas, different information can be transmitted/received over different antennas utilizing the same bandwidth. The term MIMO is often used instead of spatial multiplexing, although this term, in general, refers to the all multi-antenna configurations, like transmit or receive diversities.

3.3.1 Basic Principles

From previous discussions in this chapter, that in multi-antenna system the improvement of SNR is proportional to the number of antennas used in beam-forming application. When there are N_T transmit and N_R receive antennas the improvement, in general, is proportional to the product $N_T \times N_R$. As a result of increment of SNR the data rates also can be increased, as described in [17], if the decrements of data rates are power limited rather than bandwidth limited. Nevertheless, if the bandwidth is unchanged, soon or late, farther increment of the SNR will be useless, as the bandwidth limited rang of the operation will be reached.

This can be explained by considering the channel capacity expression (3.1), defined by Shannon [15], as the upper bound to the capacity of a link:

$$C = B \log_2(1 + \frac{S}{N}) \qquad 3.1$$

where C is the link capacity, B the bandwidth, S is the signal power and N is the noise power

SNR can be increased in proportion to $N_T \times N_{R,}$ by the help of beam-forming. In general, $\log_2(1+y)$ is proportional to y for small values of y. This means that for small SNR, capacity increases proportionally to SNR. But, for bigger y, $\log_2(1+y) \approx \log_2(y)$ which means, that for big SNR the capacity increases logarithmically with SNR.

But, if SNR for each available antenna branch are considered to be good, in case of multi antenna presence in both receiver and transmitter sides, it is possible to make and propagate up to $N_L = \min\{N_T, N_R\}$ parallel channels, but with expense of SNR values, as SNR available from each channel will be N_L time lower because of power split between those channels. The channel capacity for each channel, as a result, is expressed as follows

$$C = B\log_2(1 + \frac{N_R}{N_L}\frac{S}{N}) \qquad 3.2$$

But, there are N_L parallel channels having capacity expressed by (3.2), consequently the total capacity of the radio interface will be

$$C = BN_L\log_2(1 + \frac{N_R}{N_L}\frac{S}{N}) \qquad 3.3$$

So, under certain radio conditions, the capacity of a multi-antenna system is possible to increase, by increasing the number of antennas at both receiver and transmitter sides, and the amount of increment is linearly proportional with number of antennas. This is actually what is called spatial multiplexing.

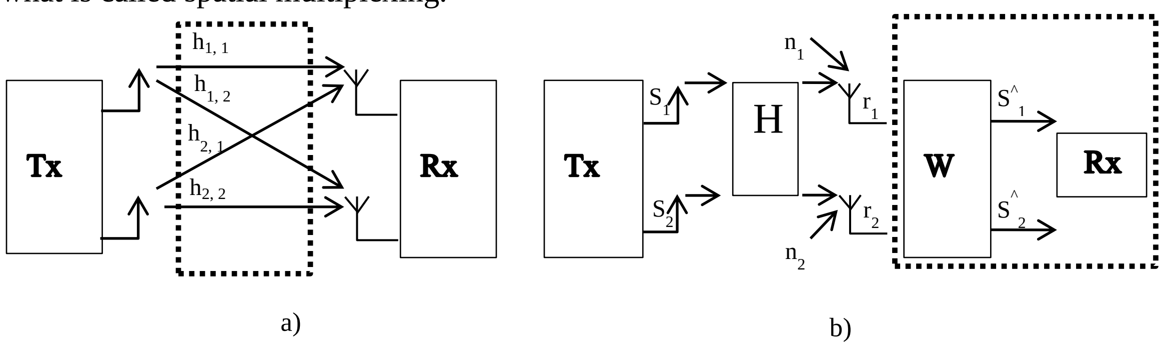


Figure 3.4 2x2 MIMO configuration linear demodulation of spatially multiplexed signals [17].

In Figure 3.4 a) 2x2 MIMO multi-antenna configuration is represented, where as it is assumed, signals are affected only by non-frequency-selective-fading and noise. According to this figure, the received signal is

$$R = \begin{pmatrix} r_1 \\ r_2 \end{pmatrix} = \begin{pmatrix} h_{1,1} & h_{1,2} \\ h_{1,4} & h_{1,3} \end{pmatrix}\begin{pmatrix} S_1 \\ S_2 \end{pmatrix} + \begin{pmatrix} n_2 \\ n_1 \end{pmatrix} = HS + N \qquad 3.4$$

where matrix H is channel response. If there is no noise, and the channel response is invertible, the vector S, and consequently, the signals s_1 and s_2 can be determined by multiplying the received vector R with matrix $W = H^{-1}$ as illustrated in Figure 3.4 b).

Anyway, the utilization of all potential N_L channels is not possible, because of bad channel conditions and in many cases the spatial multiplexing order will be less than N_L. In such situations, the capacity will follow the SNR. Thus, there will not be any gain from spatial multiplexing and it will be more beneficial to use multiple antenna system for beam-forming or diversity to increase SNR. In general, the order of the spatial multiplexing depends on $N_T \times N_R$ channel matrix. All extra antennas could be used for beam-forming in addition to spatial multiplexing. This kind of combination of beam-forming and spatial multiplexing is possible to do by pre-coder based spatial multiplexing, which is also applied in LTE as described in Chapter 4.

3.3.2 Pre-coder Based Spatial Multiplexing

In pre-coder based spatial multiplexing, linear processing is done at the transmitter side by using $V = N_T \times N_L$ pre-coder matrix, as represented in Figure 3.5. It is clear, that, pre-coder based spatial multiplexing can be considered as generalization of the pre-coder based beam-forming. The difference is that pre-coder matrix for beam-forming of size $N_T \times 1$, will be replaced with pre-coder matrix of size $N_T \times N_R$. So, when number of transmission streams N_L is equal to the number of antennas N_T, the pre-coder matrix of Figure 3.5 will be used for only spatial multiplexing and will provide good signal isolation at the receiver side. On the other hand, when $N_L < N_T$, the pre-coder matrix will provide spatial multiplexing of the N_L signals to N_T antennas in combination with beam-forming for any additional antenna.

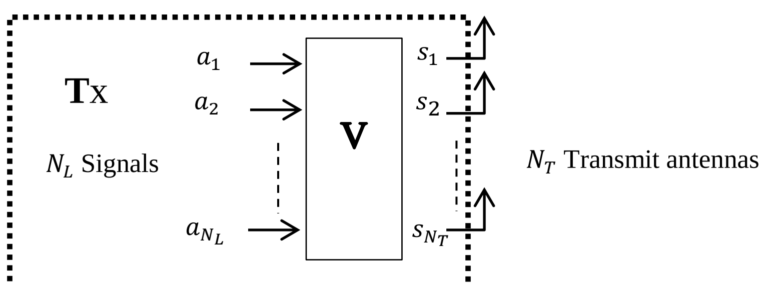


Figure 3.5 Pre-coder based spatial multiplexing [17].

Like in case of beam-forming, the information about channel matrix H is required to be known to be able to determine the pre-coder matrix V. An appropriate matrix can be chosen from the predefined code book, based on the channel estimation done by the receiver. The recommendation of the receiver about selected pre-coder matrix can be reported by the receiver to the transmitter.

3.4 Beam-Forming

When some information about transmission channels of different antennas are known, especially information about relative channel phases, the availability of multiple antennas at transmitter side can be used not only for diversity but also for so called transmitter side beam-forming. This is shaping of the radiation pattern of the transmitter to allocate maximum of radiation intensity in the direction of the desired receiver. Beam-forming can be used to improve the SNR in proportion to the number of transmit antennas N_T. Beam-forming in general provided by a multi-antenna transmit system, can be defined for two cases, high antenna correlation and low antenna correlation. Although the beam-forming is not analysed in this study, it is explained here as it is one of the 7 transmission modes specified in LTE (see Chapter 4 for more details).

3.4.1 High Mutual Antenna Correlation

In case of the high mutual antenna correlation, the fading process of channels between different transmit antenna and specific receiver are principally the same, because separation between different antennas is considerably small, as shown in Figure 3.6 a).

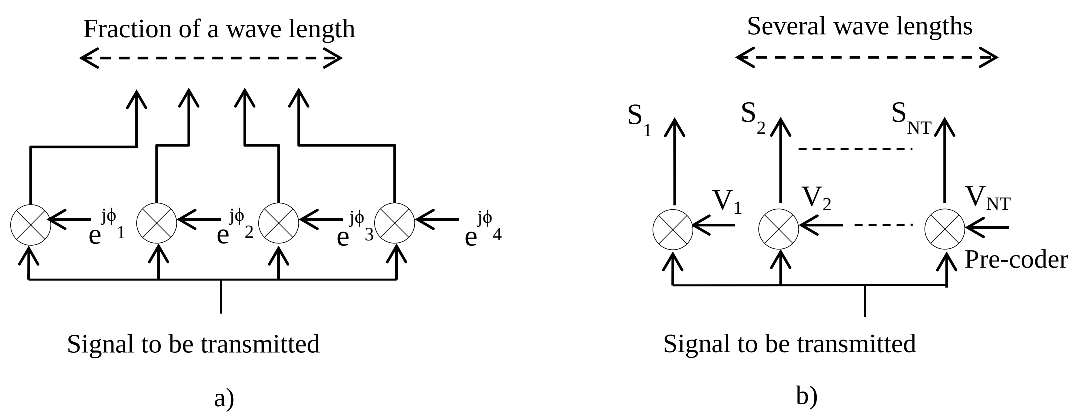


Figure 3.6 Two beam-forming methods a) Classical beam-forming with high mutual antenna correlation, b) Pre-coder based beam-forming, in case of low mutual antenna correlation [17].

By applying different phase shift to signals to be transmitted on different antennas, it is possible to align the overall radiation pattern. But, because of the high correlation between fading processes of different antennas, the classical beam-forming is only able to increase the received signal level and no diversity against fading will be provided. This method sometime refers as to classical beam-forming.

3.4.2 Low Mutual Antenna Correlation

In case of low mutual antenna correlation, the fading process of channels between different transmit antenna and specific receiver are principally the same, because separation between different antennas is considerably large, as shown in Figure 3.6 b). The overall beam-forming principle is similar to the one that is in classical beam-forming, which means that signals to be transmitted via different antennas are weighted with complex values. But the different is that not only the phase but also amplitude of the signals can be adjusted; because of the low correlation between fading processes for different antennas, not only the phase, but also instantaneous gain of each channel may vary.

This is usually done, by multiplying signals to be transmitted, with so called pre-coder matrix, which is selected from predefined codebook. For this reason, low mutual correlation beam-forming also refers as to pre-coder based beam-forming. The pre-coder matrix, which consists of different complex weights, can be described by vector notation, which means applying pre-coder vector V to the signals s to be transmitted

$$\bar{S} = \begin{pmatrix} S_1 \\ \vdots \\ S_{N_T} \end{pmatrix} = \begin{pmatrix} V_1 \\ \vdots \\ V_{N_T} \end{pmatrix} s = \bar{V} s \quad 3.5$$

where $\bar{S}$ is the transmitted signal. The classical beam-forming also can be defined using pre-coder notation (3.5), but with one difference, that the pre-coder should provide only phase shifts, so the weights should have unity-gain for all signals.

Ignoring the time dispersion of the radio-channels, and taking into account only non-frequency selective fading and white noise [18], elements of the pre-coder matrices should be chosen according to the (3.6), to be able to maximize the received signal level.

$$v_i = \frac{h_i^*}{\sqrt{\sum_{k=1}^{N_T} |h_k|^2}} \quad 3.6$$

From (3.6) it is clear that pre-coding weights defined using normalized complex conjugate of the corresponding channel response hi, consequently, the pre-coder matrix provides the following:

- Guarantees that the received signal phases are aligned, by rotating phases of the transmitted signals
- Distributes more power to the antenna with better instantaneous channel condition, ensuring high channel gain

So, it is obvious that for pre-coder based beam-forming more detailed feedback information about the channel is required than for classical beam-forming. Specifically, detailed information about instantiations channel fading needed, then an appropriate pre-coder matrix is selected form predefined codebook based on channel estimates. The fundamental difference between these two beam-forming approaches is the pre-coder based beam-forming in addition to improved SNR also provides diversity against radio channel fading.

4 3GPP LTE OVERVIEW

The Long Term Evolution (LTE) is a result of the 3GPP evolution process toward to the design of a system with higher user throughput, decreased latency and improved spectral efficiency over 3GPP legacy networks like High Speed Packet Access (HSPA). The first specifications are summarized in the 3GPP Release 8 [19]. In this chapter the overview of the LTE technology will be presented with emphasize on techniques used in Radio Access Network (RAN). The chapter starts with the representation of the drivers behind the LTE and advances to the discussions focused on physical layer structure, multiplexing and multiple transmission methods implemented in the LTE and a short overview of the key performance indicators used to analyse the performance of the LTE system.

4.1 LTE Driving Factors and Design Targets

The 3GPP Long Term Evolution is designed to serve as a mobile communication system for near future. The LTE standardization in general and radio interface in particular is based on 3GPP specifications, but not restricted with legacy 3GPP mobile communication systems. As result, it was possible to design a totally new radio interface. In this particular case purely optimized for IP transmission, which means that the legacy circuit-switch services are not required to be supported. On the other hand, new requirements have appeared based on the drivers behind the 3GPP evolution.

As the LTE radio interface is totally different than the air interface of legacy standards and supports capabilities like packet-data, there was necessities to develop new evolved core network. The overall process of specifying the core network is called System Architecture Evolution (SAE) [17].

4.1.1 Drivers Behind LTE

Before going to more technical issues it is important to understand where the requirements for the particular technical implementation is coming from, to see driver forces which motivates the LTE. Several drivers are represented below which try to cover variety of aspects having influence on a mobile communication system design.

4.1.1.1 Technology development

Wireless devices such as smartphones and most recently tablets are becoming more sophisticated every day. This becomes possible duo to the technological advancements in many spheres, for example, a dramatic progress in VLSI enabled small-area and low-power implementation of sophisticated signal processing algorithms and coding techniques, development of small colour screens replaced simple black and white numerical screens, battery lives have been extended dramatically allow for longer stand by and talk times, small digital cameras became a part of a modern mobiles, etc. As a result of the all above mentioned developments and much more other technological advances, a mobile terminal became very compact and multitask devise with very high capabilities in comparison with initial devices.

At the same time, the mobile communication technologies are also developed to meet the demand of the new advance devices. Together those advancements will enable to provide new services to meet the requirements of the growing market.

4.1.1.2 Services

The primary goal of any mobile communication system is to provide services to the end users. Thus the job of the engineers who develop a mobile communication system heavily depends on ability to predict what kind of services may be popular in 5 to 10 years. But it is not an easy task, so the design of the system should be done in a way that it could adapt to services which are not popular at the moment of system deployment but may become popular in near future.

Different applications have different requirements regarding to throughput and delay. Technological achievements allow establishing new services with high data rates and low latency requirements. At the same time, the need in conventional low data rate voice services will still be very important and also services with not so strict latency requirements may be needed to provide, that is why it is very difficult to predict the exact requirements for future applications. But, the fact that all services are going towards all-IP-based communication is quite clear and doesn't mean that conventional circuit-switch domain link GSM will disappear, instead it will ported over IP-based network

Therefore, future mobile communication systems should be designed to operate for IP-based applications.

4.1.1.3 Cost and Performance Efficiency

The aim of a mobile operator is to provide services to all users. Different users with different services need to be served as efficiently as possible. For this reason, another important driver factor for future mobile communication systems is the cost and performance efficiency requirements.

Different technological advancements can be used not only to introduce new services but also can help to reduce the cost and increase the performance of the provided services. For example, the increased processing capacity of the devices allows higher number of bits per hertz, more advance antennas and receivers are increasing coverage, new modulation and coding themes are providing higher capacities, etc.

4.1.2 LTE Design Targets

The drivers behind LTE have been shortly discussed in Section 3.1.1. In this section the design targets taken by the 3GPP as the basis for development of the LTE are summarized. These targets are taken to meet to the driver factor requirements and are well documented in 3GPP TR 25.913 [20]. It is important to note that the design targets represented in TR 25.913 are just initial requirements and the final implementation of some aspects exceeds these requirements. In [20] the LTE requirements are divided in 7 areas which are described below.

4.1.2.1 Capabilities

The target for peak data-rate for downlink and uplink are defined to be 100 Mbits/s and 50 Mbit/s, respectively, for the 20 MHz spectrum allocation. For smaller spectrum allocation the peak data-rates are scaled according to allocated spectrum. As LTE supports both Frequency Division Duplex (FDD) and Time Division Duplex (TDD) operational modes, the peak date-rate requirements cannot be reached all the time. For example in TDD, the transmission and reception take place in different time intervals, so it is impossible, simultaneously to have the peak data-rates for both uplink and downlink

Another important measure of the capabilities is the latency requirement, which is divided into user-plane and control-plane requirement. The user-plane requirement is the time needed for an IP packet to travel from the terminal to RAN and should not exceed 5 ms, in a network without load. The control-plane latency is about transition time between not active to active states and should not exceed 100 ms.

4.1.2.2 System Performance

The topics like user throughput, spectrum efficiency, coverage and mobility are covered by the LTE system performance requirements.

The user throughput and spectrum efficiency requirements are specified in reference with HSPA Release 6 [21], which is considered to be a baseline.

The coverage requirements refer to the maximum cell range when the user throughput and spectrum efficiency requirements are met: 5 km is the range without performance degradation and 30 km range allows slight degradation.

And the mobility requirements refer to terminal speeds. High performance is required for low speed up to 15 km/h and slight degradation is allowed for higher speeds up to 120 km/h. The maximum speed to be able to operate in LTE is set to 350 km/h.

4.1.2.3 Deployment requirements

Deployment requirements combine together deployment scenarios, spectrum flexibility and ability of internetworking with other 3GPP technologies like GSM and WCDMA/HSPA.

The deployment requirements are not limited by the design targets and refer to both stand alone and coexistence scenarios and the internetworking requirements refer to the mobility between LTE and other technologies like GSM and HSPA.

The idea of the spectrum flexibility requirements is about the ability of the LTE system to be deployed in existing International Mobile Communications IMT-2000 frequency bands in coexistence with the systems that are already deployed on those bands and the ability of the LTE to operate in both paired and unpaired spectrum allocations.

4.1.2.4 Other requirements

Besides the above mentioned three areas there are also four other sections in [20]: architecture and migration which refers to LTE RAN architecture requirements and covers couple of topics like packet oriented nature of the RAN, minimized number of nodes to reduce control-plane latency, etc., radio resource management requirements which is divided into end to end QoS support and load sharing and policy support between different Radio Access Technology (RAT), complexity requirements to cover questions regarding both overall system and terminal complexity and finally general requirements section covering issues like cost and service related aspects. There is also a separate document [20] to outline SAE design targets which are also divided in several sections and in many points intersects with LTE radio interface design targets.

4.2 Overview of the Multiplexing Used in LTE

The multiplexing methods used in LTE are fundamentally different from the methods used in legacy 3GPP networks. In downlink OFDMA is used, and in uplink SC-FDMA is used. These two methods are very similar to each other and in general both are based on OFDM principle with slight difference in implementation to achieve desired results in each case. SC-FDMA is a mixture of Single Carrier (SC) transmission and OFDM, thus it takes advantages of both techniques in one method.

In the case of the SC transmission, information is modulated only to one carrier by changing the carrier amplitude or phase. For example, by utilizing Quadrature Amplitude Modulation (QAM), the resulting spectrum will be a single carrier spectrum. In the case of multicarrier transmission, like OFDM, the data are divided into different sub carriers of one transmission.

4.2.1 Downlink OFDMA

The OFDMA is a radio access method used in LTE downlink which is one of the applications of the Orthogonal Frequency Division Multiple Access (OFDM). The operational principle is based on Discrete Fourier Transform (DFT) and invers operation of it (IDFT). The practical implementation is based on Fast Fourier Transform (FFT) and IFFT. The modulation of the information is done on very narrow adjacent carriers inside the allocated bandwidth. Consequently, subcarriers are mutually orthogonal to each other. Parameters that need to be considered in OFDM to adjust it to a particular application, like LTE, are the subcarrier spacing and Cyclic Prefix (CP), which together define the OFDM symbol duration and equivalently the symbol rate. The CP should be long enough to cover the time dispersion duration to avoid inter symbol interference, but at the same time, the reduction of the subcarrier spacing should be done to reduce the overhead caused by the CP insertion. In LTE two CP are used, normal CP 5.2 μs for first symbol and 4.7 μs for other symbols and extended CP with 16.7 μs length. As it was already mentioned, the subcarrier spacing should be small enough to reduce the overhead caused by the CP. On the other hand very small spacing will be affected by the Doppler spread and other frequency inaccuracies. In LTE, the subcarrier spacing is chosen to be 15 kHz. The basic operational principle of the OFDM is represented in Figure 4.1.

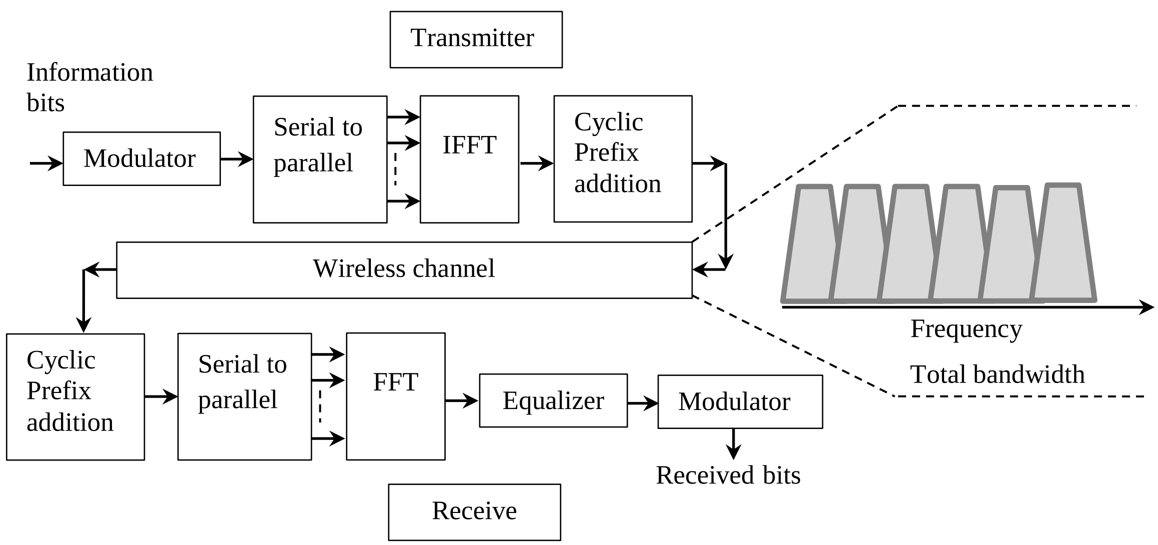


Figure 4.1 OFDM transmitter and receiver [1].

The utilization of the multicarrier principle in LTE has a couple of advantages in comparison with SC transmission. Those advantages are summarized below:

- OFDM provides higher degree of robustness against frequency selectivity, and as a result reduces complexity of the equalization at a receiver side. The complexity of the equalization increases with the increase of the bandwidth.

- As the OFDM operates in frequency domain, it provides more freedom and flexibility to the channel-dependent scheduler in comparison with HSPA.
- For the same reason it provides flexibility in transmission bandwidth to support different spectrum allocation, by changing the number of the subcarriers.

The main difference between OFDM and OFDMA is that in OFDM the divisions of sub carriers for different users are done only with respect to time but in case of OFDMA the user are assigned the subcarriers based on both time and frequency which also called time frequency multiplexing. Figure 4.2 represents the resource allocation difference between OFDM, OFDMA and SC-FDMA [1], [17].

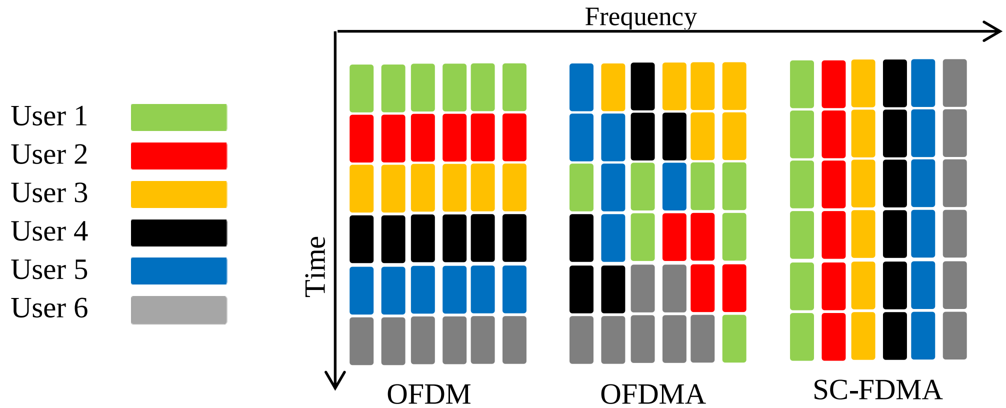


Figure 4.2 Resource allocations in OFDM, OFDMA and SC-FDMA [1].

4.2.2 Uplink SC-FDMA

The OFDMA multiple access method has also some disadvantages which make inefficient method to utilize for LTE uplink. The main reason why the SC-FDMA have been chosen for LTE uplink is the lower peak to average of transmitted signal compared to the OFDMA [23]. This is very important for uplink direction, because low peak to average power ratios allow utilizing the amplifier at the user equipment more efficiently, which results to increment of the coverage and reduction of the user terminal power consumption. At the same time SC-FDMA keeps the OFDM features, particularly orthogonality between subcarriers. The allocation of the recourses for SC-FDMA is represented in Figure 4.2. The basic operation principle of the SC-FDMA is represented in Figure 4.3.

As you can see from Figure 4.3, the only difference in comparison with OFDM is the additional DFT in the transmitter and IDFT in the receiver, that is why, the SC-FDMA also called DFT-OFDM. Duo to this operation, the information can be modulated to time domain signal, instead of modulating subcarriers on the frequency domain and thus maintaining single carrier properties.

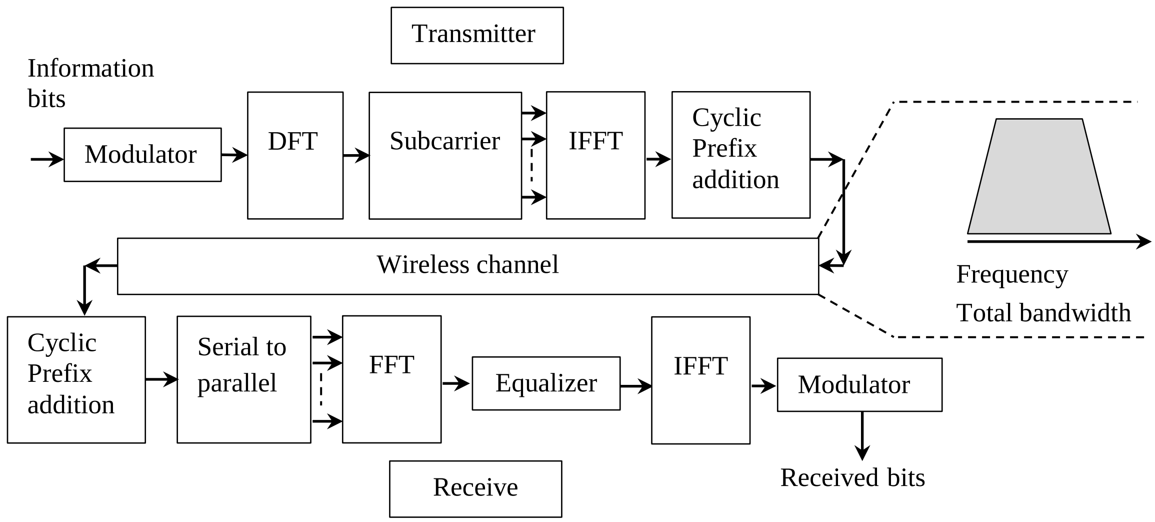


Figure 4.3 SC-FDMA transmitter and Receiver [1].

4.3 Physical Layer Structure

Figure 4.4 shows the LTE high level time domain structure, with representation of the 10 ms radio frame consisting of 10 sub-frames each with 1 ms duration. It also shows the differences between FDD and TDD operational modes. Even though overall time domain structure for both of them is similar, there are some differences; the most obvious one is the presence of a special sub-frame in TDD to provide guard time between uplink-to-downlink switching.

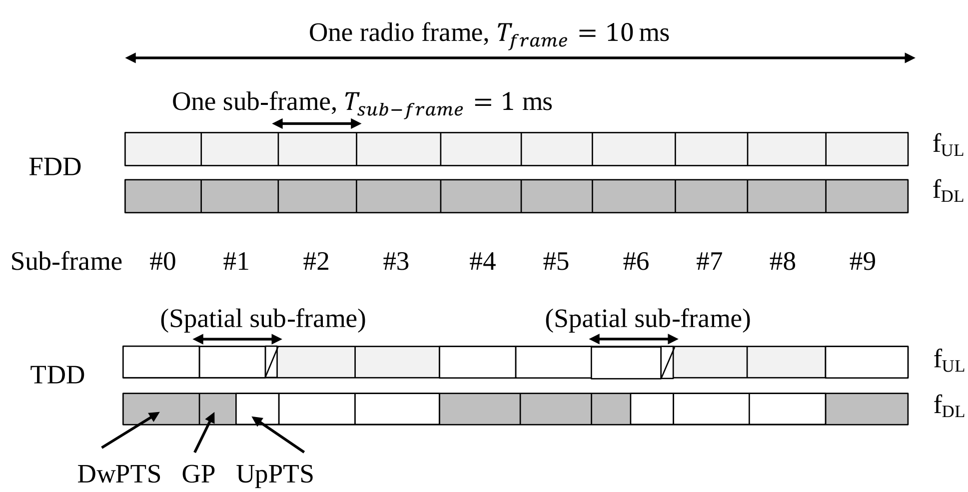


Figure 4.4 LTE uplink/downlink high level time domain structure for FDD and TDD [17].

To provide exact timing characterizations, the basic time unit $T_S = 1/30\,720\,000$ is used to define other time intervals as multiples of this basic time unit. Time intervals mentioned in Figures 4.4, 4.5 and 4.6 can also be expressed using this time unit; for example $T_{frame} = 307200\ T_S$, etc. The subcarrier spacing in LTE is defined to be 15 kHz, which corresponds to $f_S = 15000\ N_{FFT}$ where N_{FFT} is the FFT size. The basic time unit T_S is the sampling time for FFT size 2048.

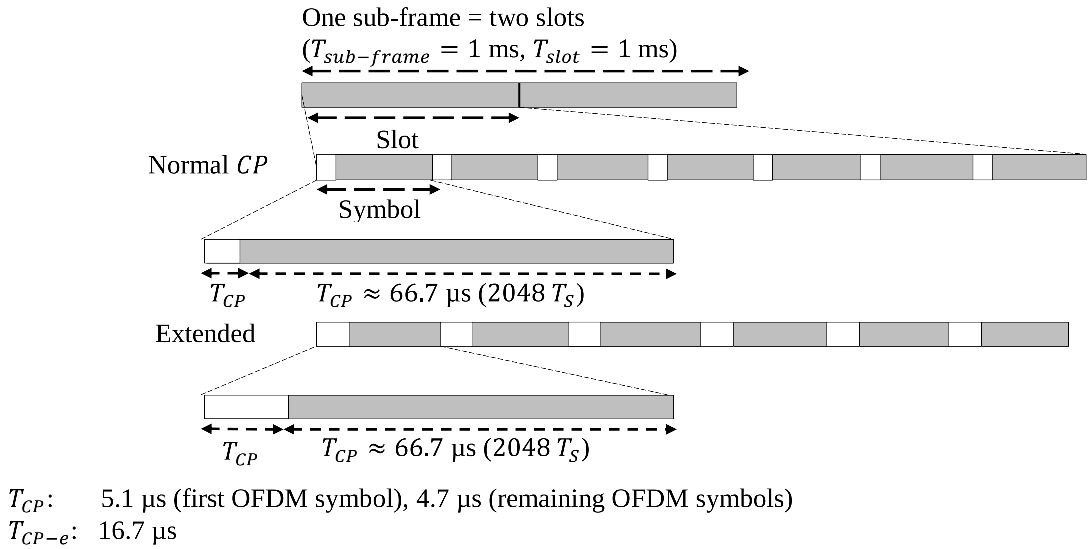


Figure 4.5 Detailed time domain structure of LTE uplink/downlink transmission [17].

More detailed view of the time domain structure of both uplink and downlink physical recourses are represented in Figure 4.5. One frame is consists of 10 sub-frames with 1 ms duration each and each sub-frame composed of two equally sized slots of 0.5 ms duration each. One OFDM slot contains 6 or 7 symbols depending on the length of the CP used to form the OFDM symbol. As illustrated in Figure 4.5, in the LTE there are two options, normal CP or extended CP. So, the symbol duration is calculated by summing the useful symbol time (1/15 kHz) = 66.7 µs) and CP.

4.3.1 Downlink Physical Resource

As it was already mentioned in Section 4.2, LTE downlink transmission is based on OFDM principle and defined by the use of time frequency grid where one resource element corresponds to one OFDM subcarrier during one OFMD symbol interval, as illustrated in Figure 4.6

The left side of Figure 4.6 shows how the subcarriers in and frequency domains grouped together to resource blocks, where one resource block comprises 12 sequential subcarriers producing a nominal bandwidth of 180 kHz. There is also a Direct Current (DC) component in the centre of the downlink band, which is not used in as it can cause to a high interference. LTE carrier can be described by channel bandwidth and number of resource blocks, the connection of which is represented in Table 4.1. And according to the LTE specifications the downlink carrier can contain any number of resource blocks ranging from 6 up to 110, consequently the channel bandwidth can range approximately form 1 MHz up to 20 MHz, providing very good bandwidth flexibility, but at least in initials specifications all radio frequency parameters are defined for the values represented in Table 4.1. If the downlink time domain is also taken into account, so a resource block consists of 12 subcarriers during 0.5 ms slot as in Figure 4.6.

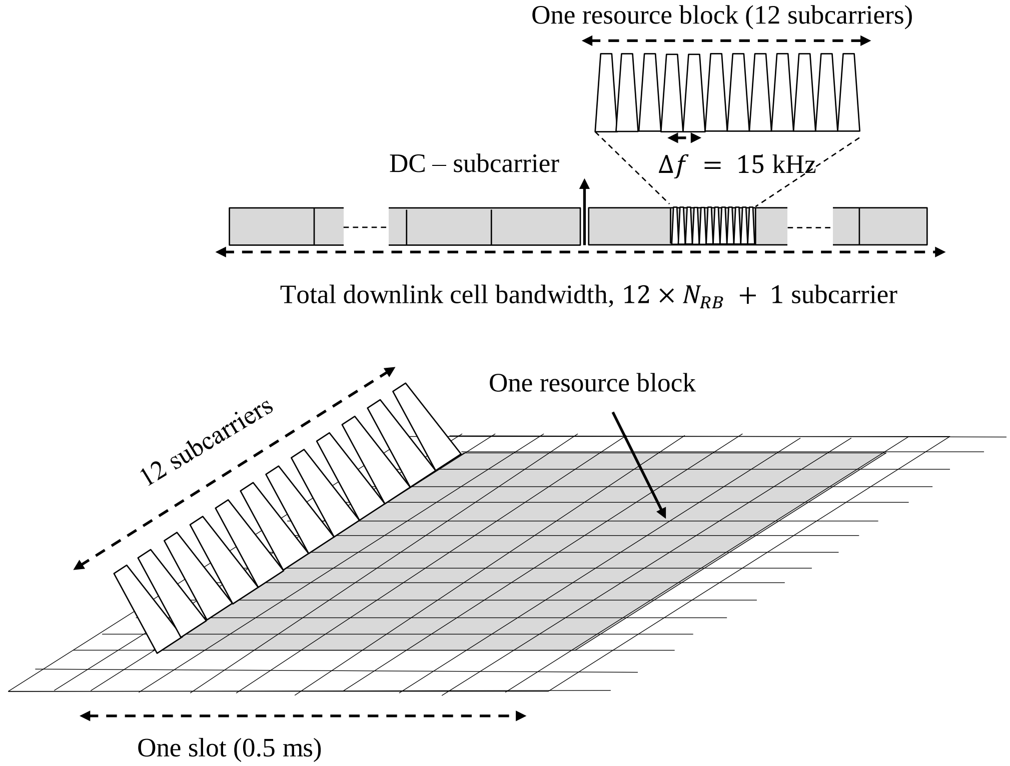


Figure 4.6 LTE downlink resource structure [17]

Table 4.1 LTE channel bandwidth for different number of resource blocks [1].

Bandwidth	1.4 MHz	3 MHz	5 MHz	10 MHz	15 MHz	20 MHz
Number of resource blocks	6	15	25	50	75	100

4.3.2 Uplink Physical Resource

Unlike downlink transmission, uplink transmission in LTE is based on so called SC-FDMA transmission method. Although, it is a SC low Peak to Average Power Ratio (PAPR) transmission scheme, it is providing orthogonality between carriers and allows flexible bandwidth allocation not only in time but also in frequency domain.

For Uplink, main transmission parameters have been taken to be, as much as possible, close to the downlink transmission. The terms and values in the detailed time domain structure are the same for both uplink and downlink as represented in Figure 4.5. In terms of the bandwidth allocation LTE physical layer specification [24] allows high degree of flexibility for uplink, as it is for downlink, but again with some limitations.

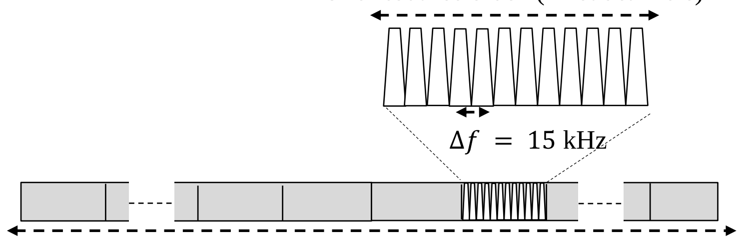


Figure 4.7 Frequency domain structure of the LTE uplink [17].

What concerns to the frequency domain structure of a resource block (Figure 4.7), it also consists of 12 sequential subcarriers with 15 kHz subcarrier spacing. But the difference in comparison with downlink is that the spectrum does not contain any unused DC subcarrier, otherwise it will not be impossible to assign the entire bandwidth to a single user.

4.3.3 Downlink Reference Signals

The channel estimation in OFDM systems could be done by inserting reference symbols, which do not carry any information bits into the OFDM frequency-time grid. Without proper channel estimation it will not be possible to do coherent demodulation of different downlink physical channels at the mobile terminal. In LTE, there are three types of reference symbols which together are called downlink reference signals:

- *Cell specific downlink reference signal* are inserted in all sub-frames to cover the whole downlink bandwidth and can be used for channel estimation and coherent demodulation. This symbols are used for all types of the downlink transmissions besides for so called non codebook based beam forming, as it is beam formed using pre-coder vector selected for a specific user.
- *UE specific reference signals* are defined especially for coherent demodulation of the Downlink Shared Channel (DL-SCH), because non codebook based beam forming is applied for that channel. This is the case when particular channel estimation is interested only by one user. Consequently the UE specific reference signal will be transmitted only inside sub-frames which also contain the blocks intended for the appropriate DL-SCH.
- *Multicast broadcast Single Frequency Network (MBSFN) reference signals* are intended only for channel estimation and coherent demodulation of the signals transmitted using MBFSN channel. MBFSN stands for Multicast Broadcast Single frequency Network and used in LTE to provide transport features for

sending the same content information to all the users in a cell, for example, to have services like mobile TV using LTE infrastructure.

4.3.4 Uplink Reference Signals

The reference signals are also required in uplink direction for the same reason as for the downlink that is channel estimation for coherent demodulation of different physical channels. For uplink there are two types of reference signals, so called uplink demodulation reference signals and sounding reference signals. The purpose of each is explained below:

- *Uplink demodulation reference signals* are used to for Physical Uplink Shared Channel (PUSCH) and Physical Uplink Control Channel coherent demodulation. The transmission of these signals is the same with some specific differences. But considerably differs from the downlink reference signal transmission [17].
- *Sounding reference signals* in comparison with uplink demodulation reference signals are used to estimate the channel quality at different frequencies, not only on the frequencies where PUSCH and Physical Uplink Control Channel PUCCH are transmitted. This kind of estimation is a good basis for the network to assign uplink resources, with instantaneously better conditions, to a user.

4.4 Multiple Antenna Support in LTE

The basic operational principles of different multi antenna techniques are described in Chapter 3. In this section, multiple antenna support for LTE is represented, which is one of the fundamental techniques included in LTE standard that significantly improves both link and system level performance in terms of peak data rates, spectral efficiency and coverage in wide range of scenarios [25]. LTE supports transmit diversity, OL-SM and CL-SM based on pre coding and contains several special cases like beam forming.

The use of the open loop or closed loop spatial multiplexing is predefined in system configurations at base station side and cannot be changed dynamically, but whether to use transmit diversity or spatial multiplexing is possible to choose dynamically based on feedbacks provided by the UE. The UE is able to provide measurement report of the channel conditions, based on reference signals transmitted in the downlink direction. The measurement report contains the following information:

- *Channel Quality Indicator (CQI)* which is used to define link adaptation parameters such as Modulation and Coding Scheme (MCS) to meet the Block Error Rate (BLER) requirements.
- *Rank Indicator (RI)* that is used to dynamically switch between transmit diversity and spatial multiplexing. It can vary from 1 to up to 4; Rank 1 means

one layer will be used, representing transmit diversity and values from 2 to 4 indicating the number of layers used in spatial multiplexing.

- *Pre-coding Matrix Indicator (PMI)*, this is used for closed loop spatial multiplexing to determine the best antenna port coding matrix from the predefined codebook.

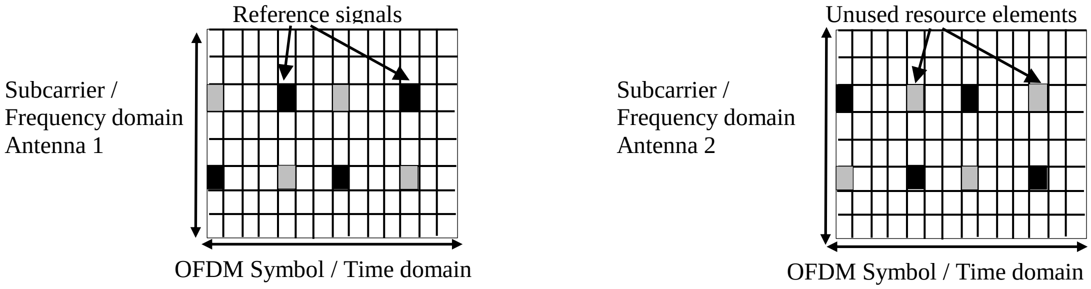


Figure 4.8 OFDMA reference symbol to support 2 transmit antennas [1].

As shortly described in Chapter 3, in spatial multiplexing multiple layers are transmitted using different antennas in parallel to each other and by which providing higher data rates for the given bandwidth. In LTE the number of layers (N_L) can be changed according to RI report and can have values up to a maximum number of antenna ports number (N_A).

LTE release 8 supports up to 4 transmitter antennas at base station side and 2 receiver and 1 transmitter antennas at UE side. Consequently there in no special multiplexing specification for uplink, only transmit diversity. But spatial multiplexing is utilized in uplink in for of Multi-User MIMO [26], where by allocating orthogonal reference signals to two different devices it is possible to double cell throughput in uplink, but not the throughput of an individual user.

The transmissions from different antennas are possible to be distinguished from each other at receiver side by the use of different reference symbols. It is possible map them in way that if a resource element carrying a reference symbol for a certain antenna port nothing is transmitted on the other antenna ports, as represented in Figure 4.8.

4.4.1 Transmit Diversity

In LTE the exact method used for transmit diversity depends on the number of the antenna ports. In case of two antenna ports transmit diversity is based on Space Frequency block Coding (SFBC) and in case of four antenna ports the transmit diversity is based on a combination of the two methods, the above mentioned SFBC and so called Frequency Shift Transmit Diversity (FSTD) [17]. Different methods of transmit diversity are shortly described in Chapter 3.

So, when the number of antenna ports is equal to two, according to SFBC principle, as illustrated in Figure 4.9, on the first antenna port two sequential symbols S_i and S_{i+1} are transmitted on neighbouring subcarriers and swapped and transformed symbols $-S_{i+1}^{*}$and S_i^* are mapped on the same subcarriers on the second antenna port.

And, when the number of antennas is four, as demonstrated in Figure 4.10, according to combined SFBC/FSTD principle, two consecutive symbols are mapped between pairs of antenna port 0 and 2 and antenna port 1 and 3 using SFBC principle. According to FSTD method, the subcarriers used in one antenna pair are not utilized for the other pair of antenna. At the receiver side, symbols going out from FFT operation should be re-organized in accordance with SFBC encoding done at the transmitter.

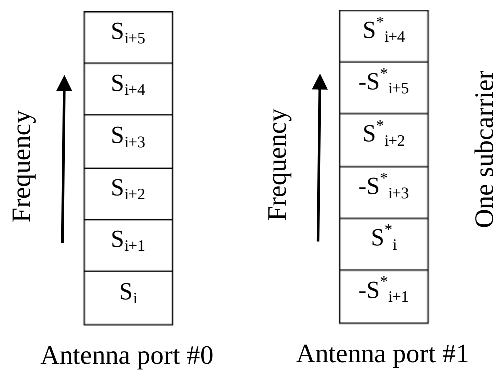


Figure 4.9 Two antenna port transmit diversity-SFBC [17]

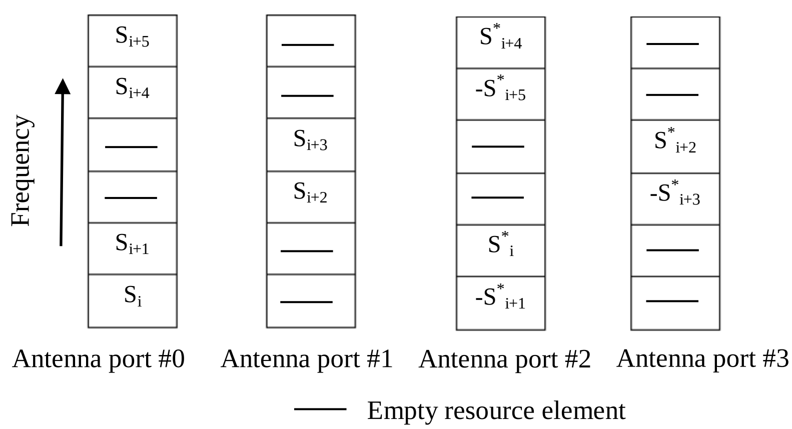


Figure 4.10 Four antenna port diversity - SFBC/FSTD [17].

4.4.2 Closed Loop Spatial Multiplexing

As it was mentioned above, in LTE there are two types of SM, OL-SM and CL-SM, where the main principle difference is that CL-SM operates using feedback from the mobile terminal in form of suggested PMI. The Basic operational principle of the CL-SM is represented in Figure 4.11. The number of codewords in the input depends on the number of transport blocks coming from higher layers and can be on or two. In case of one layer there could only one code-word, in case of two or more layers the number of codewords is always two [17]. Mapping of the symbol is done such a way that the number of symbols is always equal for all layers independent of the number of layers (N_L). This mean, that if $N_L = 3$, one of the codewords is twice bigger than the other one.

The next step after layer mapping is the antenna port mapping which is done by linearly combining and mapping one symbol per layer into one antenna port. This operation is done by using pre-coder matrix W of size $N_A \times N_L$. When $N_L = 1$, W is a vector of size $N_A \times 1$. This is a spatial case, when single symbol is mapped into N_A antenna port providing beam-forming, also known as codebook bases beam-forming, that is why, beam-forming is a spatial case of CL-SM.

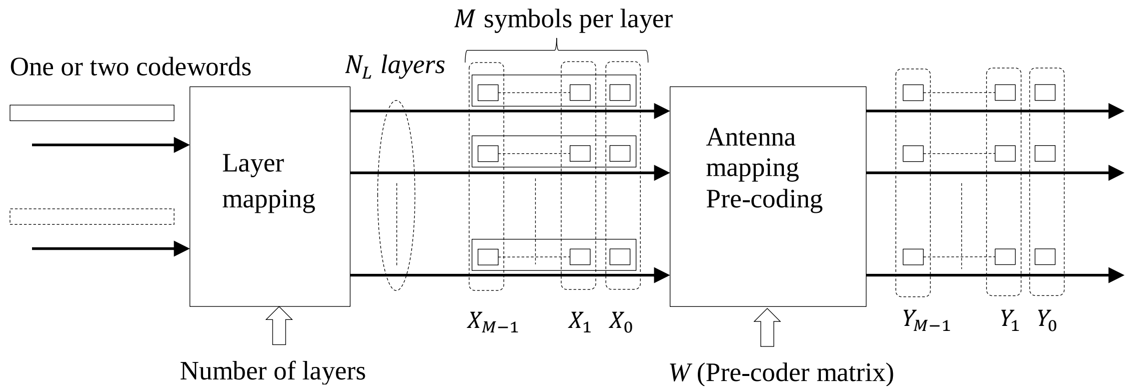


Figure 4.11 Basic structure of LTE closed-loop spatial multiplexing [17].

Pre-coding matrices are different for two and four antenna port transmissions. In case of two antenna port the pre-coding matrices are of size 2×1 and 2×2, but in case of four antenna ports, the size of matrices are 4×1, 4×2, 4×3 and 4×4 according to different number of layers. The matrix for two port antenna case is represented in Table 4.2.

Table 4.2 LTE pre-coder matrices W in case of two antenna ports [4].

One layer	$\frac{1}{\sqrt{2}}\begin{pmatrix}+1\\+1\end{pmatrix}$	$\frac{1}{\sqrt{2}}\begin{pmatrix}+1\\-1\end{pmatrix}$	$\frac{1}{\sqrt{2}}\begin{pmatrix}+1\\+j\end{pmatrix}$	$\frac{1}{\sqrt{2}}\begin{pmatrix}+1\\-j\end{pmatrix}$
Two layer	$\frac{1}{2}\begin{pmatrix}+1 & +1\\+1 & -1\end{pmatrix}$	$\frac{1}{2}\begin{pmatrix}+1 & +1\\+j & -j\end{pmatrix}$		

As it was mentioned previously, CL-SM uses PMI feedback reports from the mobile terminal to choose an appropriate pre-coding matrix from the codebook and the RI to determine the number of layers corresponding to the estimated downlink channel conditions. The system may not follow to the mobile terminal suggestions but in that case it should inform to the user about used pre-coder matrix for each downlink transmissions.

4.4.3 Open Loop Spatial Multiplexing

In LTE OL-SM technique is designed for high mobility or limited feedback capability. In contrast to CL-SM, OL-SM doesn't use PMI feedback reports and thus doesn't inform to the mobile terminal about pre-coder matrix used in downlink transmission. Consequently, it is also very convenient when CL-SM overhead is not suitable. OL-SM is also known as large-delay CDD, but large delay CDD is valid only for two or more number of layers, otherwise OL-SM operates as transmit diversity using SFBC and combined SFBC/FSTD principles. That is why the RI and CQI feedback reports still utilized by the OL-SM to be able to dynamically switch between SM and transmit diversity.

The Basic operational principle of the large-delay CDD is represented in Figure 4.12. The pre-coding matrix is a combination of two pre-coder matrices, a matrix P of size $N_L \times N_L$ and a matrix W of size $N_A \times N_L$.

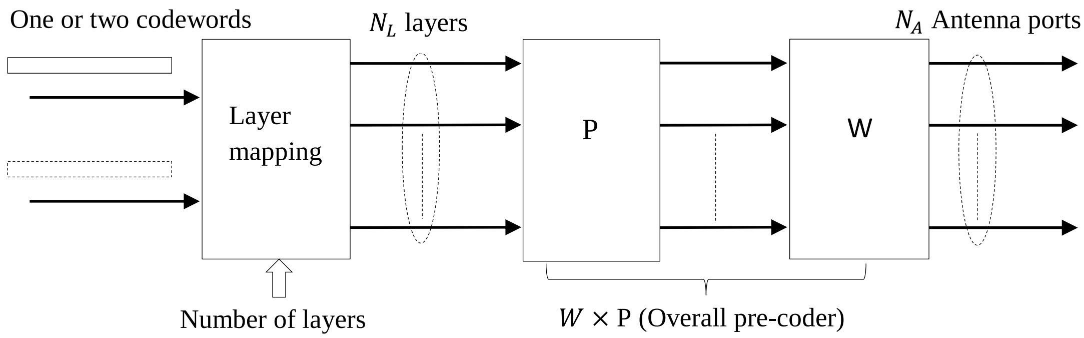


Figure 4.12 Open-Loop Spatial Multiplexing, large-delay CDD [17].

When the number of antenna ports is equal to two, the pre-coder matrix W is always the same and equal to the first matrix of the pre-coder represented in Table 4.2 with size 2×2. In case of four antenna ports the matrix W is cycling all the time, for sequential transmissions, through 4 predefined $4 \times N_L$matrices. What concerns to the pre-coder matrix P, it is the CDD part of the OL-SM and used to average channel condition differences.

4.4.4 Transmission Modes in 3GPP LTE Release 8

In LTE, data is mapped to transmitted layers, after being modulated and encoded. As it was already mentioned in above sections, LTE Release 8 allows up to four layers [25] to be transmitted in downlink and because wireless channel conditions and mobile terminal capabilities can vary dramatically, the multiple antenna system should be very flexible to increase gains in throughput. That is why it is important to understand different transmission modes specified in LTE and the conditions when they most useful. In LTE Release 8, up to four layers are pre-coded and mapped into antenna ports using one of the 7 transmission modes represented in Table 4.3 [27]. These 7 modes are designed to take into consideration different channel conditions, base station antenna configurations and mobile terminal capabilities.

Table 4.3 Transmission modes used in LTE Release 8.

Transmission Mode	Description
1	Single antenna port, port 0
2	Transmit diversity
3	Open-loop spatial multiplexing
4	Closed-loop spatial multiplexing
5	Multiuser MIMO
6	Closed-loop single layer pre-coding
7	Single antenna port, port 5

From the UE point of view, transmission modes 1 and 7 are the same, as in both cases just one layer is transmitted. The difference is that in mode 1, that single layer is always mapped into one antenna port, whereas in mode 7 in one layer can be mapped into more than one antenna port.

Transmission mode 2 is the transmit diversity mode, where SFBC principle is used to encode single layer into multiple antenna ports.

In mode 3, when the rank is more than one, OL-SM is implemented, by utilizing large-delay CDD principle that is a predefined pre recoding matrices cycling through the entire frequency band, at the same time, trying to average channel conditions for each layer. And when the rank is one, the mode 3 is exactly the same as mode two. For both mode 2 and 3, there is no need for PMI feedback in addition to RI feedback (number of layers), which means that these modes are more suitable for high mobility and feedback limited situations as well as when signalling overhead need to be reduced.

Transmission mode 4 is CL-SM, where the available layers are encoded and mapped to the antenna ports using predefined codebook based pre-coder matrices which are selected from that codebook according to the PMI reports received from the mobile terminal. This is done to maximize performance by pre-coding layer in accordance with instantaneous channel conditions.

The mode 5 is so called multiuser MIMO which allows implementation of SM in uplink direction, by receiving single layer transmitted from several mobiles with shared frequency resources, as different MIMO branches at the base station side

And finally the mode 6 is the same as mode 4 but restricted to rank one.

4.5 LTE User Equipment Measurements

Radio quality measurements implemented by UE in LTE Release 8 are specified in [28]. These specifications contain information also about network measurements that are considered as optional, as there is no regulation to be sure that vendors will implement those. Besides, there is no specification about bin size of the network measurements in 3GPP. There many parameters used to evaluate radio link quality and system performance but only a couple of them that are used in this study are represented in this section.

4.5.1 Reference Signal Received Power (RSRP)

RSRP is main measure of the LTE cell coverage and used to determine best cell for downlink direction and select it as serving cell for either initial access or cell-reselection procedure. RSRP measurement is reported by the UE in binned form and the reporting rage is defined to be from -140 dBm to -44 dBm. RSRP is defined as the linear average over the power contributions (in watts) of the resource elements that carry cell-specific reference signals within the considered measurement frequency bandwidth [28], [29].

4.5.2 Reference Signal Received Quality (RSRQ)

RSRQ is another measure of the radio link quality that is used to determine the best cell in initial cell selection and handover processes. In contrast to RSRP, RSRQ is not the absolute strength of the reference signal; it is actually signal to noise and interference ratio. RSRQ is defined as the ratio N RSRP / (Evolved Universal Terrestrial Radio Access (E-UTRA) carrier Received Signal Strength Indicator (RSSI)), where N is the number of RB's of the E-UTRA carrier RSSI measurement bandwidth. The measurements in the numerator and denominator shall be made over the same set of resource blocks [29]. Where RSSI, comprises the linear average of the total received power (in watts) observed only in OFDM. The reporting range of RSRQ is defined to be from -19.5 dB to -3 dB with 0.5 dB resolution [28]. The comparison of RSRP and RSRQ, for the same time intervals, could be used to determine whether there is a coverage or interference problem in particular location. Figure 4.13 represents the comparison of RSRQ and RSRP for both interference and coverage problem cases.

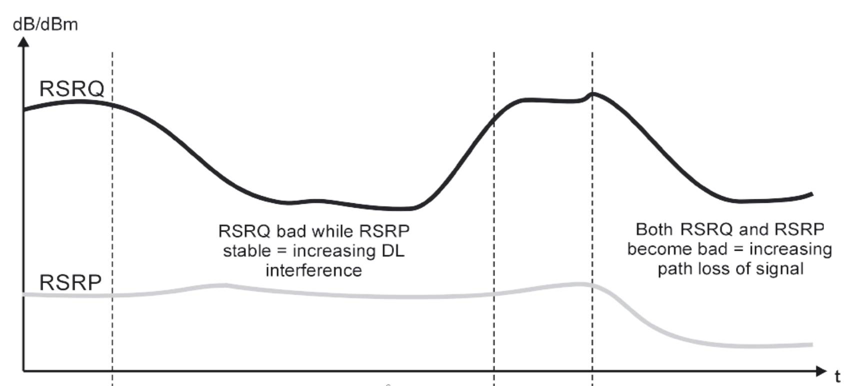


Figure 4.13 LTE coverage and interference problem [30].

If RSRP stay stable, while RSRQ is going down, this is a clear indication of interference rise. If both of them are going down at the same time, this is an area with bad coverage.

4.5.3 System Performance Parameters

Figure 4.14 represents basic performance indicator that can be used to evaluate system performance from user point of view. Table 4.4 contains explanations for the terms in Figure 4.14.

Table 4.4 Definition of data rates for downlink performance [17].

Term	**Definition**
Radio interface data rate	Data rate of the physical layer
Peak data rate	Maximum value of Radio interface data rate
User throughput	Data rate experienced above Mac layer
System throughput	Radio interface data rates per sector
Latency	End-to-end round trip time of a packet

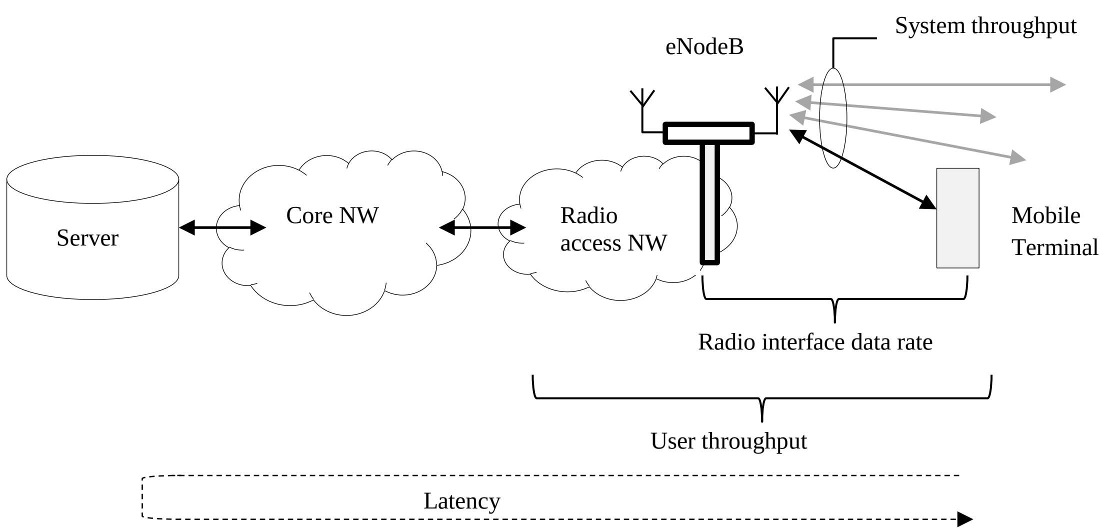


Figure 4.14 Definition of data rates for downlink performance [17].

5 MEASUREMENT PLAN

The lack of practical studies of different spatial multiplexing transmission modes available for LTE Release 8 makes this problem interesting to study. The main purpose of this study is to represent evaluation of the practical performance of these modes by means of achievable throughput and MIMO utilization. These parameters are chosen to be analysed as changes in other parameters are directly seen on them.

The main targets of the measurements is to

- Compere available capacities of different MIMO transmission modes for LTE networks in different environments.
- Determine planning thresholds for MIMO utilization in form of SNR.
- Determine efficiency of each mode for different environments.

To achieve the above mentioned goals and to be able to implement fair comparison of the results, the measurements have been conducted for different environments and channel conditions.

5.1 Measurement System, Tools and Methods

5.1.1 LTE Measurement System and Environment

The measurement campaign is carried out in both indoor and outdoor-micro environments. The reason of doing measurements in both indoor and micro is coming from the fact that propagation of the radio waves are different in different environments and characteristics used to define different environments has different values, as described in Chapter 2. Consequently, the network parameters, for example in our case the available transmission modes in LTE, which are optimal for certain type of the environment are not necessarily the optimal ones for another type of environment. Both indoor and micro measurements are implemented at the TUT campus area; the indoor measurements are done in second floor of the Tietotalo building and outdoor measurements are done around the Sahkotalo and Tietotalo buildings.

For both indoor and micro measurements, TUT LTE Release 8 test bed is used. The base station equipment is Flexi base station platform by Nokia Siemens Networks (NSN). The test bed consists of one system unit located in room TC225 and connected to the core network by Gigabit Ethernet cable. There are 6 cells connected to the system unit, four outdoor (3 micro, 1 macro) and two indoor cells. For indoor measurements only one indoor cell is used, the antenna line of which consists of X-pol antenna connected to the system unit via 10 m coaxial cable. For micro measurements, only one outdoor-micro cell is used. The antenna connected to the Remote Radio Head (RRH) by ½ inch jumper, the

RRH in its turn connected to the system unit via optical cable. The position of the above mentioned components and also measurement routes are represented in Figure 5.5.

The software version of the TUT LTE test bed, at the moment of the measurements, was the latest one, which support all the futures of the LTE Release 8. Most important system configurations of the LTE test bed are represented in Table 5.1.

Table 5.1 System configuration.

3GPP Release 8 NSN Flexi LTE BTS	**TUT LTE test bed**
Carrier Frequency	Band 1 / 2.1 GHz
System Bandwidth	10 MHz
Transmission Power	8 Watts
LTE duplex mode	FDD
Link Adaptation	OL-S ,OL-D, CL
Number of Antennas	eNB: 2 UE: 2
Antenna Polarization	X-pol

For both indoor and outdoor measurements X-pol multiband directional antenna are used, represented in Figure 5.1.

5.1.2 Measurement Equipment

Equipment used in the measurements consists of one laptop, a data card connected to it to do measurements and Nemo Outdoor, Nemo Analyze software, version 6.3, to collect and analyse the measurements. More detailed information is summarized in Table 5.2.

Table 5.2 Measurement equipment.

Measurement Tools	Type	Number of Items	Provider
Laptop	T 161 series, Win7	1	IBM Lenovo
Data card	Category 3 GSM/EDGE/HSPA+/LTE USB modem, frequency 1.8 GHz, 2.1GHz, 2.6 GHz Speed 100/50 Mbps	1	Data card: Huawei E398 Chipset: Qualcomm MDM9200TM
Measurement Software	Nemo Outdoor 6.3 Nemo Analyze 6.3	1	Anite Ltd.

The Nemo Outdoor is able to record all the information flow between UE and base station, including radio link performance parameters, UE reports, signalling and data traffic. It is able to decode the recorded data and provide all necessary information with the help of illustrative graphs, charts and tables. If more detailed analyses are required to do, all the recorded data can be exported into the Excel sheets. During this study, Excel 2012 and Matlab R2010b software also have been used along with Nemo Analyze for post processing of the measured data.

General specifications:

Frequency range	1710–2170 MHz (broadband)
Impedance	50 ohms
VSWR	< 1.4:1
Intermodulation (2x20w)	IM3: -150 dBc
Polarization	+45° and -45°
Maximum input power	150 watts per input (at 50°C)
Connector	2 x 7/16 DIN female
Cross polar ratio Main direction 0° Sector ±60°	 25 dB (typical) >10 dB
Isolation	>30 dB
Weight	3.3 lb (1.5 kg)
Dimensions	6.1 x 6.1 x 2.7 inches (155 x 155 x 69 mm)
Equivalent flat plate area	0.39 ft² (0.036 m²)
Wind survival rating*	120 mph (200 kph)
Shipping dimensions	10.1 x 6.8 x 3.6 inches (257 x 172 x 92 mm)
Shipping weight	4.4 lb (2 kg)
Mounting	Fixed mount options are available for 1.2 to 5.3 inch (30 to 135 mm) OD masts.

See reverse for order information.

Specifications:	**1710–1880 MHz**	**1850–1990 MHz**	**1920–2170 MHz**
Gain	8.5 dBi	8.6 dBi	8.7 dBi
Front-to-back ratio	>25 dB (co-polar)	>30 dB (co-polar)	>30 dB (co-polar)
+45° and -45° polarization horizontal beamwidth	70° (half-power)	68° (half-power)	65° (half-power)
+45° and -45° polarization vertical beamwidth	65° (half-power)	65° (half-power)	63° (half-power)

a) Indoor antenna

XPol Panel 1710–2170 90° 11.5dBi

Type No.	741984V01		
		1710–2170	
Frequency range	1710 – 1880 MHz	1850 – 1990 MHz	1920 – 2170 MHz
Polarization	+45°, –45°	+45°, –45°	+45°, –45°
Gain	2 x 11.3 dBi	2 x 11.5 dBi	2 x 11.6 dBi
Horizontal Pattern:			
Half-power beam width	86°	87°	88°
Front-to-back ratio (180°±30°)	Copolar: > 23 dB Total power: > 23 dB	Copolar: > 23 dB Total power: > 23 dB	Copolar: > 23 dB Total power: > 23 dB
Cross polar ratio Maindirection 0° Sector ±60°	Typically: 20 dB > 18 dB	Typically: 25 dB > 18 dB	Typically: 20 dB > 15 dB
Tracking, Avg.	0.5 dB		
Squint	±3.0°		
Vertical Pattern:			
Half-power beam width	28°	26°	26°
Sidelobe supression vertical sector ±45°	> 20 dB	> 20 dB	> 20 dB
Impedance	50 Ω		
VSWR	< 1.4		
Isolation, between ports	> 30 dB		
Intermodulation IM3	< –150 dBc (2 x 43 dBm carrier)		
Max. power per input	150 W (at 50 °C ambient temperature)		

b) Micro antenna

Figure 5.1 Antenna Specifications a) Indoor b) Micro.

For the measurements, Huawei E398 LTE USB modem have been used that is intended for commercial use and based on Qualcomm MDM9200TM chipset which provides triple-mode modem capabilities. The UE is able to operate in 1.8 GHz, 2.1GHz and 2.6 GHz LTE frequencies. The TUT LTE test bed operates at LTE band 1, 2.1 GHz. This data card is based on LTE UE category 3 specifications. The pictures of the data card are represented in Figure 5.2.

Huawei E398

Figure 5.2 Huawei E398 LTE USB modem used in measurements.

5.1.3 Measurement Methods

The main parameters that are used in all analyses are user Application Layer Throughput (APP TP) that is the throughput a user experiences above application protocol and MIMO utilization, which expressed in the form of the rank 1 and rank 2 requested and distributed percentages.

APP TP does not contain all the overhead caused by the Radio Link Control (RLC), Medium Access Control (MAC) and physical layers and represents the real throughput that the end user is experienced. Besides, APP TP is used for analyses, because it does not contain the considerably lower MAC layer TP which was recorded during the signalling between UE and base station to establish data communication and does not contain any user data information. UE does LTE data transfer in downlink direction by the use of Hypertext Transfer Protocol (HTTP) to download the same file from a local server. APP TP is averaged per each $500 \times TTI$ (Transmit Time Interval), where $1 \times TTI = 1\,ms$.

To be sure on the fairness of the comparisons and to provide more detailed information for analyses, some link performance related parameter like RSRP, SNR and UE reported parameters like RI and CQI are also used.

The TUT LTE system was empty from any other users and was operating in the LTE band 1 allocated for research purposes and not used in commercial networks at the same area as the Tampere University of Technology is located. This is done to minimize the possible interference sources that could affect the measurement results. Besides, the measurement have been done in evening do reduce the variation of the channel caused by the movement of the people.

Anyway, there are still some variations of the wireless channel caused by the people activities inside building or by vehicle movements outside buildings. To further minimize those variations the measurements have been repeated many times to find out almost identical channel conditions for different measurements.

To have fair comparison of the results, different test cases have been done by keeping the same measurement routes, locations and measurement device configurations. The measurement routes are chosen such to cover different channel conditions to be able to do reasonable conclusions. The indoor and micro pedestrian measurements have been done with slow, approximately 2-3 km/h speed, by moving table with laptop on it as shown in Figure 5.3.

Figure 5.3 Measurement devices setup.

5.2 Measurement Setup

The measurements campaign is carried out in both indoor and micro environments. In measurement plan there are two scenarios, indoor environment and micro environment, and in both scenarios there are three test cases. Each of them is corresponding to one transmission mode available to test in used LTE eNodeB.

Indoor and Micro propagation scenarios

- CL-SM
- OL-S-SM
- OL-D-SM

The main outcomes of both scenarios are performance evaluation for OL-S-SM, OL-D-SM and CL-SM in LTE indoor and micro environments and possible planning recommendations for LTE indoor and outdoor networks in terms of MIMO utilization.

5.2.1 Indoor Scenario

The measurements in this scenario are carried out in second floor of the Tietotalo building at TUT campus. The measurements combine two route measurements. The antenna configuration and place were kept unchanged for both measurement routes and test cases.

So the Indoor Scenario has one measurement setup; a X-pol directional multi-band antenna, described above, is connected to system unit via 10m coaxial cables, and there are 20 dB attenuator at the antenna ports to reduce the transmit power. This is done, to be sure that the measurement results are accurate, as the used data card is not able to measure accurately the radio link performance parameters such RSRP or SNR for very high received signal levels. The setup configuration of the whole system is represented in Figure 5.4 and the setup configuration for the Indoor Scenario is represented in Figure 5.5.

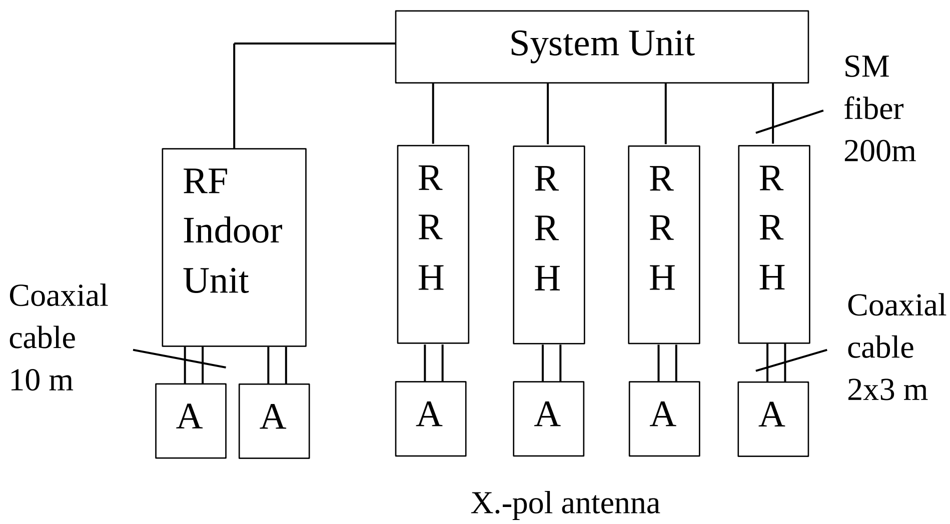


Figure 5.4 Setup configurations of the system.

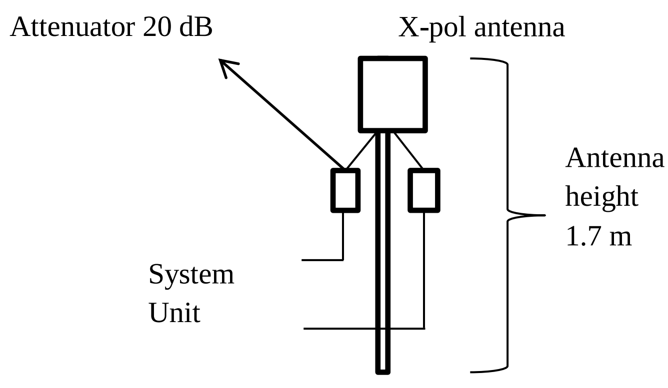


Figure 5.5 Setup configuration for the Indoor Scenario.

In this setup, in all measurements differently polarized antennas are connected to each MIMO branch, so there is no need to define antenna separation.

The both measurement routes are chosen such to cover different signal conditions, from good to very bad, which are experienced near cell edge. This will allow to see the whole dynamics of the different transmission modes and to find out the thresholds for MIMO utilizations. The antenna location, for booth measurement routes are represented Figure 5.6. This is the Tietotalo building layout of the second floor. Measurements done in different routes will help to show that the results are following the same pattern, independent of the measurement route.

In Indoor Scenario, all measurements are done only for downlink direction, and the Cumulative Distribution Function (CDF) plot of the downlink APP TP values and the MIMO utilization are used (in form of rank 2 percentage) over every $500 \times TTI$. This is used to determine the available capacity and to evaluate the performance efficiency of each test case. RSRP and SNR are used to be sure that the channel conditions are identical for all test cases, so any change in the APP TP or MIMO utilization are associated only with the change of transmission mode. Besides, MIMO utilization and SNR are used to determine the SNR threshold that defines the MIMO utilization border.

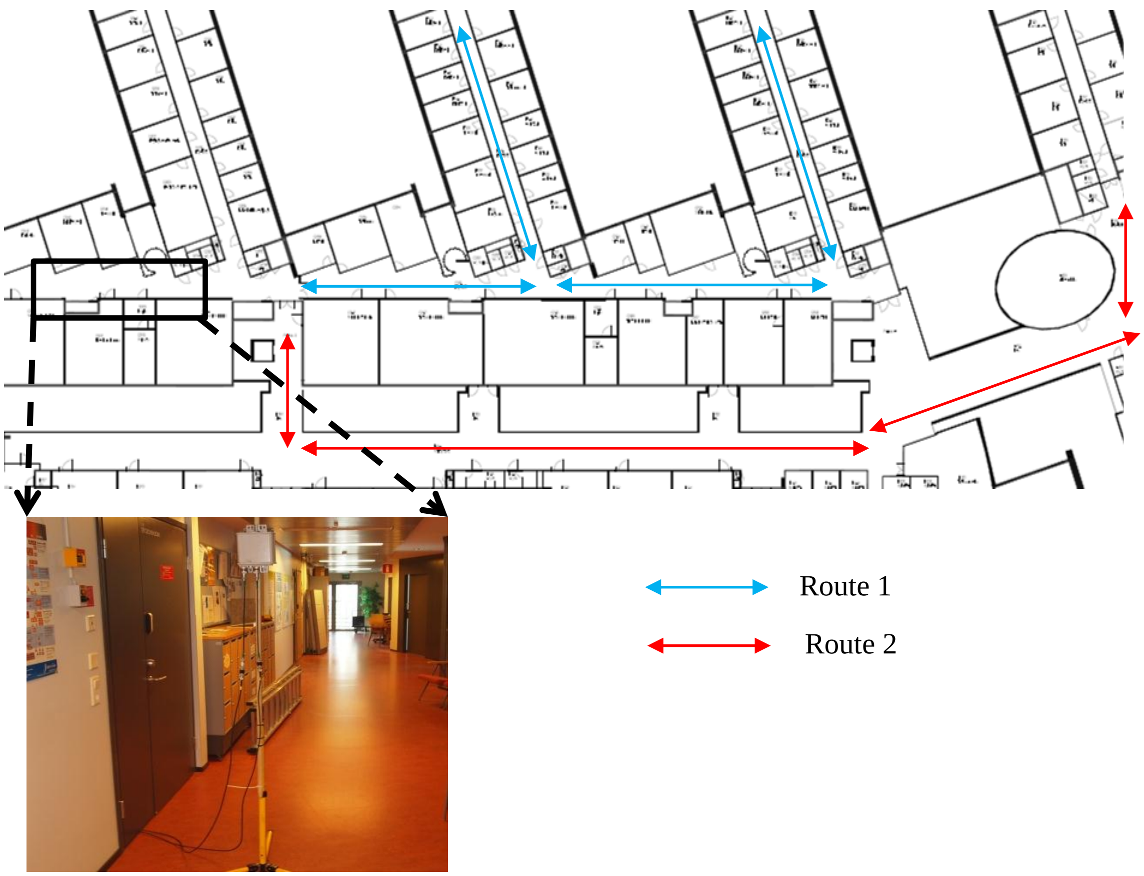


Figure 5.6 Measurement route and location for Indoor Scenario

5.2.2 Micro Scenario

The measurements in this scenario are carried out in TUT campus area, by waking around Tietotalo and Sähkötalo buildings. The measurements combine one route measurement. The antenna configuration and place were kept unchanged for all measurement test cases.

So the Micro Scenario has one measurement setup. One X-pol directional multi-band antenna, described above, is connected to the system unit via optical cables and located on the outer wall of the Tietotalo building, on height 7 m, which faced to the Sähkötalo building. The measurement setup is represented in Figure 5.4.

There is no static measurement location in this scenario, only a route measurement is conducted to cover different channel conditions. The measurement route and antenna locations are represented in Figure 5.7.

In Micro Scenario, similarly to the Indoor one, all measurements are done only for downlink direction, and the CDF plot and average values of the downlink APP TP and the MIMO utilization are used, to determine the available capacity and to evaluate the performance efficiency of each test case. In addition, RSRP and SNR are used to be sure that the channel conditions are identical for all test cases, so any change in the APP TP or MIMO utilization are associated only by the change of transmission mode. Besides, MIMO utilization and SNR are used to determine the SNR threshold that defines the MIMO utilization border. This can help to operators in planning process of the LTE network, to provide necessary SNR in certain locations to provide optimal performance for their networks.

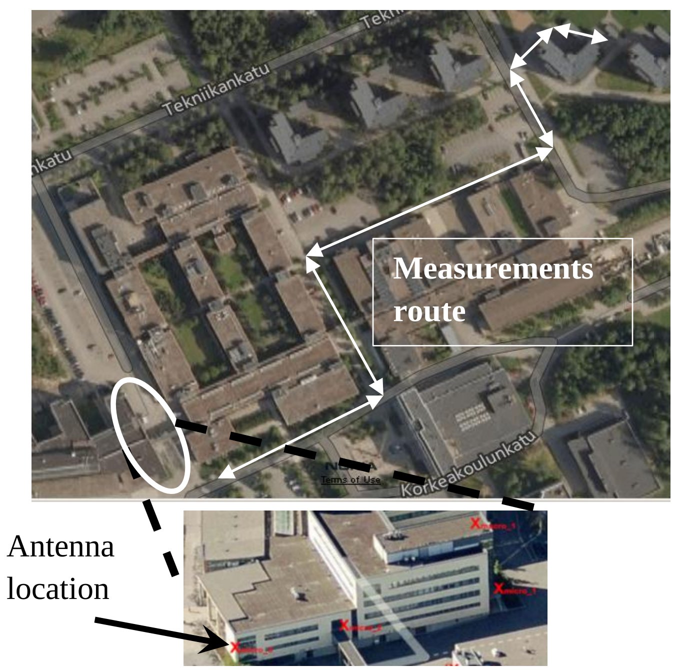


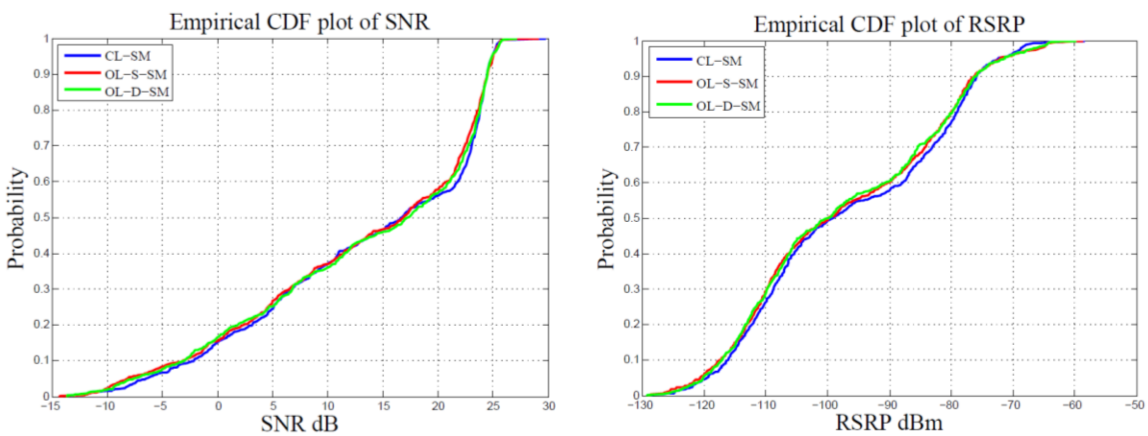
Figure 5.7 Measurement route for the Micro Scenario.

5.3 Measurement Results

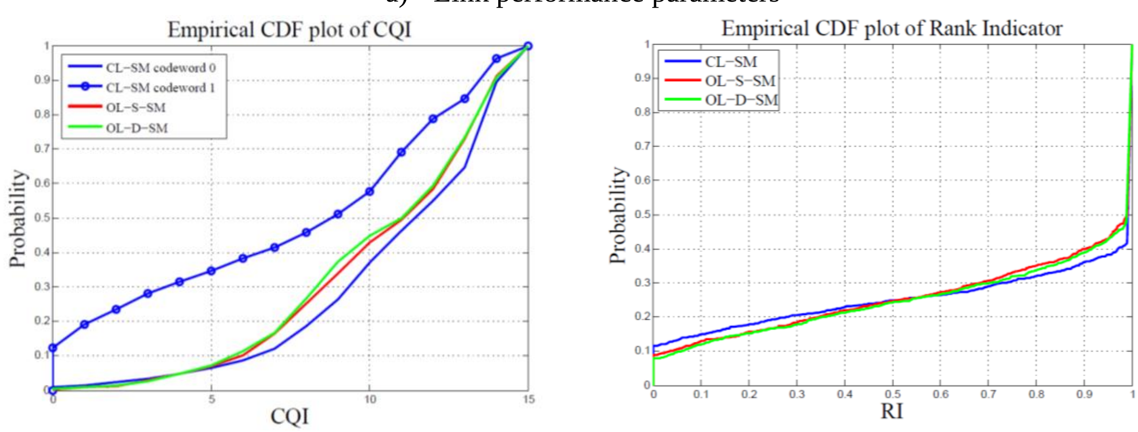
The first target of the measurement campaign is to compere the available capacities for different LTE transmission modes for particular system configuration in both indoor and micro environments. This information will help to understand which one is the better one from provided throughput point of view. The second target is to analyse the MIMO utilization for different modes, along with APP TP, to be able to show the measured SNR threshold when the system switches from MIMO to MISO. Additionally it will be also possible to show the comparison of SM and transmit diversity for bad channel conditions.

5.3.1 Comparison of Available Capacity for Different Transmission Modes

To be able to provide fair comparisons and analyses of the obtained APP TP values for each test case, the channel conditions should be as close to each other as possible. For this purpose we used the channel condition related parameters SNR and RSRP, and mobile reports RI and CQI, which are represented in Figure 5.8 and 5.9 for Indoor and Micro scenarios accordingly.

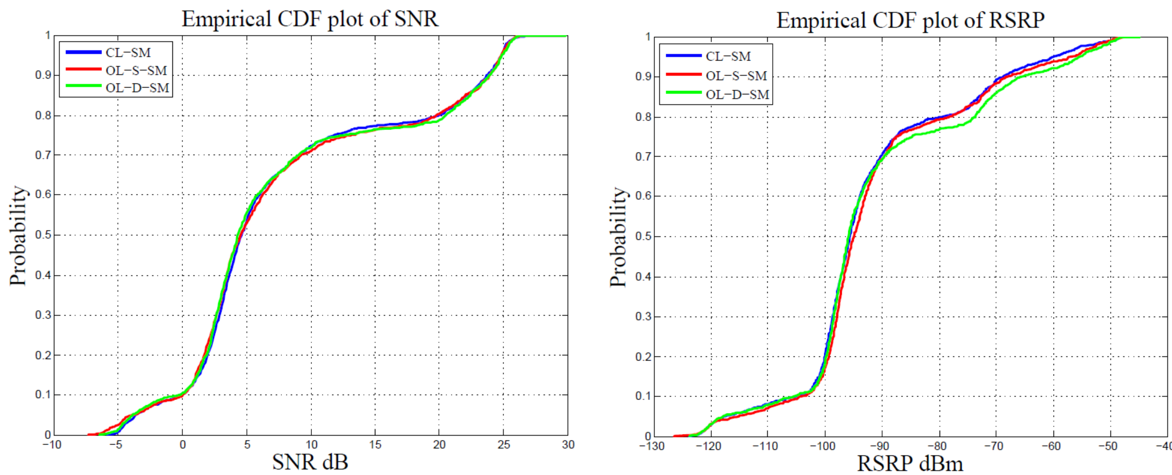


a) Link performance parameters

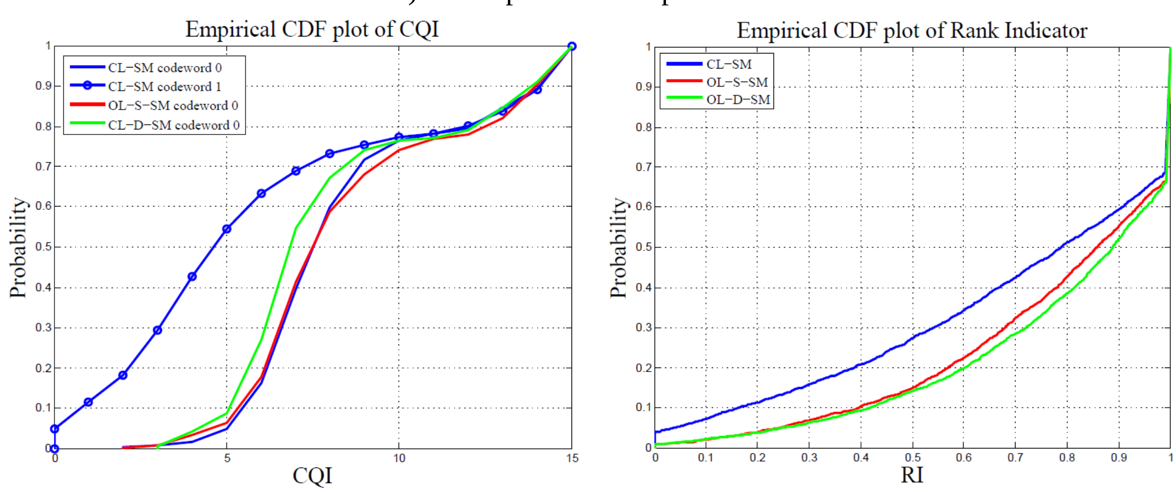


b) Mobile reports

Figure 5.8 Channel condition comparisons for Indoor Scenario in route 1.



a) Link performance parameters

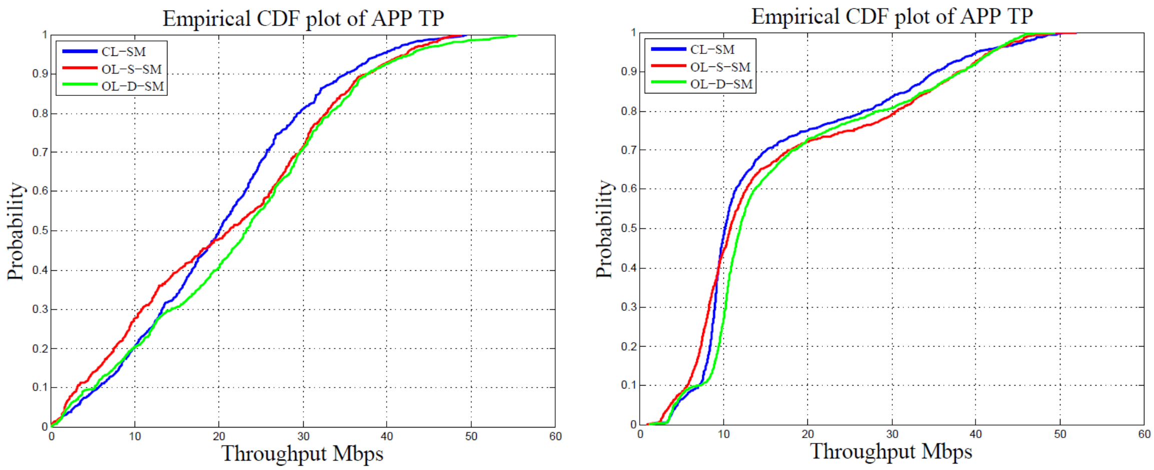


b) Mobile reports

Figure 5.9 Channel condition comparisons for Micro Scenario.

For simplicity, in all further representations and analyses, only the results of the route 1 will be considered for Indoor Scenario, as the dynamics of all parameters are similar in both routes. The reason to have several routes was to be sure that the observed phenomenas are similar independent of the measurements routes. But anyway, the measurement results of the route 2 are represented in the Appendix A.

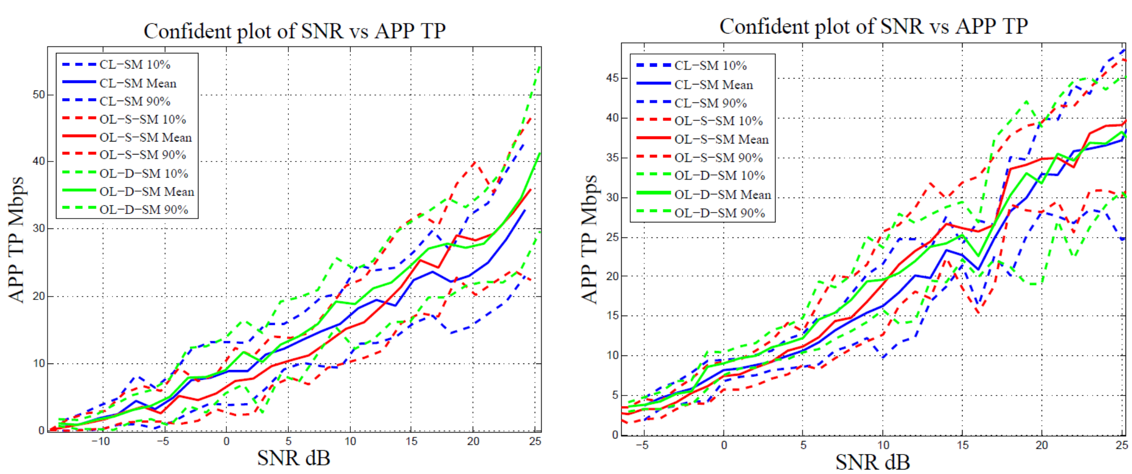
So, for both Indoor and Micro Scenarios the channel conditions are almost the same for all test cases, as represented in Figure 5.8 and 5.9. This means, that we can go to the capacity comparisons being sure that all the changes in APP TP is coming from the transmission mode change. From Figure 5.10, which represents the empirical CDF plots of the achieved APP TP in both indoor and Micro, it is clear that in different channel conditions the behaviour of each mode is different.



a) Indoor b) Micro

Figure 5.10 Empirical CDF plot of the APP TP a) Indoor Scenario b) Micro Scenario.

For more detailed comparison, the confident plot of SNR vs. APP TP is represented in Figure 5.11. Now, by using SNR we can make comparisons of the modes according to different channel conditions. The results represented in Figure 5.11 are obtained by analysing the measurements of the route 1 in indoor and the micro route using Matlab software. Having this knowledge, it is possible to compare very easily the performance of each mode in different channel conditions.



a) Indoor b) Micro

Figure 5.11 Confident plot of SNR vs. APP TP a) Indoor Scenario b) Micro Scenario.

So, from Figure 5.11, we can see that the overall behaviour of different modes is similar for both indoor and micro. For both indoor and micro measurements, they provide similar throughputs when the SNR is higher than 20 dB, this is corresponds to very good channel conditions. Then for SNR < 20 dB, the performance of the CL-SM starts to degrade. What concern to OL-S-SM, the performance degrades for SNR < 15 dB for indoor and SNR < 10 dB for micro. And finally, for SNR below -5 dB, the performance of all three modes is again the same. These kinds of SNR values are possible in cell edge region. So, near the antenna and at cell edge all modes behave similarly.

And finally, Figure 5.12 and Table 5.3 represent the average APP TP values over the all measurement route for both route 1 and route 2 in the Indoor Scenario and for route in the Micro Scenario. The results, one more time, confirm that the dynamics of different modes in different channel conditions are independent of the chosen route.

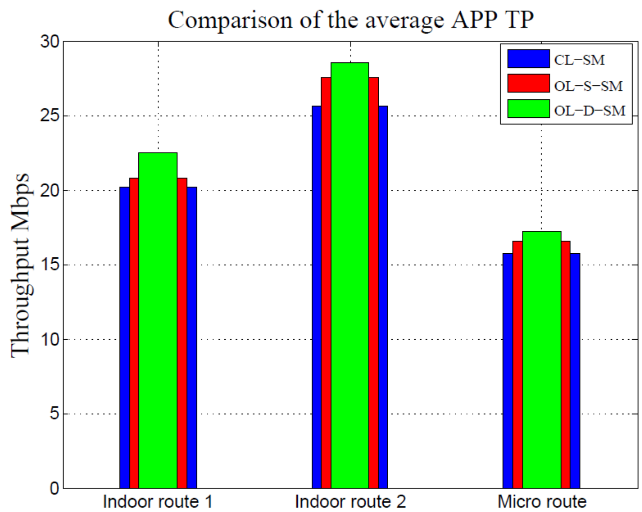


Figure 5.12 Average APP TP for each test case in each route.

Table 5.3 Average TP for each test case in each route.

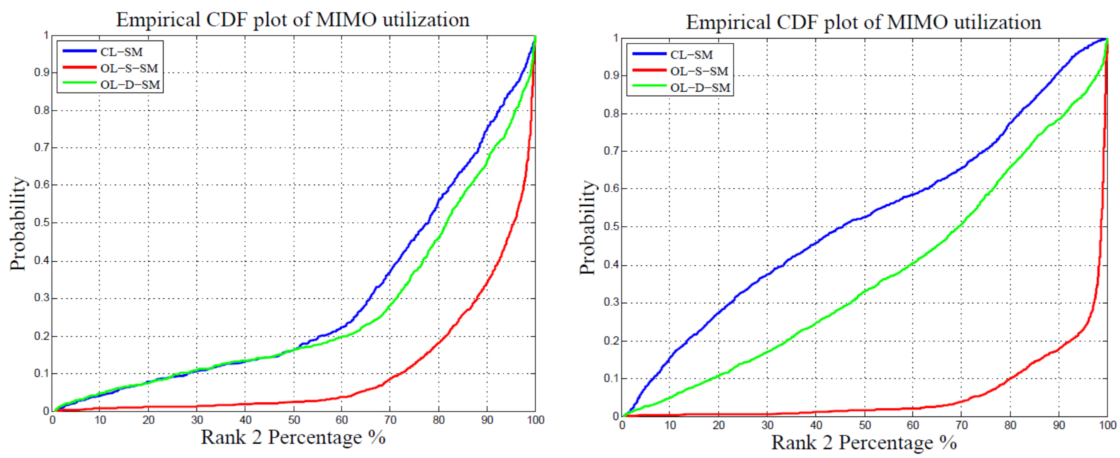
Average TP Mbps	Route 1	Route 2	Micro
CL-SM	20.2	25.6	15.7
CL-S-SM	20.8	27.6	16.5
OL-D-SM	22.5	28.5	17.2

The average APP TP values show that the OL-D-SM is the best in all routes and in both environments. We can see from Figure 5.12 that the difference between different modes is not exactly the same for different routes. The reason is that in one route there is more good channel conditions that in another or vice-versa. From Table 5.3, it is clear that OL-D-SM provides from 1.5 Mbps to 3 Mbps higher throughput that is from 9.5% to 11.7% advantage over CL-SM. And, the OL-S-SM provides from 0.5 Mbps up to 2 Mbps or from 2.5% up to 9% improvement over CL-SM. It seems that the advantage of the OL-D-SM is independent of the measurement route and propagation environment.

5.3.2 MIMO Utilization and SNR Threshold

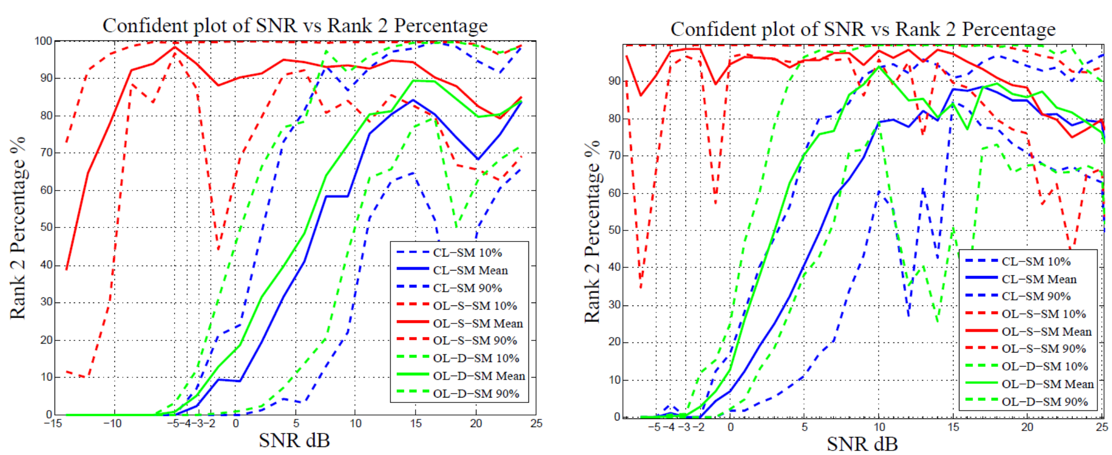
Now, it is time to represent the MIMO utilization for each test case in Indoor route 1 and Micro route. By using this information along with corresponding SNR values, it will be possible to determine the SNR threshold for MIMO utilization in each test case. The

CDF plot of the MIMO utilization, in the form of rank 2 percentage, is represented in Figure 5.13. In Figure 5.14 the confident plot of the rank 2 percentage and the corresponding SNR values are plotted for each test case. Figure 5.14 helps to determine two important SNR thresholds. First threshold shows the SNR values below which the rank 2 percentage that is MIMO utilization is zero, and the second one shows the opposite, the SNR values higher which only MIMO is utilized. Consequently, the SNR values between them will indicate the region where the system dynamically switches between transmit diversity and SM.



a) Indoor b) Micro

Figure 5.13 MIMO utilization a) Indoor Scenario b) Micro Scenario.

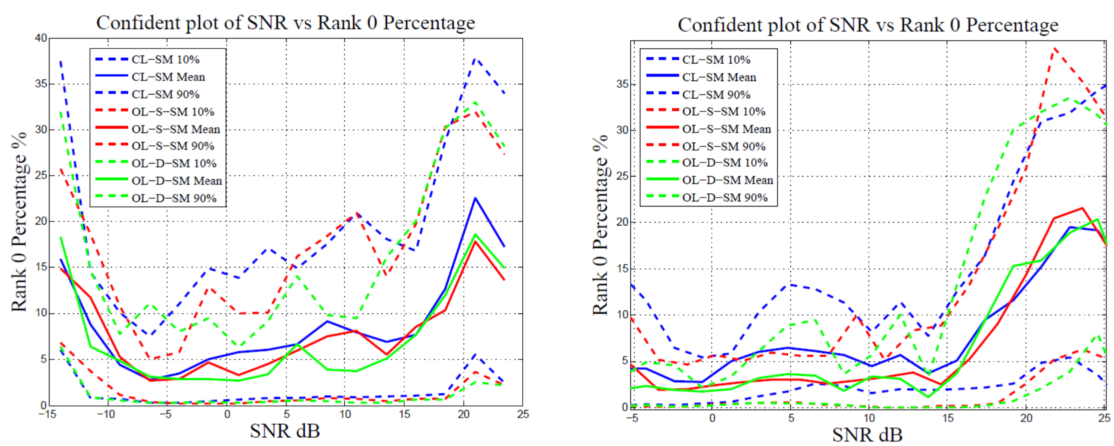


a) Indoor b) Micro

Figure 5.14Confident plot of SNR vs. Rank 2 a) Indoor Scenario b) Micro Scenario.

So, Figures 5.13 and 5.14 illustrate that the OL-S-SM provides highest percentage of MIMO utilization and actually never switches to transmit diversity. What concerns to OL-D-SM and CL-SM, they both switch dynamically between SM and transmit diversity. We can see that the upper threshold for MIMO utilization approximately equal to 15 dB for indoor and 10 dB for outdoor. And the lower threshold values are approximately between -2 dB to -5 dB, besides it is interesting to note that CL-SM switches to transmit diversity slightly earlier than OL-D-SM. So, the SNR values between these two thresholds are the region where the rank 1 is not equal to zero and this is the region where OL-S-SM is performing worse that OL-D-SM. This result allow to assume that dynamic switch between transmit diversity and SM is more efficient than SM for SNR values that are between these SNR thresholds. The same way, we can say that the SM and transmit diversity perform the same way for SNR values below -5 dB.

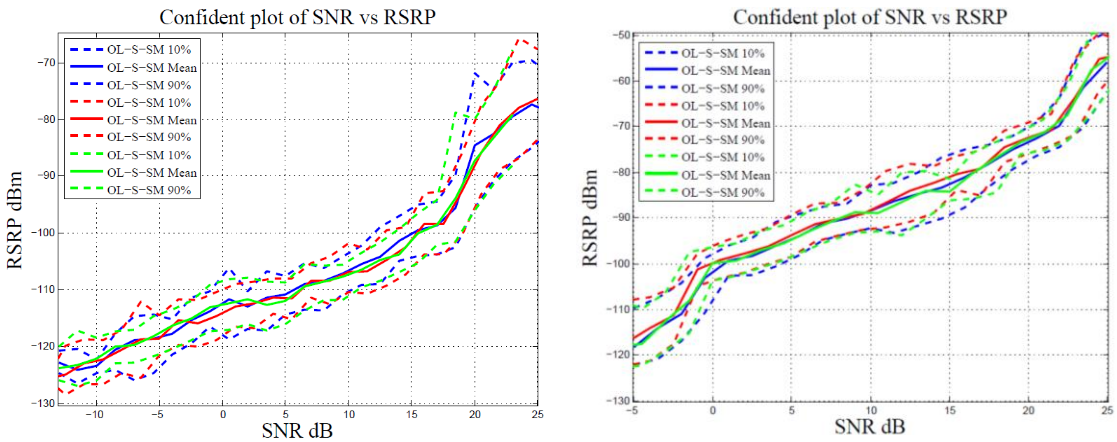
Interesting information is provided also by the confident plot of zero transmission, denoted as rank 0, as it will show the level of interference caused by parallel transmission of two codewords. The confident plot of SNR vs. rank 0 is represented in Figure 5.15. From this figure it is possible to observe that the percentage of no transmission (rank 0), is going up from approximately 5% to 20% after SNR > 15 dB, which is the upper SNR threshold for MIMO utilization. This means that as higher the MIMO utilization percentage as bigger the interference between two parallel data streams. The pre-coder is not able to properly isolate the data streams from each other. For the indoor case, the rank 0 percentage is also high, just because the UE is close to cell edge.



a) Indoor b) Micro

Figure 5.14 Confident plot of SNR vs. rank 0 a) Indoor Scenario b) Micro Scenario.

And finally, Figure 5.16 represents the confident plot of SNR vs. RSRP. This plot illustrates the channel dynamics and can help to determine the regions of high interference, if they are. This type of representation is useful especially for Micro Scenario, as the measurements are done in outdoor environment where the possibility of interference from other systems is much higher than in indoor environment. Figure 5.16 illustrates that for the same SNR values the RSRP values for micro environment are approximately 10 dB higher than in indoor environment, which indicates the presence of interference. On the other hand, there is no a single place with very high or low interference both in indoor and micro measurements as there are no flat regions in the plot. It is worth to not that the above mentioned interference is true only for the place where the measurements have been done.



a) Indoor b) Micro

Figure 5.15 Confident plot of RSRP vs. SNR a) Indoor Scenario b) Micro Scenario.

According to theory represented in books [1], [17] and simulation based studies [4] the CL-SM should perform slightly better than OL-D-SM, as the CL-SM algorithm utilizes the PMI reports of the UE. This means that the pre-coder matrix selection in case of the CL-SM should provide better isolation, consequently lower interference between parallel data streams. As a result, the APP TP should be higher because of higher percentage of MIMO utilization. But this is unfortunately only in theory. As illustrated in Figures 5.8 and 5.9 UE CQI reports of the codeword 1 are very low in comparison with codeward 0. As a result, the modulation and coding index for codeword 0 is smaller in comparison with codeword 1 (Appendix A) On the other hand, the OL-D-SM uses the same CQI for both codewords, so providing higher modulation and coding index for codeword 1 than CL-SM. This is the reason for low performance of the CL-SM represented in above measurement results. The reason for low CQI report for codeword 1 can be associated with the fact that UE records 2 to 3 dB low SNR for second branch to reduce the interference between parallel transmissions.

What concerns to the fairness of the measurement results and possibility to generalize them, it is important to note that the measurements have been conducted with commercial, non-professional LTE data card, which is based on the Qualcomm chipset. The device could cause some measurement errors and inaccuracies. Besides, the measurements have been done for only one network equipment vendor, which also restricts the possibility of generalization of the results. And, the results can be fairer if the number of measurement samples were several times more than the current number.

To provide wider generalization and development of the obtained results the measurements can be done with different network and data card brands.

6 CONCLUSIONS

In this study the performance analyses of different SM modes available in LTE Release 8 have been done. Although, various studies have been done regarding different aspects of LTE, there is a lack of practical studies for different SM modes available in LTE. This topic refers to the parameterization phase of the LTE planning process. Understanding of the advantages and disadvantages of different SM modes in different channel conditions and propagation environments will help to provide high quality performance of the network.

The analyses have been done for 3 SM modes available in used eNodeB. CL-SM and OL-D-SM, are designed to dynamically switch between SM and Transmit Diversity, OL-S-SM always transmits 2 parallel data streams. Furthermore, the analyses have been done in indoor and outdoor-micro environments, where the rich scattering and multipath propagation allows creating independent and uncorrelated channels.

According to the theory, represented in several books [1], [17], and also in simulation based study represented in [4], the performance of the CL-SM should be better the than the performance of OL-D-SM, as it utilizes the mobile PMI reports. On the other hand the performance of the CL-SM heavily depends on the ability of the mobile to do accurate channel estimations and appropriate predictions for pre-coder. But, the measurements that are done in this study show different results.

First of all, the OL-D-SM is the best and provides from 1.5 Mbps to 3 Mbps higher throughput that is from 9.5% to 11.7% advantage over CL-SM. And, the OL-S-SM provides from 0.5 Mbps up to 2 Mbps or from 2.5% up to 9% improvement over CL-SM. These results are independent of the measurement route if the measurement route covers a big range of RSRP and propagation environment. But the behaviour of the CL-SM and OL-S-SM is different in different channel conditions. For both indoor and micro measurements, they provide similar throughputs when the SNR is higher than 20 dB. Then for 15 dB < SNR < 20 dB in indoor and 10 dB < SNR < 20 dB in micro, the performance of the CL-SM starts to degrade. These SNR values, 15 dB in indoor and 10 dB in micro, are thresholds to determine the beginning of the rank 2 percentage decrease for OL-D-SM, while the OL-S-SM will continue to utilize SM. When SNR is below 15 dB in indoor or 10 dB in micro, the performance of the OL-S-SM is going down. This is a clear indication that the dynamic switch between SM and Transmit Diversity is more efficient than the SM when the SNR is below 15 dB in indoor or 10 dB in micro. And finally, for SNR below -5 dB, the performance of all three modes is again the same. This is quite interesting; because the SNR values -2 dB to -5 dB are found to be the MIMO utilization thresholds (percentage of rank 2 is equal to zero). This means that the Transmit Diversity and SM are behaving similarly at the cell edge.

One more similarity between indoor and micro measurements is that for both of them, the percentage of no transmission is going up after 15 dB. This means that as higher the percentage of the rank 2, as bigger the interference between parallel streams. As a result, the percentage of the no transmission is going up from 5% up to 20%. This is an indication of the fact that the isolation of the parallel streams is not ideal. This is the task of the pre-coder to insure isolation of the parallel streams.

Although, the overall behaviour of SM modes is the same in both indoor and micro environments, there are slight differences between them. In indoor, the highest percentages of the MIMO utilization, is achieved at SNR values equal to 15 dB, but in Micro in 10 dB. The SNR thresholds for switching between SM and Transmit diversity are between -2 to -5 dB, but for micro it is happening slightly earlier than for indoor.

The unexpected behaviour of the CL-SM is associated with the fact that the CQI reports for the codeword 1 are lower that for the codeword 0. As a result, lower modulation and coding scheme is assigned to the codeword 0 (Appendix A). This can be associated with the fact that mobile equipment reduces the SNR for codeword 1 by 2 to 3 dB in comparison with codeword 0 to decrease interference between them.

It is important to note that the results can be generalized only for LTE Release 8 networks which use the equipment of the same vendor as it is used in this study. The reason is that different vendors have different implementations of the aspects which are not specified in 3GPP specifications. The additional measurements with other vendor equipment can be considered as the next step after this work to be able to generalize the results independent of network equipment manufacturer.

Now it is obvious, that the understanding of different SM transmission modes behaviour in different environments and channel conditions can play a key role for high quality and cost efficient LTE network deployment.

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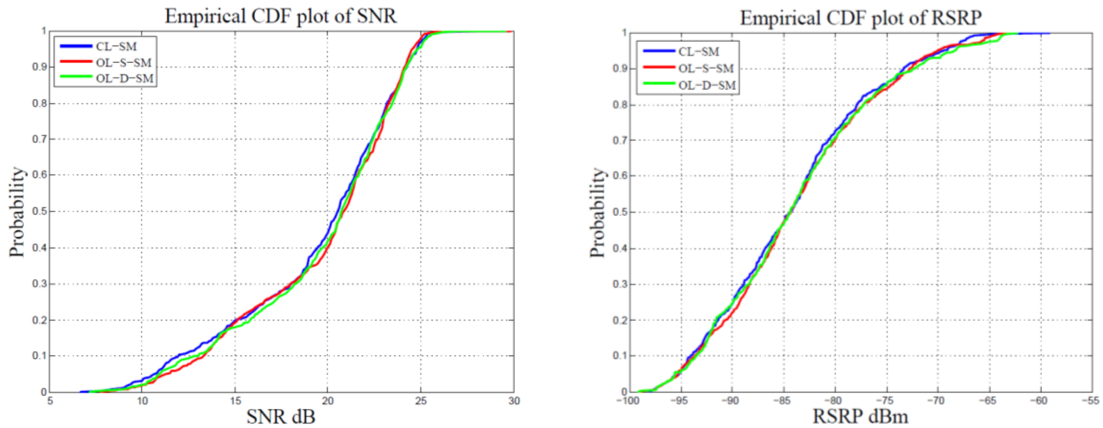
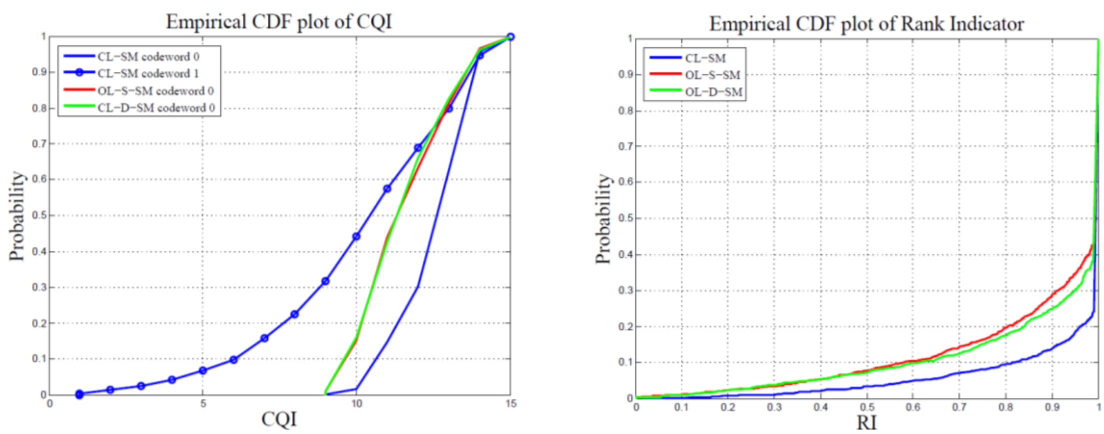
APPENDIX A

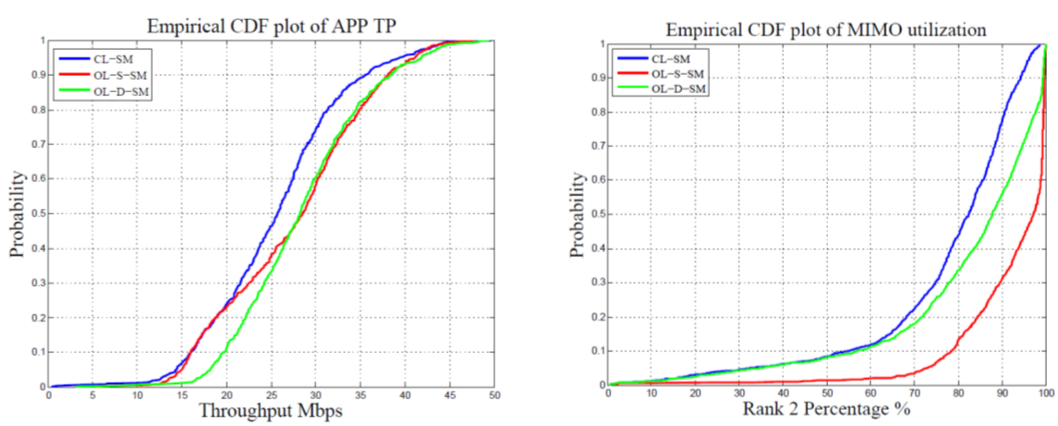


a) Link performance parameters



b) Mobile reports

Figure A.1 Channel condition comparisons for Indoor Scenario in route 2 a) Link parameters b) Mobile reports.



a) b)

Figure A.2 CDF plot for route 2 in Indoor Scenario a) APP TP b) MIMO utilization.

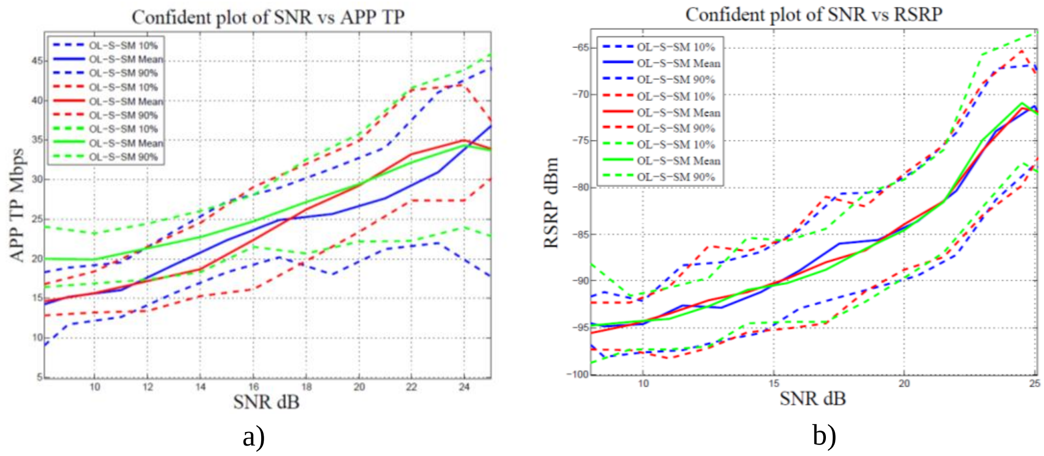


Figure A.3 Confident plot for route 2 in Indoor Scenario a) SNR vs. APP TP b) SNR vs. RSRP.

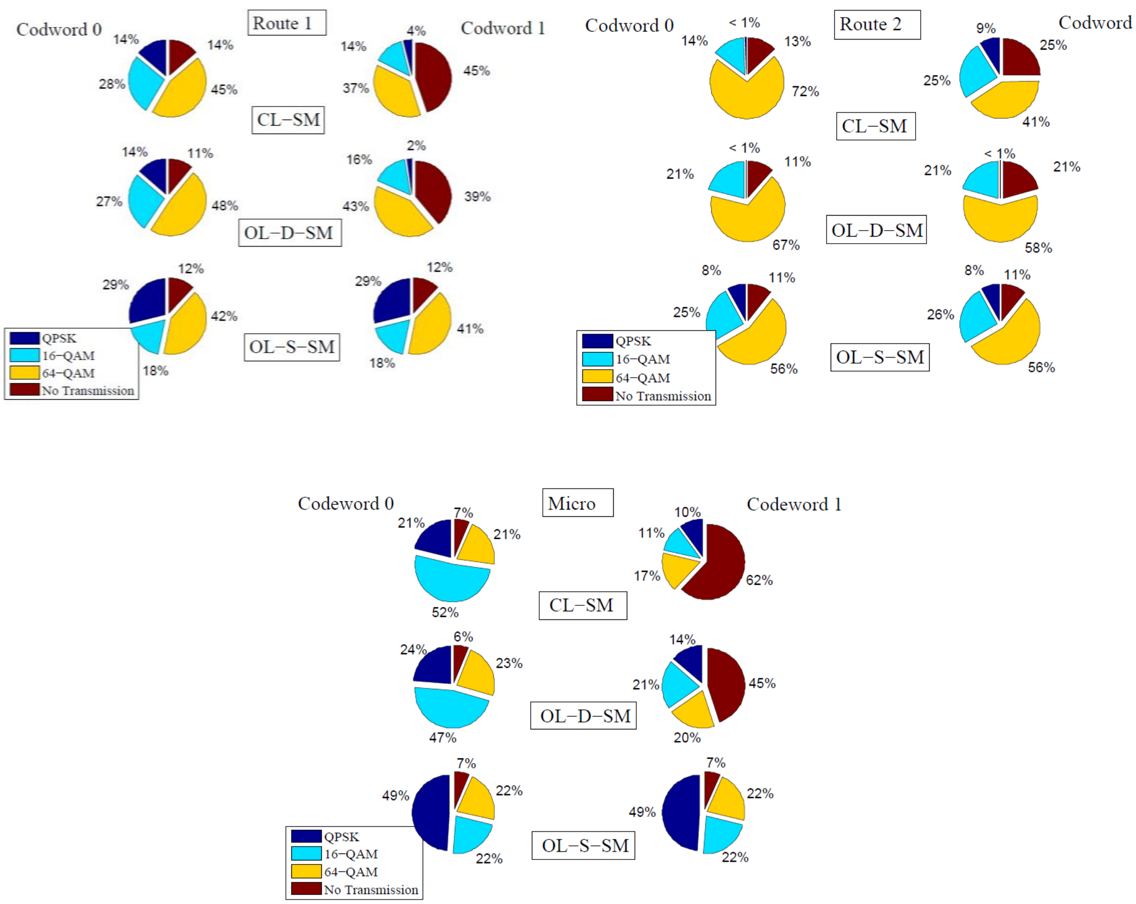


Figure A.4 Modulation distribution for all measurement routes.