UNIVERSITY OF VAASA

FACULTY OF TECHNOLOGY

TELECOMMUNICATION ENGINEERING

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THROUGHPUT OPTIMIZATION AND ENERGY EFFICIENCY OF THE DOWNLINK IN THE LTE SYSTEM

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ABBREVIATIONS

3G	Third Generation
3GPP	Third Generation Partnership Project
4G	Fourth Generation
ACK	Acknowledgement
A-MPR	Additional Maximum Power Reduction
AMPS	Analogue Mobile Phone System
BCCH	Broadcast Control Channel
BCH	Broadcast Channel
BS	Base Station
BSRs	Buffer Status Reports
CCCH	Common Control Channel
CDMA	Code Division Multiple Access
CFO	Carrier Frequency Offset
CN	Core Network
CP	Cyclic Prefix
CQI	Channel Quality Indicators
DCCH	Dedicated Control Channel
DFT	Discrete Fourier Transform
DL-SCH	Downlink Shared Channel
DRX	Discontinuous Reception
DTCH	Dedicated Traffic Channel
EE	Energy Efficiency
EPC	Evolved Packet Core
EU	User Equipment
FDD	Frequency Division Duplex
FDMA	Frequency Division Multiple Access
FFT	Fast Fourier Transform
FPLMTS	Future Public Land Mobile Telecommunications Systems
GSM	Global System for Mobile Communication
HARQ	Hybrid Automatic Repeat Request
HSDPA	High Speed Downlink Packet Access
HSS	Home Subscriber Service
HSUPA	High Speed Uplink Packet Access
HW	Hardware
ICI	Inter-Carrier Interference
IDFT	Inverse Discrete Fourier Transform
IMT	International Mobile Telecommunication
IRC	Interference Rejection Combining Receiver
IP	Internet Protocol
ISI	Inter Symbol Interference
ITU-R	International Telecommunication Union – Radio Communication Sector
ITU	International Telecommunication Union
J-TACS	Japanese Total Access Communication System
LTE	Long-Term Evolution

MAC	Medium-Access Control
MBMS	Multimedia Broadcast Multicast Services
MBSFN	Multicast-Broadcast Single Frequency Network
MCCH	Multicast Control Channel
MCH	Multicast Channel
MIMO	Multiple Input Multiple Output
MME	Mobility Management Entity
MPR	Maximum Power Reduction
MTCH	Multicast Traffic Channel
NACK	Negative Acknowledgement
NMT	Nordic Mobile Telephone
OFDMA	Orthogonal Frequency Division Multiple Access
OFDM	Orthogonal Frequency-Division Multiplexing
PAs	Power Amplifiers
PAPR	Peak to Average Power Ratio
PCCH	Paging Control Channel
PCH	Paging Channel
PCRF	Policy and Charging Rules Function
PDCCH	Physical Downlink Control Channel
PDCP	Packet Data Convergence Protocol
PDUs	Protocol Data Units
P-GW	Packet Data Network Gateway (PDN Gateway)
PF	Proportional – Fair scheduler
PHY	Physical layer
QPSK	Quadrature Phase-Shift Keying
QoS	Quality–of–Service
RACH	Random Access Channel
RAN	Radio-Access Network
RLC	Radio-Link Control
ROHC	Robust Header Compression
RR	Round- Robin scheduler
RRM	Radio Resource Management
SAE	System Architecture Evolution
SC-FDMA	Single-Carrier Frequency Division Multiple Access
SDOs	Standards Development Organizations
S – GW	Serving Gateway
SNR	Signal to Noise Ratio
SRSs	Sounding Reference Signals
SW	Software
TACS	Total Access Communication System
TBs	Transport Blocks
TDMA	Time Division Multiple Access
TD-SCDMA	Time Division Synchronous Code Division Multiple Access
TF	Transport Format
TPC	Transmitter Power Control
TSGs	Technical Specification Groups
TTI	Transmission Time Interval

UL-SCH	Uplink Shared Channel
UMTS	Universal Mobile Telecommunication Services
WARC-92	World Administrative Radio Congress
WCDMA	Wideband Code Division Multiple Access
WGs	Working Groups

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ABSTRACT:

Nowadays, the usage of smart phones is very popular. More and more people access the Internet with their smart phones. This demands higher data rates from the mobile network operators. Every year the number of users and the amount of information is increasing dramatically. The wireless technology should ensure high data rates to be able to compete with the wire-based technology. The main advantage of the wireless system is the ability for user to be mobile. The 4G LTE system made it possible to gain very high peak data rates.

The purpose of this thesis was to investigate the improvement of the system performance for the downlink based on different antenna configurations and different scheduling algorithms. Moreover, the fairness between the users using different schedulers has been analyzed and evaluated.

Furthermore, the energy efficiency of the scheduling algorithms in the downlink of LTE systems has been considered.

Some important parts of the LTE system are described in the theoretical part of this thesis.

KEYWORDS: LTE, 4G, 3GPP, OFDMA, Scheduling, MIMO, Energy Efficiency, Smart Phones, Internet

1. INTRODUCTION

People are working with a huge amount of information every day. The modern life is very dynamic and humanity is willing to spend as less time on downloading files as possible. They would like to get everything immediately. It became very important to provide a high mobility and a fast access to the Internet resources. In the very beginning people could use the wireless network to make a call only. 2G was developed to deal with real time services and had the opportunity to carry the data services. The problem was in the very low data rates and expensive service. Further researches lead to the 3G which provided the user with a cheaper and fast connection. Nowadays, 4G becomes the new technology that is able to provide very high data rates and allows people to be very mobile. They can get an access to the Internet from almost every place.

Long Term Evolution can achieve a very high data rate competitive with a wire-based technology due to OFDMA (Orthogonal Frequency Division Multiple Access). It uses larger bandwidths with a maximum of 20 MHz, the higher order modulation up to 64QAM, and spatial multiplexing in the downlink. LTE uses the IP protocol to carry the real time services and data services. In the uplink it can get the highest theoretical data rate on the transport channel equal to 75 Mbps, and in the downlink, the rate can reach up to 300 Mbps with a spatial multiplexing scheme.

Many investigations about wireless technology have been done to achieve the high data competitive with a wire-based connection. The scheduling algorithm and different antenna schemes is the one of the tasks that could improve the throughput. The effective scheduling algorithm could improve the system performance. It is the main component to utilize the radio resources in a more efficient way. The eNodeB makes the decision regarding scheduling in the downlink and the uplink. The fairness between the users has to be considered when the scheduling algorithm is chosen.

The increasing number of users and data rates makes the control of the power consumption important. There are many reasons why the solution for the green communication has to be found. One of the reasons is the very high pollution to the atmosphere. Nine percent of all carbon emissions are produced by the cellular communication. This number will be more with a growing population. Another reason to develop a green communication is to reduce the cost that operators spend on the fuel.

The main purpose of this thesis is to analyze how different algorithms and antenna configuration could improve the throughput in the downlink of the LTE system. Also, the survey of the power consumption of different scheduling algorithms in the downlink was investigated.

The thesis consists of 6 chapters. The first and the second chapters include the introduction, the history of LTE and main characteristics. Chapter 3 gives the description of main part of the LTE system. Chapter 4 introduces the scheduling algorithms and energy efficiency. Different simulation scenarios will be presented and the explanation of the results will be given. The simulation results are given in chapter 5. Chapter 6 summarizes the results received from simulation and proposes the future work.

2. HISTORY OF LTE

Nowadays, the performance of wireless network plays an important role. Wired networks have the advantage of being able to provide the highest data rate to compare with the wireless one. Wireless networks need to achieve the data rates comparable with cable networks. Long-Term Evolution (LTE) offers the solution for this problem.

Since 1990 the internet has become a supplier of different services. As an evolution, mobile devices started to provide internet-based services. The main impact for development of LTE became the ability to maintain the same Internet Protocol (IP)-based services in mobile devices that costumers use with the fixed broadband connection. There are a lot of capabilities for wireless networks due to the mobility and roaming of mobile technology. (Dahlman, Parkvall & Sköld 2011.)

In 1980s the first mobile communication system came to the world and was called “First Generation” system. First Generation was based on the analog technology. There are some systems that were created and used during that time: in America it was Analogue Mobile Phone System (AMPS), in Europe it was Total Access Communication System (TACS) and Nordic Mobile Telephone (NMT), Japan and Hong Kong use the system called Japanese Total Access Communication System (J-TACS). (Sesia, Toufik & Baker 2011.)

The second step in developing of the mobile system was “Second Generation” System with the name Global System for Mobile communication (GSM). GSM was the digital based technology. The aim of GSM was to use a smaller mobile terminal with a longer battery life. GSM made the communication between users more easy and provide more advanced data services. Also, in developing countries where cable lines did not exist and where the installation of cable lines was too expensive, GSM connected peoples and communities together. (Sesia et al. 2011.)

Third generation (3G) technology started to maintain the circuit switched data with the packet switched services. 3G started to use the broadband data. Fourth generation (4G) of mobile systems is considered as the LTE technology. But some claim that LTE-Advanced technology is the 4G. (Dahlman et al. 2011.)

Technology for mobile systems is developing very fast. Mobile devices are filling in with new services which demand more speed. It becomes one of a reason for evolution 3G to 4G. Also, more spectrum resources were needed to increase the system with the flexibility in spectrum allocation. The existing core network of GSM was focused on the circuit-switched domain. Due to the new radio interface of LTE the core network had to be renewed. LTE was intended to provide the packed-switched services. Furthermore, LTE involved the evolution of the non-radio parts of a whole system called “System Architecture Evolution” which also contains the Evolved Packet Core (EPC). The core network and the radio access were both packet-switched in LTE and SAE. (Sesia et al. 2011.)

Due to the reason, that the radio spectrum is shared between plenty of different technologies which also interfere with each other, International Telecommunication Union – Radio communication sector (ITU-R) is taking care of sharing radio spectrum between technologies. ITU-R decides how much bandwidth each technology and service can get and it uses the standardization of families of radio technologies. Technologies which meet the requirements of ITU-R are assigned as the member of International Mobile Telecommunication (IMT). There are three main organizations working on the development of new standards to satisfy the IMT requirements. These standards are shown in Figure 1.

The relationship between the standardization organizations and regulatory authorities can be seen in the following way (Sesia et al. 2011):

$$Aggregated\ data\ rate = \underbrace{bandwidth}_{\substack{regulation\ and\ licences\\ (ITU-R,\ \ regional\ regulators)}} * \underbrace{spectral\ efficiency}_{technology\ and\ standards} \tag{1}$$

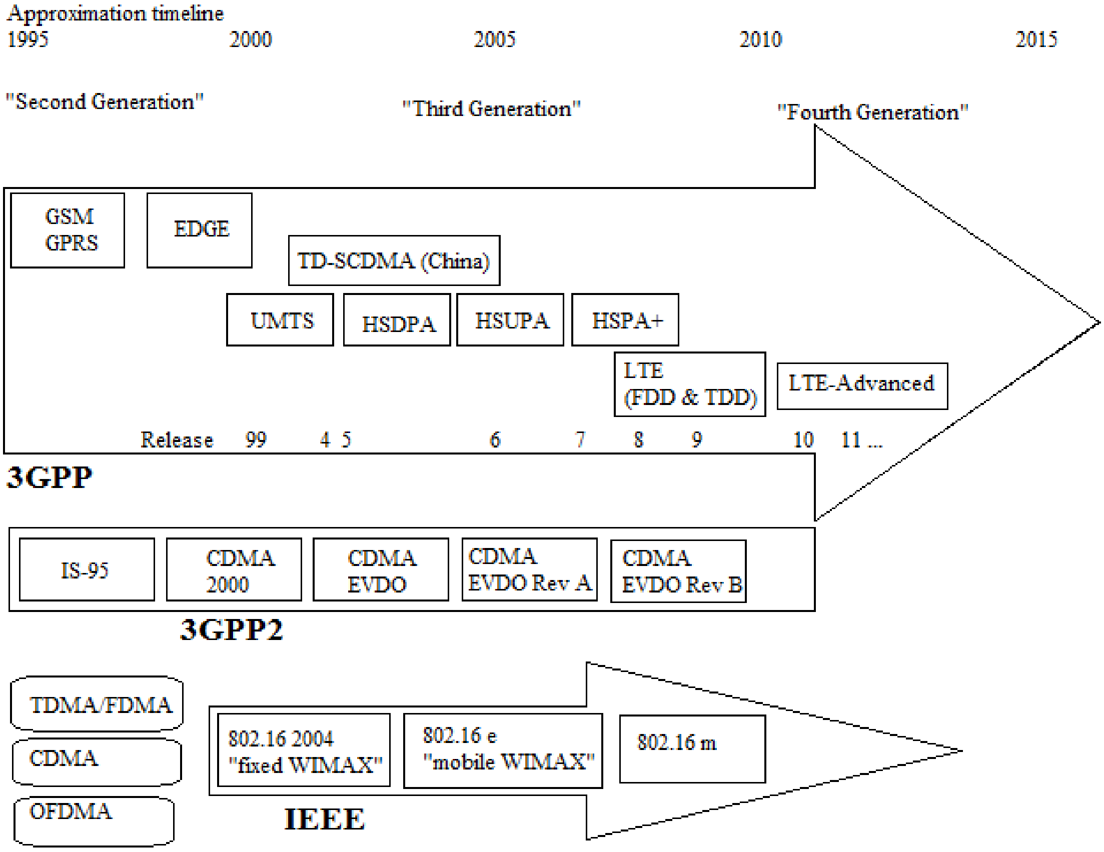

Figure 1. Mobile communication standards. (Sesia, Toufik & Baker 2011.)

International Telecommunication Union (ITU) started to work on a 3G wireless communication in 1980s with a label called Future Public Land Mobile Telecommunications Systems (FPLMTS) and then switched to the IMT-2000. IMT-2000 was given a spectrum of 230 MHz by the World Administrative Radio Congress (WARC-92). The research on 3G was made in parallel with the evolution of 2G. The Universal Mobile Telecommunication Services (UMTS) was the name for 3G in Europe. Europe and Japan proposed the Wideband CDMA for UMTS and it was accepted in 1998. In the end of 1998 the Third Generation Partnership Project (3GPP) was established from different organizations all over the world. So, all organizations now started to work not on parallel but together on the same problem. (Dahlman et al. 2011.)

The 3GPP was created and in 2011 containing 380 companies as members. 3GPP consists of six regional Standards Development Organizations (SDOs): USA (ATIS), Europe (ETSI), China (CCSA), Korea (TTA) and Japan (ARIB & TTC). 3GPP made several procedures to create a successful process of development. 3GPP is divided into 4 Technical specification groups (TSGs), every group consists of Working Groups (WGs) which are responsible for developing a certain part of the specifications. All reports and technical documents are published on the 3GPP website. (Sesia et al. 2011.)

The 3GPP organization was working on the development of using three different multiple access technologies: 2G (GSM/GPRS/EDGE) used Time Division Multiple Access (TDMA) and Frequency Division Multiple Access (FDMA); 3G UMTS employed the Code Division Multiple Access (CDMA) and later the Wideband CDMA (WCDMA) as a part of evolution; and nowadays LTE is deployed using the Orthogonal Frequency-Division Multiplexing (OFDM) which became the primary technology for all mobile standards. (Sesia et al. 2011.)

LTE was developed by the Third Generation Partnership Project (3GPP). 3GPP also tries to improve the previous releases. It is desirable for network operators who put a lot of money to the development of WCDMA technology, as they want to get the income from the new services provided to their subscribers with old terminals. (Sesia et al. 2011.) There is the list of 3GPP releases:

1. Release 99 or WCDMA release. It was announced in December 1999. This release had a theoretical data rate of up to 2 Mbps and based on WCDMA characteristics. It met all requirements of the IMT-2000. Packet-switched and circuit-switched carriers were responsible for data services and circuit-switched voice and video services;
2. Release 4 was accomplished in March 2001. It contained TD-SCDMA;
3. Release 5 was completed in March 2002. It developed the High Speed Downlink Packet Access (HSDPA);
4. The development of Release 6 was finished in December 2004. High Speed Uplink Packet Access (HSUPA) was created for WCDMA;

5. Release 7 was announced in June 2007. It performed the improvement of HSDPA and HSUPA. These release improved the HSPA with a higher order modulation and using multistream Multiple Input Multiple Output (MIMO) operation;
6. Release 8 was done in December 2008. It brought the development of HSDPA and HSUPA;
7. Release 9 was finished at the end of 2009;
8. Release 10 was accomplished in March 2011;
9. Release 11 was completed in 2012. (Holma & Toskala 2011.)

The 3G evolution to 4G began with release 99, the first release of WCDMA Radio Access. In releases 5 and 6 the new feature High Speed Packet Access (HSPA) was added in the first time. HSPA pushed mobile system beyond the definition of 3G. In 2004 the development of 3GPP Long Term Evolution began with a workshop. Six month were spent to define the requirements and design for LTE. (Dahlman et al. 2011.)

Release 8 is the first LTE release. LTE used some characteristic of HSDPA and HSUPA. It contains retransmissions of physical layer, base station scheduling with physical layer feedback, and link adaptation. Also, Release 8 applies structure and platforms of WCDMA technology. The data rate which LTE release can achieve is 300 Mbps in the downlink and 75 Mbps in uplink. (Holma et al. 2011.)

The discussion of LTE system made it necessary to create a “Study Item”. Study item had to include the properties of the LTE to make this system be competitive at the moment when it will be released for the public use. Finally, in June 2005 LTE release 8 were accepted with the proper requirements. Due to the high competition between wireless and wireline technologies LTE have to satisfy the following main goals:

1. Peak rate must be more than 100 Mbps in the downlink and 50 Mbps in the uplink;
2. Round trip time have to be less than 10 ms;
3. It has to provide high level of mobility and security;
4. Terminal power efficiency must be optimized;

5. Flexible frequency from 1.5 MHz to 20 MHz;
6. Spectral efficiency is four times more than in Release 6;
7. Network architecture is more simple;
8. Lower cost per bit. (Holma et al. 2011.)

The evolution of LTE is called LTE-Advanced and it is the part of release 10 of the LTE. The important components were included to this release as a wider bandwidth and improved antenna techniques for downlink and uplink.

Table 1 was taken from the book Sesia et al. 2011 and it illustrates the performance requirements for LTE system Release 8.

Table 1. The performance requirements for LTE system Release 8 (Sesia, Toufik & Baker 2011.)

		Absolute requirement	Release 6 for comparison	Comments
Downlink	Peak transmission rate	>100 Mbps	14,4 Mbps	20 MHz FDD, 2×2 spatial multiplexing. Reference: HSDPA in 5 MHz FDD, single antenna transmission.
	Peak spectral efficiency	> 5 bps/Hz	3 bps/Hz	
	Average cell spectral efficiency	> 1,6-2,1 bps/Hz/cell	0,53 bps/Hz/cell	2×2 spatial multiplexing, Interference Rejection Combining (IRC) receiver. Reference: HSDPA, Rake receiver, 2 receive antennas.
	Cell edge spectral efficiency	> 0,04-0,06 bps/Hz/cell	0,02 bps/Hz/cell	As above, 10 users assumed per cell.
	Broadcast spectral efficiency	> 1 bps/Hz	N/A	Dedicated carrier for broadcast mode
Uplink	Peak transmission rate	>50 Mbps	11 Mbps	20 MHz FDD, single antenna transmission. Reference: HSUPA in 5 MHz FDD, single antenna transmission
	Peak spectral efficiency	> 2,5 bps/Hz	2 bps/Hz	
	Average cell spectral efficiency	> 0,66-1,0 bps/Hz/cell	0,33 bps/Hz/cell	Single antenna transmission, IRC receiver. Reference: HSUPA, Rake receiver, 2 receive antennas.
	Cell edge spectral efficiency	> 0,02-0,03 bps/Hz/cell	0,01 bps/Hz/cell	As above, 10 users assumed per cell.

System	User plane latency (two way radio delay)	< 10 ms		LTE target approximately one fifth of Reference
	Connection set-up latency	< 100 ms		Idle state → active state
	Operating bandwidth	1,4-20 MHz	5MHz	(initial requirement started at 1,25 MHz)
	VoIP capacity	NGMN preferred target > 60 sessions/MHz/cell		

Good performance of LTE system became possible due to the progress in the mobile technology. The multicarrier technology, multiple antenna technology and packet-switched radio interface allowed to implement the essential requirements for 4G. In 2005 the decision about multiple-access technology was made. OFDMA has been chosen for the downlink and SC-FDMA for the uplink. OFDMA is a very flexible multiple-access technology and it has the following advantages:

- There is no need to change the fundamentals system parameters to assign the different spectrum bandwidth;
- It brought the possibility to re-use the frequency and coordinate the interference level between cells;
- Users can get resources of different bandwidth and can be scheduled easily. (Sesia et al. 2011.)

SC-FDMA was chosen for the uplink because of low PAPR compared to the OFDMA. Later in chapter 4 the SC-FDMA will be described in more details.

Multiple antenna technology gave the opportunity to employ the spatial-domain. The utilization of it allowed getting higher spectral efficiencies. The following principles are improving the overall performance of the system:

- Diversity gain helps to deal with multipath fading thereby provides the better robustness;
- Array gain – the energy is concentrated in one or more direction using beamforming or precoding, by that users from different locations can be served simultaneously;
- Spatial multiplexing gain – numerous signal streams can be transmitted to one user on few spatial layers using available antennas. (Sesia et al. 2011.)

Packet switched radio interface of LTE uses the packet of duration equal to 1ms. The cooperation of MAC and physical layer became tighter with such short duration of transmission interval. The cross-layer techniques between two layers contain the following methods:

- "Adaptive scheduling in frequency and spatial dimensions"; (Sesia et al. 2011.)
- "Adaptation of the MIMO configuration including the selection of the number of spatial layers transmitted simultaneously"; (Sesia et al. 2011.)
- "Link adaptation of modulation and code-rate, including the number of transmitted codewords"; (Sesia et al. 2011.)
- "Several modes of fast channel state reporting". (Sesia et al. 2011.)

For new technology on the market it is very important to be able to support different user equipment (EU). However, the maintenance of the various numbers of users will increase the complexity of the testing and will require more signaling information. That is why the first release of LTE was supporting a few categories of EU. There are five different categories of UE supported by Release 8 and described in Table 2 taken from Sesia et al. 2011.

Table 2. The categories of UE supported by Release 8 (Sesia, Toufik & Baker 2011.)

	User equipment category				
	1	2	3	4	5
Supported downlink data rate (Mbps)	10	50	100	150	300
Supported uplink data rate (Mbps)	5	25	50	50	75
Number of receive antennas required	2	2	2	2	4
Number of downlink MIMO layers supported	1	2	2	2	4
Support for 64QAM modulation in downlink	+	+	+	+	+
Support for 64QAM modulation in uplink	-	-	-	-	+
Relative memory requirement for physical layer processing (normalized to category 1 level)	1	4,9	4,9	7,3	14,6

3. DESCRIPTION OF LTE

3.1. Review of OFDMA

Nowadays, OFDMA is a wide used technology in broadband wireless systems. Orthogonal Frequency-Division Multiplexing (OFDM) is the basis of LTE downlink transmission scheme. It is used as a multiple access technology for the air interface in broadband wireless systems such as 3 GPPP LTE/ LTE-Advanced, 802.16e and 802.20. The advanced features of OFDMA are its scalability, sub-channel orthogonality and the ability to take advantage of the channel frequency selectivity.

“Orthogonal Frequency Division Multiplexing is a multiplexing technique that subdivides the available bandwidth into multiple orthogonal frequency sub-carriers.” (Yin & Alamouti 2006.)

OFDM is a point to point system. In OFDM system a single user receive the data on all subcarriers at any time. The short description of the following system was given there to see the difference with OFDMA. Orthogonal frequency division multiple access (OFDMA) is an extension of OFDM. OFDMA is a point to multipoint system. Multiple users can receive data at any time.

One of the main problems to get a high data rate is a reduced symbol duration that causes an inter symbol interference (ISI) problem. When the symbol duration T_s is smaller than the channel delay spread T_d it will cause ISI.

To mitigate ISI problem the data sequence in OFDMA is divided into M parallel sequences. With this action the data rate of each data sequence is reduced and the symbol duration is increased. So, the T_s become longer than the channel delay spread. The parallel data sub-streams are transmitted on separate orthogonal sub-carriers. Also, this operation allows making a less complex equalizer in the receiver. The principles of

OFDM modulation can be seen in the Figure 2 below. (Dahlman, Parkvall & Sköld 2011.)

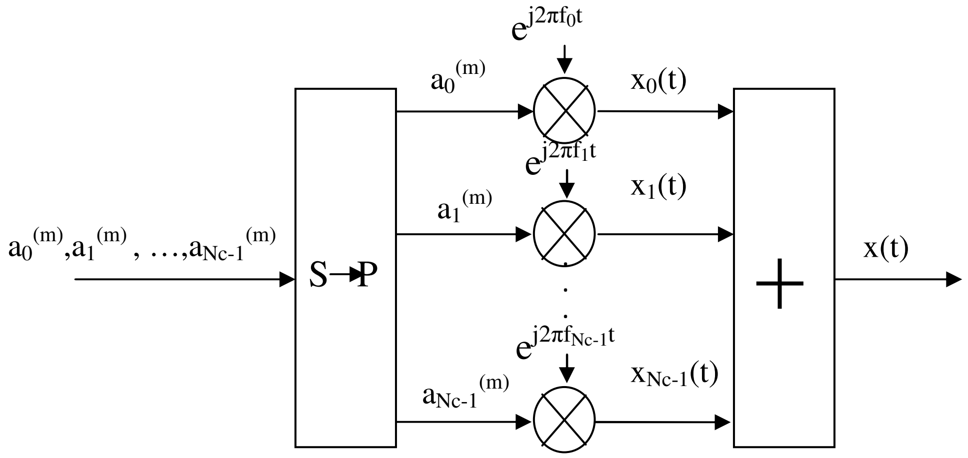

Figure 2. Principles of OFDM modulation. (Dahlman, Parkvall & Sköld 2011.)

Basic OFDM modulator consists of N_c complex modulators. Each modulator is responsible for one OFDM subcarrier. Expression for OFDM signal during the time interval $mT_u \leq t < (m+1)T_u$ is the following:

$$x(t) = \sum_{k=0}^{Nc-1} x_k(t) = \sum_{k=0}^{Nc-1} a_k^{(m)} e^{j2\pi k \Delta f t}, \tag{2}$$

where $x_k(t)$ is the kth modulated subcarrier with frequency $f_k = k \cdot \Delta f$ and $a_k^{(m)}$ is the modulation symbol (usually complex) applied to the kth OFDM symbol during the symbol interval $mT_u \leq t < (m+1)T_u$. (Dahlman et al. 2011.)

The modulation has been done using inverse Fast Fourier transform. It enables large number of sub-carriers with low complexity. Also, the guard period Cyclic Prefix (CP) was added in the beginning of the data stream. It is a replication of the last samples of the data stream. The duration of CP should be longer than the channel delay spread to eliminate the ISI caused by multipath propagation.

The information symbols are $x_k^{(i)}$ and they are gathered to the data blocks $x^{(i)}$ of size M. After that the data blocks are precoded with an MxM matrix M. M-sized output $s^{(i)}$ is mapped into a set of M out of N inputs. User subcarrier mapping matrix Q (NxM) makes N inputs to the inverse discrete Fourier transform (IDFT). A cyclic prefix has to be longer than the largest multipath delay. It is usually included before the transmission to remove the inter symbol interference occurring from multipath propagation. (Ciochina & Sari 2010.)

Advantages of OFDMA:

1) High spectrum efficiency – the spacing between neighboring subcarriers can be very small, from several hundred kHz to few kHz, so there would be no wasted spectrum.
2) Multiple subcarriers are transmitting in parallel that helps to use longer symbol duration. Because of this fact, OFDMA is strong enough to multipath environment and better for handling the elimination of ISI.
3) Also, using a cyclic prefix can minimize inter – symbol interference. OFDM optimally shares power and rate between narrowband sub-carriers (scheduling). The wide spectrum allows the frequency diversity.
4) OFDM can resist to the harmful effects of multipath delay spread (fading) in the radio channel. Without multipath protection, the symbols in the received signal can overlap in time, leading to inter – symbol interference (ISI). (Prasad, Shukla & Chisab 2012.)

However, some challenges arise from the division of bandwidth to narrowband subcarriers. Because of this the OFDMA systems are very sensitive to the frequency offset.

Transmitter and receiver have to operate exactly with the same frequency reference for OFDMA to be orthogonal. Otherwise, the orthogonality of the subcarriers is lost, causing the Inter-Carrier Interference (ICI).

The frequency errors occur due to the different frequencies of the transmitter and the receiver local oscillators. It is important to use low – cost components in the mobile devise and this causes bigger drifts in local oscillator frequency than in the eNodeB. The frequencies difference is known as Carrier Frequency Offset (CFO). In addition, the phase noise in the UE receiver may also result in frequency errors. (Sesia, Toufik & Baker 2009.)

Another problem is the high peak to average power ratio (PAPR). "In the general case, the OFDM transmitter can be seen as a linear transform performed over a large block of independently identically distributed (i.i.d) QAM – modulated complex symbols (in the frequency domain)." (Sesia et al. 2009.)

OFDM symbol may be approximated as a Gaussian waveform using the central limit theorem. Because of it, the amplitude variations of the OFDM modulated signal can be very high. Practical Power Amplifiers (PAs) of RF transmitters are linear only within a bounded dynamic diapason. In this way, the OFDM signal probably will suffer from non-linear distortion caused by clipping. It leads to the increasing of out of-band spurious emissions and in-band corruption of the signal.

The PAs have to operate with large power back – offs, resulting in inefficient amplification and expensive transmitters to cancel such distortion. "The PAPR is one measure of the high dynamic range of the input amplitude (and hence a measure of the expected degradation)." (Sesia et al. 2009.)

3.2. IFFT/FFT process in OFDM

OFDM subcarrier spacing Δf is equal to the per-subcarrier symbol rate $1/T_u$. Fast Fourier Transform (FFT) processing allows low-complexity implementation of OFDM. Assume that the sampling rate f_s of time – discrete OFDM signal is equal to the multiple of the subcarrier spacing Δf, so, $f_s = 1/T_s = N \cdot \Delta f$. The choice of parameter N has to satisfy the sampling theorem. Also the nominal bandwidth of the OFDM signal is equal to $N_c \cdot \Delta f$, this means that N has to be greater than N_c.

Now, we can express the time – discrete OFDM signal as follows:

$$x_n = x(nT_s) = \sum_{k=0}^{N_c-1} a_k e^{j2\pi k\Delta f nT_s} = \sum_{k=0}^{N_c-1} a_k e^{j2\pi kn/N} = \sum_{k=0}^{N-1} a'_k e^{j2\pi kn/N}, \qquad (3)$$

Where $$a'_k = \begin{cases} a_k, & 0 \le k < N_c \\ 0, & N_c \le k < N \end{cases}$$

The sequence x_n is the sampled OFDM signal and also the size – N Inverse Discrete Fourier Transform (IDFT) of the block of modulation symbol $a_0, a_1, \ldots, a_{N_c-1}$ extended with zeros to length N. Figure 3 shows the OFDM modulation with IDFT processing and digital to analog conversion. (Dahlman et al. 2011.)

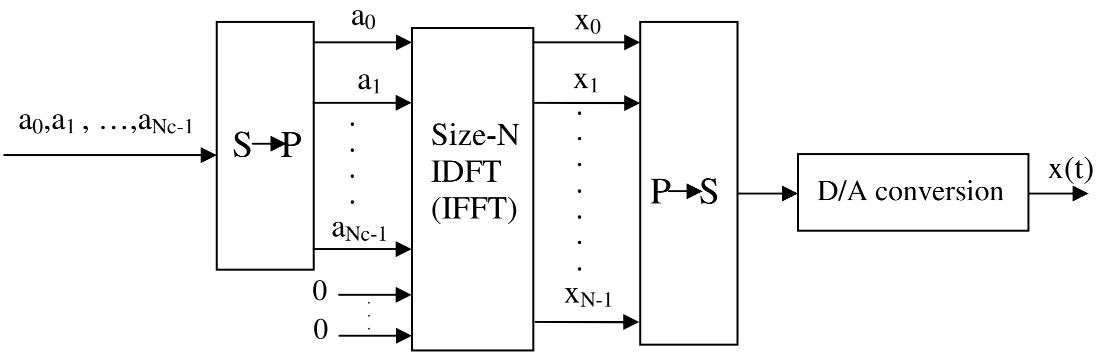

Figure 3. OFDM modulation with IFFT process. (Dahlman, Parkvall & Sköld 2011.)

IDFT size N is selected equal to 2^m. Also, the OFDM modulation can be implemented with Inverse Fast Fourier Transform (IFFT). The ratio N/N_c is an over-sampling of the time-discrete OFDM signal and is non-integer number. For 3GPP LTE the number of subcarrier N_c is about 600 in the case of a 10 MHz spectrum allocation. So, the IFFT size can be selected as N=1024. This refer to a sampling rate $f_s = N \cdot \Delta f = 15{,}36$ MHz, where $\Delta f = 15$ kHz is the LTE subcarrier spacing. (Dahlman et al. 2011.)

LTE radio – access specification doesn't require the IDFT/IFFT –based implementation of an OFDM modulator and the precise IDFT/IFFT size. It is the transmitter – implementation choice. As an example, OFDM modulator can be seen as a set of parallel modulators, like in Figure 2. Moreover, the IFFT size can be chosen as 2048, even with a smaller number of OFDM subcarriers.

OFDM demodulation can be done with FFT processing with parallel demodulators of a N-size DFT/FFT. Figure 4 shows the demodulation process with FFT process. (Dahlman et al. 2011.)

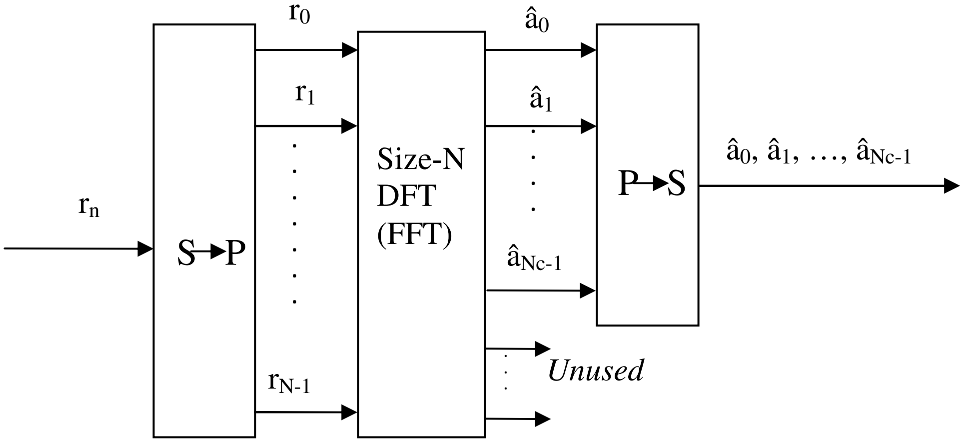

Figure 4. OFDM modulation with FFT process. (Dahlman, Parkvall & Sköld 2011.)

3.3. Cyclic-prefix in OFDM

The discussion of the cyclic prefix insertion in OFDM is given next. The received signal y(t) need the time equal to T_{max} to reach the steady state *exp(j2πf(k)t)H(k).* Also, to stay at the steady state for a time interval equal to T_s , the transmitted signal need to have a duration of $T_s + T_{max}$. This tells us why we need to use a cyclic prefix. So, the transmitted OFDM signal x(t) should be extended to time interval $t \in [-T_{cp}, T_s)$. This interval is longer that we used in equation 2. T_{cp} is a length of the cyclic prefix:

$$x(t) = x(t + T_s), t \in [-T_{cp}, 0) \quad (4)$$

OFDM modulation scheme with the total OFDM symbol duration equal to $T_s + T_{cp}$ is illustrated in Figure 5 below. Notice that the extended part x(t) where $t \in [-T_{cp}, 0)$ is the same copy of the part where $t \in [T_s - T_{cp}, T_s)$. Now, it can be assumed that $T_{cp} = T_{max}$. (Li, Wu & Laroia 2013.)

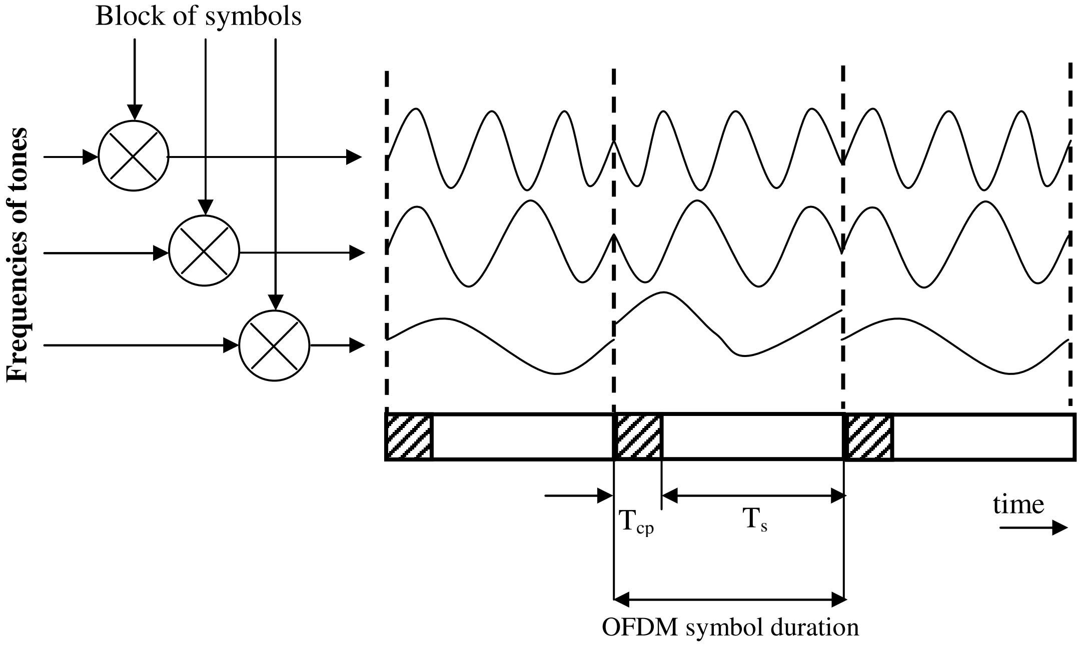

Figure 5. OFDM modulation in the time and frequency domain. (Li, Wu & Laroia 2013.)

Now, let's consider the sequence of OFDM symbols which transmitted both directions. During the transmission in the wireless channel, the delay spread produces the interference between successive symbols which is called inter–symbol interference (ISI). Figure 6 below shows that the cyclic prefix becomes a guard interval and helps to eliminate the ISI between two OFDM symbols. It is obvious from the picture above that the cyclic prefix enables the removal of ISI of two received symbols. (Li et al. 2013.)

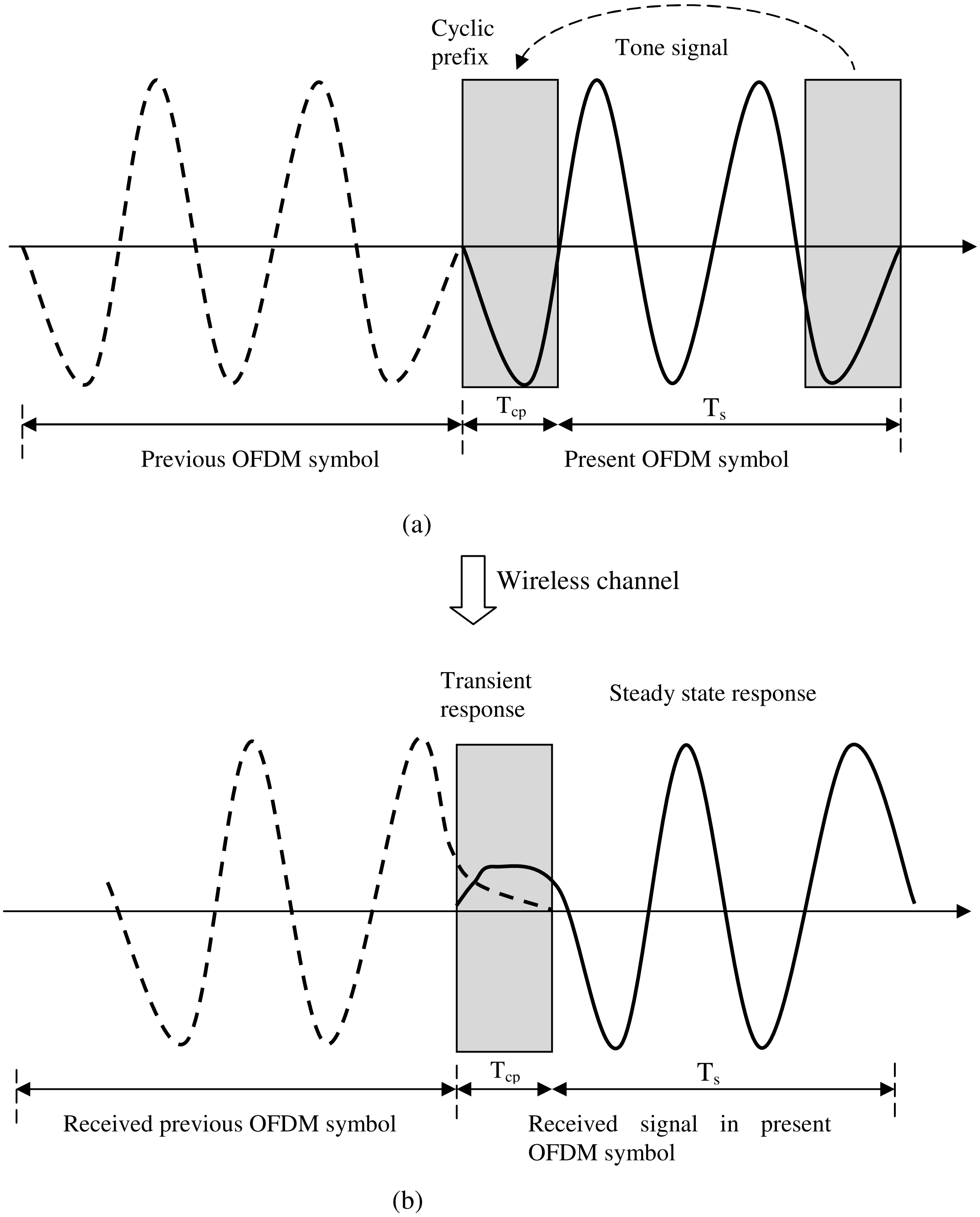

Figure 6. Cyclic prefix. a) A transmitted tone signal of two OFDM symbols. b) The channel response of the two OFDM symbols. (Li, Wu & Laroia 2013.)

There are some comments about using the cyclic prefix:

- When OFDM symbol go through the wireless channel, the cyclic prefix helps to reach the steady state. After that, the receiver will deal with the steady state response;
- A cyclic prefix enables to settle down the cannel response of the previous OFDM symbol. It enables the elimination of the interference with the steady state period of the present symbol;
- A cyclic prefix is rejected at the receiver side before further processing. The bandwidth efficiency is reduced by the factor of T_{cp}/T_s. The OFDM symbol duration T_s is Nc times longer than in single-carrier communication with the same total bandwidth because of N_c data symbols that are transmitted simultaneously. (Li et al. 2013.)

3.4. Selection of the basic OFDM parameters

The basic parameters for OFDM transmission are described below:

- The subcarrier spacing $\Delta f= 1/T_u$;
- The number of subcarriers N_c. The subcarrier spacing and number of subcarrier together determine the transmission bandwidth of OFDM signal;
- The cyclic prefix length T_{cp}. The cyclic prefix with subcarrier spacing defines the OFDM symbol time or OFDM symbol rate. (Dahlman et al. 2011.)

Two factors that limit the selection of the OFDM subcarrier spacing are given:

- The OFDM subcarrier spacing have to be small enough to minimize the interval for cyclic prefix (that mean that T_u have to be as large as possible);
- Also, it is important to consider, that very small subcarrier spacing will cause the high sensitivity of the OFDM signal to Doppler spread and frequency inaccuracies.

OFDM subcarrier orthogonality at the receiver side means that the instant channel does not change significantly during the demodulator correlation interval T_u. However, a high Doppler spread will cause channel variations and orthogonality between subcarriers will be lost. That will bring inter – subcarrier interference. The acceptable amount of inter – subcarrier interference depends on the service that has to be provided. Also, it depends on the amount of the corrupted received signals because of noise and other degradation. For instance, the signal to noise ratio (SNR) on the border of the large cell will be comparatively low and achievable data rate will be also low. In that case some amount of inter – symbol interference is insignificant. But, if we have a small sized cell with low traffic with high data rates, the same amount of interference will cause much more negative effect. (Dahlman et al. 2011.)

Another OFDM parameter is the number of subcarriers. It can be selected based on the amount of available spectrum and appropriate out – of – band emissions. As we already know that the bandwidth of the OFDM signal is equal to $N_c \cdot \Delta f$ (number of subcarrier multiplied by the subcarrier spacing). But the spectrum of the OFDM signal decreases very slow outside the basic OFDM bandwidth even slower than for the WCDMA signal. Large out-of-band emission of OFDM signal is caused by using of the rectangular pulse shaping. Figure 7 below depicted the spectrum of OFDM signal compared with WCDMA signal. (Dahlman et al. 2011.)

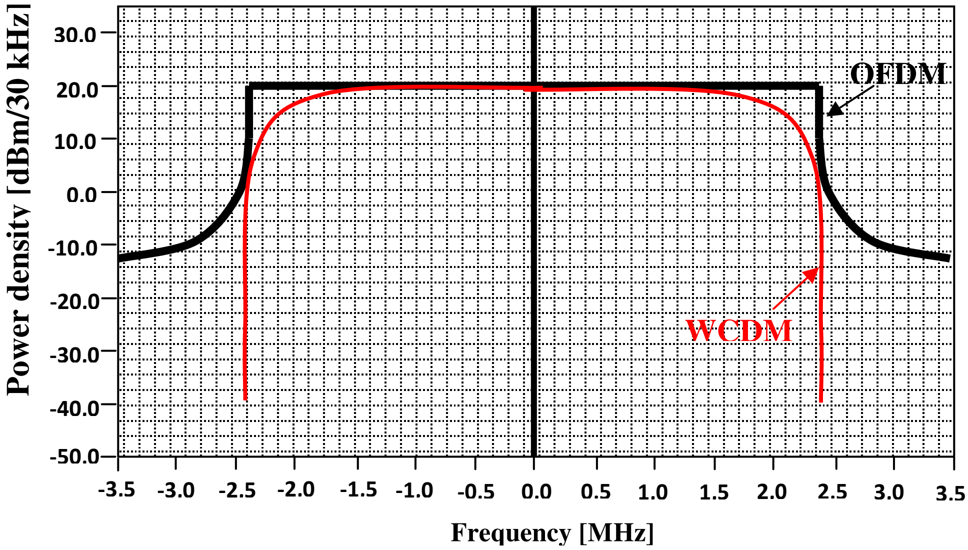

Figure 7. 5MHz OFDM signal spectrum with WCDMA spectrum. (Dahlman, Parkvall & Sköld 2011.)

In practice to deal with large out – of – band emissions time – domain windowing is used. Also, a 10% guard – band is required to imply the OFDM signal. For instance, in spectrum allocation of 5 MHz, the basic OFDM bandwidth $N_c \cdot \Delta f$ has to be maximum 4.5 MHz. Let's take a little example, subcarrier spacing equal to 15 kHz is selected for OFDM, the number of subcarrier will be about 300 in a 5 MHz spectrum. (Dahlman et al. 2011.)

The last parameter considered in this sub – chapter is Cyclic-Prefix (CP) Length. Ideally the length of CP has to be chosen so that will cover the maximum length of the time dispersion. In practice increasing the CP length will increase the power and bandwidth. When the size of cell is growing, the system performance faces a limit in power. This brings us to a choice to lose the power due to the cyclic prefix or signal corruption because of time dispersion without using enough cyclic prefix length. The amount of time dispersion is growing with the cell size. Sometimes when the cell size is very big, there is no need to further increase the CP, because the relative power loss will cause the greater negative effect than the signal corruption caused by time dispersion that is not covered with CP. So, that is why different transmission scenarios are using different lengths of CP. Short CP could be used in an environment with small cells and a longer CP in case of great time dispersion. (Dahlman et al. 2011.)

3.5. Orthogonal Frequency Division Multiple Access

In the beginning of this chapter it was already mentioned that OFDM is a point to point modulation scheme between transmitter and receiver. Orthogonal Frequency Division Multiple Access (OFDMA) shares the time – frequency recourses between multiple users.

Let's consider the cell and its sectorization. Usually one cell is divided into three sectors using multiple directional antennas. During the transmission one signal can interfere with another transmitted signal. The interference may happen within the same sector (intra – sector interference), in different sectors of the same cell (inter – sector interference), or in neighboring cells (inter–cell interference). Intra–sector and inter – sector interference combined together is called intra – cell interference. (Li et al. 2013.)

The OFDMA bandwidth resources are shared using the following principles:

- Zero intra–cell interference. To avoid the intra–sector interference the tone-symbols assigned to different users within a sector are different. Every sector of the cell reuse the tone – symbols assigned to users. Inter-sector interference is zero in case of perfect sectorization;
- Average inter – cell interference. The same tone – symbols are reused in different cell and it results in inter – cell interference. Tone hopping can be used to average the inter – cell interference. (Li et al. 2013.)

OFDMA tone – symbol allocation is flexible. It is possible to assign any number of tone-symbols to one user. Also, the tone hopping means that tone – symbols assigned to one user can hop between different frequency tones over time. One example of averaged interference is shown in Figure 8. (Li et al. 2013.)

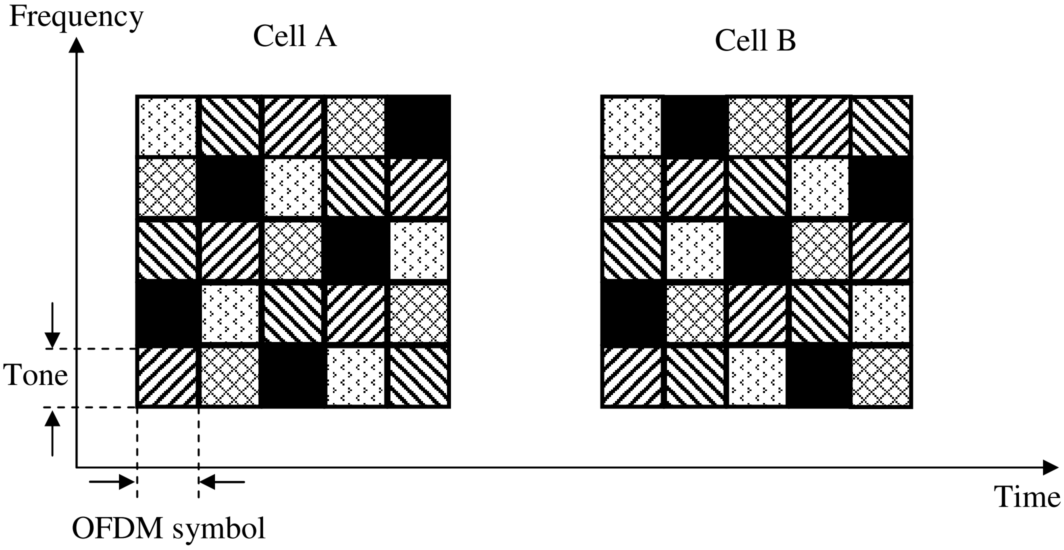

Figure 8. OFDMA tone hopping in cells A and B. (Li, Wu & Laroia 2013.)

There are two cells in Figure 8. A small squares painted with the same pattern performs set of tone-symbols assigned to one user. There are five different users in cell A and also another five users in cell B. The frequency tone of the allocated tone-symbol changes from one OFDM symbol to another. In one cell, the tone-symbols assigned to two various users never interfere with each other. Also, cells A and B use special tone hopping pattern, where the user in cell A and the user in cell B interfere with each other at different OFDM symbols. (Li et al. 2013.)

3.6. Single-Carrier Frequency Division Multiple Access

In the beginning of this chapter the problem of PAPR was already mentioned. It is one of the main problem associated with OFDM. 3GPP found a decision for LTE uplink. Single-carrier frequency division multiple access (SC-FDMA) was chosen as another option of modulation scheme for LTE uplink with a low PAPR technique. Table 3 shows the power amplifier (PA) back off for SC-FDMA and OFDMA signals using the cubic metric. Cubic metric is connected to the allowed back – off to a formula that comprised the cube of the voltage waveform relative to a standard QPSK waveform. (Rumney 2013.)

Table 3. SC-FDMA compared to OFDMA using cubic metric. (Rumney 2013.)

Modulation depth	Cubic metric	
	SC-FDMA	OFDMA
QPSK	1.2	4
16QAM	2.2	4
64QAM	2.4	4

A short description of SC-FDMA symbol is given next. Discrete Fourier Transform (DFT) is used to convert data symbols in the time domain to the frequency domain.

When symbols are in frequency domain they are located to the assigned place in the general channel bandwidth. After this, symbols are converted to the time domain again by using IFFT. At the end cyclic prefix is inserted. (Rumney 2013.)

Let us see and discuss Figure 9 which compares the transmission of OFDMA and SC-FDMA symbols.

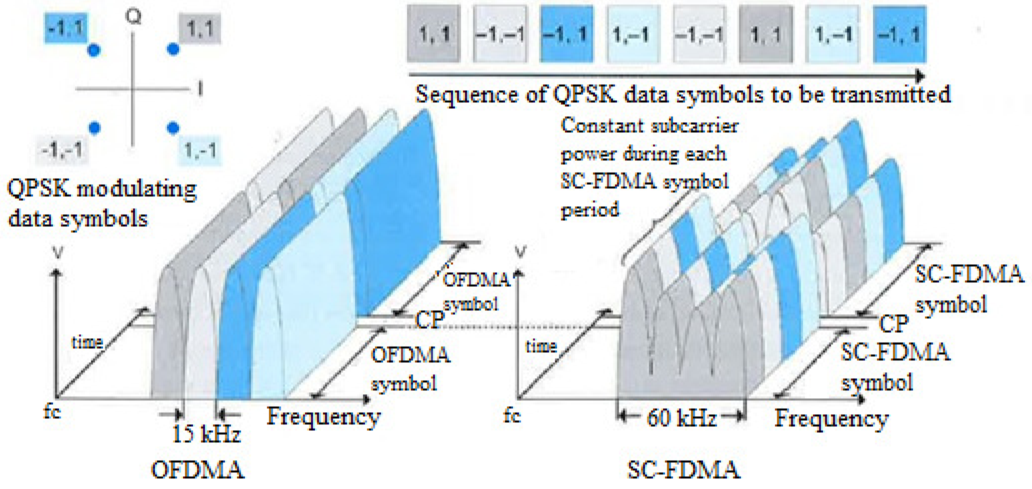

Figure 9. Comparison of OFDMA and SC-FDMA transmitting symbols. (Rumney 2013.)

There are four (M) subcarriers and two symbol periods in Figure 9. The transmission of OFDM signal is presented on the left side. M neighboring 15 kHz subcarriers are placed in the channel bandwidth. Every subcarrier is modulated by one QPSK data symbol. That means four subcarriers transmit four symbols in parallel. Cyclic prefix is inserted in the beginning of next four data symbols. In the figure CP is shown as a gap, but in reality it is the copy of end of next symbol. (Rumney 2013.)

SC-FDMA signal is presented on the right side of Figure 9. The difference between SC-FDMA and OFDMA is that SC-FDMA transmits the four data symbols in series when

OFDMA transmit them in parallel. The data symbol in SC-FDMA occupies a wider bandwidth equal to M x 15kHz. Due to the parallel transmission the PAPR of OFDMA is very high. Many narrowband waveforms added together create greater peaks than one wide band in SCFDMA. PAPR in OFDMA increases with M, but in SC-FDMA regardless M the PAPR will be the same as used for original data symbols. (Rumney 2013.)

3.7. Radio-Interface Architecture

3GPP was working on the LTE radio – access technology as well as on overall system architecture. System Architecture Evolution (SAE) is the name of the work on improvement of Radio-Access Network (RAN) and Core Network (CN). The product of this work was a flat RAN architecture and new core network called as Evolved Packet Core (EPC). The RAN is in charge of radio-related functionality of the whole network and contains scheduling, retransmission protocols, radio – resource handling, antenna schemes and coding. EPC functions contain setup of end-to-end connections, charging and authentication. (Recommendation ITU-R M.1457-9 2010.)

The EPC differs a lot from core network used in 2G and 3G. EPC provides an access to the packet-switched domain only, and does not support the access to the circuit-switched domain. Figure 10 shows the nodes of EPC. The brief description of them is given next. (Recommendation ITU-R M.1457-9 2010.)

According to the Dahlman et al. (2011) “Mobility Management Entity (MME) is the control – plane node of the EPC.” The functionalities of MME are the handling of the Idle to Active transitions, connection/release of bearers to a terminal and the handling of security keys.

“The Serving Gateway (S – GW) is the user–plane node connecting the EPC to the LTE RAN.” (Dahlman et al. 2011.) The functions of S-GW are to be a mobility connector when the terminals are moving between eNodeBs and to be a connector for different

3GPP technologies such as GSM/GPRS and HSPA. Also, S-GW collects necessary information for charging.

“The Packet Data Network Gateway (PDN Gateway, P-GW) connects the EPC to the internet.” (Dahlman et al. 2011.) P-GW has the responsibilities for the allocation of the IP address for a terminal and the enforcement of quality–of–service (QoS) due to the policy managed by PCRF. Another function of P-GW is to be a mobility connector for non-3GPP radio-access technologies as CDMA2000 with EPC.

Policy and Charging Rules Function (PCRF) is another node of the EPC. It is responsible for the handling and charging of QoS. Home Subscriber Service (HSS) is a node responsible for a database with information about subscribers. (Dahlman et al. 2011.)

There are also more nodes that belong to the network as Multimedia Broadcast Multicast Services (MBMS). All those nodes are logical nodes. Several nodes, for instance, MME, P-GW, and S-GW can be easily combined into one physical node. (Dahlman et al. 2011.)

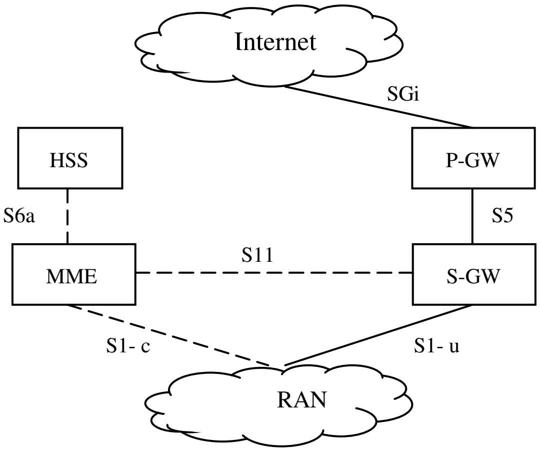

Figure 10. EPC architecture. (Dahlman, Parkvall & Sköld 2011.)

Now let's consider Figure 11 and the description of RAN architecture. The main difference of LTE radio-access network from 3G and below is a single type of node called eNodeB. All radio functions are in the responsibility of eNodeB. Also, it is worse to mention that eNodeB is a logical node. Usually the eNodeB is responsible for transmissions in three cells. Also, another implementation of eNodeB can be possible as a lot of indoor cells belong to the same eNodeB. (Recommendation ITU-R M.1457-9 2010.)

In Figure 11 the eNodeB and EPC are connected to each other using S1 interface. S1 user-plane part (S1-u) connects eNodeB and S-GW and S1 control-plane part (S1-c) connects eNodeB and MME. "One eNodeB can be connected to multiple MMEs/S-GWs for the purpose of load sharing and redundancy." (Dahlman et al. 2011.) Also, X2 interface connects eNodeB between each other. Radio resource management (RRM) can also use the X2 interface. (Dahlman et al. 2011.)

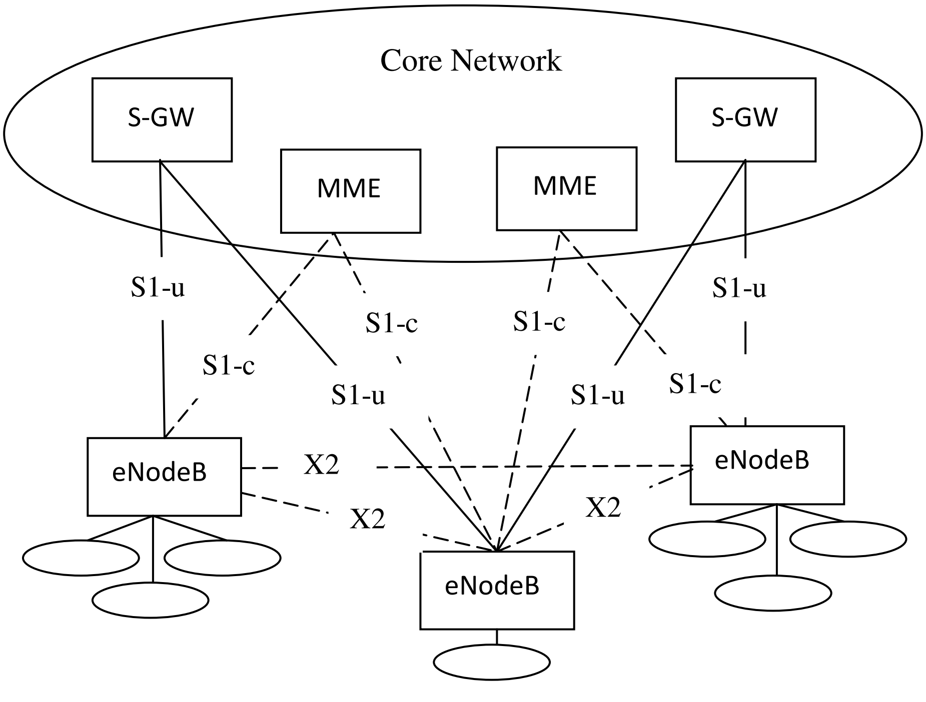

Figure 11. RAN architecture. (Dahlman, Parkvall & Sköld 2011.)

3.8. Radio Protocol Architecture

This subchapter will summarize and describe a little bit the protocols of the radio-access network in LTE. Figure 12 presents the RAN protocol architecture. MME is included to the figure for completeness and it is not a part of RAN. (Dahlman et al. 2011.)

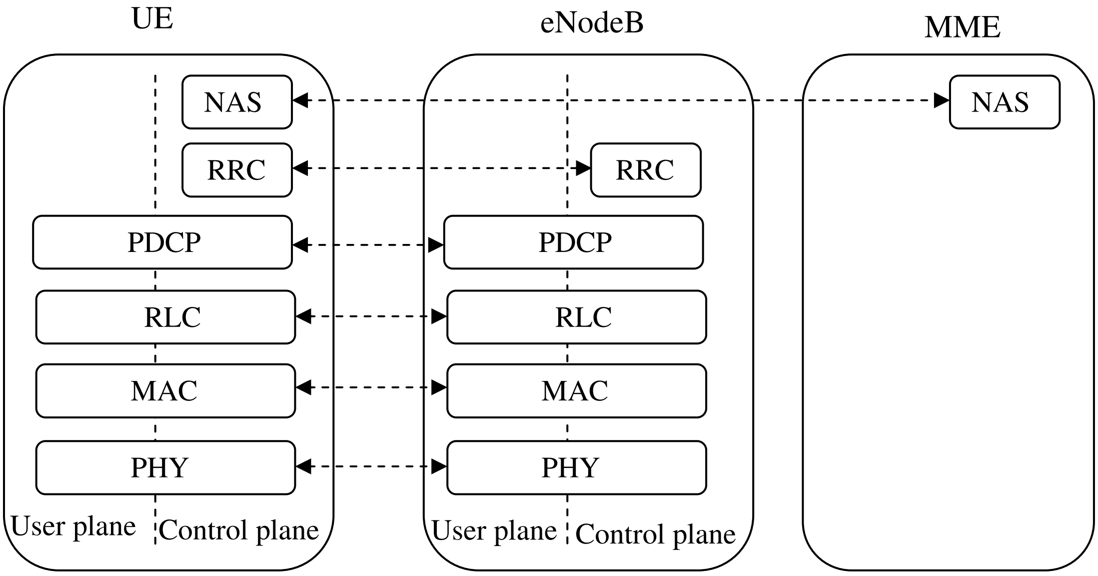

Figure 12. RAN protocol architecture. (Dahlman, Parkvall & Sköld 2011.)

Packet data convergence protocol (PDCP) compresses the IP header, trying to decrease the number of transmitted bits. Robust header compression (ROHC) is an algorithm used for a header-compression. Other functions of PDCP are ciphering, protecting the integrity of transmitted data, in-sequence transmission and removing the duplicate for handover. At the receiver, the PDCP protocol implements deciphering and decompression procedure. (Recommendation ITU-R M.1457-9 2010.)

Radio-link control (RLC) functions are segmentation, detection of duplicates, retransmission and in-sequence transmission to higher layers. Radio bearers ensure services from The RLC to the PDCP. (Recommendation ITU-R M.1457-9 2010.)

Medium-Access Control (MAC) is responsible for multiplexing logical channels, uplink and downlink scheduling and Hybrid-ARQ retransmissions. The eNodeB contains a scheduling function for uplink and downlink. Transmitting and receiving ends of the MAC protocol contains the Hybrid-ARQ protocol part. Logical channels provide the service from the MAC protocol to the RLC. (Dahlman et al. 2011.)

“Physical layer (PHY) handles coding/decoding, modulation/demodulation, multi-antenna mapping and other physical-layer functions.” (Dahlman et al. 2011.) Transport channels provide services from the PHY to the MAC layer.

3.9. Medium Access Control

In this subchapter we will focus more on MAC layer due to its responsibility for scheduling. As already mentioned, the MAC uses the logical channels for providing services to the RLC. The architecture of the MAC layer is illustrated in Figure 13 taken from the Sesia et al. 2011.

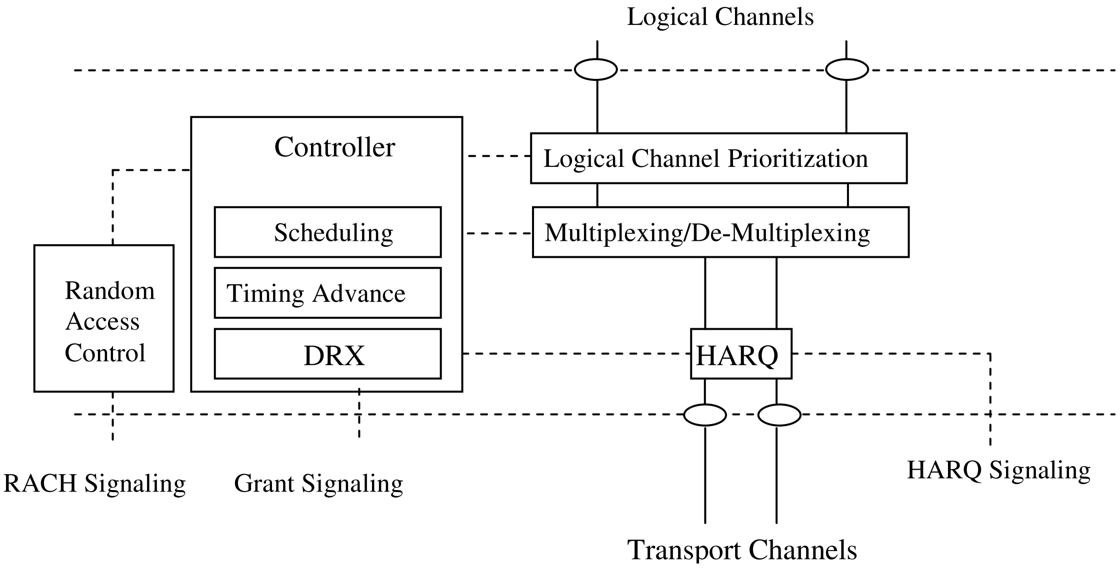

Figure 13. MAC architecture. (Sesia, Toufik & Baker 2011.)

The function of the logical channel prioritization is to give an order of priority for the data from the logical channels. After that, the decision will be made about the amount of data and the logical channels required for the MAC PDU. (Sesia et al. 2011.)

Multiplexing and demultiplexing function in MAC layer multiplexed/demultiplexed data from logical channels to/from one transport channel. During multiplexing, the MAC Protocol Data Units (PDUs) are produced from the MAC Service Data Units (SDUs) according to the logical channel prioritization decision. The demultiplexing function includes the generation of the MAC SDUs from MAC PDUs and sending them to the RLC facilities. (Sesia et al. 2011.)

The responsibility of HARQ is to receive and transmit the Hybrid Automatic Repeat Request (HARQ) operations. The receive HARQ operation is in charge of receiving the Transport Blocks (TBs), producing the Acknowledgement/Negative Acknowledgement ACK/NACK signaling and merging the received data. (Sesia et al. 2011.)

The purpose of random access control is to control the Random Access Channel (RACH). The functions of controller are the following: scheduling process, uplink time alignment, and Discontinuous Reception (DRX).

There are two types of logical channels: control and traffic channel. Traffic channel carriers the user’s data and the control channel are responsible for the control and configuration information used for LTE system. Types of logical channels are the following:

- The broadcast control channel (BCCH) – it sends the system information to all terminals in the cell. Terminals have to know the configuration of the system to make a proper decision of how to behave within a cell;
- The paging control channel (PCCH) – sends paging messages of terminals with unknown location on a cell level to the network. Also, it informs UE about incoming call;
- The common control channel (CCCH) – sends the control information in a random access;

- The dedicated control channel (DCCH) – transmits the dedicated control information to or from terminal. Different handover messages are send with this channel for the special configuration of the UE;
- The multicast control channel (MCCH) – sends the control information necessary for reception of multicast traffic channel (MTCH);
- The dedicated traffic channel (DTCH) – it transmits the user data from or to terminal. The transmission is done for uplink and non-MBSFN (multicast-broadcast single frequency network) downlink user data;
- The multicast traffic channel (MTCH) – responsible for downlink transmission of MBMS (multimedia broadcast / multicast service) services.

Another type of channel is the transport channel. It provides the services from PHY to MAC layer. The transport block organizes the data on a transport channel. Only one transport block of a dynamic size can be transmitted from/to a terminal every Transmission time interval (TTI). Two transport blocks per TTI can be transmitted in case of the spatial multiplexing.

There is a special format to establish the form of a transport block and it is called Transport format (TF). TF has the following information about the transport block: the size, the scheme of modulation, the coding and the antenna mapping. Different data rates can be set by MAC using the transport format.

Different types of transport channel for LTE are the following:

- The broadcast channel (BCH) transmits the part of BCCH system information. BCH has the fixed transport format;
- The paging channel (PCH) transmits the paging information from the PCCH logical channel. Discontinuous reception (DRX) of PCH helps to save battery power of the mobile. PCH turns on only if needed;
- "The downlink shared channel (DL-SCH) is the main transport channel used for transmission of downlink data in LTE." (Dahlman et al. 2011.) It is responsible for dynamic rate adaptation and channel depended scheduling, spatial multiplexing and hybrid ARQ with soft combining. Terminal power is reduced using DRX.

Some information of BCCH is also transmitted by DL-SCH. There are multiple DL-SCH channel in a cell;

- “The multicast channel (MCH) is used to support MBMS.” (Dahlman et al. 2011.) The characteristics of MCH are semi-static transport format and semi-static scheduling;
- The uplink shared channel (UL-SCH) is used to transmit the uplink data;
- Random Access Channel (RACH) – it allows accessing the network in case of inaccurate information about uplink timing synchronization from UE, or when there are no allocated uplink transmission resources for UE.

4. SCHEDULING ALGORITHMS AND ENERGY EFFICIENCY

4.1. Scheduling in LTE

The channels in mobile communication can be characterized by significantly changing radio conditions. It is happening due to the frequency selective fading, shadow fading and etc. The channel-depended scheduling is responsible for sharing the radio resources between different users in the channel and provides efficient resource utilization. The scheduler is minimizing the total amount of resources per one user and also gives the opportunity to keep more users in the system. (Recommendation ITU-R M.1457-9 2010.)

The scheduler is responsible for the decision about transmitting data: which terminal will transmit the data or where to transmit it, and also, how many blocks of the resources will be used. The eNodeB transmits the scheduling information every 1ms of transmission time interval (TTI) and controls the transmission of the uplink and the downlink. This operation called dynamic scheduling. The decisions were made about scheduling are transmitted on the Physical Downlink Control Channel (PDCCH). The semi-persistent scheduling was used to decrease the amount of control signaling. (Recommendation ITU-R M.1457-9 2010.)

The downlink scheduler dynamically controls to which terminal to transmit and the amount of resource blocks by using the DL-SCH. The selection of modulation and coding scheme, antenna mapping, transport block size, and resource-block allocation for every carrier in downlink are under control of the eNodeB. Figure 14 shows this process. The uplink scheduler is controlling the transmission of terminals on the UL-SCH and the amount of block resources. The terminal regulates the logical-channel multiplexing and the scheduler is responsible for the transport format. This is also illustrated in Figure 14. (Recommendation ITU-R M.1457-9 2010.)

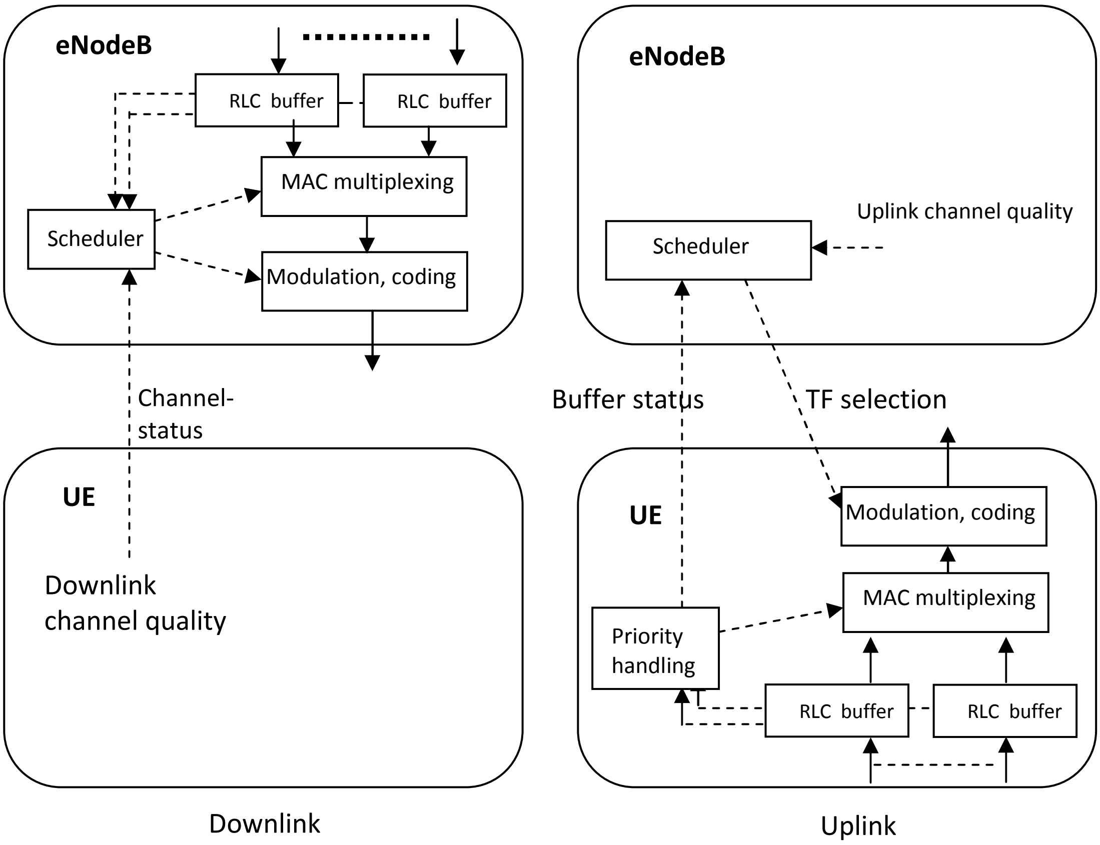

Figure 14. Selection of the transport format in the downlink and the uplink. (Dahlman, Parkvall & Sköld 2011.)

The semi-persistent scheduling is a scheduling which allows reducing the control signaling. The scheduling decision together with the information that it is appropriate for nth subframe is sent with PDCCH. So, the control information is not been sent in every subframe and this reduces the overhead.

The scheduling algorithms have to provide the fairness between users. There is one metrics to measure the fairness which is based on the Cumulative Distribution Function (CDF) of the throughput of all users. The scheduler will be fair if the CDF of the throughput is placed on the right side of the special line. Figure 15 illustrates this example.

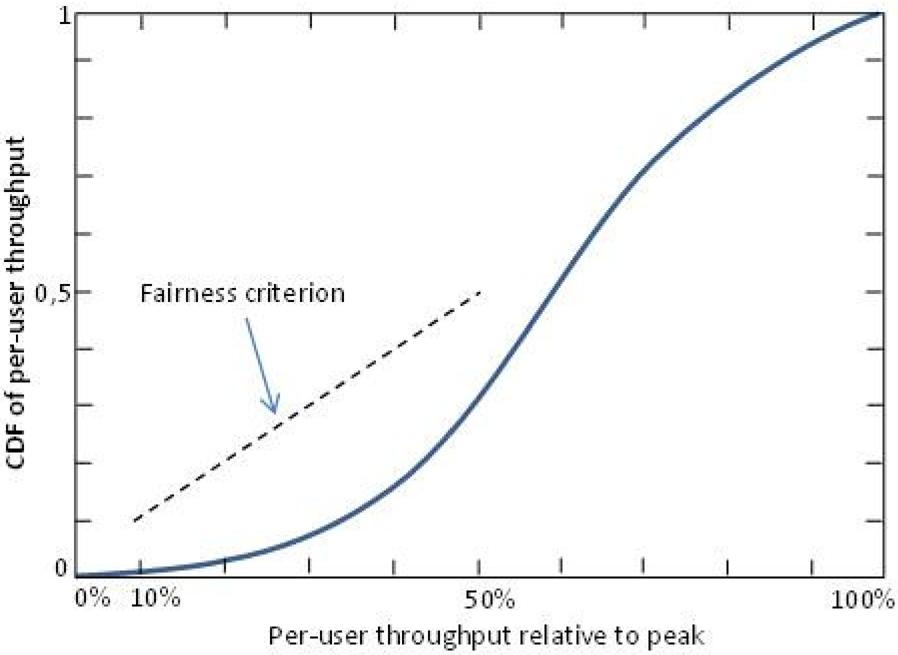

Figure 15. Evaluation of the scheduler's fairness based on the CDF of the throughput. (Sesia, Toufik & Baker 2011.)

Another common used metric to evaluate the fairness is called Jain index. It shows the variation in the throughput among all users.

$$J = \frac{\bar{T}^2}{\bar{T}^2 + var(T)}, 0 \leq J \leq 1 \qquad (5)$$

Where $\bar{T}$ is the mean and the var(T) is the variance of the average user throughputs. When var(T)→0 it means that the average user throughputs are similar to each other, and also the value of J become higher. So, in that case the scheduler providing high fairness to all users. (Sesia et al. 2011.)

The resource scheduling algorithm in the eNodeB has to be affected by the QoS statement about every logical channel. This information need to be very accurate to provide an effective scheduling. The scheduler in uplink and downlink receives the information regarding the channel quality in a different way. For the downlink case this knowledge is sent using the feedback of the Channel Quality Indicators (CQI) from UEs. The Sounding Reference Signals (SRSs) which are transmitted by the UEs provide the information about channel quality for the uplink case. The performance of scheduling algorithm depends on time when the CQI report and SRS have been received. The performance will be reduced if this information is received much earlier than the decision about scheduling was taken.

One more important factor for the scheduler is to get information about the queue status. For the downlink, the eNodeB has information about the amount of data in the buffer waiting for their transmission. For the uplink case, the Buffer Status Reports (BSRs) are used to inform the amount of data waiting for the transmission. BSRs are sent from the UE to the eNodeB.

4.2. Scheduling in the downlink

The downlink scheduler dynamically makes a decision which terminal will be chosen for receiving data and the amount of the resource blocks. The different terminals could be scheduled in a parallel using different amount of spectrum resources. Downlink scheduler is responsible for choosing the instantaneous data rate, MAC multiplexing and Radio link control (RLC) segmentation:

- RLC – for low data rate a part of RLC in TTI will be delivered and segmentation will be needed. For high data rate few RLC will be grouped together;
- MAC – the different streams have different priorities for a logical channel multiplexing. For example, the handover commands superiors streaming data, and streaming data is more important than background files;
- L1 – the scheduler affects the decision about modulation, coding, and amount of transport layers. (Dahlman et al. 2011.)

Downlink L1/L2 control signaling is used to send a scheduling decision to every scheduled terminal through PDCCH channel. All terminals get the scheduling

assignments with a subframe. The terminal whose identity is matching the assignments will receive the data. The main purpose of the schedulers is to consider the channel variation between terminals and to use it in a better way. There is information needed for scheduling:
- The terminal’s channel condition. The terminals send a channel state reports to the eNodeB;
- Condition of the buffer and data flows priorities. Different flows have different priorities and the scheduler takes it into account. Also, the terminals with empty buffer will obviously not be scheduled;
- The interference in the neighboring cells. One cell could send a signal to another cell to decrease the power due to high interference for the users. This information will be considered by a scheduler. (Dahlman et al. 2011.)

The downlink transmission from base station to different users inside one cell is mutually orthogonal. Theoretically, it means that the interference between transmissions does not exist. Time-division multiplexing (TDM), frequency-division multiplexing (FDM) or code-domain multiplexing (CDM) can be used to achieve the intra-cell orthogonality in downlink. The downlink multiplexing in LTE is a combination of TDM and FDM. The shared resources could be time, frequency and code. During parallel transmission the total transmit power in the cell will be also one of the shared resources. (Dahlman et al. 2011.)

In case of TDM-based downlink when one user is scheduled at a time, the maximum utilization of the radio resources will be achieved if all resources are given to the user with the best channel condition:
- The interference between transmissions can be minimized when the minimum transmit power is given for the required data rate. It is called the link adaptation based on the power control;
- The maximum link utilization can be reached when for a given transmit power the maximum data rate is achieved. It is called the link adaptation based on rate control. (Dahlman et al. 2011.)

In the downlink case the rate control is used more often. When the scheduler considers the instantaneous radio-link condition the scheduling is called channel-dependent. The maximum rate scheduling (max-C/I) is a case when the user with the best radio-link conditions will be scheduled. The channel condition is different every time. That means there is always a link with the best quality and the high data rate for scheduled user can be used. The expression of max-C/I scheduling can be found below:

$$k = argmaxR_i \tag{6}$$

Where R_i is the instantaneous data rate for user i.

Max-C/I scheduling could not be beneficial all the time. There can be a situation when one link is showing the worst condition all the time. In such case this terminal will not be scheduled at all. (Dahlman et al. 2011.)

Another type of scheduling is round-robin scheduling. This type of strategy does not consider the instantaneous channel conditions and users are taking the resources turn by turn. The round-robin scheduling is more fair than max-C/I because it gives the same amount of radio resources for each links. But in the sense of quality of service round-robin is worse than max-C/I. The round-robin can give the maximum resources for the link with a bad channel conditions. (Dahlman et al. 2011.)

It is important for scheduling technique to be able to use the fast channel variations to provide the high cell throughput and also provide at least the minimum throughput for all users. There are different types of variation in the service quality that have to be considered when chosen the type of scheduler:

- Fast multi-path fading and fast changes in the interference level can cause the fast changes in the service quality;
- Because of the long distances to the cell long-term changes in the services quality may happen. (Dahlman et al. 2011.)

There is one more scheduler that works between round-robin scheduler and max-C/I scheduler called proportional-fair scheduler. The mathematical expression of such technique is given below.

$$k = argmax\frac{R_i}{\overline{R_i}} \tag{7}$$

Where R_i is the instantaneous data rate for user i, $\overline{R_i}$ is the average data rate. The average data rate is calculated within the average period T_{PF}. The average period T_{PF} was chosen to find the average data rate. This period should be longer than the short-term variations and also short enough so user will not notice the variations. Basically this period can be chosen to be about 1 second. (Dahlman et al. 2011.)

In all examples above TDM with single user scheduled at a time was assumed in the downlink. There are some situations when TDM cannot work alone and CDM and FDM are also used. When user does not have a lot of data to transmit, the utilization of all channel capacity is not sufficient, so another user can also be scheduled using FDM or CDM. (Dahlman et al. 2011.)

Greedy filling approach can be used in situation with small payloads when one user needs to transmit the small amount of data. Another user (the second best user according to the scheduling scheme) can be scheduled in such case. (Dahlman et al. 2011.)

It is worth to mention that in standards of LTE the right scheduling strategy is not specified. The base station is aware of the scheduling algorithm. The standards only support the scheduling with quality measurements and reports. (Dahlman et al. 2011.)

Figure 16 illustrates the behavior of three different scheduling algorithms.

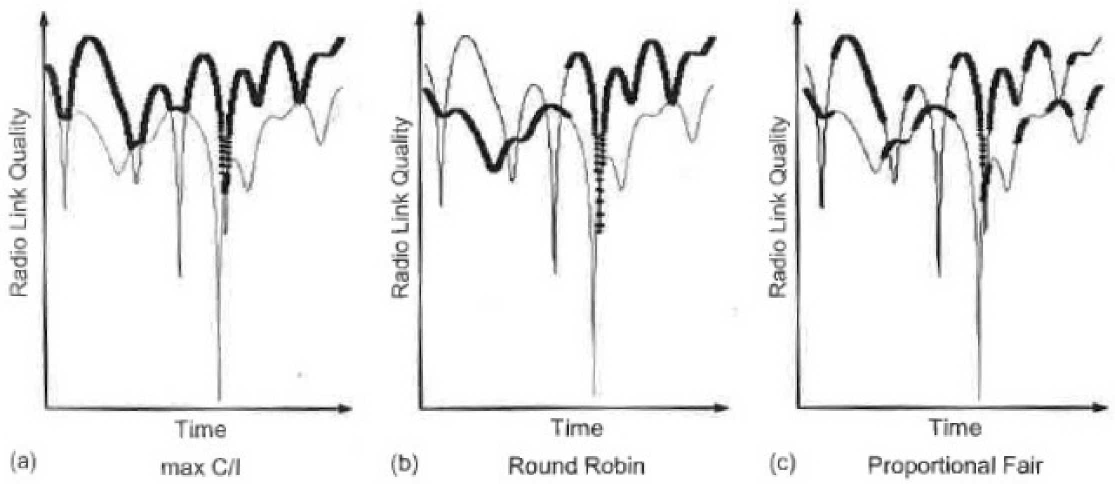

Figure 16. The behavior of three different scheduling algorithms. (Dahlman, Parkvall & Sköld 2011.)

4.3. Scheduling in the uplink

The discussion above was about scheduling in the downlink. Now, the uplink case will be considered. The uplink scheduler maintains similar function as the downlink scheduler. The eNodeB is responsible for sharing the time-frequency resources and it controls the transport format that the terminal will use. It makes possible not to send the control signaling information from the terminal to the eNodeB. When the scheduler is responsible for the selection of the transport format it helps to get detailed information about the terminal, for example about buffer and available power. The scheduling grants contain the information about scheduling decision and transport format. When terminal receive the valid grant it can send the data using UL-SCH. As in the downlink case, terminals control the PDCCH to detect the appropriate grant.

The uplink scheduler as the downlink scheduler operates with the information about the buffer, the channel quality, the interference and the flow’s priorities. The channel-dependent scheduler is also used in the uplink. When the variations of the channel are very fast the uplink diversity can be used. The frequency hopping is one way to make the uplink diversity. Inter-cell interference is also controlled by exchanging information between different cells. (Dahlman et al. 2011.)

In the uplink all users share the power resources. The power used by one user is noticeably lower than the power used by one base station. This fact influences on the scheduling in the uplink. One terminal usually cannot have enough power to fully use the link capacity. TDMA with FDMA and CDMA is used in the uplink as shared resources.

The type of multiple access, orthogonal or non-orthogonal, have an effect when scheduling in uplink is chosen.

The power control will be used if in the uplink non-orthogonal multiple access scheme is chosen. It is important to control the interference level when transmitting data. Power control will prevent too high data rate and will allow other users also to transmit their data. (Dahlman et al. 2011.)

In orthogonal case the power control is not required and the scheduling will be as in the downlink case. The users will be given some part of the whole bandwidth.
Max-C/I scheduler is also the one of the strategy in the uplink. The resources will be given to the user with the best radio link conditions. Also, in non-orthogonal case the greedy filling algorithm is used. In that case, the user will be given as much data rate as possible. If the interference level is lower than the maximum another second best user will be scheduled.

Round-robin scheduler can be used when scheduler has no information about instantaneous channel condition. So, the resources will be given to the users turn by turn.

The power that the terminal can transmit is limited. So, uplink resources are shared also in frequency and time domain. The data rate for terminals far from base station will not be increased with more bandwidth. It is better to allocate some small amount of bandwidth to such terminal and give more for other terminals that are closer to the BS. (Dahlman et al. 2011.)

Low and high system load have an impact for the scheduling performance. At high load the acting of schedulers is visibly different unlike at low system load where the difference is not so noticeable. It is very important to provide a trade-off between fairness and system throughput even if the fairness is higher when the throughput of the system decreases. Also, the traffic characteristics have a big effect on the trade-off between the service quality and the throughput.

Three schedulers will be considered to show this:
– Round- robin (RR) scheduler – the channel quality is not considered;
– Proportional – fair (PF) scheduler – the average data rate during long-term channel variations is used;
– Max-C/I scheduler – the user is scheduled if it has the best instantaneous channel conditions. (Dahlman et al. 2011.)

The full buffers and web-browsing traffic model were taking into account. For the first case, the max-C/I scheduling will not provide fairness to user with a bad channel conditions. In contrast, the proportional-fair scheduling will select the user considering the highest data rate with respect to its average data rate. So, the fairness between users will be provided. In case of web-browsing traffic model the situation will be different. The user will need a web page, after transmitting it there is no data to transmit until the user will click another page to open. When it happens the max-C/I scheduler will find another user to schedule with the highest data rate. It will give some fairness between users. Figure 17 (Dahlman et al. 2011.) shows the difference between the full buffer and the web- browsing traffic.

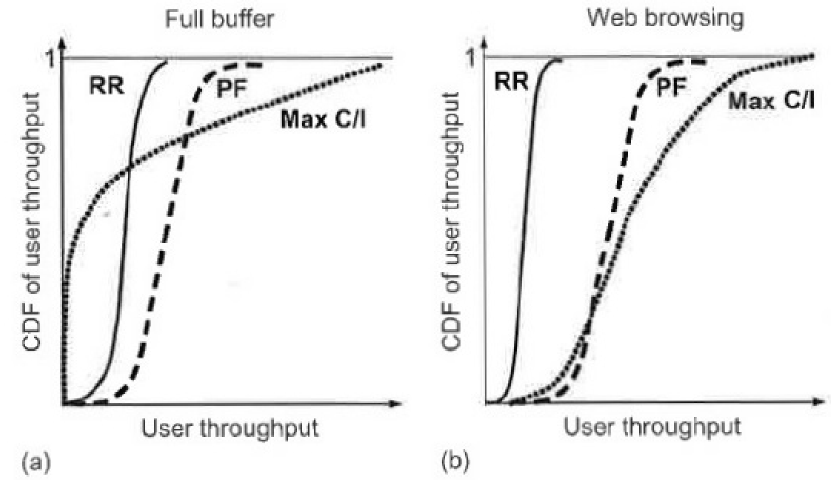

Figure 17. Schedulers' behavior for a) full buffer; b) web-browsing model. (Dahlman, Parkvall & Sköld 2011.)

4.4 Uplink power control and energy consumption

Uplink power control is used in LTE to make sure that the signals are received with enough power for detection and demodulation. Also, the power used for transmission should not be very high because it will bring the undesirable interference to the other cells. The channel properties such as level of noise and interference and the channel attenuation are used for setting the transmit power. Moreover, if the power will be low in case of transmission on PDSCH, it will be possible to increase the power or to reduce the data rate. (Dahlman et al. 2011.)

The power control has to deal with the interference from the other users, path-loss, fast fading and shadowing. LTE provides a combination of closed-loop and open-loop power control. This combination needs less feedback than the single closed-loop scheme. The open-loop mechanism means that the transmitted power relies on the estimation of the downlink path loss and the term "closed-loop" indicates the transmit power can be regulated by power-control commands from downlink transmission. (Sesia et al. 2011.)

Every physical channel has an independent power control. Sometimes when there are multiple transmissions in parallel of the physical channels the total power of all channels can be greater than the maximum output power of the terminal P_{TMAX}. In that case, the required power is first assigned for the transmission of the L1/L2 control signaling. The rest of the power will be allocated for the remaining physical channels. (Dahlman et al. 2011.)

Physical Uplink Control Channel (PUCCH), Physical Uplink Shared Channel (PUSCH) and Sounding reference signals (SRSs) in LTE have the detailed power control formula.

Nowadays, the problem of decreasing the battery life of mobile phones became more dramatic. New technology allows user to use more application, with a faster download speed and more services are provided for their usage. All this factors lead to the fact that the battery discharging very fast. The mobile's energy consumption can be decreased with an optimized hardware (HW) and software (SW). Energy consumption of the HW can be decreased using more power efficient components and applying power management, for example choosing the sleep mode for the idle details of the HW. The energy consumption can be minimized by optimizing the resources of the mobile phone. It is possible to reduce the energy consumption with SW control of transmitted data from every application. Another possibility is to modify the modem of the UE to reduce the energy consumed by the mobile. For this purpose, the optimized network control parameters. (Lauridsen, Jensen & Mogensen 2011.)

According to the Sesia et al. 2011 the equation used for the power control in the uplink is the following:

$$UE\ transmit\ power = \underbrace{P_0 + \alpha \cdot PL}_{\substack{basic\ open-loop \\ operating\ point}} + \underbrace{\Delta_{TF} + f(\Delta_{TPC})}_{dynamic\ offset} + \underbrace{10 \log_{10} M}_{bandwidth\ factor} \qquad (8)$$

Where P_0 is the base level for the PUSCH (-126dBm to +24dBm per RB), α is the fractional path-loss compensation factor, PL is the downlink path-loss estimate, Δ_{TF} is a

Transmitter Power Control (TPC) command, $f(\Delta_{TPC})$ introduces the accumulation, M is the number of RB.

The equation (8) illustrates the fact that allocation of the Physical Resource blocks has an impact on the energy consumption in the uplink.

There are three steps to set the output power level of UE:

- There is a maximum output power for each UE power class, with 4 classes in total. The latest specification of Release 9 give the maximum power equal to 23dB±2dB defined for the UE power class 3;
- Maximum Power Reduction (MPR) - the reduction of the maximum output power for higher order modulation and for transmission of resource blocks Table 4 give the MPR for power class 3;
- Additional Maximum Power Reduction (A-MPR) is used to reduce the power in addition to the MPR due to some spectrum emission requirements. (3GPP TS 36.101 version 9.19.0 Release 9.)

Table 4. Maximum power reduction for power class 3. (3GPP TS 36.101 version 9.19.0 Release 9.)

Modulation	Channel Bandwidth / Transmission bandwidth (N_{RB})						MPR (dB)
	1.4 MHz	3.0 MHz	5 MHz	10 MHz	15 MHz	20 MHz	
QPSK	> 5	> 4	> 8	> 12	> 16	> 18	≤ 1
16 QAM	≤ 5	≤ 4	≤ 8	≤ 12	≤ 16	≤ 18	≤ 1
64 QAM	> 5	> 4	> 8	> 12	> 16	> 18	≤ 2

The output power dynamic for the UE are the following:

- Minimum output power – it is the broadband transmit power of the UE, the mean power in one subframe (1 ms). The value for UE minimum output power is set to -40 dBm.

- Transmit off power – the mean power when transmitter is off. The value for that power cannot exceed the -50 dBm.
- On/Off time mask – it is the period between transmit on and off power and vice versa.
- Power control can be: absolute power tolerance, relative power tolerance and aggregate power control tolerance.

Absolute power tolerance allows to the UE transmitter to select its initial output power for the first subframe at the start of a contiguous transmission or non-contiguous transmission with a transmission interval more than 20 ms.

Relative power tolerance allows to the UE transmitter to choose the output power for the required subframe similar to the power of the last transmitted subframe in case when the transmission gap between those subframes is bigger less than 20 ms.

“Aggregate power control tolerance is the ability of a UE to maintain its power in no-contiguous transmission within 21 ms in response to 0 dB TPC commands with respect to the first UE transmission, when the power control parameters are constant.” (3GPP TS 36.101 version 9.19.0 Release 9.)

4.5. Power consumption in the downlink

The main energy consuming components are Base Stations (BSs) or eNodeBs as denoted in LTE standard. Among all components in the BS the power amplifier (PA) consumes the most energy. There is no requirement for output power of the base station. However, there is a limit for the maximum output power to be 24 dBm for Local Area base stations and for Home base station the maximum output power have to be 20 dBm. It is also allowable for the maximum power to vary from the defined power. In addition, the total power control has a dynamic range for a resource element, which allows configuring the power range. (Dahlman et al. 2011.)

According to the 3GPP specification there are the following definitions for the power of a BS:

- "Output power (P_{out}) of the base station – it is the mean power of one carrier delivered to a load with resistance equal to the nominal load impedance of the transmitter"; (3GPP TS 36.104 version 9.13.0 Release 9.)
- "Maximum output power (P_{max}) of the base station – it is the mean power level per carrier measured at the antenna connector during the transmitter ON period in a specified reference condition"; (3GPP TS 36.104 version 9.13.0 Release 9.)
- "Rated output power (P_{RAT}) of the base station – it is the mean power level per carrier that the manufacturer has declared to be available at the antenna connector during the transmitter ON period." (3GPP TS 36.104 version 9.13.0 Release 9.) The P_{RAT} of the BS is specified in Table 5 that was taken from the specification 3GPP TS 36.104 version 9.13.0 Release 9.

Table 5. Base station rated output power. (3GPP TS 36.104 version 9.13.0 Release 9).

BS class	P_{RAT}
Wide Area BS	no upper limit
Local Area BS	≤ +24 dBm (for one transmit antenna port) ≤ +21 dBm (for two transmit antenna port) ≤ +18 dBm (for four transmit antenna port)
Home BS	≤ +20 dBm (for one transmit antenna port) ≤ +17 dBm (for two transmit antenna port) ≤ +14 dBm (for four transmit antenna port)

- P_{max} of the base station can vary from the P_{RAT} within the range of +2dB to -2dB in normal conditions. When extreme conditions happen, the P_{max} can deviate from the P_{RAT} within the range of +2.5 dB to -2.5 dB. (3GPP TS 36.104 version 9.13.0 Release 9.)

Power control is used for BS to limit the interference. The BS output power dynamic range includes the following areas:

- Power control dynamic range for resource element (RE) – it is the difference between the RE power and the average RE power. Table 6 gives the minimum requirements for the RE power control dynamic range;
- Total power dynamic range – the difference between the maximum and the minimum transmit power of one resource block. The minimum requirements is stated in Table 7;
- Transmitter off power – it is the mean power estimated during 70 us filtered with a square filter over the transmitter OFF period. Power spectral density of the transmitter OFF power have to be < -85 dBm/MHz;
- Transient period – it is the period when transmitter is turning from off period to the on period and reverse. The length of transient period is 17 us; (3GPP TS 36.104 version 9.13.0 Release 9.)

Table 6. RE power control dynamic range. (3GPP TS 36.104 version 9.13.0 Release 9.)

Modulation scheme	RE power control dynamic range	
	(down)	(up)
QPSK (PDCCH)	-6 dB	+4 dB
QPSK(PDSCH)	-6 dB	+3 dB
16QAM (PDSCH)	-3 dB	+3 dB
64QAM (PDSCH)	0 dB	0 dB

Table 7. Total power dynamic range. (3GPP TS 36.104 version 9.13.0 Release 9.)

E-UTRA channel bandwidth	Total power dynamic range
1.4 MHz	7.7 dB
3 MHz	11.7 dB
5 MHz	13.9 dB
10 MHz	16.9 dB
15 MHz	18.7 dB
20 MHz	20 dB

There are several works that propose the following decision for saving energy from the BS:

1) Switching off the redundant base station (BS);
2) Energy efficient deployment strategy;
3) Improvement of the hardware components. (Bousia, Kartsakli, Alonso &Verikoukis, 2012.)

There are some factors that have an influence for the power consumption in a base station:

- DC power supply efficiency. All components of transceiver in the base station require a dc power supply. Power supply efficiency is about 85-90%; (Kumar & Gurugubelli 2011.)
- Cooling loss. All components of the BS during the operation disperse the power in the form of heat. In that case the cooling equipment is required to maintain the necessary temperature. Such equipment also needs the power to operate. Cooling loss of the base station is the power required for the cooling equipment; (Kumar et al. 2011.)
- PA linearity. Power amplifier has to be linear. It is very important because the system performance and efficiency depend on it. If PA is nonlinear it will bring a distortion to the signal's waveform in time domain. In frequency domain the spectrum will be increased leading to the interference in the neighboring bands. PA power consumption and safety margin between bands will be also increased. This makes the reduction of the spectral efficiency. That's why the power leakage should be minimized to make the PA more efficient; (Kumar et al. 2011.)
- BS utilization. Base stations have to be better utilized. BS's design required to handle the peak traffic. That is why 80-90% of the time the BS is underutilized. So, minimization of the energy consumption for low traffic is needed; (Kumar et al. 2011.)
- Peak to average power ratio. The number of subcarriers and the autocorrelation of the data is affecting on the PAPR. The PAPR is very high for the OFDMA systems. OFDMA has more than 256 subcarriers and PAPR is about 10-15 dB; (Kumar et al. 2011.)

- Cable and coupling losses. Base station is connected with the antenna using cables. Usually BS is set on the ground. The cable transmits a very high power RF signal from the transceiver to the antenna. It leads to the power loss in cables. (Kumar et al. 2011.)

4.6. Green communication in LTE

Mobile communication is developing very fast. This also leads to the growing of the energy consumption. The 4th generation requires a huge amount of energy due to the complexity of the methods it uses. OFDMA in downlink and SC-FDMA in uplink use a complex computation, which leads to an increased power consumption of the transceiver hardware. The growth of the energy consumption brought a high cost to the operators. It also enhances the carbon emission bringing a vast pollution to the environment. That is why the energy issue draw such a big attention now and before. (Zhang, Ma, Yang & Leng, 2013.)

When thinking about saving energy it is important to keep the system performance on a high level. It is a very challenging task because some of the proposed methods cause the degradation in system throughput.

Before starting with the methods that save the energy, the meaning of energy efficiency have to be given. Energy efficiency can be seen as the ratio of useful work to the total consumed energy. A useful work is a work that needs to transmit and receive the modulated signal.

Also, there are two methods to measure the energy efficiency. One is the ratio of output energy/power to the total input energy/power. Power supply, power amplifier, and antennas are using this method for the measurement. Another method is the performance per unit of energy consumption. This is used for the throughput in communication systems. (Chen, Yang, Zhang, Kim & Korneman, 2011.)

The modulation of information to the form of electrical, electromagnetic and optical waveform is required for transmitting the data. For this reason the electronic components are needed, that in reality are not so perfect. They turn out a huge amount of energy to the heat. In wireless systems there are a space between transceiver and receiver. Only some amount of energy arrives to the receiver. All those challenges have to be improved. (Chen et al. 2011.)

The formula of energy efficiency in communication system is given below. The channel is assumed to be Gaussian. (Chen et al. 2011.)

$$\eta_{EE} = \frac{R}{P} = \frac{B}{P} log_2(1 + \frac{P}{BN_0}) \tag{9}$$

Where R – is a bit rate of information, P – is the received power, B – is the bandwidth, N_0 – is noise power spectral density.

This equation shows the measurement of energy efficiency (EE) for a general communication system. In a wireless system the equation will be more complicated with more parameters to consider. Also, from the given equation some details about EE can be seen. EE does not monotonically increases with B or P. There is a trade-off between the bandwidth and the energy. The high throughput performance and the maximum EE are conflicting with each other. The optimum solution has to be found. (Chen et al. 2011.)

The discussion of the energy saving methods in a base station is given below. Figure 18 shows some techniques for saving energy in a BS. The solution is divided into time, frequency, spatial and hybrid. (Chen, Zhang, Zhao & Chen, 2010.)

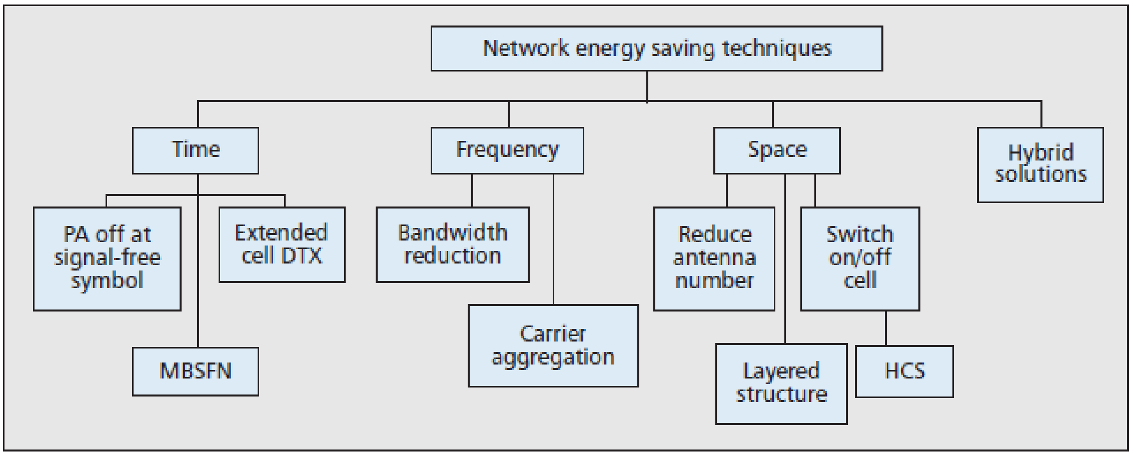

Figure 18. Network energy saving methods for LTE. (Chen, Zhang, Zhao & Chen, 2010.)

The idea of the time domain solution is to turn off the PA if there is no traffic in the downlink. There are three ways to do it. One way is to close PA when downlink data symbol is a signal-free. The number of a reference signal remains the same. Reference signals (RS) are transmitted in each subframe to receive the channel state information (CSI). (Chen et al. 2010.)

The second way is the Multicast broadcast single frequency network (MBSFN) structure to reduce the number of RS. Six subframes out of ten transmit only one RS, when in the normal case the number of RS is four. (Chen et al. 2010.)

The third way of the time domain solution for saving energy is extended cell Discontinuous Transmission (DTX) approach. This solution also reduces the number of RS. If there is no traffic in the downlink there is no transmission in eight subframes. The problem is that during the day such situation without traffic is very rare. Also, this method reduces the system performance. The reduced number of RS could cause the problems of synchronization BS with the mobile equipment. (Chen et al. 2010.)

There are two methods for the frequency domain solution. The first solution is to reduce the bandwidth when the downlink traffic load is low. This method is suitable for the low traffic load. But also it doesn't turn off the PA. In the operating mode the PA spends more energy than in inactive mode. Also, the PA operates at some optimum output power range. (Chen et al. 2010.)

Another method for saving energy in the frequency domain is carrier aggregation. In this case, carriers are divided into groups and each group is served by different PA. If some group of carriers has no traffic the PA will be turned off. (Chen et al. 2010.)

One way of the spatial domain solution is to reduce the number of antennas. In this case the cell size will be smaller. PA of deleted antennas will be turned off. Figure 19 illustrates this approach.

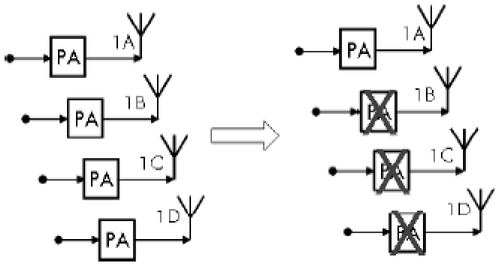

Figure 19. Reducing the antenna number. (Chen, Zhang, Zhao & Chen, 2010.)

Second approach is to switch off the base station. When the downlink traffic is low, some BSs are switched off and mobiles are served by another active BS. In busy times, the BS can be switch on again. There is a special case of BS switching off method. It is called hierarchical cell structure (HCS). In this method the macrocell is used for the basic coverage and a small cell is used when the traffic is getting higher. (Chen et al. 2010.)

A hybrid solution is a combination of different solutions together. It adjusts the energy consumption of the base station in a different traffic condition. For example, if the traffic is low the carrier aggregation can be used, together with single antenna and a reduced bandwidth together. All this significantly save the energy. “The challenge of hybrid solutions is the processing/interruption time and signaling for system reconfiguration, as well as avoidance of the impact on UE performance.” (Chen et al. 2011.) Figure 20 shows the energy consumption for the different energy saving methods in LTE.

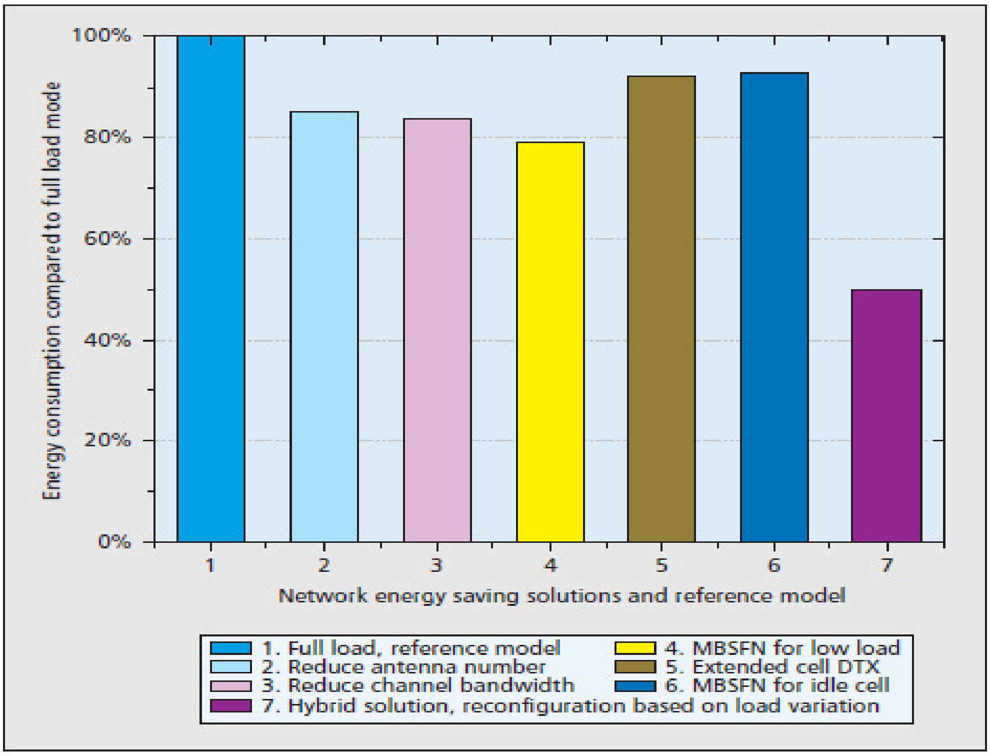

Figure 20. The energy consumption of different energy saving methods in LTE. (Chen, Zhang, Zhao & Chen, 2010.)

5. SIMULATION RESULTS

The simulations in this chapter were made with the simulator LTE_System_Level_1.6_r885. The LTE downlink OFDMA scenario will be considered in the following simulations. Figure 21 illustrates the mean, edge and peak throughput. Three different scheduling algorithms were chosen : Round Robin, Best Channel Quality Indicator and Proportional Fair. Closed loop spatial multiplexing with 2x2 antenna configuration, 20 MHz bandwidth and 20 users in the cell. The simulation time is chosen equal to 50 TTI. Where TTI is equal to 1ms. The pathloss model was chosen according to the 3GPP technical specification TS 36.942. The scenario in the following simulation is done for the urban area model. The propagation model is the following:

$$L = 40(1 - 4 \cdot 10^{-3} \cdot Dhb) \cdot \log_{10}(R) - 18 \cdot \log_{10}(Dhb) + 21 \cdot \log_{10}(f) + 80dB \quad (10)$$

Where Dhb is the height of the base station antenna measured in metres from the average rooftop level, R is the base station UE separation in km, and f is the carrier frequency in MHz.

The carrier frequency was taken equal to the 2000 MHz and Dhb = 15 m above the average rooftop level according to the 3GPP technical specification TS 36.942. Then the equation 10 will be in the following form:

$$L = 128.1 + 37.6 \log_{10} R \quad (11)$$

After L propagation factor is found the pathloss can be described by the following formula:

$$Pathloss_{macro} = L + LogF \quad (12)$$

Where LogF is the log-normally distributed shadowing with the standard deviation of 10 dB.

For the first mean throughput it can be seen that the Best CQI has the maximum value and the Round Robin has the smallest one. The drawback of the Best CQI scheduler is a very low fairness among the users. It is happennig because this scheduler give the resources only to the user with the best channel conditions. The users that have all the time a bad channel quality will be not scheduled at all. In contrast, the Proportional Fair scheduler has the best fairness among the users. Despite on the very high peak throughput of Best CQI scheduler it is not serving the users that have a bad channel condition, the edge throughput is equal to 0.

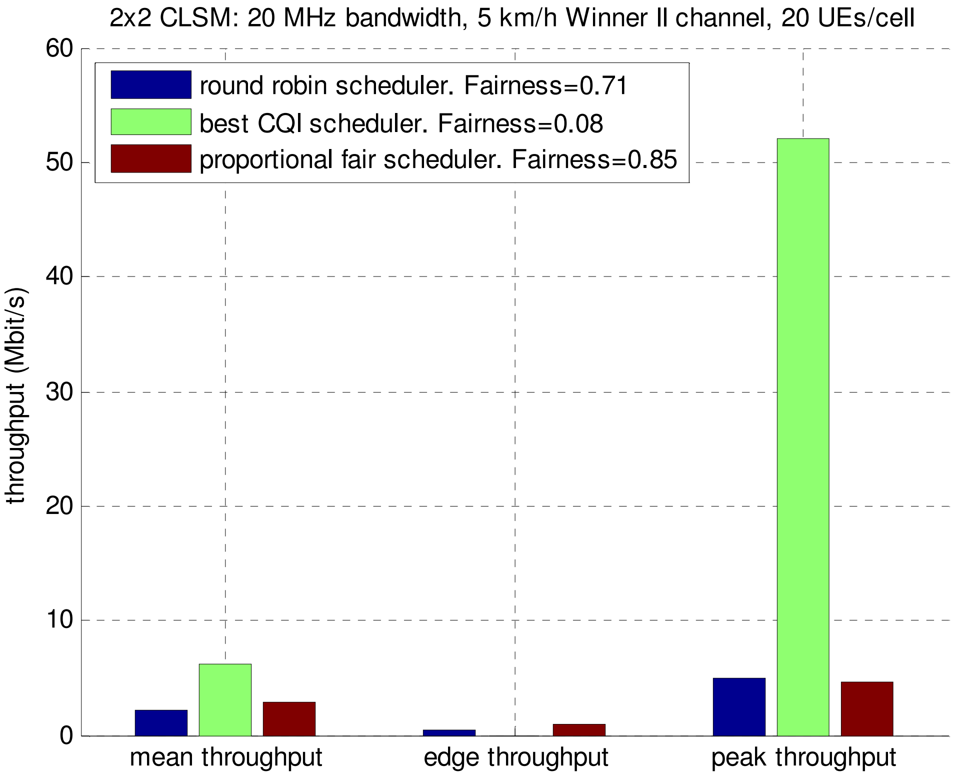

Figure 21. UE Throughput comparison for different scheduling algorithms.

Figure 22 illustrates the empirical CDF of throughput of different scheduling algorithms. It can be seen that the probability of throughput to be equal to 0 for max CQI scheduler has the very big chances, the ECDF of it is about 0.64. But from the other side it can achieve the higher throughput than Proportional fair and Round Robin schedulers. The black dots on the graphs correspond to the mean value.

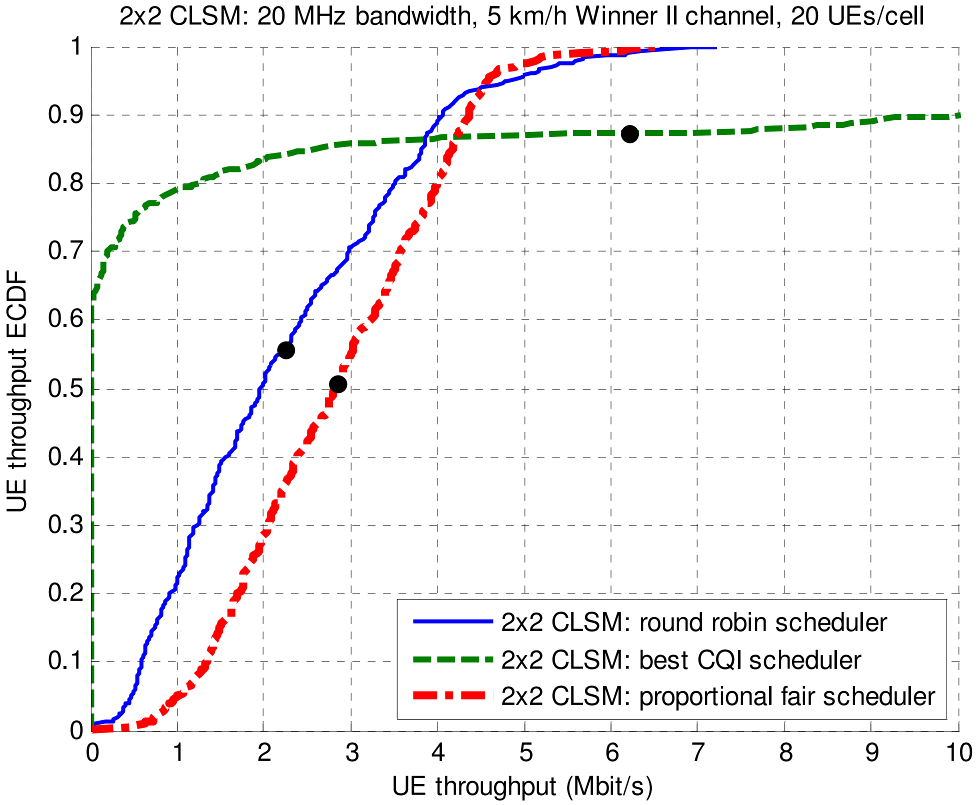

Figure 22. The empirical CDF of the throughput of different scheduling algorithms.

Figure 23 compares the throughput of different antenna configurations. The 4x4 antenna configuration can achieve the highest throughput.

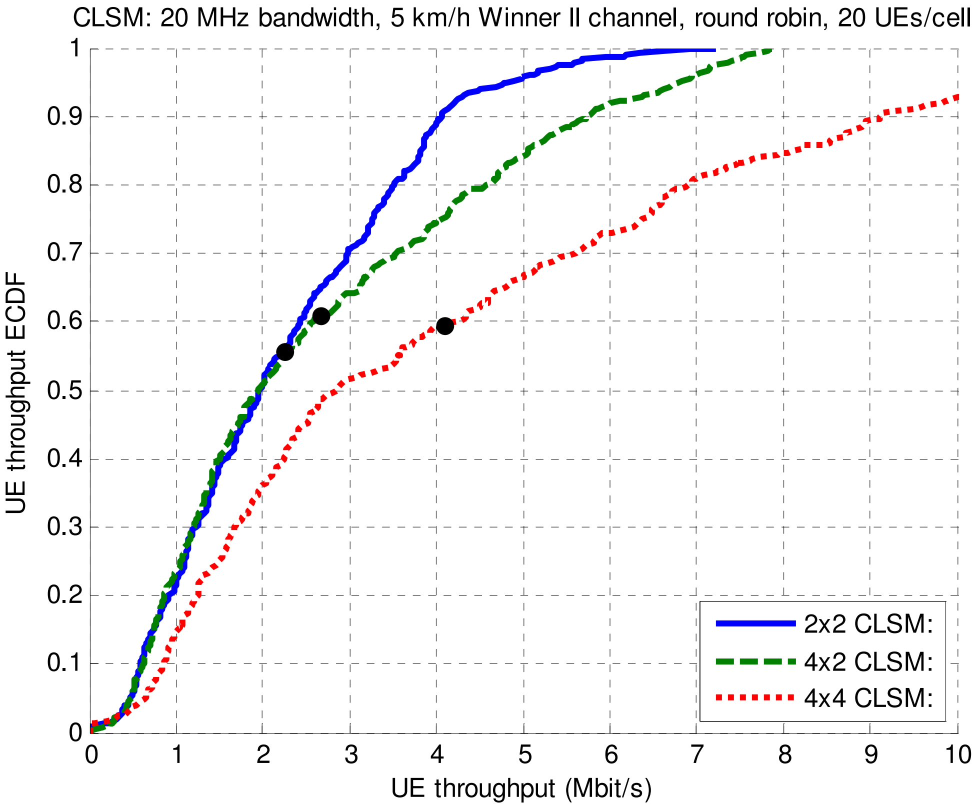

Figure 23. The comparison of throughput with different antenna configurations.

Figure 24 compares the throughput of the different antenna configuration regarding to the SINR. When the SINR is less than 5 dB the increasing the number of antenna will not significantly increase the throughput. The result shows that more receiver and transmitter antennas can improve the performance of the system when the SINR is higher than 5 dB.

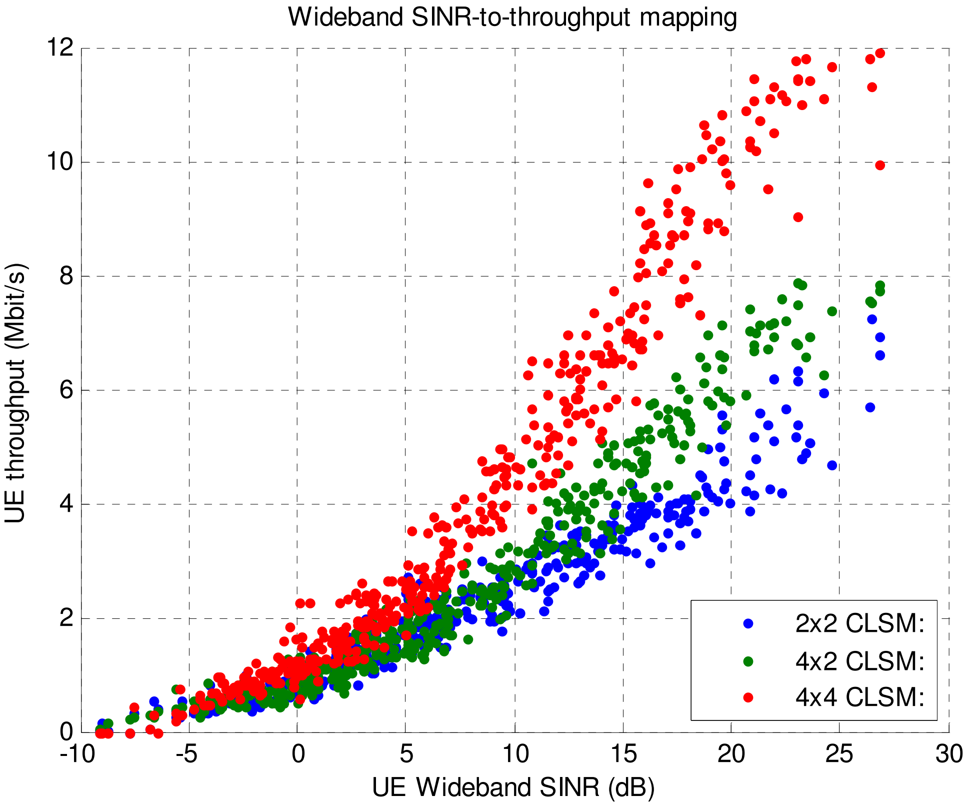

Figure 24. UE throughput vs. SINR.

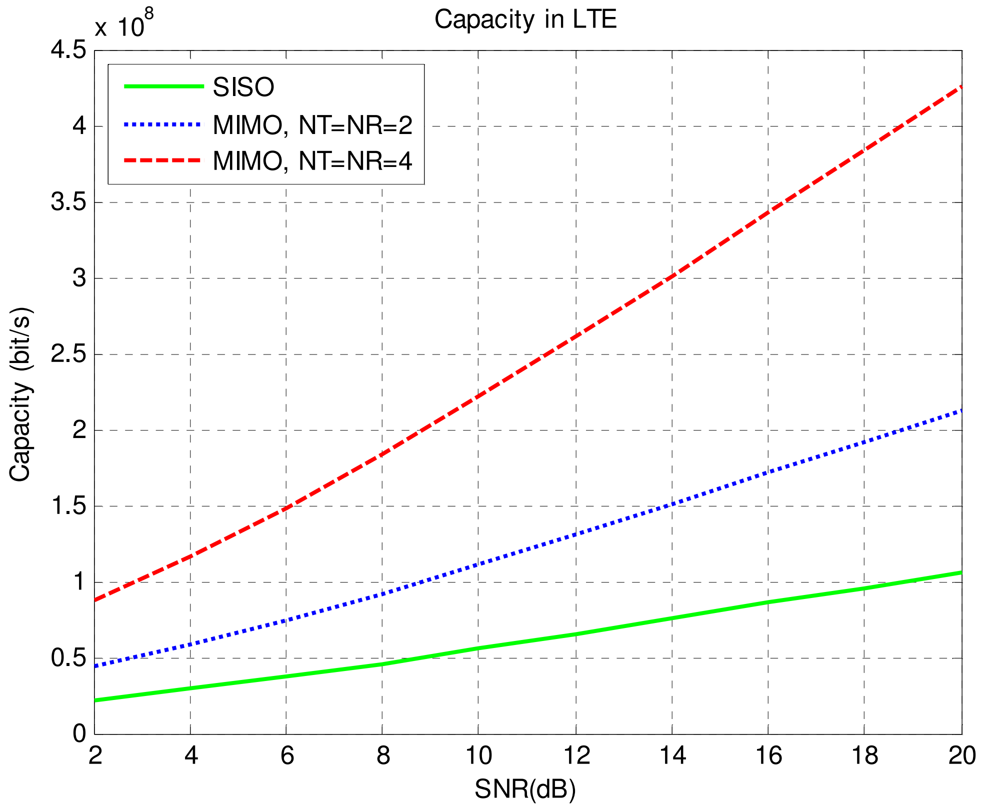

Figure 25. Shannon capacity vs. SNR.

For the following results the LTE_Link_Level_1.7_r1089 simulator were used. Figures 26, 28, 30, 32 give the result of throughput with different transmissions modes: Transmit Diversity (TxD); Open Loop Spatial multiplexing (OLSM); Single Antenna (SISO) and different number of retransmissions. The simulation time is 5000 TTI or 5000 subframes and the bandwidth is equal to 1.4 MHz. Number of Channel Quality Indicators (CQI) is 7.

Figure 26 illustrates the situation where the number of retransmissions (re-tx) is three. The channel type is considered as ITU Pedestrian B channel model PedB type according to the Recommendation ITU-R M.1225. The pathloss model for PedB channel is the following:

$$L = -10\log_{10}\left(\frac{\lambda}{2\sqrt{2\pi R}}\right)^2 - 10\log_{10}\left(\frac{\lambda}{2\pi^2 r}\left(\frac{1}{\theta} - \frac{1}{2\pi+\theta}\right)^2\right) - 10\log_{10}(d/R)^2 \tag{13}$$

where R is the mobile to base separation,

$$\theta = tan^{-1}\left(\frac{|\Delta h_m|}{x}\right) \tag{14}$$

$$r = \sqrt{(\Delta h_m)^2 + x^2} \tag{15}$$

Δh_m is the difference between average mobile height and average building height and x is the distance between mobile and diffracting edges,
d is the average separation between the buildings.

Table 8 gives the rest of the PedB channel's characteristics.

Table 8. Channel model B. (Recommendation ITU-R M.1225.)

Tap number	Relative tap delay value (ns)	Tap amplitude distribution	Parameter of amplitude distribution (dB)	Average amplitude with respect to free space propagation	Rice factor (dB)	Doppler spectrum
1	0	LOS: Rice NLOS: Rayleigh	10log(c) 10log(P_m)	0.0 -9.5	7 -	Rice Classic
2	100	Rayleigh	10log(P_m)	-24.1	-	Classic
3	200	Rayleigh	10log(P_m)	-25.1	-	Classic

The usage of more retransmissions could improve the system performance during bad channel conditions. The Hybrid Automatic Repeat request (HARQ) is used in LTE for retransmission. Figure 26 and Figure 30 were compared to each other. The channel type is the same and the number of retransmission is different. It is become obvious that the HARQ procedure will not increase the throughput comparing to the procedure with no

HARQ when SNR is higher than 10dB. That mean when the channel is good enough, the packets will not be lost so often and more retransmission is not required.

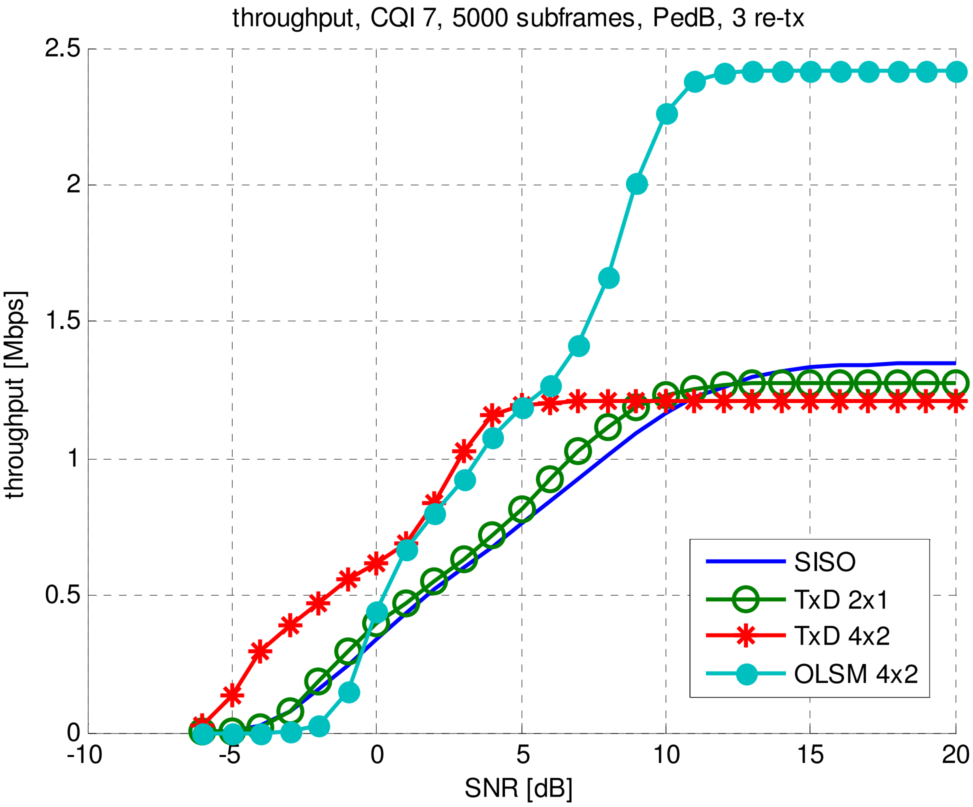

Figure 26. Throughput vs. SNR with different transmission schemes, the channel type PedB and 3 re-tx.

The Block Error Rate for the PedB channel type is lower than for flat Rayleigh channel type. The difference between BLER curves with HARQ retransmission and with no HARQ is only 2 dB after SNR is more than 0. The transmission mode TxD 4x2 is enhancing the system performance by decreasing the number of erroneous block, the blocks with errors. The OLSM scheme demonstrates the receiving of more blocks with errors. The SISO model has the worst case scenario for the BLER. This shows how the transmission schemes could improve the system performance.

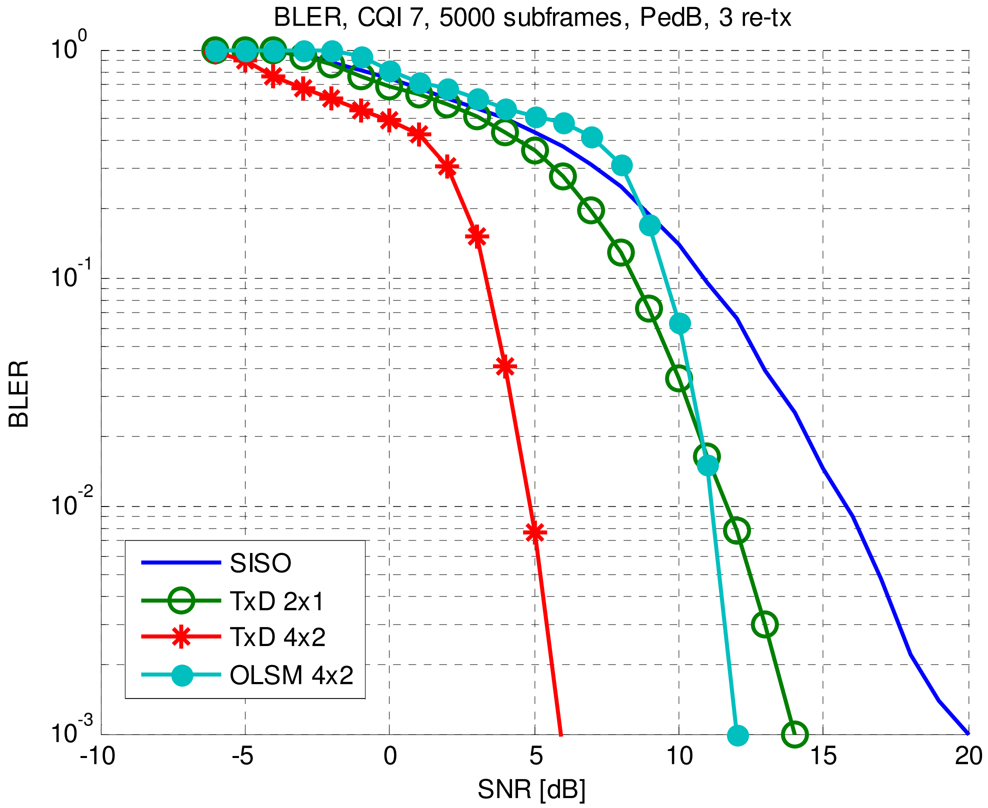

Figure 27. BLER for PedB channel and 3 re-tx.

The utilization of the transmit diversity scheme TxD 4x2 is showing a better result than OLSM 4x2 for SNR < 5 dB. Thus, the transmit diversity scheme is more beneficial in a situation with low SNR. In case of a better channel quality the OLSM 4x2 scheme is giving the highest throughput in comparison with other transmission modes. The feedback from the user in the case of an open loop spatial multiplexing includes only the number of the transmitted layers and not primary precoding matrix.

For flat Rayleigh channel the situation is almost the same as for PeB channel. The different transmission modes make an effect for the throughput. When the SNR is low the TxD 4x4 illustrates higher throughput then OLSM 4x2. This can be useful to adapt the transmission mode when the channel quality is getting better or worse. When SNR is high enough the OLSM scheme achieves the highest data rate between the rest of the modes demonstrated in the figure.

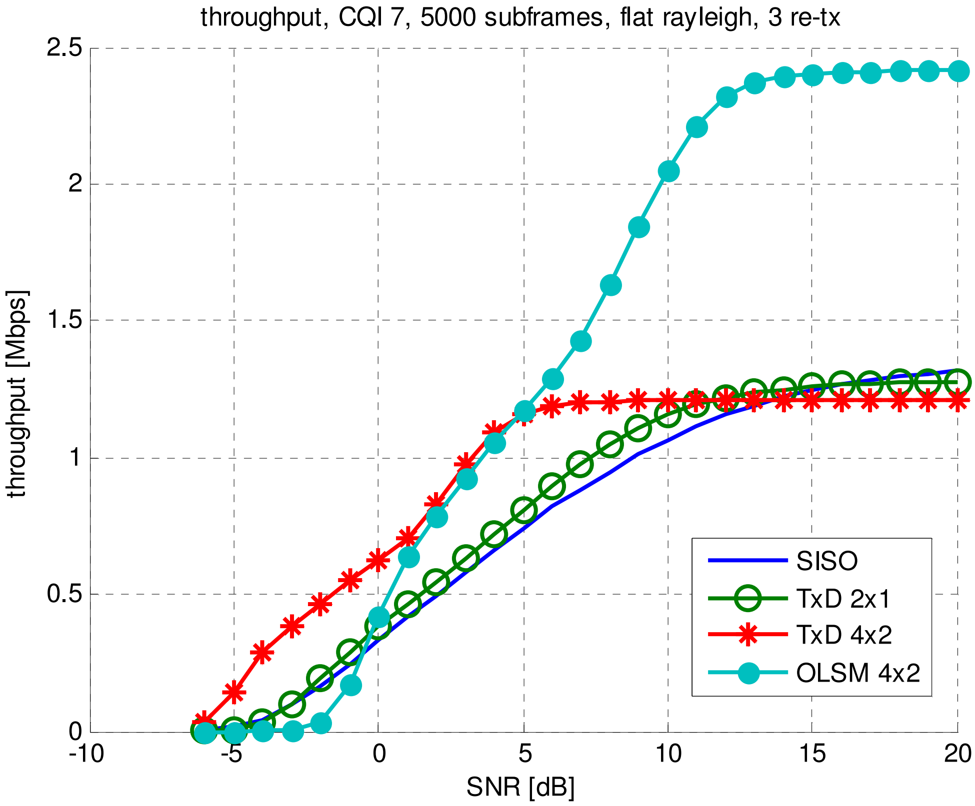

Figure 28. Throughput vs. SNR with different transmission schemes, the channel type flat Rayleigh and 3 re-tx.

Different channel types also bring some changes to the results of BLER. For flat Rayleigh channel the BLER is higher than for the same transmission modes with 3 retransmissions in PedB channel type.

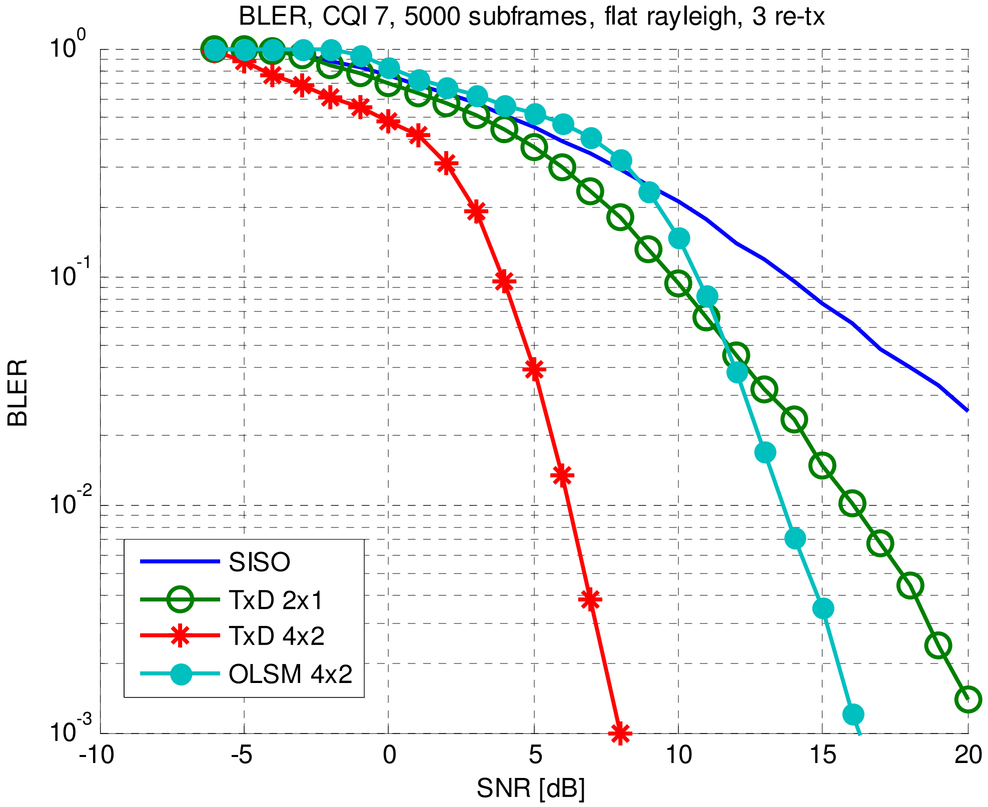

Figure 29. BLER for flat Rayleigh channel and 3 re-tx.

As it was mentioned before, the number of retransmission is useful with a low SNR. Figure 30 show that for zero retransmissions the throughput is zero when SNR is less the 0 dB. When SNR is higher than 10 dB the number of retransmissions is not making any differences to the UE throughput.

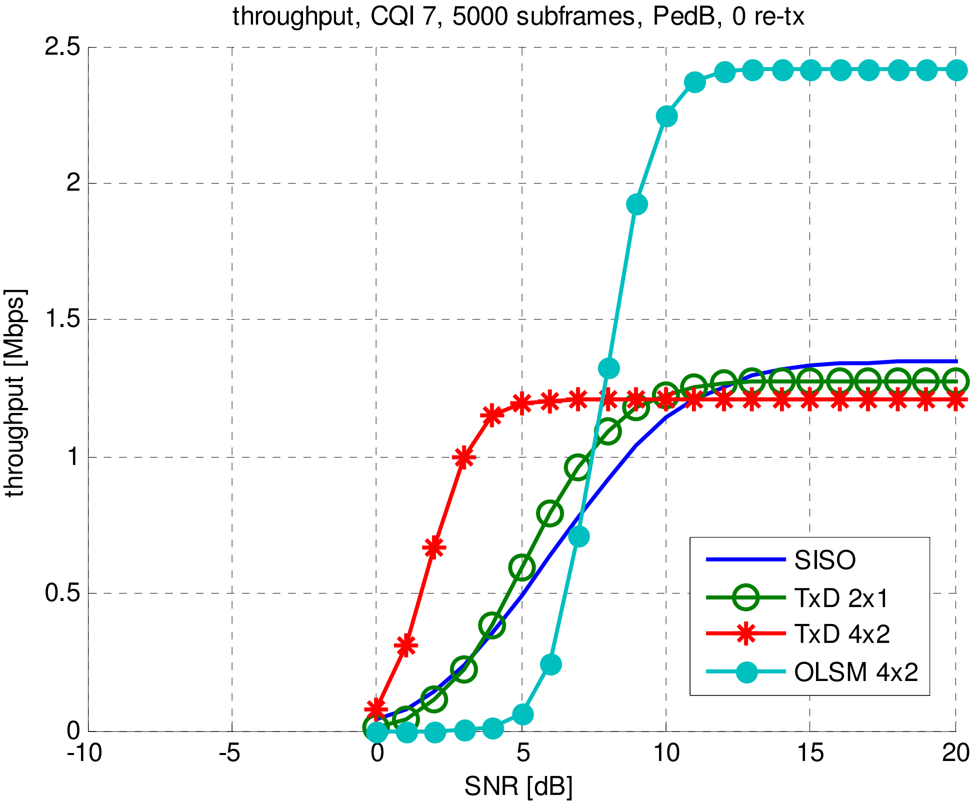

Figure 30. Throughput vs. SNR with different transmission schemes, the channel type PedB and 0 re-tx.

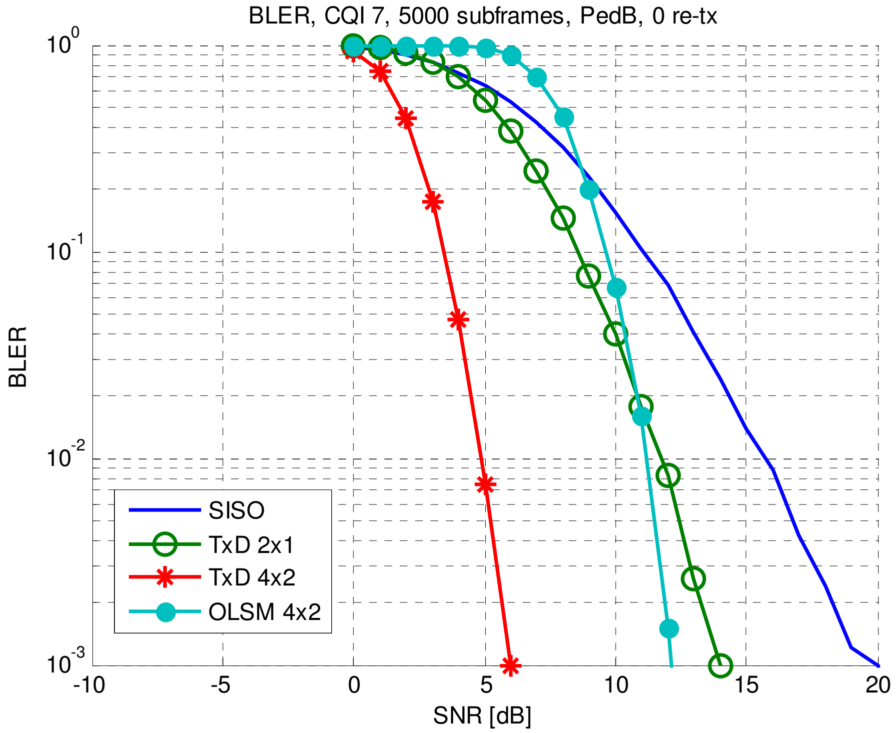

Figure 31. BLER for PedB channel and 0 re-tx.

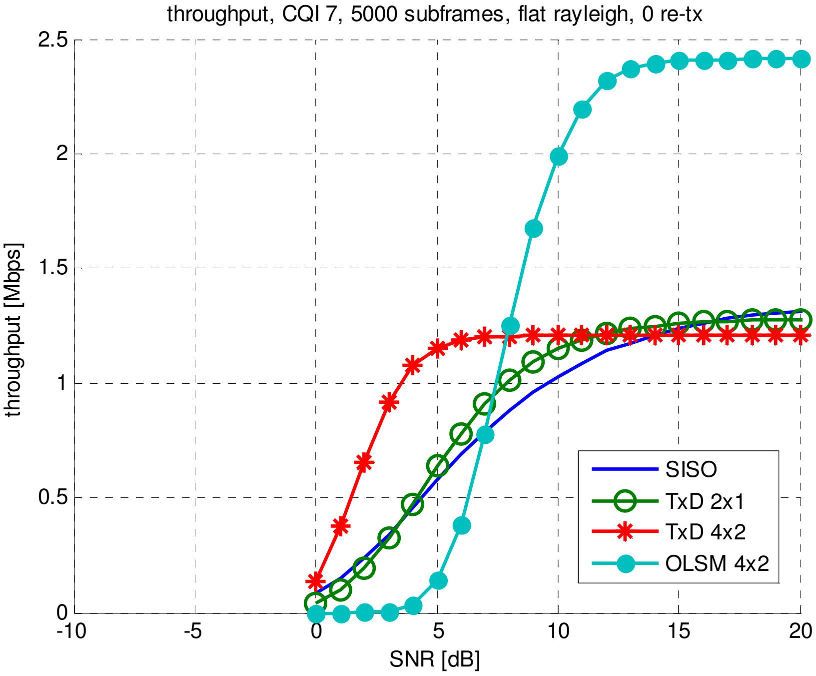

Figure 32. Throughput vs. SNR with different transmission schemes, the channel type flat Rayleigh and 0 re-tx.

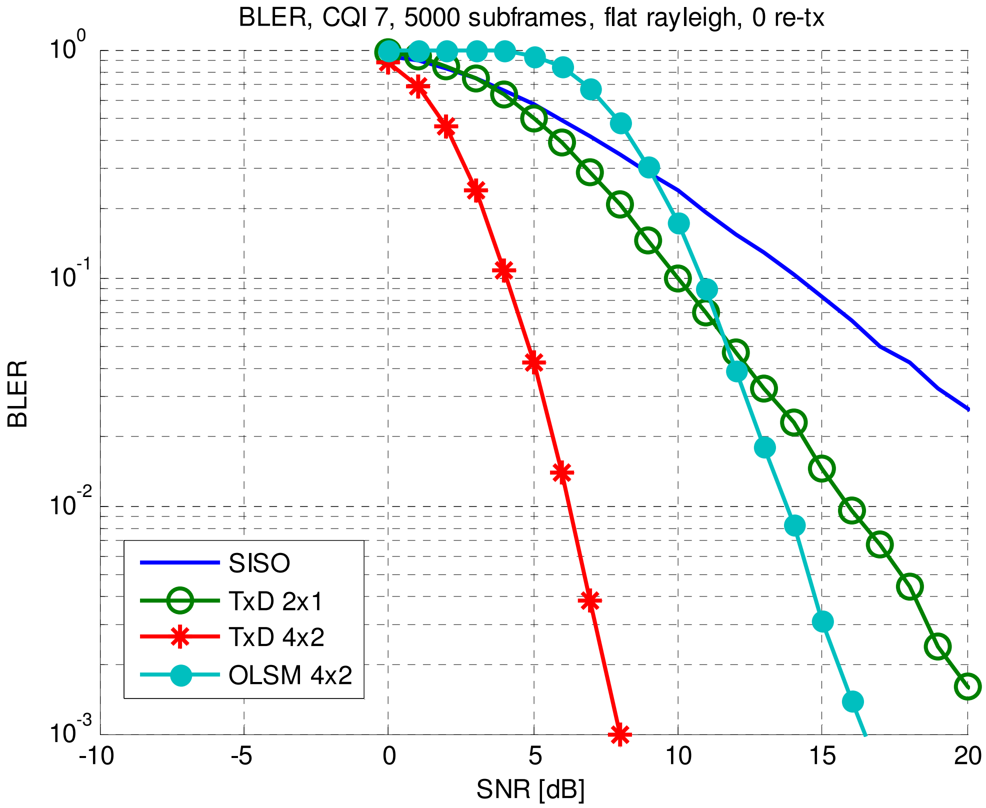

Figure 33. BLER for flat Rayleigh channel and 0 re-tx.

The CQI mapping is illustrated in Figure 34 and 35. The reports of channel quality indicators (CQI) are used to select the appropriate Modulation and Coding scheme (MCS) for downlink transmissions. For the case with a higher SNR, the CQI value will be also higher. According to Table 9 the different CQI have the different modulation schemes.

Table 9. CQI values. (3GPP TS 36.213 version 9.3.0 Release 9, 2010).

CQI index	Modulation	Approximate code rate	Efficiency (information bits per symbol)
1	QPSK	0.076	0.1523
2	QPSK	0.12	0.2344

3	QPSK	0.19	0.3770
4	QPSK	0.3	0.6016
5	QPSK	0.44	0.8770
6	QPSK	0.59	1.1758
7	16 QAM	0.37	1.4766
8	16 QAM	0.48	1.9141
9	16 QAM	0.6	2.4063
10	64 QAM	0.45	2.7305
11	64 QAM	0.55	3.3223
12	64 QAM	0.65	3.9023
13	64 QAM	0.75	4.5234
14	64 QAM	0.85	5.1152
15	64 QAM	0.93	5.5547

For every different SNR the CQI value is different and the BLER and the throughput are also changing. The flexibility of modulation type makes the LTE system more efficient. In case of a bad channel quality the CQI value will be equal to one and the modulation type will be QPSK, so the distance between symbols will be more and the probability of error and lost packets decreases. The UE uses the PUSCH channel to report the CQI values.

Figure 34 illustrates the BLER for different SNR values. The CQI reports the indicator for every SNR value. When SNR is high, more efficient modulation type is used. It will not increase the erroneous number of packets comparing to the low SNR situation. For the low SNR the CQI value is also lower and the modulation type of transmission is adapting to the current channel quality, the order of modulation becomes lower and the distance between symbols is higher. Thus, it reduces the probability of error to occur.

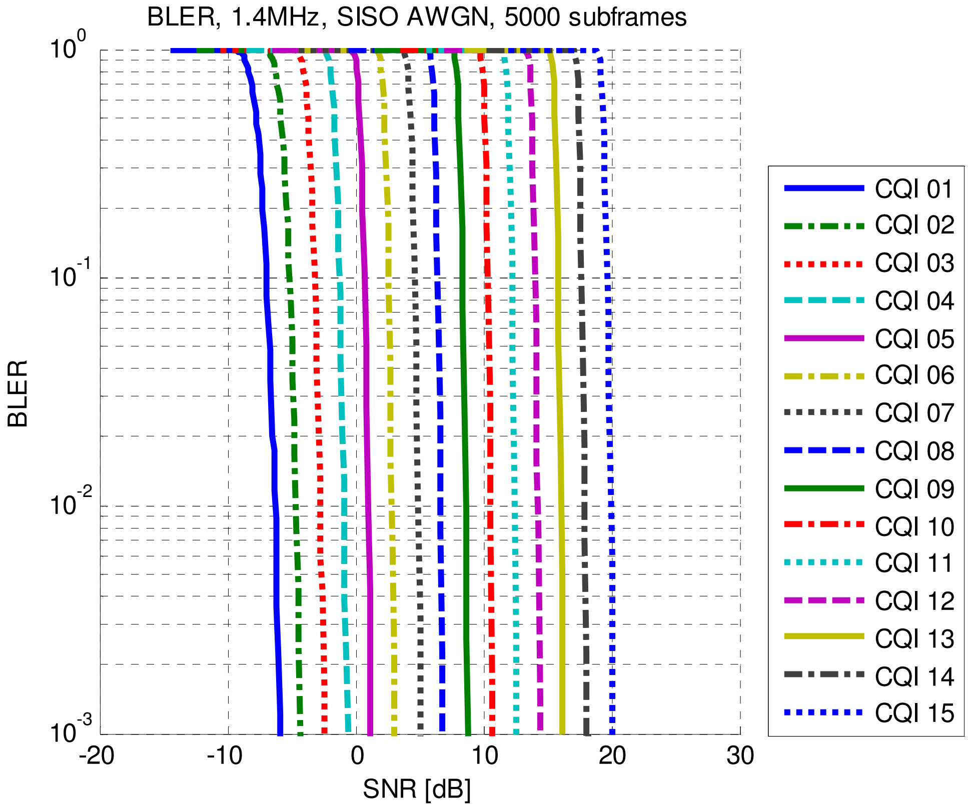

Figure 34. BLER for 15 MCS.

For a higher CQI value the higher modulation type is used for transmission. When the channel is good the higher order modulation will give a better throughput and the probability of error will be small enough and will not decreases the system performance.

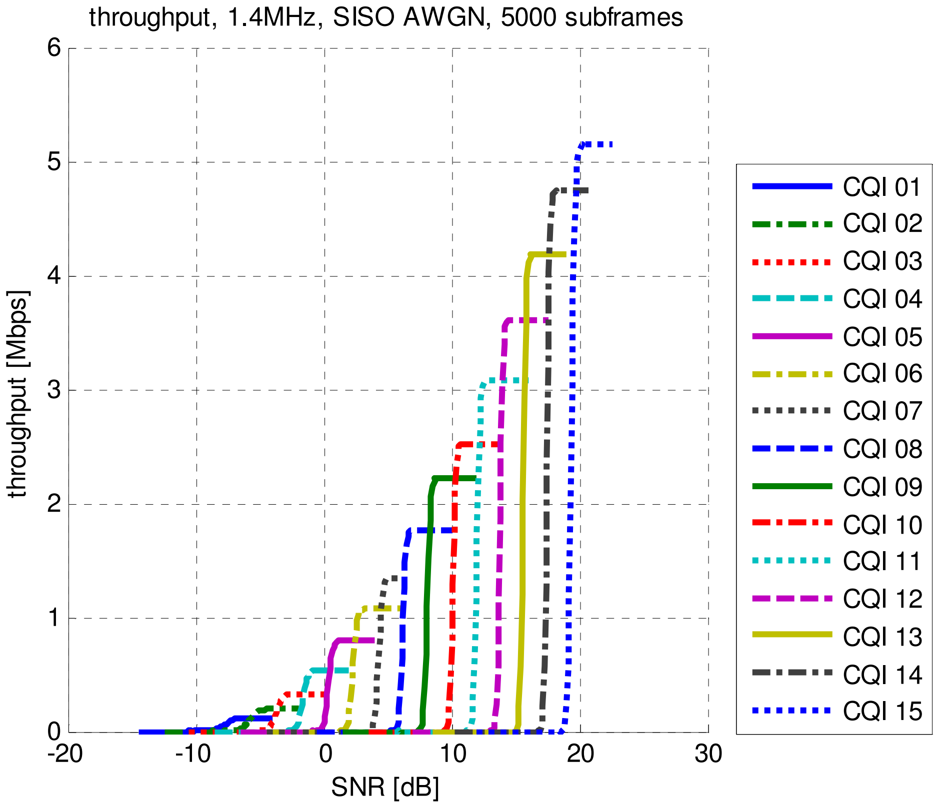

Figure 35. Throughput for 15 MCS.

6. CONCLUSION AND FUTURE WORK

Long Term Evolution is the Fourth Generation that was developed in the 3GPP project. The first release of LTE was Release 8. The release 10 is considered as the LTE-Advanced. All technical specifications are open for everyone on the website of the 3GPP. Long Term Evolution has improved the performance of the wireless communication significantly. It has the ability to achieve very high data rates using new technologies as OFDMA and MIMO. The problem of energy consumption of the LTE system plays an important role for the operators and for the environment. Because of the complicated equipment the energy consumption became greater. The research regarding green communication became very significant.

This master thesis gives an overview of the important theoretical parts of the LTE system. It gives the understanding of OFDMA principles, radio-interface architecture, scheduling in the uplink and downlink, and the power control and consumption.

The different multiplexing schemes, scheduling algorithms and the utilization of HARQ retransmission schemes of the downlink were simulated in this work. The Vienna LTE simulators which contain the LTE System level simulator and the LTE Link level simulator were used. The results that were achieved demonstrate the multiple ways of how to improve the system performance.

The following results were collected after the simulation of different schemes:

- The scheduling algorithm can improve the system performance. The right allocation of radio resources could increase the throughput of the system. Furthermore, the fairness between users has to be taken into account. According to the simulation results the best scheduler between Round Robin, Proportional Fair and Max CQI in respect to the fairness, became the Proportional Fair algorithm. Though, the Max CQI gave the highest peak data rate.
- The increased number of transmitter and receiver antenna made the system get a higher data rate than SISO would provide.

- The retransmission schemes allow users to achieve a higher throughput. The HARQ procedure improves the system performance by reducing the errors.
- The transmit modes are also important. In situation with a better channel quality the OLSM is more preferable than TxD mode. However, it is more preferable to use the transmit mode in case of the low SNR.
- The CQI report is also can significantly improve the system performance. It makes the LTE be more flexible regarding to the different channel quality. Different modulation type is used when the channel is varying from good to bad one.

For the future work the research of energy efficiency of the whole LTE system will be considered. The aim is to save energy to reduce the cost of wireless network, and to protect the environment. The downlink and uplink scenario will be simulated and different approaches will be given to find an optimum solution for an energy efficient LTE system.

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