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Link Adaptation Improvements for Long Term Evolution (LTE)

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Abstract

The Long Term Evolution (LTE) link adaptation is based on measured instantaneous Signal to Interference and Noise Ratio (SINR) which is used for selecting Modulation and Coding Scheme (MCS) for transmissions. In addition, depending on the scheduler, SINR may be used to determine which users are scheduled for a certain transmission time interval and on which frequency resources. The measured SINR can be inaccurate due to measurement errors, rounding errors due to quantization of the SINR values, and delay from time of measurement until the actual data transmissions.

To compensate for SINR inaccuracies, the SINR can be adjusted by a certain offset before being used for link adaptation and scheduling. This offset value, referred to as the link adaptation margin in this thesis, can be a fixed value common to all the users in the system at all times or adaptively adjusted for each user based on some algorithm via a feedback loop, referred to as differentiated link adaptation.

This thesis tries to improve the system performance for LTE downlink and uplink by using differentiated link adaptation based on packet error occurrences of each user as feedback. The performance of the differentiated link adaptation was compared to the best performance that is achievable using a fixed link adaptation margin.

We investigated the influence of several parameters on the link adaptation error characteristics, such as settings for SINR estimation, scheduling algorithms, traffic patterns. It was shown that there are error clusters, but that these are short and difficult to react to on time.

A performance gain was only possible in the downlink for FTP traffic with a proportional fair in time and frequency (PFTF) scheduler which was the scenario with the largest variations with regards to both scheduling and traffic model. It was seen that the gains of using differentiated link adaptation increased in the downlink as the transmissions got more random. For more stable situations, a fixed link adaptation margin performed better. The uplink performance was worse with differentiated link adaptation than with a fixed optimized link adaptation margin. This could be because the uplink SINR estimation was much better than in the downlink, with low estimation error variance, in which case frequent SINR adjustments could make the situation worse off.

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List of Abbreviations

3G	3rd Generation
3GPP	3rd Generation partnership project
ACK	Positive Acknowledgement
algo.	Algorithm
ARQ	Automatic repeat request
avg.	average
BLER	Block Error Rate
bps	bits per second
CDMA	Code division multiple access
CQI	Channel quality information/indicator
CRC	Cyclic redundancy check
dB	Decibels
DRS	Demodulation reference signals
eNodeB	E-UTRAN NodeB
E-UTRAN	Evolved UTRAN
FDD	Frequency division duplex
FDM	Frequency division multiplexing
FEC	Forward error correction
FLA	Fast link adaptation
FTP	File transfer protocol
GHz	Giga Hertz
h	hours
HARQ	Hybrid automatic repeat requests
HSDPA	High-speed downlink packet access
HSPA	High-speed packet access
Hz	Hertz
IMT	International mobile telecommunications
InH	Indoor Hotspot environment
IP	Internet protocol
ITU	International telecommunication union
km	Kilo metres
LAM	Link adaptation margin
LOS	Line of sight
LTE	Long term evolution
m	metres
MAC	Medium access control
MBMS	Multimedia broadcast/multicast service
Mbps	Mega bits per second
MCS	Modulation and coding scheme
MHz	Mega Hertz
MIMO	Multiple-Input Multiple-Output

ms	Milliseconds
NACK	Negative acknowledgement
NLOS	Non line of sight
OFDM	Orthogonal frequency division multiplexing
PBCH	Physical broadcast channel
PCFICH	Physical control format indicator channel
PDCCH	Physical downlink control channel
PDCP	Packet data convergence protocol
PDSCH	Physical downlink shared channel
PFTF	Proportional fair in time and frequency
PHICH	Physical Hybrid-ARQ indicator channel
PHY	Physical layer
PMCH	Physical multicast channel
PRACH	Physical random access channel
PUCCH	Physical uplink control channel
PUSCH	Physical uplink shared channel
QAM	Quadrature amplitude modulation
RAN	Radio access network
RB	Resource block
RE	Resource element
RLC	Radio link control
RR	Round robin
s	seconds
SC-FDMA	Single carrier-Frequency division multiple access
SINR	Signal to interference and noise ratio
SRS	Sounding reference signals
TDD	Time division duplex
TTI	Transmission time interval
UE	User equipment
UMi	Urban-Microcellular channel model
UMTS	Universal mobile telecommunications system
UTRAN	Universal terrestrial radio access network
var	variance
WCDMA	Wideband code division multiple access
WiMax	Worldwide interoperability for microwave access
WLA	Window-based link adaptation

1. Introduction

1.1. Background

Driven by demand for high data rates, low delays and a wide range of services while being cost-effective, 3GPP has been continuously setting and developing standards for future wireless communication networks. 3G in Europe was named Universal Mobile Telecommunications services (UMTS) for which Wideband CDMA (WCDMA) was selected as the radio access technology. In 3GPP/WCDMA specifications, release 5, High-Speed Downlink Packet Access (HSDPA) was introduced as an evolution of WCDMA which was soon complemented by Enhanced Uplink in release 6 [1] [2]. HSDPA and Enhanced Uplink together are known as High-Speed Packed Access (HSPA). HSPA can provide peak data rates up to approximately 14 Mbps in the downlink and 5.7 Mbps in the uplink, with efficient support for services such as Multimedia Broadcast Multicast services (MBMS) (e.g. mobile TV). The latest enhancement to HSPA came with the advent of HSPA Evolution in release 7 and 8 of the 3GPP/WCDMA specifications. HSPA Evolution further increases peak rates with the introduction of Multiple Input Multiple Output (MIMO) transmission. This allows peak data rates of 42 Mbps in the downlink and11 Mbps in the uplink [3].

However, HSPA Evolution has strict requirements on being backwards compatible with HSPA and earlier releases of WCDMA. This gives rise to some constraints in its design such as keeping certain physical layer aspects unchanged.

In 2004 – 2005, 3GPP specified requirements for a new radio access network standard which was named Long-Term Evolution (LTE), intended to be developed in parallel to other standards such as HSPA evolution, with no requirements on being backwards compatible. Thus, LTE has more spectrum flexibility and can operate at the basic bandwidths of 1.25, 1.6, 2.5, 5, 10, 15 and 20 MHz [4]. Through carrier aggregation, which is in discussion for LTE rel. 9 and LTE-advanced, carriers can be combined to reach different bandwidths but at most 100 MHz is possible [5]. Increased spectrum flexibility increases the deployment possibilities. Other key targets of LTE is to achieve low delays and higher data rates at cell edges and to achieve peak rates up to 100 Mbps in the downlink and 50 Mbps in the uplink for a bandwidth of 20 MHz.

The mentioned peak rates are seldom achievable since they require the channel conditions to be good enough to use a high modulation order and little coding redundancy (high code rates). Therefore an error rate criterion is used to select which data rate that is possible. This is called link adaptation, which is an integral part of LTE. In LTE, the link adaptation chooses the Modulation and Coding Scheme (MCS), based on the Signal to Interference and Noise Ratio (SINR) estimates [6]. SINR estimates are measured on some reference signal as experienced by the receiver. Therefore, the more accurate the SINR estimation, the better is the link adaptation and the chosen MCS for the prevailing channel conditions. Hence the accuracy of link adaptation directly affects the system throughput. This thesis seeks to explore whether it is possible to further improve the link adaptation and to improve system throughput. The specific details will be made clear in the next section.

1.2. Problem Statement

In the LTE downlink, the User Equipments (UEs) measure the received Signal-to-Interference and Noise Ratio (SINR) and report to the base station. In the uplink, the UEs may transmit a known wideband signal called, channel-sounding reference signal from time to time, usually on a periodic basis. The base station measures the received SINR of this reference signal [6]. Alternatively, the SINR can be measured on the demodulation reference signals (DRS) which are available in every transmission time interval where a particular UE is scheduled, but only for the frequency resources where the UE was transmitting. The uplink simulations of this thesis were based on the latter. More details on CQI measurements and reporting are given in 2.3.

The data rate is determined by the chosen MCS and the error rate depends on the MCS and the prevailing channel quality. A higher order modulation scheme such as 64QAM or 16QAM would allow more bits per modulation symbol allowing a higher data rate and bandwidth efficiency, while at the same time requiring better SINR at the receiver for error-free demodulation. Similarly a high code rate will reduce redundancy at the cost of lower error correction capability. Therefore choosing the MCS that best matches the prevailing instantaneous channel conditions is essential.

But it is almost impossible for the SINR estimations to perfectly reflect the actual channel conditions at the time of transmission. There are several sources of errors. Firstly, there can be errors when measuring the received channel quality by the UEs for the downlink and by the base stations for the uplink. Also, there are rounding errors when quantizing the SINR values. Finally, there is an inevitable delay from the time the SINR measurement is taken until the actual transmission takes place, due to processing and transmission delays. In addition to this, the reporting period is usually much higher than once every transmission time interval (TTI) due to the overhead for measuring and reporting. During this time the channel conditions may change considerably and unpredictably due to fast fading and varying levels of interference making the SINR measurements outdated at the time they are being used. Thus, the selected MCS can be too conservative or too aggressive for the prevailing channel conditions at the time of transmission resulting in waste of resources or too many errors, respectively. In either case the system throughput will fall below what is achievable with perfect channel information.

It makes sense to believe that if the selected MCS for a certain UE is too conservative or too aggressive for the instantaneous channel conditions, the particular UE may show certain short term trends in its performance such as periods of unusually low error rates or sudden error bursts. If such short term trends last long enough, it may be possible to adjust the SINR value accordingly to optimize the throughput. The work of this thesis mainly focuses on analysing how long such trends last and how the system performance can be improved by adapting to such trends.

1.3. Related work

Differentiated link adaptation with an outer loop has been studied thoroughly, mostly for technologies prior to LTE, such as WCDMA and HSPA. Several approaches have been studied such as CQI adjustment based on BLER, CQI averaging, and CQI prediction. In [13], some techniques to predict the CQI have been studied for HSDPA which showed some improvement for high UE speeds but not for low speeds. In [11], CQI averaging over a number of consecutively received CQI reports have been studied. A method to improve throughput of best effort traffic in a mixed traffic scenario has been proposed in [12]. Also, the two algorithms which were examined in this thesis have been previously proposed in order to stabilize the BLER.

Although a lot of work have been done on CQI adjustment for link adaptation, studies that are focused on LTE are not common. Also, most of the studies have focused on BLER stabilization and mainly on the downlink, such as HSDPA. This thesis intends to investigate the possibility of optimizing some of the algorithms to deliver higher throughput for LTE downlink and uplink.

1.4. Scope

The analysis in chapter 4 and the main simulations in this thesis were done for LTE downlink and uplink based in an urban micro cellular environment with modified user speeds *(see 3.2.1)*. This environment was chosen to provide heterogeneity since it specifies both indoor and outdoor users. The simulations were limited to the following cases due to large time and resources needed to run simulations.

LTE downlink:

- Full buffer traffic and FDM scheduler
- Full buffer traffic and PFTF scheduler
- FTP traffic and PFTF scheduler

LTE uplink:

- Full buffer traffic and FDM scheduler
- Full buffer traffic and channel quality dependent FDM scheduler

The traffic models and schedulers were chosen to provide more and more interference variations.

1.5. Outline

The structure of this thesis report is organized as below.

Chapter 2 gives a brief introduction to essential theoretical background on LTE and chapter 3 discusses the simulation models such as the environment, channel model, traffic models and performance metrics.

Chapter 4 presents an analysis on link adaptation error patterns and the effect of CQI related parameters. Chapter 5 and 6 presents the main simulation results and performance evaluation of the two simulated differentiated link adaptation algorithms for downlink and uplink, respectively. General discussion and conclusions are given as the results are presented and also summarized at the end of the chapter. Finally, chapter 7 presents the overall conclusion and chapter 8 lists future work.

2. Theoretical background

This chapter intends to introduce some of the basic theoretical background including a basic introduction to LTE and some specific details required on link adaptation, CQI reporting, scheduling, hybrid Automatic Repeat requests (HARQ), and information on the link adaptation algorithms studied in this thesis.

2.1. LTE basics

The LTE base stations are called Evolved NodeBs (eNodeBs) which is the main component of the LTE radio access network (RAN) architecture. The mobile terminals are commonly referred to as user equipments (UEs). The functionalities of eNodeB and UEs are divided into different protocol layers.

The figure 2-1 shows a simplified diagram showing the different layers and the data flow for downlink transmission [6].

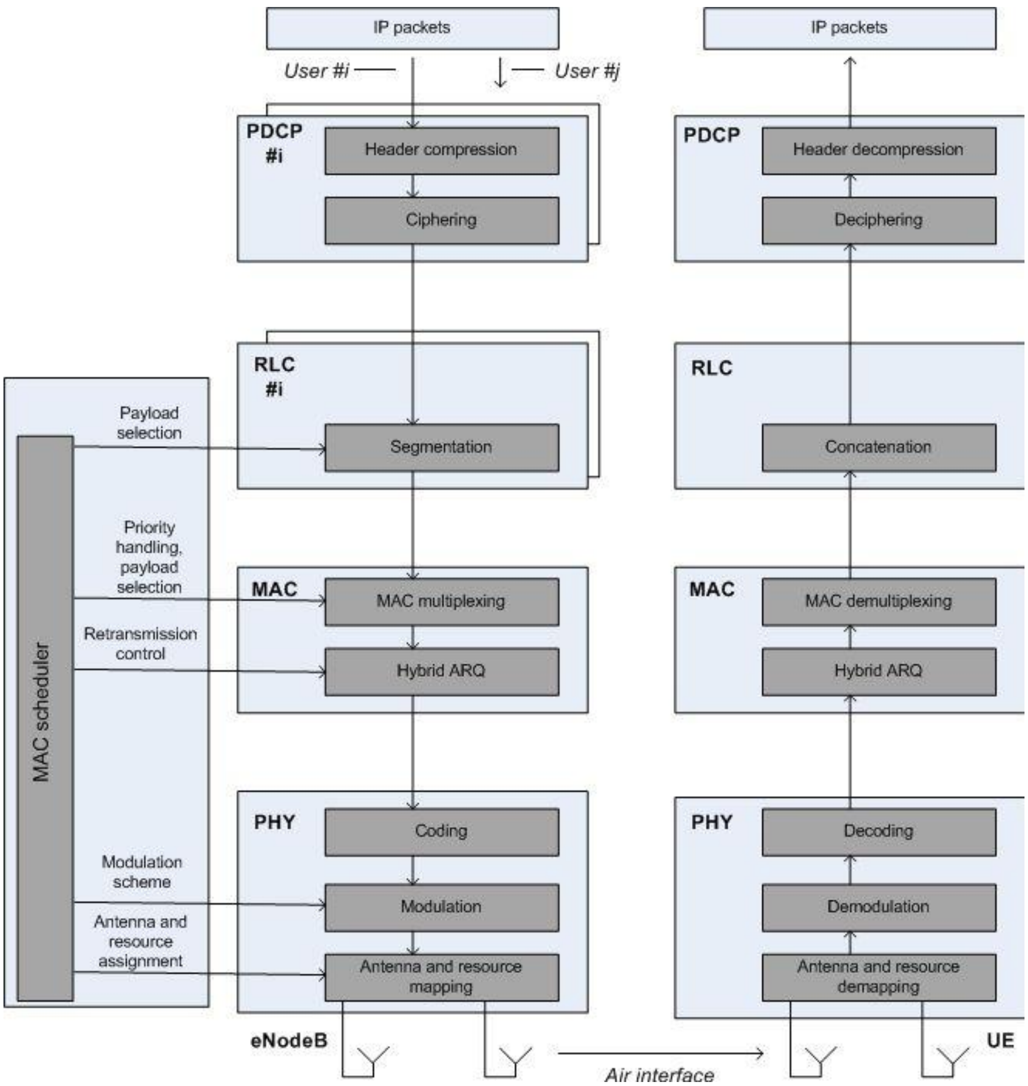

Figure 2-1: LTE protocol stack

The IP packets enter the protocol stack at Packet Data Convergence Protocol (PDCP) layer and flows through the protocol stack down to the Physical layer before entering the radio interface. Some of the basic functions of each block are mentioned below.

Packet Data Convergence Protocol (PDCP):

At the transmitter side PDCP is responsible for IP header compression (optional), ciphering and integrity protection of data and at the receiver side it performs deciphering and decompression. PDCP operates as a dedicated entity for each radio bearer in eNodeB.

Radio Link Control (RLC):

RLC performs segmentation (at the transmitter), concatenation (at the receiver), retransmission handling and in-sequence delivery for higher layers. RLC also operates as one entity per each radio bearer in eNodeB.

Medium Access Control (MAC):

MAC performs Hybrid Automatic Repeat Request (HARQ) retransmissions handling and scheduling transmissions. Both uplink and downlink scheduling is handled by the MAC layer in eNodeB. There is only one common MAC entity per cell in the eNodeB.

Physical Layer (PHY):

PHY performs coding and modulation (at the transmitter), demodulation and decoding (at the receiver) and multi-antenna mapping.

The scope of this thesis is limited only to the MAC and PHY layers, hence only the functionalities of these two layers will be discussed further.

2.1.1. Physical Channels and Physical Signals

The physical layer comprises physical channels and physical signals. The physical channels are physical resources that carry data or information from the MAC layer. The physical signals are also physical resources that supports the functions of the physical layer, but do not carry any information from the MAC layer.

Downlink:

- **Physical channels**
    - **Physical downlink shared channel (PDSCH)** – user data from MAC
    - **Physical broadcast channel (PBCH)** – broadcast data from MAC
    - **Physical multicast channel (PMCH)** – multicast data from MAC
    - **Physical downlink control channel (PDCCH)** – control signalling for PDSCH and PUSCH
    - **Physical control format indicator channel (PCFICH)** – to indicate the no. of OFDM symbols used for control signalling in the current sub frame, (i.e. the point at which the data region starts in the current sub frame)

- **Physical hybrid ARQ indicator channel (PHICH)** – to transmit acknowledgements in response to uplink data

- **Physical signals**
    - **Reference signals to support coherent demodulation in downlink**
    - **Synchronization signals to be used in cell-search procedure**

Uplink

- **Physical channels**
    - **Physical uplink shared channel (PUSCH)** – user data from MAC
    - **Physical random access channel (PRACH)** – to transmit information necessary to obtain scheduling grants and to obtain timing synchronization for asynchronous random access.
    - **Physical uplink control channel (PUCCH)** – to send downlink CQI information to the eNodeB, ACK/NACK for downlink transmissions and scheduling requests.
- **Physical signals**
    - **Reference signals to support coherent demodulation in uplink**
    - **Reference signals for uplink channel sounding** – in order to obtain channel quality for the entire bandwidth for each user

The channel quality can be estimated both from the demodulation and sounding reference signals in the uplink.

2.1.2. LTE time-frequency structure

LTE is designed to work in both FDD (frequency division duplex) and TDD (time division duplex) modes of operation for sharing resources between uplink and downlink transmissions. Since FDD mode is what has been studied, only the time-frequency domain structure in this mode is discussed here.

In FDD mode, the time domain structure is the same for both downlink and uplink and is illustrated in figure 2-2.

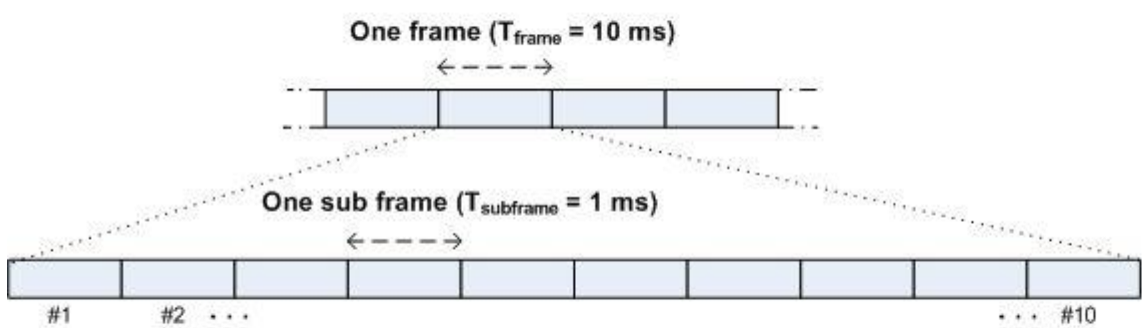

Figure 2-2: LTE time domain structure

Each LTE radio frame is of length 10 ms, which is divided into 10 sub frames of length 1 ms each. Each sub frame is also divided into two slots of equal length of 0.5 ms. But the usual scheduling unit is the sub frame of 1 ms and the slots are relevant only when using frequency hopping.

LTE downlink transmission is using OFDM and the uplink transmission is using SC-FDMA.

In the OFDM downlink, the downlink physical resources take the form of a time-frequency grid as shown in figure 2-3 [13].

The OFDM sub carrier spacing for LTE is usually defined as 15 kHz, although a reduced sub carrier spacing of 7.5 kHz can also be defined [11]. The minimum defined resource unit called *resource element (RE)* spans one OFDM symbol in time domain and one OFDM sub carrier in frequency domain. The number of OFDM symbols per OFDM sub carrier during a downlink slot of 0.5 ms is denoted as N_{symb} in figure 2-3. The value of N_{symb} can be 7, 6, or 3 depending on the sub carrier spacing and the type of OFDM cyclic prefix used (a normal cyclic prefix or extended cyclic prefix). In the frequency domain N_{sub} contiguous OFDM sub carriers form a *chunk carrier* as the figure 2-3 shows. The value of N_{sub} is defined as 12 when the sub carrier spacing is 15 kHz and as 24 when sub carrier spacing is 7.5 kHz. One *resource block (RB)* spans one slot in time domain and one chunk carrier in frequency domain. Since the minimum TTI is one sub frame, which consists of 2 slots, the minimum *scheduling block* comprises two RBs.

In the LTE uplink, SC-FDMA is used instead of OFDM, but the definition and hierarchy of sub carriers, chunk carriers, resource elements, resource blocks, and scheduling blocks remain the same. The time-frequency grid for LTE uplink resources is shown in figure 2-4 [13].

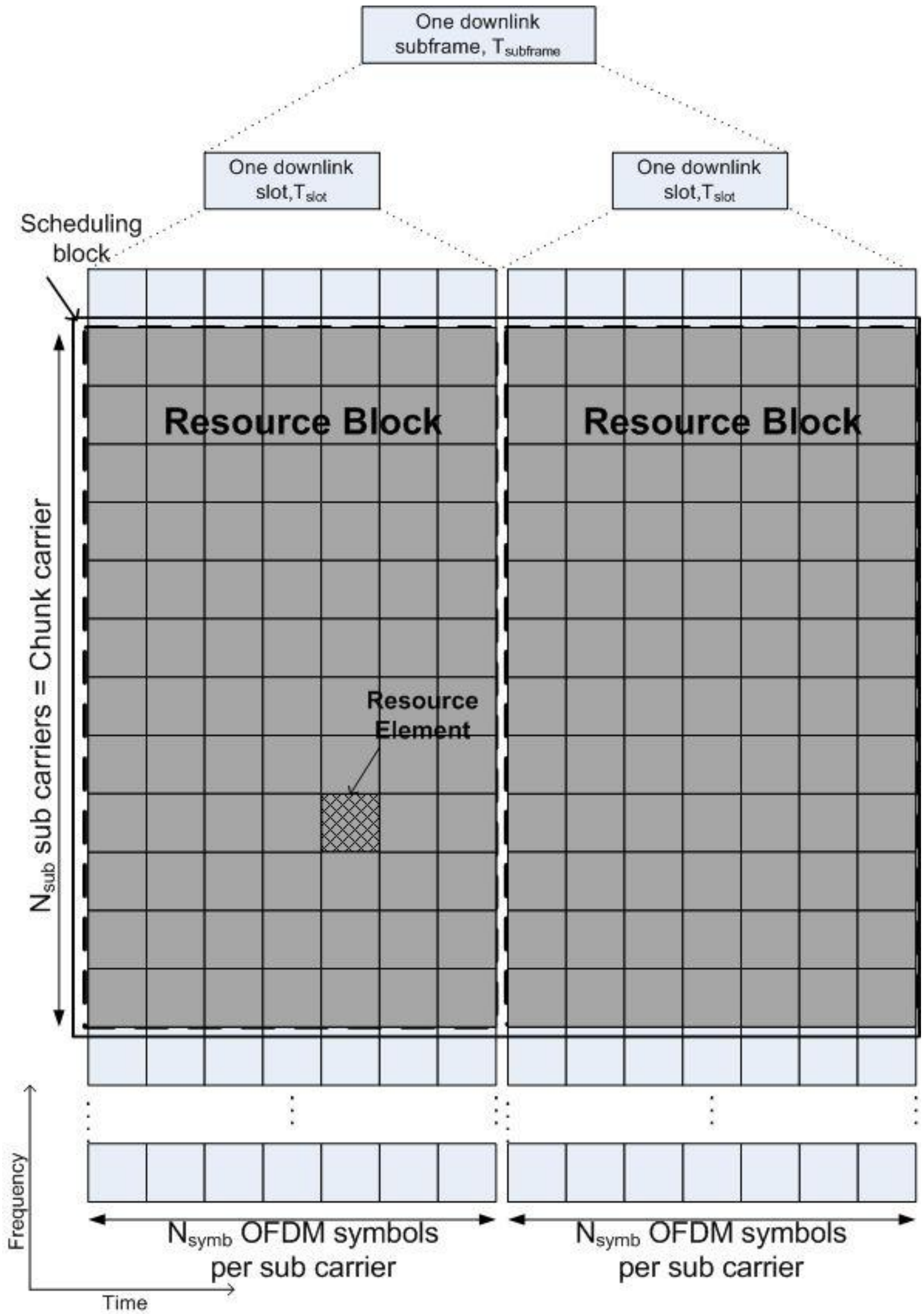

Figure 2-3: Downlink time frequency resource grid

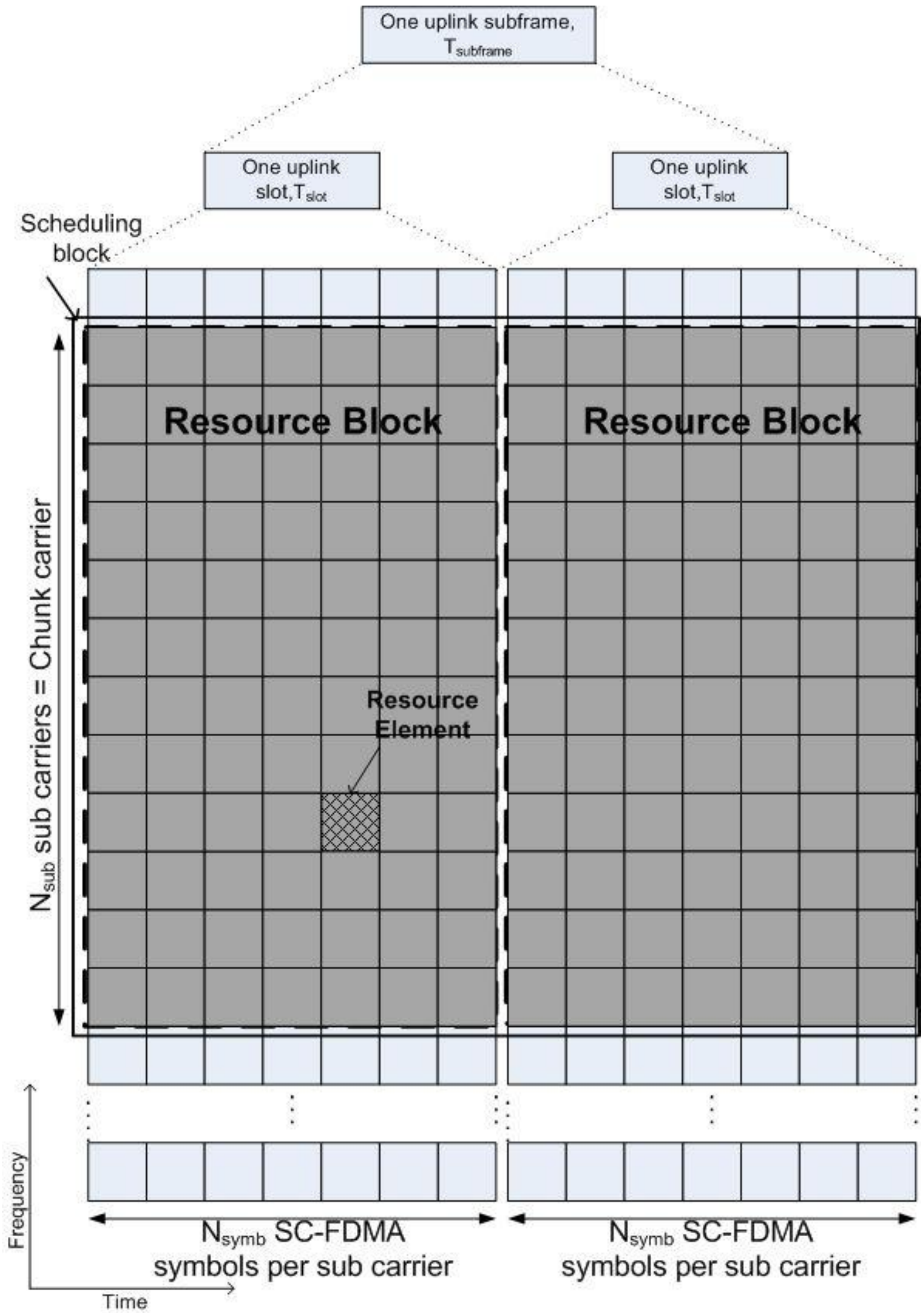

Figure 2-4: Uplink time frequency resource grid

2.2. Hybrid automatic repeat requests (HARQ)

Hybrid automatic repeat requests or HARQ is a technique used by almost all modern communication systems and it employs forward error correction (FEC) to correct a subset of errors and conventional ARQ to detect any further errors and requests for data retransmission [6]. After FEC is used to correct a subset of errors, the receiver makes use of an error detecting code, usually a cyclic redundancy check (CRC) to detect if the packet is still erroneous. If so, the data is discarded and a *Negative Acknowledgement* (NACK) is sent to notify the transmitter to retransmit the data. Otherwise an *Acknowledgement* (ACK) is sent confirming that the data was received error-free. The process is repeated until the maximum number of allowed retransmission attempts is reached.

2.2.1. HARQ with soft combining

LTE uses *HARQ with soft combining* to handle retransmissions. In HARQ with soft combining the erroneous packets are buffered at the receiver because the received signal still contains some information although it could not be decoded correctly. The buffered packets are later combined with its retransmission and passed to the decoder for forward error correction followed by error detection [6].

The retransmissions may not necessarily contain exactly the same coded bits as long as they contain the same information bits. Depending on whether the retransmissions contain the exact coding bits or not, HARQ with soft combining is categorized as *Chase combining* or *Incremental redundancy.*

In *Chase combining*, the same set of coded bits as the original transmission are retransmitted and combined with the original bits at the receiver side. Therefore there is no increased redundancy in the combined packet; hence there is no coding gain. But, the accumulated E_b/N_o increases with each retransmission.

In *incremental redundancy,* multiple sets of coded bits are generated for the same set of information bits. Therefore, each retransmission can add additional parity bits which were not present in the previous transmission. This increases the redundancy and lowers the coding rate of the resulting packet.

In this thesis work, HARQ with chase combining is used.

2.3. CQI measurements and reporting

Channel quality indicator (CQI) is a measure of prevailing channel conditions for each user in the system and is used by the scheduler and link adaptation as will be discussed in the next section.

The CQI is a quantized value (usually 30 levels) of the measured SINR at the receiver, mapped to an integer index to a table with different modulation and coding scheme (MCS) combinations and represented with a sufficient number of bits (e.g. 5 bits for 30 levels) [12].

In the simulator environment, such as the one on which this thesis work was carried out, the bit level representation is not necessary and CQI is simply reported as the measured

SINR value and rounded to an allowed SINR value (quantization) during MCS selection, which is a part of link adaptation.

2.3.1. Downlink CQI measurements and reporting

Downlink channel quality is measured by the UEs and reported to the eNodeB. The channel quality can be measured on any of the downlink reference symbols which are inserted to the downlink OFDM time-frequency resource grid. The reference symbols are collectively known as reference signals. Three types of reference signals are defined for the LTE downlink [6].

- *Cell-specific downlink reference signals* – span the entire cell bandwidth (all the chunk carriers) and are transmitted in every sub frame.
- *UE-specific reference signals* – are for channel estimation by a specific UE and spans only the frequencies of the RBs assigned to that UE.
- *MBFSN reference signals* – are for channel estimation of signals that are transmitted by means of multicast broadcast single frequency networks (MBFSN).

The simulator settings for this thesis work assume that the channel quality measurements are being made on cell-specific downlink reference signals.

Different CQI reporting modes have been specified for LTE downlink [12]. This thesis work only deals with two simple CQI reporting modes, which are *sub band CQI reporting* and *wideband CQI reporting*.

In *sub band CQI reporting,* the UEs measure the channel on all chunk carriers spanning the bandwidth, but average them over a number of contiguous chunk carriers and report to the eNodeB only the average value as the CQI representing the chunk carriers on which the average was calculated. At the eNodeB, the reported average value is assumed as the CQI for all the contiguous chunks on which it was calculated.

The number of chunks which are averaged is determined by the parameter *frequency granularity* which is known by both the UE and eNodeB. The default value of frequency granularity used was 6 chunk carriers. If frequency granularity is set to 1, the UEs report the measured CQI for each chunk carrier.

Wideband CQI reporting can be considered as a special case of sub band CQI reporting, where the channel quality measurements are averaged over all chunk carriers and reported as one CQI representing the entire measured bandwidth.

The reason for selecting a higher value for frequency granularity is due to the reporting overhead which will require higher capacity on PUCCH, on which the downlink CQI values are reported. *(There are CQI modes in which the CQI is reported on PUSCH, such as a-periodic CQI, which is out of the scope of this brief theoretical introduction).*

The system can choose the *CQI reporting period*. If the CQI reporting period is set to 1 sub frame, a new CQI report is available every sub frame. But due to the overhead of measuring and reporting, this value is usually larger than 1 sub frame. In this thesis work a default value of 5 sub frames or 5 ms is assumed.

Practically, there is an inevitable delay from the time the channel measurement begins until MCS selection and scheduling is performed. This delay, which is referred to as *CQI report delay*, is specified as at least 6 ms for practical purposes.

2.3.2. Uplink CQI measurements and reporting

In the uplink, the channel measurements are done by eNodeB. The eNodeB converts them to CQI values, does MCS selection and scheduling and informs the UEs using the PDCCH. The uplink channel measurements are made on uplink reference signals that are transmitted by the UEs. They can be categorized as below [6].

- *Demodulation reference signals (DRS*) – These are meant for channel estimation for coherent demodulation in the uplink and can be used for SINR estimation for CQI. DRS are transmitted in every TTI when a UE is scheduled and is transmitted time and frequency multiplexed with the actual data transmission. DRS usually span only the bandwidth of the physical resources that are being allocated for a particular UE. In the case of FDM or Channel quality dependent FDM scheduling where all users are scheduled during each TTI, the *CQI reporting period*, defined similar to the downlink, becomes 1 sub frame or 1 ms.
- *Uplink channel sounding reference signals (SRS)* – These are transmitted for channel estimation spanning a much larger bandwidth, usually the entire uplink bandwidth assigned for a cell so that more efficient channel dependent scheduling can be performed. The period of SRS transmission is dependent on the parameter, *sounding RS period*, which may range from 2 sub frames to 160 sub frames. But due to the transmission overhead, such as fewer time and frequency resources for data transmissions, the period is set to a much larger value such as 20 sub frames. SRS can be beneficial when users are not scheduled often, in which case DRS will not be regularly available.

In this thesis work, uplink channel estimation is based on DRS.

Similar to the downlink, there is an inevitable delay in the uplink CQI, which was set to 6 ms for the simulations.

2.4. Scheduling and Link adaptation

Scheduling is the process of dynamically allocating the physical resources among the UEs based on some set of rules, i.e. scheduling algorithm.

The link adaptation in this context refers to rate adaptation or MCS selection depending on CQI. In general, link adaptation can also involve transmission power control.

Both, scheduling and link adaptation require the CQI (depending on the scheduling algorithm) as input, the link adaptation requires the scheduler output in order to know which users are scheduled and what RBs are allocated to them, and the output of both scheduler and link adaptation, (i.e. the UE Ids of the scheduled users, the resources allocated and the MCS to be used for transmission), are sent to the UEs via PDCCH [6].

2.4.1. Scheduling algorithms

The scheduler may use various algorithms in order to decide which users are to be scheduled and which resources to be allocated to the scheduled users. These techniques may take different aspects into account such as spectral efficiency and fairness. Some of the basic algorithms that are relevant for this thesis work are described below.

2.4.1.1. Round Robin (RR) scheduler

The round robin (RR) scheduler is the simplest form of scheduling where the users who have data to transmit are allowed to take turns without taking the channel quality information into consideration. The RR scheduler is fair in the sense that every user gets the same amount of time and frequency resources. Since the users are scheduled without considering their instantaneous channel quality, the RR scheduler gives lower spectral efficiency.

2.4.1.2. Frequency Division Multiplexing (FDM) scheduler and Channel quality dependent FDM scheduler

The FDM scheduler can be considered a special case of the RR scheduler where all the users are scheduled each time and are allocated an equal share of frequency resources. The FDM scheduler is as fair as RR scheduler in terms of the amount of time and frequency resources allocated to the users, but suffers from lower overall system performance similar to RR. The Channel quality dependent FDM scheduler also considers the channel quality when distributing frequency resources.

2.4.1.3. Max-C/I (maximum rate) scheduler

Max-C/I scheduler always schedules one user for a TTI who is selected as the user who has the best instantaneous channel quality, thus the highest possible data rate. This scheduler maximizes the system performance in terms of spectral efficiency, but it is not fair.

2.4.1.4. Proportional Fair in Time and Frequency (PFTF) scheduler

PFTF lies in between RR (or FDM or Channel quality dependent FDM) and Max-C/I schedulers in terms of system performance and fairness. It selects a certain number of users for scheduling based on the ratio of their instantaneous channel quality over their average channel quality during the last averaging window period, which may be defined by the scheduler. Thus the users who have the best channel quality relative to their average channel quality get scheduled.

2.4.2. Link adaptation

Once the users are scheduled and RBs are allocated among the users, the link adaptation takes over to determine the MCS to be used for transmissions for each user. The LTE specifications do not strictly specify the method of MCS selection, but usually a technique is employed where the MCS, which achieves highest data rate (maximum transport block size, *see 4.6*) while not exceeding a certain target block error probability, is selected. In this case, the link adaptation functionality on the simulator was based on a mutual information based link quality model [13].

2.4.2.1. CQI adjustments

Link adaptation and scheduling uses channel quality indicator (CQI) as an input to perform resource allocation and MCS selection. As mentioned before, the CQI is derived from SINR measurements made by the receivers (by the UEs in the downlink and by the eNodeBs in the uplink).

However due to previously mentioned sources of inaccuracies such as quantization, delay, long CQI reporting periods and SINR averaging to reduce transmission overheads, it is beneficial to have some kind of CQI adjustment at eNodeB. The simplest way of doing this is to adjust the CQI values by a certain margin, from now on referred to as the *Link Adaptation Margin* (LAM) as it is defined in the simulation environment. The adjustment can be written as below,

$$\left[CQI_{eff}\right]=\left[CQI\right]-\left[LAM\right] \tag{2.1}$$

The values are denoted as matrices of arbitrary size, where their sizes may depend on the number of users in the cell, number of resource blocks and number of transmission streams in case of MIMO, etc. CQI_{eff} is the effective CQI value that will be passed to the scheduler and link adaptation.

The LAM can be regarded as an amount by which the CQI is backed off before passing to the scheduler and link adaptation. When the LAM is a positive value, $\mathrm{CQI}_{\mathrm{eff}}$ will be less than the original CQI. Therefore the link adaptation will tend to select a lower data rate, in other words, a more robust MCS (more conservative) than what it would have selected if not for the CQI adjustment. Similarly, when the LAM is negative, the link adaptation will tend to select a high data rate, in other words, a less robust MCS (more aggressive) than what it would have selected without CQI adjustment. Regardless of whether the LAM is positive or negative, a higher LAM is more conservative than a lower LAM and vice versa.

2.4.2.2. Fixed link adaptation

Fixed link adaptation refers to adjusting the CQI for all the users, for all the resource blocks and for all the transmission streams by the same constant value. In this case the matrix LAM in equation 2.1 can be regarded as a constant scalar or a matrix where all the elements are equal and constant. The constant value is to be optimized through simulations for a given scenario (such as environment, traffic model, or offered load).

2.4.2.3. Differentiated link adaptation

Having the link adaptation fixed as mentioned above serves only as a correction of some bias which may exist on average. It does not serve the purpose of adjusting the CQI values for the CQI inaccuracies that may exist on instantaneous basis. In *Differentiated link adaptation*, the link adaptation margins are allowed to change according to some algorithm. In this case the matrix LAM in equation 2.1 is not a constant and its elements may change independently of each other.

The algorithms that perform the update of LAM may act as a control loop that takes the current set of LAMs and some form of feedback from the system and output the new set of LAMs. The most common feedback to use is the ACK and NACK feedback for the recent transmissions.

The two algorithms which were applied to LTE and compared with the performance of fixed link adaptation during this thesis are described below. The two algorithms are referred to as *Fast Link Adaptation (FLA) algorithm* and *Window-based Link Adaptation (WLA) algorithm*.

Fast Link Adaptation (FLA) algorithm

FLA algorithm is a simple algorithm that adjusts the LAM of each user based on the ACK/NACK feedback for the last transmission. The algorithm details are as below,

1. If an ACK is received for the last transmission for a particular user, meaning that the last transmission was successful, the LAM for that user is *decreased* by a positive constant *ACKadj* dBs.

   (To be more aggressive in MCS selection for the next TTI.)

2. If a NACK is received for the last transmission for a particular user, meaning that the last transmission was unsuccessful, the LAM for that user is *increased* by a positive constant *NACKadj* dBs,

   (To be more conservative in MCS selection for the next TTI.)

The update of LAM is done for each user independently based on ACK/NACK feedback for each user.

The ratio, *ACKadj/NACKadj* can be regarded as a target BLER and will be referred to as *BLERtarget*, from now on, in the context of FLA algorithm.

The two parameters *ACKadj* and *NACKadj* have to be optimized through simulations for a particular scenario.

The algorithm can be easily extended to support multiple transmission streams in the case of MIMO, where ACK/NACK feedbacks will be received for each stream separately and the LAMs can be defined for each user and for each stream. This was done in the LTE downlink simulations for the 2x2 antenna configuration.

Window-based Link Adaptation (WLA) algorithm

WLA algorithm adjusts the LAM of each user independently, based on each user's Block Error Rate (BLER) during a window period. The algorithm details are as below for a single user.

1. During the last *WINsize* transmissions, count the number of NACKs (Block errors) received for the user.

2. At the end of the *WINsize* transmissions, calculate the BLER of the user.

3. If, BLER<=*LOWerr*, decrease the LAM of the user by 1 dB.

4. If, BLER>=*HIGHerr*, increase the LAM of the user by 1 dB.

5. Start a new window period and repeat the steps 1-4.

Algorithm steps are to be run in parallel for all the users. *WINsize* is the length of the window period or the number of transmissions during which the BLER is to be calculated. It is difficult to define a window period of certain number of frames as viewed from the system point of view, because it is possible that some users may not have any transmissions or very little transmissions during the last *WINsize* frames, depending on the traffic model and scheduler. Therefore the period of BLER calculation has to be defined as last *WINsize* transmissions for a particular user.

LOWerr and *HIGHerr* are the thresholds to decide if the BLER can be considered low or high, respectively.

3. Simulation models and performance metrics

This chapter serves as an introduction to the simulator which was used, the system models and some of the important basic simulation parameters. The more specific parameters and their values will be given in the respective chapters and sections in connection to the results.

3.1. Simulator in general

All simulations were run on a Matlab based simulator. It models OFDM transmissions and supports OFDM based systems such as LTE and WiMax. It has support for a variety of user environments and scenarios and also for Multiple-Input Multiple-Output (MIMO) antenna schemes.

In addition to the existing simulator setup, new functionalities for TTI-wise logging of data such as, SINR estimation errors, ACK/NACK indicators, transport block sizes (*see 4.6*), and MCS were implemented. Also, the studied link adaptation algorithms, as well as the tools for data analysis, such as error clusters were implemented in addition to the existing simulator setup.

3.2. User environments and channel models

3.2.1. Urban micro-cellular environment with modified user speeds

The simulations were performed for the urban micro cellular environment specified by ITU for evaluation of radio interface technologies for IMT-advanced [14]. This environment was chosen since there are both outdoor and indoor users who are covered by outdoor base stations, thus adding more heterogeneity. The environment was modified to include users of higher speeds. The urban micro outdoor user speed is specified to be a constant of 3 km/h. Here, it was modified to be either 3 km/h or 30 km/h with equal probability. The basic environmental parameters for this environment are given in table 3-1.

Table 3-1 : Environmental parameters for Urban Micro with modified user speeds

Layout	Hexagonal grid
Inter-site distance	200 m
Carrier frequency	2.5 GHz
Base station antenna height	10 m
UE antenna height	1.5 m
Mean Outdoor-to-Indoor penetration loss	20 dB
User distribution	Randomly and uniformly distributed over the area, 50% outdoor, 50% indoor

Indoor user speeds	3 km/h
Outdoor user speeds	50% - 3 km/h , 50% - 30 km/h
User mobility	Constant speed, randomly and uniformly distributed direction

3.2.2. UMi channel model

The channel model for urban micro-cellular environment is called urban micro (UMi). The exact parameters are specified by ITU and can be found in [14]. The simulator divides the path loss into 3 components, namely distance dependent path loss, shadow fading, and fast fading.

The distance dependent path loss, *PL(d)* is calculated in the simulator as,

$$PL(d) = \beta + 10.\alpha.\log_{10}(d) \ \text{[dB]}$$

Here, d is the distance from the transmitter to the receiver. The values of α and β are functions of carrier frequency, base station and mobile antenna heights, the link type (LOS, NLOS, outdoor-to-indoor), and the environment. The exact formulae can be found in [14].

Slow channel variations due to shadowing are modelled by a lognormal distribution of mean zero and standard deviation σ, where the value of σ is dependent on the environment and the link type. In [14] values of σ are given for UMi channel model as 3, 4 and 7 dB for link types LOS, NLOS, and outdoor-to-indoor respectively.

Fast fading due to multi path propagation occurs when the channel changes faster than the symbol duration. The simulator calculates fast fading using the ray-based propagation model.

3.3. Traffic models

3.3.1. Full buffer traffic with drop based user arrivals

Most of the simulated cases were based on full buffer traffic model. In full buffer traffic, each user has an infinite amount of data in the buffer to transmit or receive depending on whether it is uplink or downlink. Although this is not a practical assumption, full buffer traffic model serves as a good base-line traffic model since scheduling and user throughputs are independent of the amount of data in the transmit buffer, thus making it easier to analyse the trends and user behaviours.

Also, another simplification was done with respect to user arrivals. The users are created at start with uniformly distributed random placement such that,

$$Total\ no.of\ users = no.of\ cells \times offered\ load$$

Here, the offered load is specified as the average number of users per cell, for full buffer traffic.

3.3.2. FTP download traffic

During FTP traffic simulations, the users enter and exit the system dynamically according to a Poisson process. The new user arrival rate λ is given as,

$$\lambda = \frac{\text{offered load}}{8 \times \text{mean file size}} \quad [\text{users / s / cell}],$$

Where *offered load* is given in 'bits per second per cell (bps/cell)' and *mean file size* is given in 'bytes'. The initial number of users is determined using an estimated *bit rate* which translates into the mean session time (*meansesst*) as,

$$meansesst = \frac{8 \times mean\ file\ size}{bit\ rate[bits\ /\ s]} \quad [s].$$

The initial number of users is set to 90% of the number of users expected during *meansesst* seconds which is $0.9 \times \lambda \times meansesst$. Thereafter it grows steadily according to a Poisson process. The users who have finished downloading the file exit the system.

3.4. Performance metrics

This section describes how the performance comparison between simulation results for fixed link adaptation and differentiated link adaptation will be done in chapter 5 and 6.

The performance metrics used for full buffer traffic simulations are: average cell throughput and cell-edge user throughput. For FTP traffic simulations average user data rate is also used.

Average cell throughput:

Average cell throughput here is synonymous with cell spectral efficiency, where it is calculated as below.

$$Average\,cell\ throughput = \frac{sumrxbits}{(simtime) \times (bw) \times (numcells) \times (numitr)} [bps\ /\ Hz\ /\ cell]$$

Where,

sumrxbits : - Total number of correctly received bits for all users (from all the simulation iterations)

simtime : - length in seconds of a simulation iteration

bw : - system bandwidth in Hertz

numcells : - number of cells in the system

numitr : - number of simulation iterations

Cell-edge user throughput:

Cell edge user throughput is the 5th percentile value of the total number of received bits, normalized by simulation time and system bandwidth. It is expressed in bps/Hz. In the simulations, the 5th percentile value was calculated as the average of the 4th, 5th and 6th percentile values.

Average user data rate:

Average user data rate is included as a performance metric for FTP traffic simulations. It is simply the average of the file download data rate in Mbps experienced by all users.

$$Average\,user\ data\ rate = \frac{1}{N}\sum_{i=1}^{N}\frac{rxbits_i}{end\_time_i - start\_time_i}\times 10^{-6}\ [Mbps]$$

Where,

$rxbits_i$	: - Total number of bits correctly received by ith user.
end_time_i	: - Time in seconds when the ith user finished downloading the file
$start\_time_i$	: - Time in seconds when the ith user started downloading the file
N	: - Total number of users that entered the system during the simulation

Note: *The system allows a user to download only one file. A user enters the system, downloads a file and exits. If a user is still in the system (file has not yet fully downloaded) at the time the simulation ends, the data rate is calculated as the number of bits downloaded so far divided by the time in seconds elapsed since the user entered the system until the simulation time ends.*

The performance will be compared at points where each of the above metrics maximizes and for the point chosen as the best combination. If there is more than one combination that maximizes a certain metric, the best combination among them is chosen.

Choosing the best combination:

The best combination point is chosen to be the point that maximizes the sum of the performance metrics, normalized by their maximum values, which can be calculated as below:

for full buffer traffic,

$$i_{best\_combination} = \arg\max_i\left(\frac{avg\_cell\_thr_i}{\max(avg\_cell\_thr)} + \frac{celledge\_user\_thr_i}{\max(celledge\_user\_thr)}\right)$$

for FTP traffic,

$$i_{best\_combination} = \arg\max_i\left(\frac{avg\_cell\_thr_i}{\max(avg\_cell\_thr)} + \frac{celledge\_user\_thr_i}{\max(celledge\_user\_thr)} + \frac{avg\_user\_data\_rate_i}{\max(avg\_user\_data\_rate)}\right)$$

4. Analysis on error patterns and effect of CQI related parameters (Downlink/Uplink)

This chapter presents the results of an analysis on a LTE system based in an urban micro-cellular environment, intended to study the effects of various CQI related parameters on system throughput and to study the packet error patterns and SINR estimation biases.

4.1. Simulation parameters

The following general simulation parameters and settings were used to obtain the results presented in the remaining sections of this chapter, except where it is explicitly stated otherwise.

Table 4-1 : Simulation parameters LTE Downlink/Uplink for general analysis on user behaviour

	Downlink	***Uplink***
Environment	**Urban Micro-cellular with modified user speeds *(see 3.2.1)***	
Channel model	**UMi *(see 3.2.2)***	
Number of cells	**21 cells (7 sites x 3 sectors per site)**	
Offered load	**10 users per cell**	
Antenna configuration	**2 tx X 2 rx**	**1 tx X 2 rx**
Scheduler	**FDM**	
Traffic model	**Full buffer**	
CQI reporting mode	**Wideband**	**Not applicable (DRS based)**
CQI reporting period	**5 ms (5 sub frames)**	**1 ms (1 sub frame) (DRS based)**
CQI report delay	**6 ms (6 sub frames)**	**6 ms (6 sub frames)**
Maximum transmission attempts	**1**	
Link adaptation margin	**0 dB (No CQI adjustment)**	

Reasons for selecting the FDM scheduler and setting the maximum number of transmissions attempts to 1 are explained below.

<u>FDM scheduling</u>

Since in FDM all the users are scheduled in all the sub frames with equal number of resources, it avoids some of the unpredictability and randomness that is introduced by PFTF scheduler. Although the RR scheduler does not introduce any randomness, each user gets its turn for transmission/reception once during a certain number of sub frames. In this case error occurrences can occur once in every few frames, although the actual channel variations happen in real time. In order to consider short term trends in user behaviour such as error clusters *(see 4.3)* as a reflection of sudden variations in channel conditions and inaccuracies in CQI reporting, it is helpful if all the users are scheduled in all sub frames. Therefore FDM scheduling was selected as the scheduling scheme.

Maximum transmission attempts = 1

The default value for the maximum number of transmission attempts is 6. Since each successive retransmission attempt soft combines packets from previous transmissions, each one is less prone to errors than the previous. This is advantageous in real life. However, to assess the user behaviour trends that would reflect sudden variations in channel and CQI reporting inaccuracies; it is more suited to have maximum transmission attempts set to 1 as a base case.

4.2. Actual SINR vs. measured SINR

When studying link adaptation it is interesting to know its limits, (e.g. what is the performance of the system if the instantaneous channel conditions were known?). Table 4-2 presents a comparison of average cell throughput (bps/Hz/cell) and cell-edge user throughput (bps/Hz) for the practical situation where the CQI is based on pre-measured SINR values and an ideal situation where the actual SINR experienced by the user at the time of transmission is known. It should be noted that the ideal situation is never practically possible and only available in the simulation environment.

Table 4-2: Comparison between the performance of actual SINR and Measured SINR

	Actual SINR (Ideal situation)		*Measured SINR (practical situation)*		*Percentage degradation*	
	Downlink	**Uplink**	**Downlink**	**Uplink**	**Downlink**	**Uplink**
Avg. Cell-throughput (bps/Hz/cell)	1.3327	0.9833	0.9281	0.7996	30.4%	18.68%
Cell-edge user-throughput (bps/Hz)	0.0288	0.011	0.0177	0.0101	38.5%	8.18%

It is evident from the numbers in Table 4-2, that the degradation caused by imperfect CQI is very large in the downlink and the goal would be to gain back at least a fraction of it. In the uplink there is a significant degradation in terms of average cell throughput, but the degradation is smaller than in the downlink.

4.3. Error clusters

This thesis focuses on adjusting the link adaptation margin of each user based on HARQ feedback e.g. the packet error occurrences. For such an approach to be effective, it is advantageous if a large majority of the packet error occurrences are concentrated as error clusters. On the other hand, if errors mostly occur randomly on an ad hoc basis, it would be quite difficult to use error occurrences as feedback to a link adaptation algorithm.

Figure 4-1 and Figure 4-2 show the average number of error clusters longer than a certain length per user per 500 sub frames for downlink and uplink respectively. Lengths of error clusters are shown on the x-axis and the average number of error clusters longer than the particular length per user per 500 sub frames is shown on the y-axis.

An ***error cluster*** here is defined as a period where there are no more than 3 consecutive error-free frames for a particular user. If 4 consecutive error-free frames were received, the error cluster was considered ended.

The 'Stream-2' in the Figure 4-1 for downlink refers to error clusters occurred for packets transmitted on stream-2 of transmissions of rank-2. The 'Stream-1' includes error clusters for packets transmitted from stream-1 of rank-2 transmissions as well as rank-1 transmissions.

It can be seen that the number of error clusters for stream-2 is significantly lower than stream-1, although the overall BLER for stream-1 and stream-2 are quite close, being 0.272 and 0.282, respectively. Since stream-2 transmissions are less frequent it is less likely to have error clusters in stream-2 as compared to stream-1. Therefore it is more suitable to look at stream-1. For the uplink, a 1x2 antenna configurations is used. Hence only rank-1 transmissions are possible. Therefore Figure 4-2 has only one plot which is for stream 1.

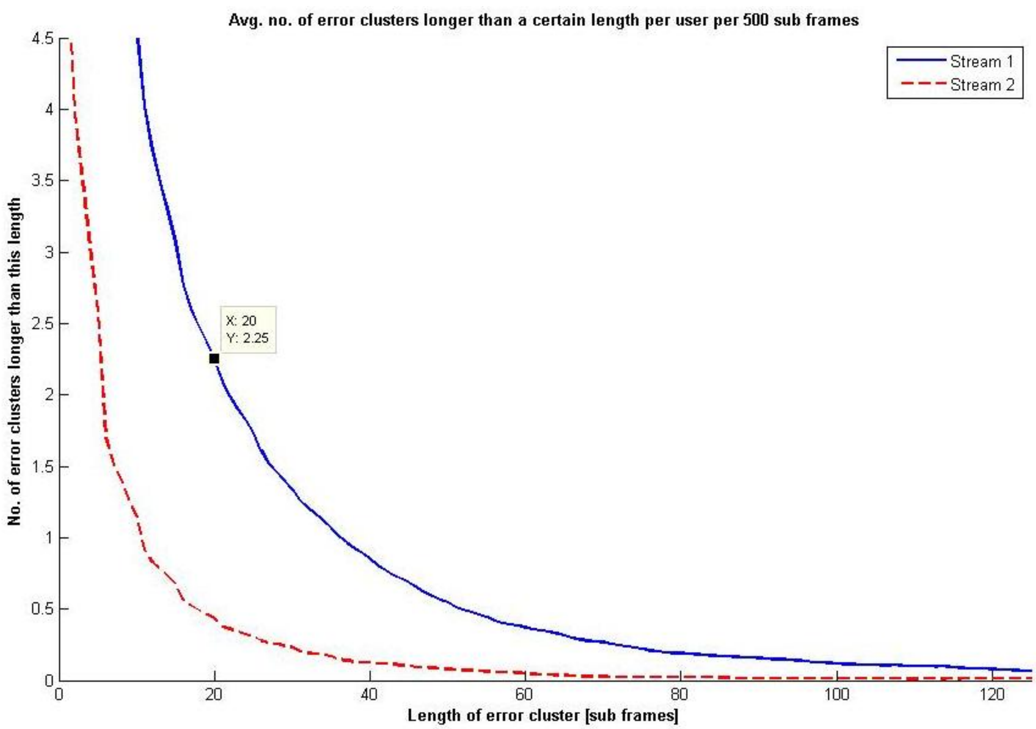

Figure 4-1: Avg. number of error clusters per user per 500 sub frames – downlink

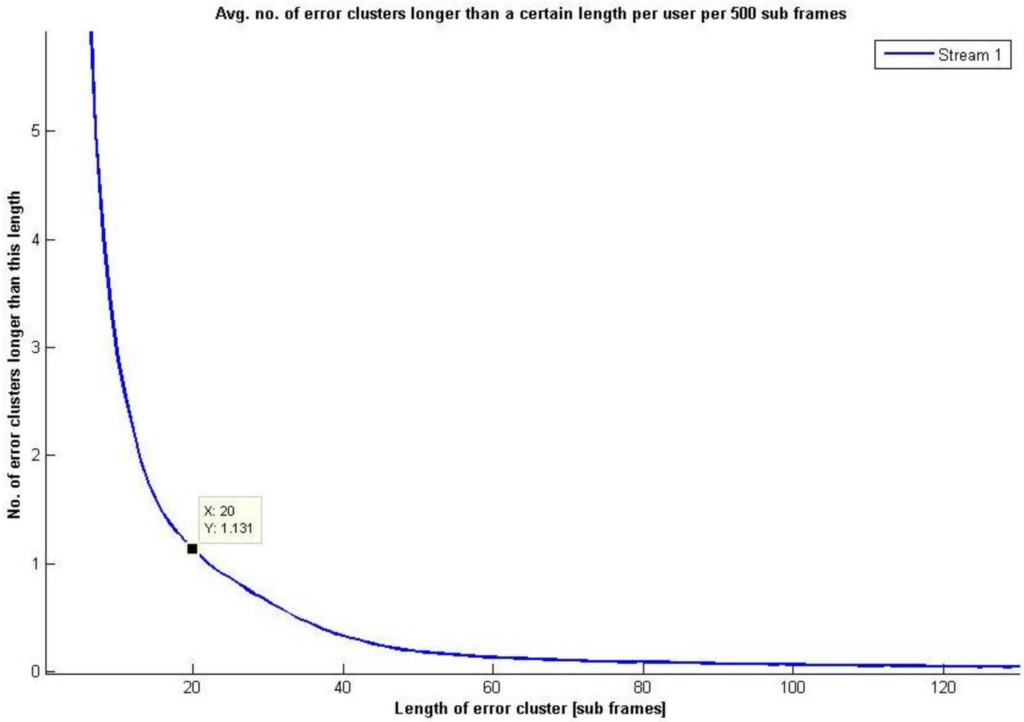

Figure 4-2: Avg. number of error clusters per user per 500 sub frames - uplink

For downlink stream-1 it can be seen from the Figure 4-1 that there are only 2.25 error clusters which are at least of length 20 sub frames, on average per user per 500 sub frames. The length of 20 was simply chosen here as a sufficiently long period to detect an error cluster, make necessary adjustments on the link adaptation margin and to benefit from the change for the next couple of transmissions. For the uplink, as the Figure 4-2 shows, this value is around 1.131.

Therefore it may be possible that the packet errors rarely occur as long clusters, but rather ad hoc and scattered, which may be undesirable for a link adaptation algorithm based on error feedback.

Error clusters by user categories

As an additional analysis, the users were divided into five categories and the error cluster lengths were plotted similarly for each user category. The user categories are,

- Indoor users
- Outdoor line-of-sight (LOS) slow users
- Outdoor non line-of-sight (NLOS) slow users
- Outdoor line-of-sight (LOS) fast users
- Outdoor non line-of-sight (NLOS) fast users

These categories were chosen to be non-overlapping, meaning that a given user cannot be in more than one category. For LOS and NLOS, the conventional definitions follow.

Indoor users are the users who stay indoors but are covered by outdoor base stations, thus are affected by outdoor to indoor penetration loss *(see 3.2.1)*. The slow users are the users who move at 3 km/h and the fast users are the users who move at 30 km/h *(see 3.2.1)*. Although it is not easy in a practical situation for the base station to know precisely which category a user belongs to, it could be interesting in a simulation environment to gain some insight into relative behaviour of users belonging to different categories. Figure 4-3 and Figure 4-4 shows the error cluster length plots, for different user categories for downlink and uplink, respectively.

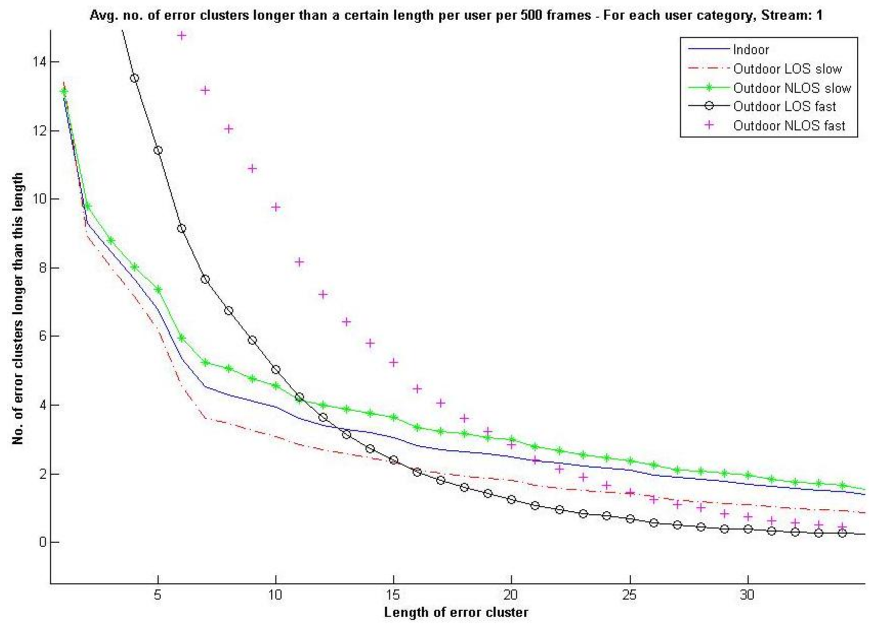

Figure 4-3: Avg. number of error clusters per 500 sub frames per user of each category– downlink

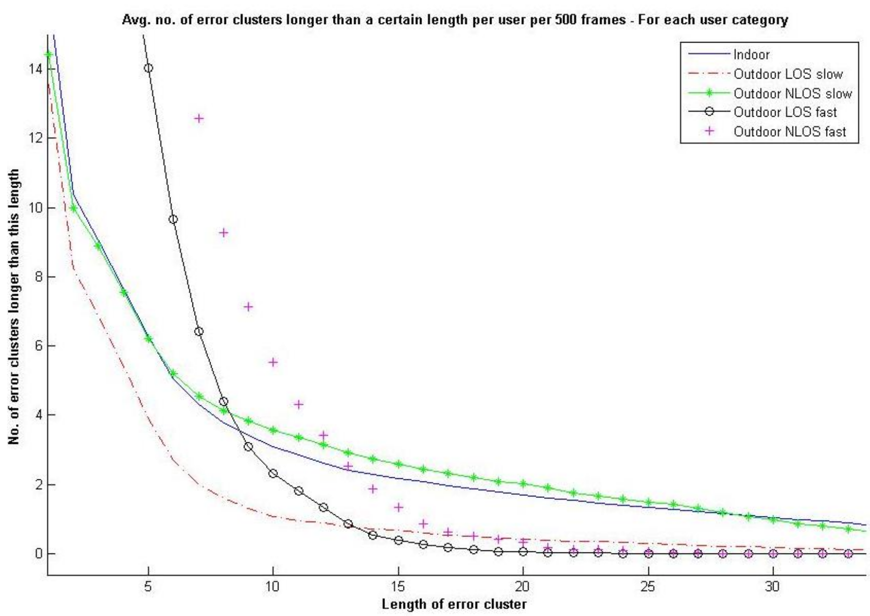

Figure 4-4: Avg. number of error clusters per 500 sub frames per user of each category– uplink

From Figure 4-3 and Figure 4-4, it can be seen that none of the user groups show considerably high number of long error clusters, for example, 20 frames or longer. The approximate shapes of the plots in Figure 4-3 and Figure 4-4 look the same, meaning that all the user categories show similar trends relative to each other in downlink and uplink. Naturally, it is expected that the outdoor LOS slow users would have the best channel conditions among the given categories and they are also shown to have the lowest number of error clusters for the shorter cluster lengths. Indoor users and outdoor NLOS slow users show similar error cluster distributions for both uplink and downlink. It is true that the indoor users are invariably NLOS and slow for urban micro-cellular environment, but the effect of having outdoor to indoor path loss is not apparent from the plots. Interestingly, the two fast user categories have the highest number of short error clusters but less long error clusters than the other user categories. Since it is known that the channel conditions vary rapidly for the fast moving users, this trend could possibly suggest that for the fast users, the poor channel conditions could improve quicker than for the slower users thus making long error clusters quite rare.

The Table 4-3 shows the overall BLER for each user category for downlink and uplink.

Table 4-3: Overall BLER for each user category for downlink and uplink

User category	**BLER**	
	Downlink	***Uplink***
Indoor	0.2754	0.2169
Outdoor LOS slow	0.2017	0.0913
Outdoor NLOS slow	0.2912	0.1825
Outdoor LOS fast	0.2576	0.2698
Outdoor NLOS fast	0.4096	0.4147

For both downlink and uplink, the outdoor LOS slow users showed the lowest BLER while outdoor NLOS fast users showed the highest BLER. This is in no contradiction to what one would naturally expect. In the downlink, the outdoor NLOS slow users showed higher BLER than outdoor LOS fast users whereas in the uplink the opposite is true. This could probably be due to the downlink transmissions being more affected by interference than the uplink transmissions; the presence of a LOS signal path greatly helps to overcome interference whereas in the uplink where the interference is lower than the downlink, the rapid channel variations that result due to faster speeds could make a greater impact. Also, the relationship between indoor users and outdoor NLOS slow users are opposite for downlink and uplink. The BLER of indoor users being higher than outdoor NLOS slow users in the uplink can possibly be explained by the fact the uplink transmission power is limited by the power available for mobile user equipments, hence the outdoor to indoor path loss could have a greater effect than in the downlink where more power is available. Overall, the BLER of slow users, including the indoor users is considerably lower in the uplink than in the downlink and the BLER of fast users are approximately the same for both links. Since the uplink uses the DRS based SINR estimation, a new SINR estimate is available every sub frame as opposed to downlink where a new CQI report is available only every 5 sub frames. Therefore, the tracking of channel variations for slow users in the uplink could be more effective than in the downlink, while the effect is lower for more rapidly varying channel conditions of fast users.

4.4. SINR estimation errors

In the simulation environment, due to the availability of the actual value of SINR that the user experiences at the time of transmission, it is possible to calculate the SINR estimation error for each sub frame. SINR estimation error here is simply the difference between the estimated SINR value and the actual SINR value in dB.

The probability density function of SINR estimation error empirically derived from values accumulated over all the sub frames and across simulation iterations would reveal if there is any considerable bias in users estimating the SINR, i.e. over-estimation or under-estimation.

The probability density function of SINR estimation error is shown in Figure 4-5 for downlink and Figure 4-6 for uplink.

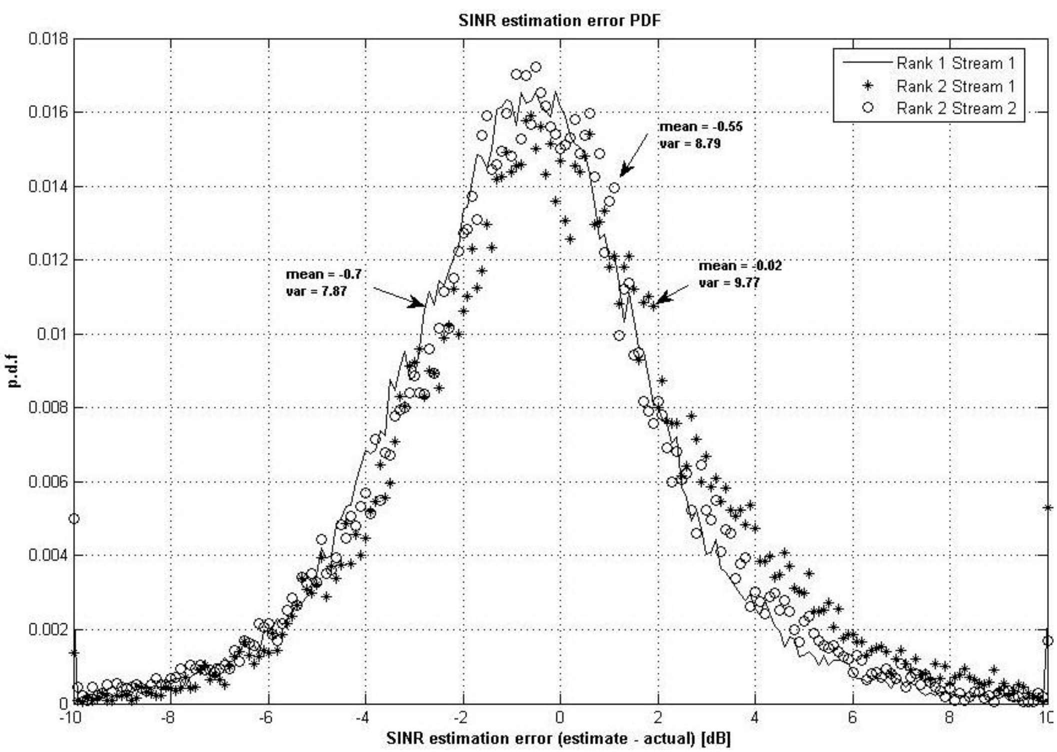

Figure 4-5: probability density function. of SINR estimation errors – Downlink

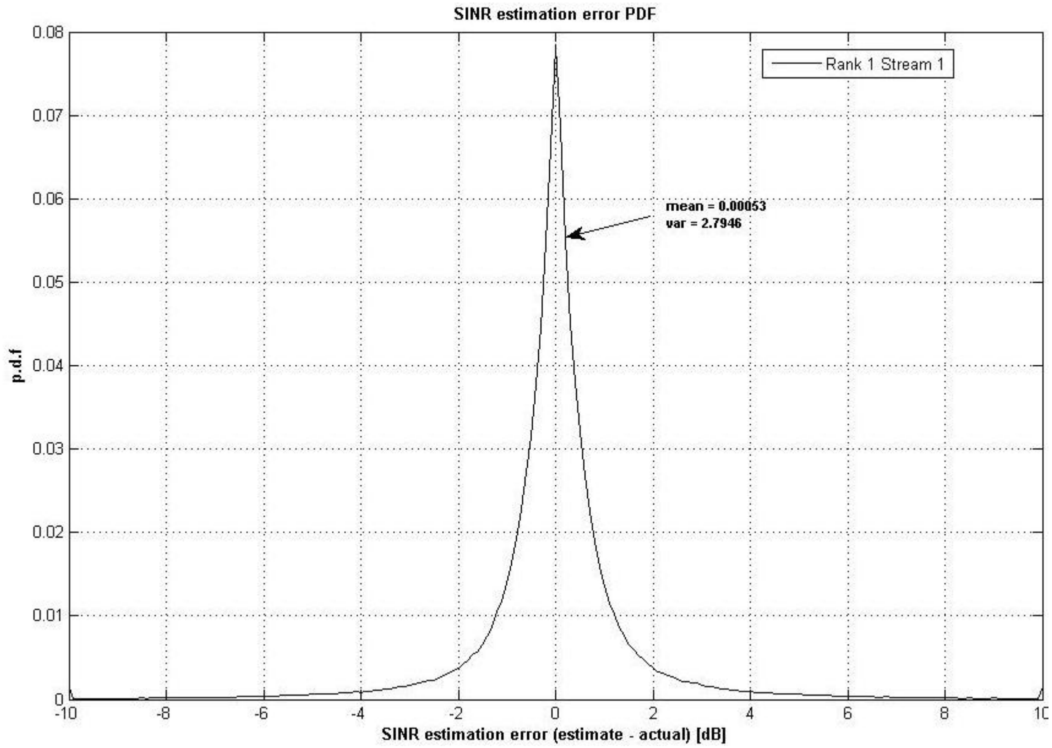

Figure 4-6: probability density function of SINR estimation errors - Uplink

As it can be seen from the figures, the downlink p.d.f is quite symmetrical around zero, while the uplink looks perfectly symmetric. This implies that there is no considerable overall bias towards either over-estimation or under-estimation for SINR.

The p.d.f for downlink shows a very large variance compared to the uplink, implying that uplink SINR estimation is more accurate than downlink. In the uplink most of the estimates seem to differ from the actual value only by less than 1.5 dB. But, in the downlink there is a large portion of estimates that are in error by a margin of more than 3-4 dB. The better SINR estimation in uplink is most likely due to the use of demodulation reference signals (DRS) for channel estimation and since the FDM schedules all the users in every sub frame, a new CQI report is available for each sub frame.

4.5. Performance variation with CQI related parameters

4.5.1. CQI report delay vs. throughput/BLER

Downlink CQI report delay *(see 2.3.1)* is inevitable in practice as explained before. Similarly, in the uplink, the CQI delay *(see 2.3.2)* corresponds to the time from the channel measuring begins until the measured CQI is used for link adaptation.

4.5.1.1. Downlink

Figure 4-7 shows the variation in average cell throughput, cell-edge user throughput and BLER with changing CQI report delay. Also, it should be noted that the lowest CQI report delay for LTE in practice is 6 ms (6 frames) and the values lower than that were simulated for completeness.

As seen in the figure the decrease in performance with increase in CQI report delay is not very significant. The decrease in average cell throughput for the increase in CQI report delay from 1 frame to the practical operating point of 6 frames is about 2.2%.

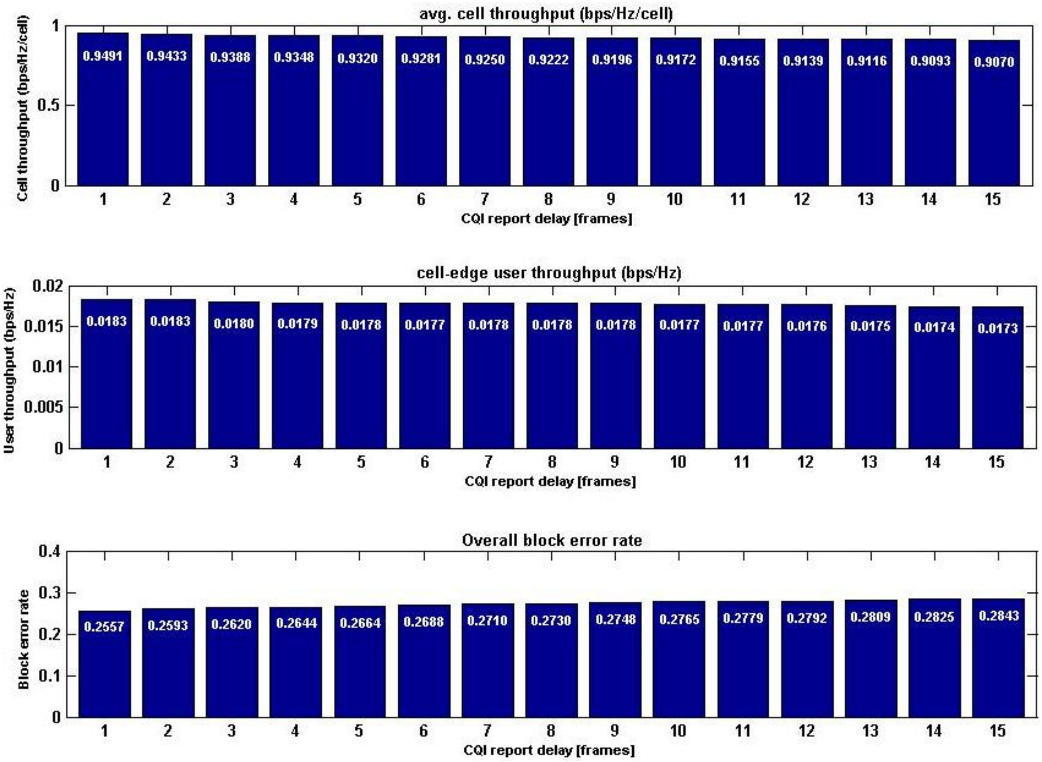

Figure 4-7: Downlink CQI report delay vs. cell-throughput, cell-edge user throughput and BLER

4.5.1.2. Uplink

Figure 4-8 shows the variation in average cell throughput, cell-edge user throughput and BLER for the uplink with changing CQI delay. Similar to the downlink, the lowest CQI delay in practice is 6 ms (6 frames) for the uplink.

Unlike in the downlink, the degradation of performance is significant as the uplink CQI delay increases. The decrease in average cell throughput for the increase in CQI delay from 1 to the practical point of 6 frames is about 14.6%. Also it is worth noticing that the cell-edge user throughput of 0.011 bps/Hz when the CQI delay equals 1 is the same as what was achievable with actual SINR (perfect situation) given in Table 4-2.

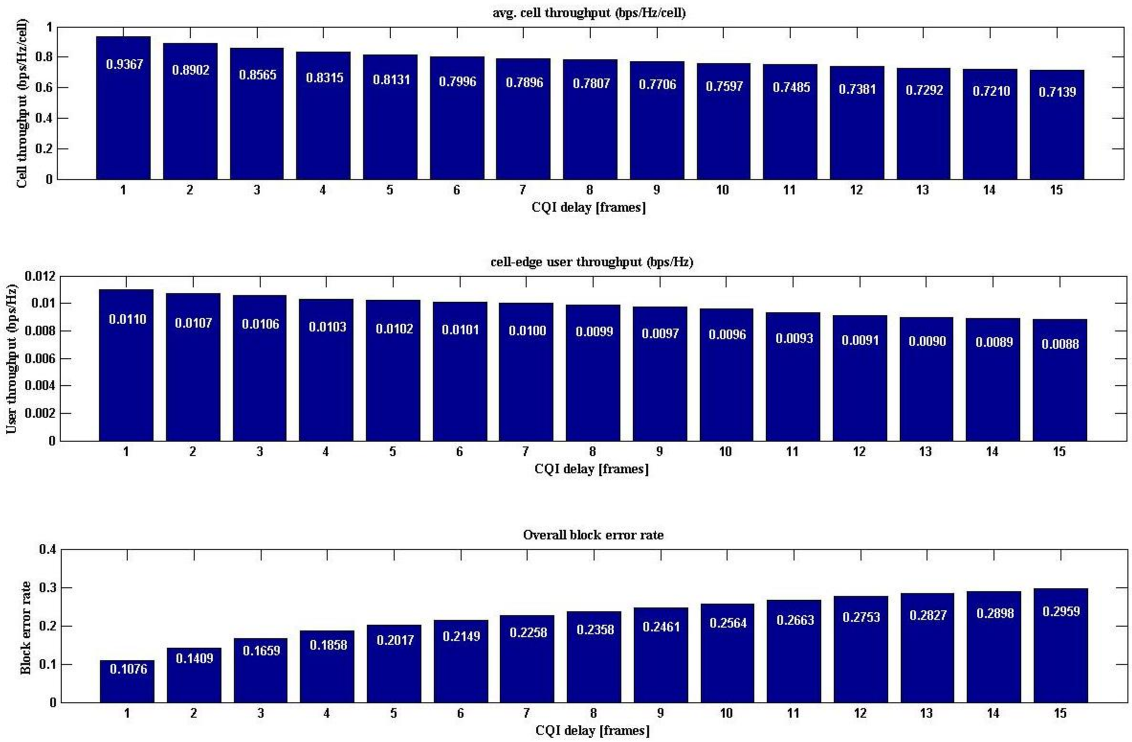

Figure 4-8: Uplink CQI delay vs. cell-throughput, cell-edge user throughput and BLER

4.5.2. CQI reporting period vs. throughput/BLER

Downlink CQI reporting period *(see 2.3.1)* would ideally be 1 frame, meaning that channel quality is measured and reported on every frame. But, due to overhead in transmitting reference signals, measuring and reporting, the default value is set to 5 ms (5 frames).

Similarly, for the uplink, in the case where the channel is estimated by measuring the channel sounding reference signals (SRS) *(see 2.3.2)*, the period of transmission of SRS is set to a default of 20 ms (20 frames). But in this case, since the demodulation reference signals (DRS) are used for channel estimation and FDM schedules all users in every frame, the channel is estimated with a period of 1.

Shorter reporting periods are necessary to capture fast channel variations. On the other hand longer periods may have the advantage of measuring over a long period to give a more accurate measurement on average.

4.5.2.1. Downlink

Figure 4-9 shows the variation in average cell throughput, cell-edge user throughput and overall BLER with changing CQI reporting period.

As seen in the figure, the performance decrease with increase in CQI reporting period is quite negligible. The decrease in average cell throughput for the increase in CQI reporting period from 1 frame to the default operating point of 5 frames is only 0.72%.

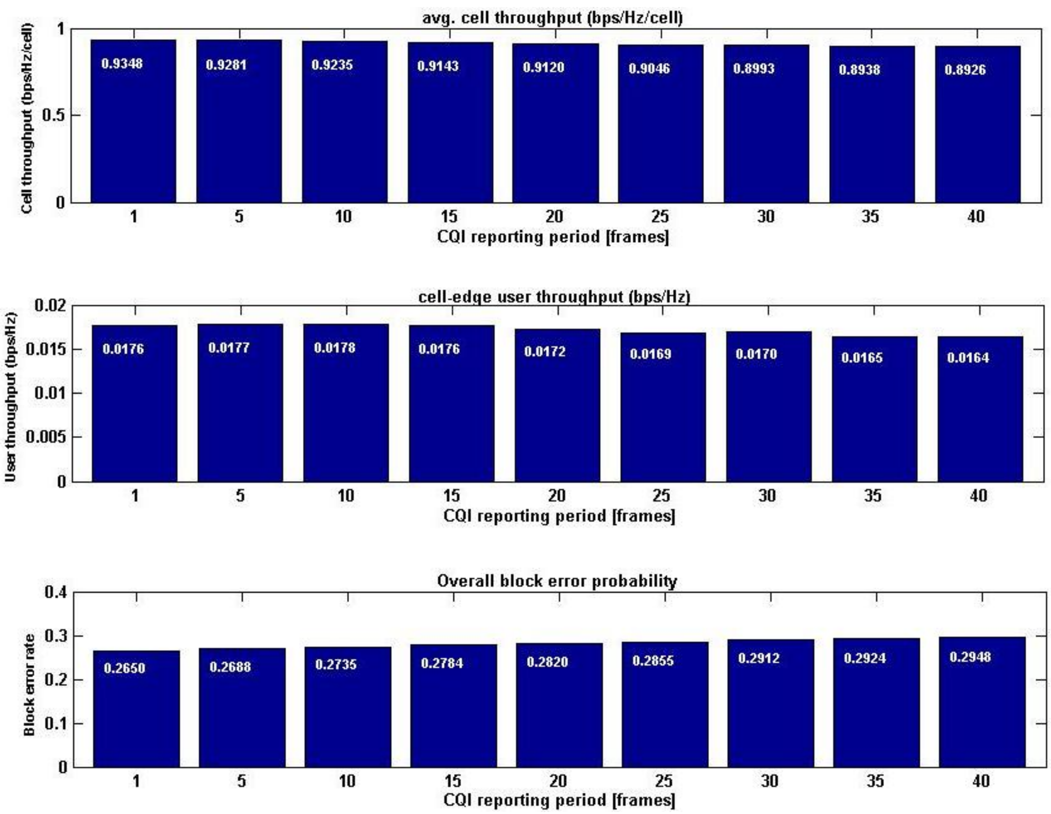

Figure 4-9: CQI reporting period vs. cell-throughput, cell-edge user throughput and BLER

4.5.2.2. Uplink

As mentioned before, the DRS are used for channel estimation in these simulations. Hence it is not possible for a similar analysis on the uplink.

4.5.3. Age of CQI report vs. block error rate

Due to CQI report delay and CQI reporting period, the CQI report that is used for the link adaptation is always a couple of frames old.

4.5.3.1. Downlink

In the downlink for the default scenario where CQI report delay is 6 frames and CQI reporting period is 5 frames, the report is at least 6 frames old. Since the next report will be available only in another 5 frames, the link adaptation for the next 4 frames has to rely on the same CQI report. Hence in this case, a report can be 6 to 10 frames old.

Figure 4-10 presents simulation results that show the block error rates for transmissions for which the link adaptation was based on CQI reports of different age. If there is a marked increase of block error rate as the CQI report ages, it could be possible to vary the link adaptation margin from aggressive to conservative (low to high) as the CQI report ages and gain some increase in overall system throughput. But, as evident from Figure 4-10, although the block error rate seems to increase with the age of CQI report, the increases are quite negligible and can be considered almost constant throughout. It suggests that in the given range, the age of the CQI report does not seem to show much significance when the BLER is concerned.

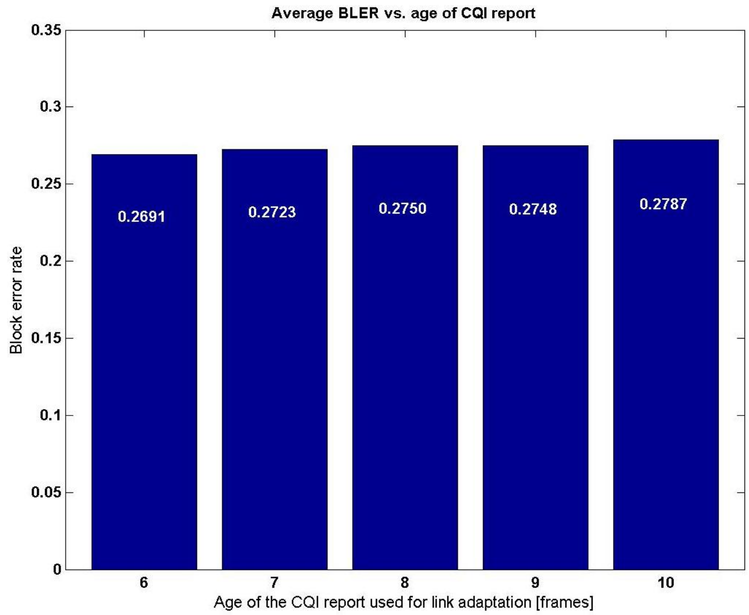

Figure 4-10: Block error rate vs. age of the CQI report used for link adaptation - Downlink

4.5.3.2. Uplink

Similar to 4.5.2.2, a similar analysis for the uplink is not possible due to uplink channel estimation being done using DRS. As a new CQI report is available on every frame if the user is scheduled, the age of the CQI report being used for link adaptation for a particular transmission is 6 frames plus scheduling delay.

4.6. Analysis on transport block sizes vs. BLER

The following analysis on BLER and transport block sizes intends to serve only as a general analysis and is not directly related to the scope of the thesis.

Transport block size for each user during each transmission was defined here as the number of transmitted data bits per chunk carrier during each frame as given below.

$$Transport\,block\ size = \frac{No.of\ transmitted\ data\ bits}{No.of\ chunk\ carriers\ used}\ \ [bits]$$

On the other hand, the transport block size is directly related to the modulation order and coding rate as,

$$Transport\,block\ size = \begin{pmatrix} Modulation \\ order \end{pmatrix} \times \begin{pmatrix} No.of\ Modulation \\ symbols\ per\ chunk\ carrier \end{pmatrix} \times (Coding\ rate)\ \ [bits]$$

Figure 4-11 and Figure 4-12 show the block error rate for each transport block size obtained through simulations for downlink and uplink respectively. Although it is difficult to draw clear conclusions from the results, one interesting point to note is that in the uplink, the BLER is considerably higher for the smallest transport block size. The smallest transport block size refers to the lowest modulation order and the coding rate, thus the most robust MCS. The high BLER could be due to all the transmission attempts for the users whose latest CQI report indicates very bad channel conditions that transmits using the most robust MCS although the channel conditions may even be worse than what is necessary for correct reception using the most robust MCS.

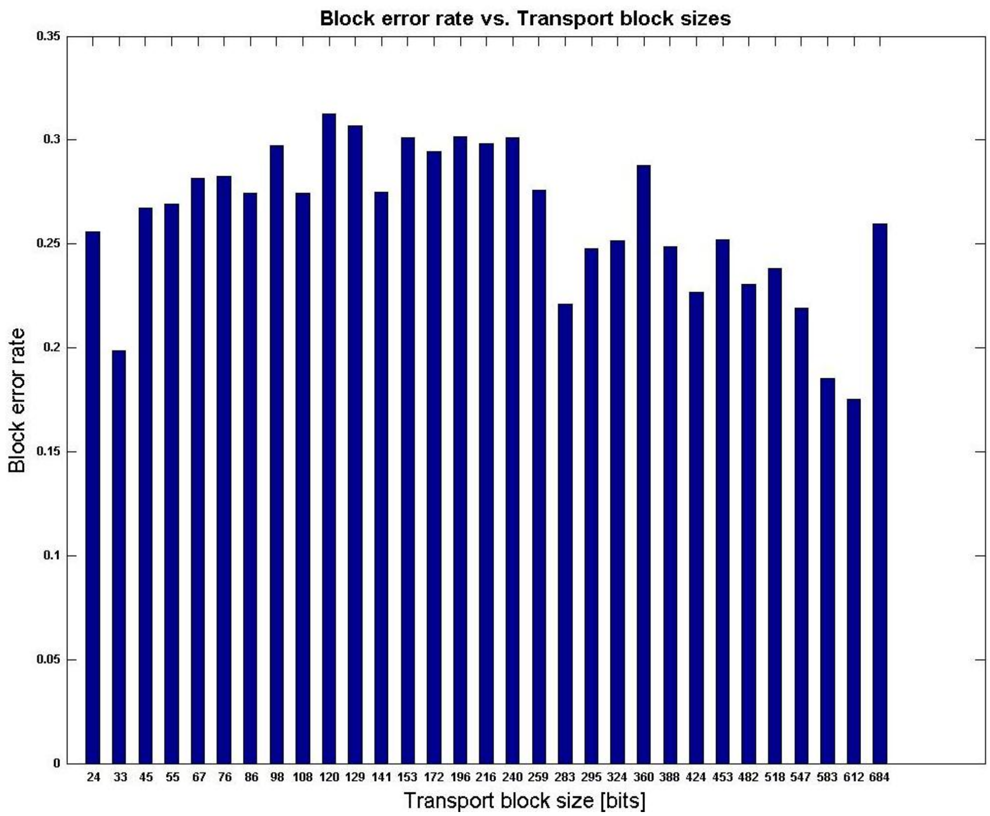

Figure 4-11: Block error rate vs. transport block sizes – Downlink

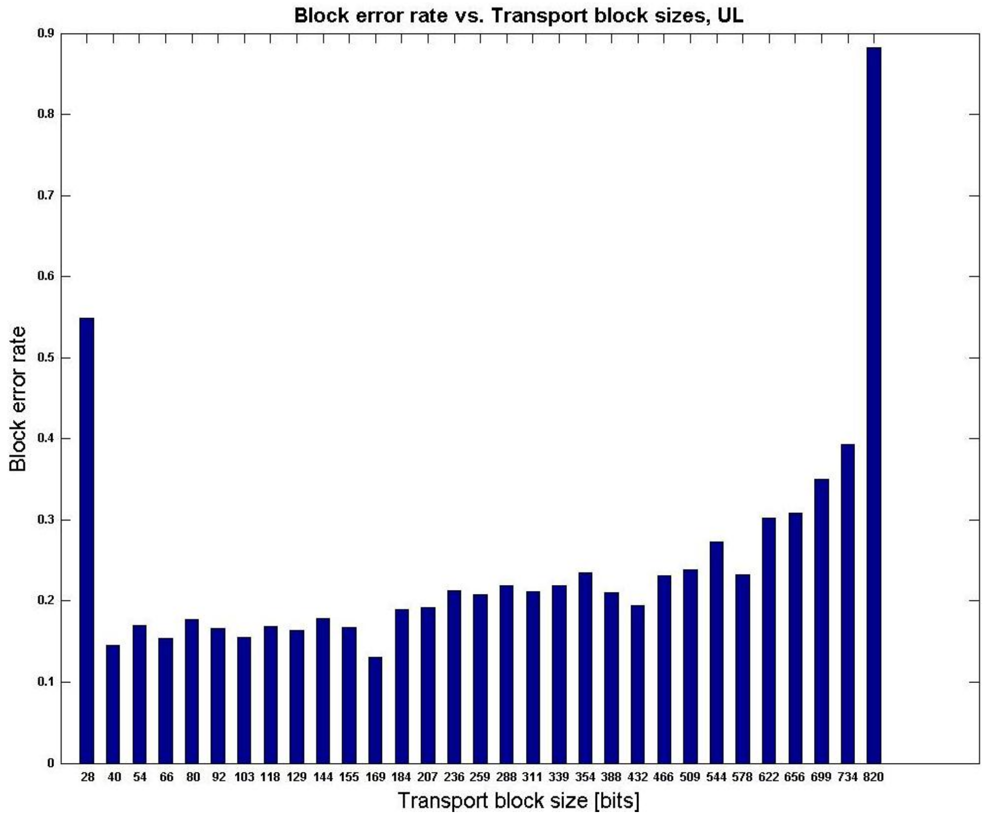

Figure 4-12: Block error rate vs. transport block sizes – Uplink

4.7. Summary

The results presented in 4.2 showed that for the downlink, there was a very large decrease in performance in terms of average cell throughput and cell-edge user throughput, due to imperfect CQI, when compared to the ideal situation. But, as seen in 4.3, long packet error clusters are rare to occur and as seen in 4.4, the probability density function of SINR estimation errors showed a very high variance. This may suggest that the degradation in performance could largely be attributed to sudden short term variations in channel conditions and measurement errors. Therefore a link adaptation algorithm that seeks to improve performance by using feedbacks from error occurrences would have to act reasonably quickly, probably based on instantaneous errors rather than periods of high error rates.

In the uplink however, the degradation of performance due to imperfect CQI was far less than in the downlink, although still significant. The probability density function of uplink SINR estimation errors in 4.4 showed a far lower variance than the downlink. As compared to the downlink, the error cluster occurrences were rarer. Also, the overall BLER was lower for the uplink. This can be seen in Figure 4-7 and Figure 4-8, where for the downlink, the default operating point at CQI report delay of 6 ms showed a BLER of 0.27 and for the uplink, the default operating point showed a BLER of 0.21.

Nevertheless, two algorithms that perform differentiated link adaptation were selected for performance analysis. They are the fast link adaptation (FLA) algorithm *(see 2.4.2.3)* and the window BLER based link adaptation (WLA) algorithm *(see 2.4.2.3)*.

5. LTE downlink – Differentiated link adaptation

This chapter presents simulation results for differentiated link adaptation for LTE downlink using FLA algorithm and WLA algorithm. The performance of the algorithms will be compared with each other and with the performance of using a fixed link adaptation margin.

5.1. Simulation parameters

Table 5-1 shows the simulation parameters used to obtain the results in this section, which are the same as what were presented in chapter 4 except the CQI reporting mode, maximum number of transmission attempts and the link adaptation margin.

The CQI reporting mode was changed to sub band CQI with frequency granularity of 6 *(see 2.3.1)*. Although sub band CQI could be more sensitive to frequency selective channel variations as compared to wideband CQI, it can be considered more accurate in representing CQI values on sub band level. The maximum transmission attempts were changed to the default value of 6, to be more realistic. The link adaptation margins will be specified later in each section.

Table 5-1: Simulation parameters LTE Downlink - differentiated link adaptation

Environment	Urban Micro-cellular with modified user speeds *(see 3.2.1)*
Channel model	UMi *(see 3.2.2)*
Number of cells	21 cells (7 sites x 3 sectors per site)
Offered load	10 users per cell
Antenna configuration	2x2 MIMO
Scheduler	FDM / PFTF
Traffic model	Full buffer / FTP
CQI reporting mode	Sub band CQI
CQI report frequency granularity	6
CQI reporting period	5 ms (5 sub frames)
CQI report delay	6 ms (6 sub frames)
Maximum transmission attempts	6
Link adaptation margin	Fixed/Differentiated
Number of mobile positions	For full buffer traffic: 630 (21 cells x 10 users per cell x 3 iterations) For FTP traffic: No. of mobile positions=No. of file transfers (depends on the offered load in bps/cell, mean file size and an estimated bit rate)

5.2. Simulation results

The downlink simulations were run for 3 different scenarios and the results are presented below. The 3 scenarios are full buffer traffic-FDM scheduler, full buffer traffic -PFTF scheduler and FTP traffic-PFTF scheduler. The first scenario, which is full buffer traffic-FDM scheduler, will be discussed in more detail than the other two, in order to explain how the simulations were run and the comparisons are done. The results for the other two scenarios will be presented briefly.

5.2.1. Full buffer traffic – FDM scheduler

5.2.1.1. Throughput for various fixed link adaptation margins

In order to compare the performance of algorithms that perform differentiated link adaptation, it is necessary to choose a benchmark. Since the goal is to assess, if any, the gain in average cell throughput and cell-edge user throughput achievable via differentiated link adaptation, the comparison has to be made against the performance achievable in terms of average cell throughput and cell-edge user throughput with a fixed link adaptation margin. Three comparison points were chosen as described in 3.4, which are, the point that maximizes the average cell throughput, the point that maximizes the cell-edge user throughput, and the point that is chosen as the best combination.

The link adaptation margins were chosen to be in the range of -2 to 2 dB with steps of 0.5 dB. The simulation results are shown in Figure 5-1.

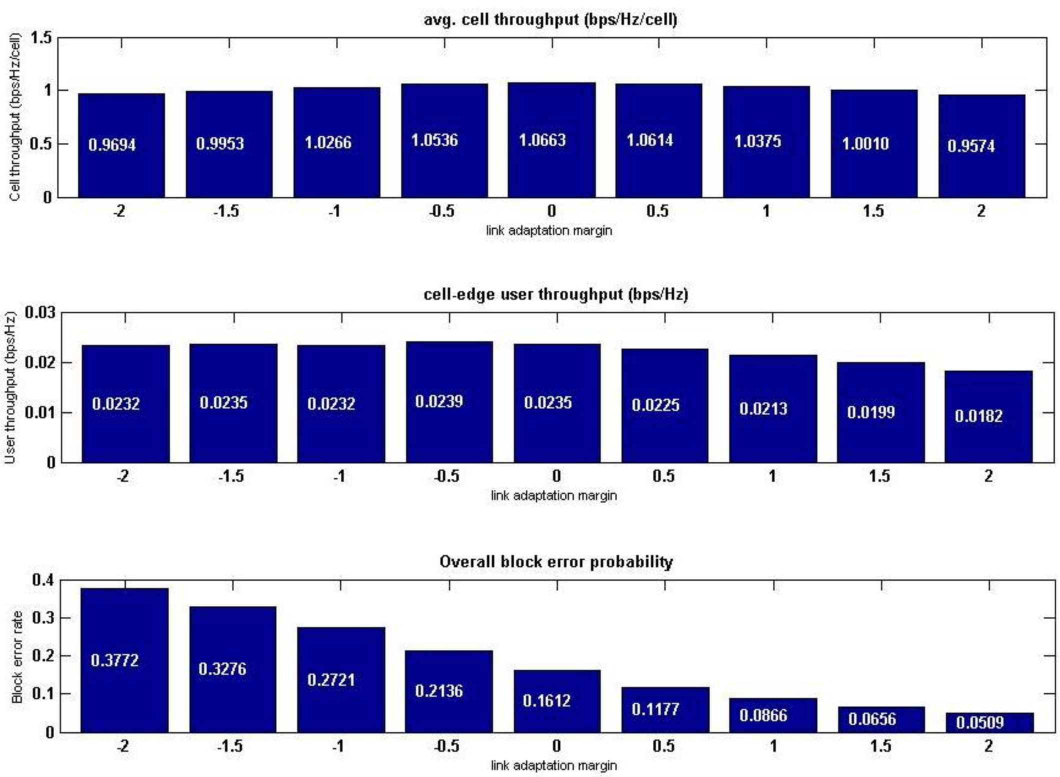

Figure 5-1: Downlink - Avg. cell throughput, cell-edge user throughput and BLER for various fixed link adaptation margins – full buffer traffic-FDM scheduler

As shown in Figure 5-1, the maximum average cell throughput of 1.0663 bps/Hz/cell is achieved with a link adaptation margin of 0 dB whereas the maximum cell-edge user throughput of 0.0239 bps/Hz is achievable with a link adaptation margin of -0.5 dB. The best combination was found to be the link adaptation margin of -0.5 dB.

Having chosen the benchmarks for comparison of average cell throughput and cell-edge user throughput, the remainder of this section presents the performance comparison for the downlink differentiated link adaptation using the FLA and the WLA algorithm.

5.2.1.2. Differentiated link adaptation

FLA algorithm

As described in 2.4.2.3, the FLA algorithm is a simple algorithm that adjusts the individual user's link adaptation margin on a frame by frame basis depending on whether the last transmission attempt was successful or not. It involves two parameters, the adjustment made to the link adaptation margin if the last transmission was successful (ACKadj) or unsuccessful (NACKadj). The optimum values of the parameters could depend on the user environment, the type of scheduler, traffic model and various other factors. Therefore it is necessary to run the simulations for several values in a reasonable range in order to select the best values for the given situation.

In this case the values for ACKadj were chosen to be 0.05, 0.10, 0.15 and 0.20. For each value of ACKadj, the values of NACKadj were chosen such that the values of BLERtarget are 0.05, 0.10, 0.15, 0.20, 0.25, 0.30, 0.35, 0.40, 0.45, and 0.50 giving 40 sets of values.

Out of the different ACKadj and NACKadj combinations, the highest average cell throughput of 1.0613 bps/Hz/cell was achieved when ACKadj = 0.1 and NACKadj=0.6667. The highest cell-edge user throughput of 0.0233 bps/Hz was achieved when ACKadj = 0.15 and NACKadj=0.4286. The best combination was found to be the combination with ACKadj = 0.05 and NACKadj=0.2

Neither combination performed better than the fixed link adaptation margins as summarized in table 5-2. Table 5-2 as well as the other tables of similar format should be self-explanatory. For example, table 5-2 compares the average cell throughput and cell-edge user throughput of fixed link adaptation margin with that of FLA algorithm at all three comparison points (6 comparisons overall). The columns with the percentage change from fixed link adaptation margin shows negative quantities in this case indicating that the FLA algorithm resulted in lower average cell throughput and cell-edge user throughput at all three comparison points.

WLA algorithm

The WLA algorithm *(see 2.4.2.3)* has 3 parameters to be optimized. They are, the window size (WINsize), the low and higher BLER threshold for determining if the last window should affect the current link adaptation settings.

In order to optimize the parameters for the given scenario, 80 combinations of the 3 parameters were simulated. The results at the three comparison points are summarized in table 5-3 and compared with the fixed link adaptation margins.

Again, the performance achieved with the fixed link adaptation margin was better than that of WLA algorithm at all comparison points.

Table 5-2: Downlink - FLA algorithm, comparison with fixed link adaptation margin – full buffer traffic-FDM scheduler

	Combination for highest avg. cell throughput			**Combination for highest Cell-edge user throughput**			**Best combination**		
	Fixed link adapt. margin	***FLA algo*.**	*% change from fixed margin*	*Fixed link adapt. margin*	***FLA algo.***	*% change from fixed margin*	*Fixed link adapt. margin*	***FLA algo*.**	*% change from fixed margin*
Average cell throughput bps/Hz/cell	1.0663	**1.0613**	**-0.47**	1.0536	**1.0169**	**-3.48**	1.0536	**1.0450**	**-0.82**
Cell-edge-user throughput bps/Hz	0.0235	**0.0211**	**-10.21**	0.0239	**0.0233**	**-2.51**	0.0239	**0.0229**	**-4.18**

Table 5-3: Downlink - WLA algorithm, comparison with fixed link adaptation margin – full buffer traffic-FDM scheduler

	Combination for highest avg. cell throughput			**Combination for highest Cell-edge user throughput**			**Best combination**		
	Fixed link adapt. margin	***WLA algo*.**	*% change from fixed margin*	*Fixed link adapt. margin*	***WLA algo.***	*% change from fixed margin*	*Fixed link adapt. margin*	***WLA algo*.**	*% change from fixed margin*
Average cell throughput bps/Hz/cell	1.0663	**1.0409**	**-2.38**	1.0536	**1.0046**	**-4.65**	1.0536	**1.0233**	**-2.88**
Cell-edge-user throughput bps/Hz	0.0235	**0.0210**	**-10.64**	0.0239	**0.0230**	**-3.77**	0.0239	**0.0227**	**-5.02**

FLA algorithm and WLA algorithm comparison

It was seen in the results presented in this section that differentiated link adaptation using the FLA algorithm and the WLA algorithm for the case of full buffer traffic-FDM scheduler fell short of fixed link adaptation margin in terms of average cell throughput and cell-edge user throughput. Out of the two algorithms, the FLA algorithm performed, at least marginally better in terms of average cell throughput and cell-edge user throughput at all three comparison points. This was expected from the results shown in chapter 4, where it was seen that the packet errors are quite ad hoc and rarely occur as long enough clusters. Since the WLA algorithm acts based on the BLER during window periods whereas the FLA algorithm acts based on instantaneous packet errors, FLA algorithm could have an advantage compared to the WLA algorithm.

It is also worth noting that for the WLA algorithm, the average cell throughput increased as the window size (WINsize) was increased step by step from 5 to 50 frames. This is more clearly verifiable from the plots for the uplink in chapter 6, where the WLA algorithm was run for window sizes in the range 5-100 frames. For the uplink, the same effect could be seen for cell-edge user throughput as well, except for few points of deviation at low window sizes. When WINsize approaches the length of the simulation, the link adaptation margin is never updated and it is in effect the same as using a fixed link adaptation margin that is the same as the default value to which it was initialized, in this case 0 dB. Having found in 5.2.1.1 that a fixed link adaptation margin of 0 dB is quite optimal, this observation could be suggesting that the differentiated link adaptation using the WLA algorithm is not having any positive effect, but the lesser the update of link adaptation margin the better is the performance.

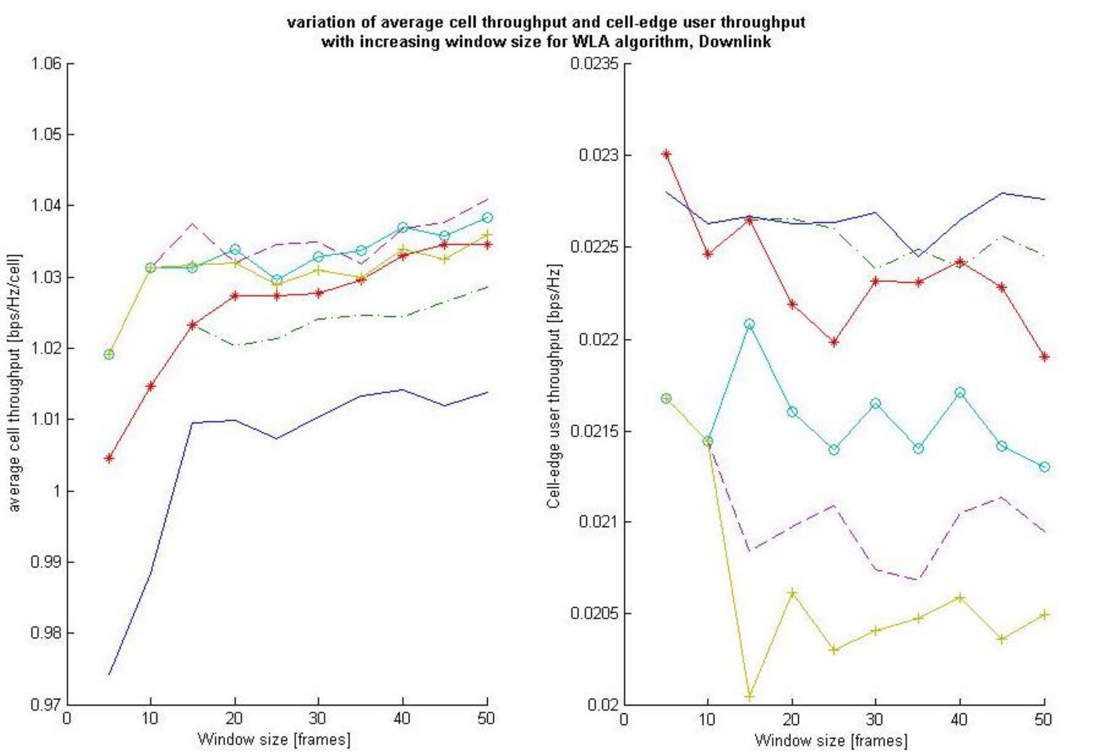

Figure 5-2: WLA algorithm UMi downlink Full buffer traffic - FDM scheduler -variation of avg. cell throughput and cell-edge user throughput with increasing window size

Next, the results for full buffer traffic-PFTF scheduler and FTP traffic-PFTF scheduler will be presented. Since PFTF scheduler and FTP traffic introduce more randomness to the distribution of each user's transmission attempts, hence to packet error occurrences, WLA algorithm should be a worse candidate than it was for full buffer traffic-FDM scheduler scenario. Therefore WLA algorithm was omitted from the rest of the downlink simulations and only comparisons between fixed link adaptation margin performance and FLA algorithm will be made.

5.2.2. Full buffer traffic – PFTF scheduler

This section presents simulation results for the LTE downlink transmission with full buffer traffic and PFTF scheduler. Unlike FDM scheduler, the PFTF scheduler makes use of each user's CQI for resource allocation. Although the PFTF scheduler introduces randomness into scheduling and transmissions, it may benefit more than the FDM scheduler if accurate CQI adjustments can be done, due to its CQI dependent resource allocation,

Similar to full buffer traffic-FDM scheduler scenario, benchmarks for comparison were chosen through simulations with different fixed link adaptation margins in the range -2 to 2 dB. Figure 5-3 shows the average cell throughput, cell-edge user throughput and BLER for different fixed link adaptation margins. The three comparison points were chosen in the same way as in 5.2.1 and the results are summarized and compared with that of the fixed link adaptation margin in table 5-4.

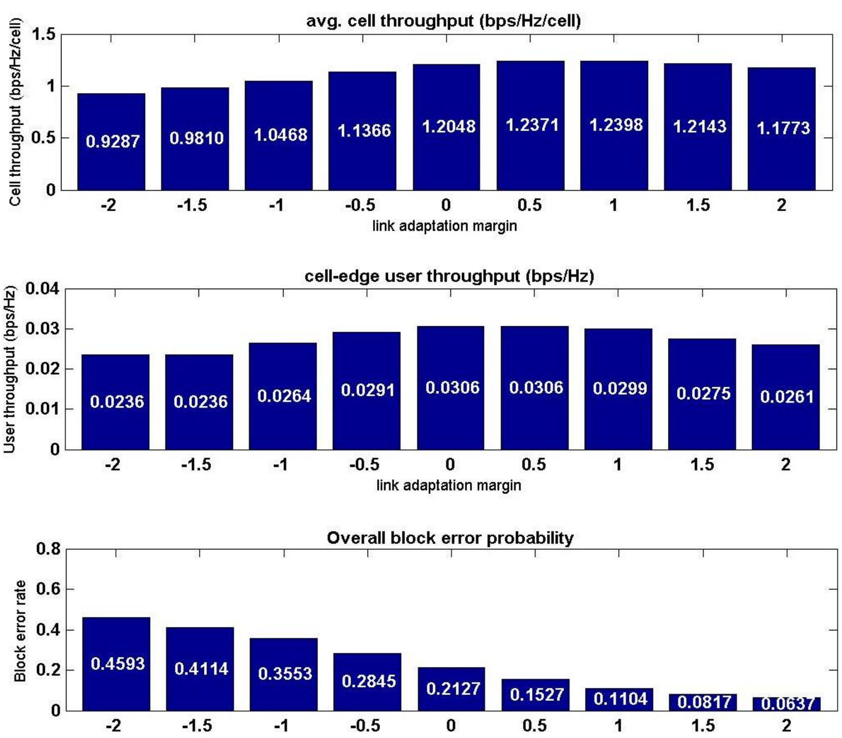

Figure 5-3: Downlink - Avg. cell throughput, cell-edge user throughput and BLER for various fixed link adaptation margins – full buffer traffic-PFTF scheduler

Table 5-4: Downlink - FLA algorithm, comparison with fixed link adaptation margin – full buffer traffic-PFTF scheduler

	Combination for highest avg. cell throughput			**Combination for highest Cell-edge user throughput**			**Best combination**		
	Fixed link adapt. margin	***FLA algo.***	*% change from fixed margin*	*Fixed link adapt. margin*	***FLA algo.***	*% change from fixed margin*	*Fixed link adapt. margin*	***FLA algo.***	*% change from fixed margin*
Average cell throughput bps/Hz/cell	1.2398	**1.2666**	**+2.16**	1.2371	**1.2244**	**-1.03**	1.2371	**1.2244**	**-1.03**
Cell-edge-user throughput bps/Hz	0.0299	**0.0295**	**-1.34**	0.0306	**0.0309**	**+0.98**	0.0306	**0.0309**	**+0.98**

The performance of the FLA algorithm relative to the fixed link adaptation margin can be considered better with PFTF scheduler than with FDM scheduler, with the FLA algorithm performing approximately 1-2% better at some points and worse at others. The possible reasons for this may be that due to the additional randomness of transmission instances in time introduced by the scheduler, a fixed link adaptation margin may not be suitable as it was with the FDM scheduler.

5.2.3. FTP traffic – PFTF scheduler

In this section, results are presented for the last simulated scenario for downlink which is FTP traffic – PFTF scheduler. A brief description on FTP traffic parameters and how the number of users is determined was given in 3.3.2. In addition to the simulation parameters given in table 5.1, the below settings were chosen for mean file size and offered load.

Case 1: Mean file size = 1 megabyte, offered load = 1 Mbps/cell

Case 2: Mean file size = 1 megabyte, offered load = 2 Mbps/cell

The comparison between fixed link adaptation margin and differentiated link adaptation using FLA algorithm for case 1 is given in table 5-5 and for case 2 is given in table 5-6. Note that for FTP traffic, as mentioned in 3.4, four comparison points are considered due to the additional performance metric, average user data rate.

For case 1, at the combination for highest cell-edge user throughput the FLA algorithm has been able to increase the average user data rate by over 9% and for case 2 the average cell throughput and average user data rate was increased by around 12%. At the best combination, for case 1, the average user data rate was increased by around 6% and for case 2, by around 8%. Also for case 2, at the combination for highest average cell throughput the cell-edge user throughput was increased by around 7%.

Overall, it can be seen that the differentiated link adaptation using FLA algorithm was more effective with FTP traffic than with full buffer traffic, out of which case 2 with offered load of 2 Mbps/cell showed more improvement over case 1. It is again in line with the observation that the performance of the FLA algorithm was better with PFTF scheduler than with FDM scheduler for full buffer traffic, where FLA algorithm performed better with increased randomness of transmissions instances in time. In this case, the performance of the FLA algorithm increased further compared to full buffer traffic-PFTF scheduler scenario with the increased randomness of transmission instances introduced by FTP traffic model. Therefore, the reasonable conclusion from these observations would be that the potential to improve the system performance using differentiated link adaptation (using an algorithm such as FLA algorithm), for the LTE downlink increases as the randomness of transmission instances in time increases.

5.3. Summary

This chapter presented simulation results for the LTE downlink for three scenarios, namely,

- full buffer traffic-FDM scheduler
- full buffer traffic-PFTF scheduler
- FTP traffic-PFTF scheduler.

The performance of differentiated link adaptation was compared to that of a fixed link adaptation margin in terms of average cell throughput, cell-edge user throughput, and average user data rate. The performance was evaluated at three comparison points for the first two scenarios and four comparison points for the third scenario *(see 3.4)*.

For full buffer traffic-FDM scheduler, the performance of differentiated link adaptation using FLA algorithm and WLA algorithm was evaluated against the use of a fixed link adaptation margin. The simulation results showed that both of the algorithms fell short of the performance of the fixed link adaptation margin. Out of the two algorithms, FLA algorithm performed better than the WLA algorithm. This can be explained from the analysis on error clusters in chapter 4, where it was seen that errors rarely occur in long clusters but tend to be rather short term. Due to this, WLA algorithm which acts based on the BLER during a window period is too slow to react as compared to FLA algorithm. Therefore, only the FLA algorithm was considered in the remaining two scenarios.

In full buffer traffic-PFTF scheduler scenario, the FLA algorithm performed almost on par with the fixed link adaptation margin, with performance falling short by around 1-2% at some comparison points and exceeding by around 1-2% at other comparison points. Although, there was no performance gain from differentiated link adaptation using FLA algorithm for this scenario, the performance of FLA algorithm relative to the fixed link adaptation margin was increased compared to full buffer traffic-FDM scheduler scenario.

FTP traffic-PFTF scheduler scenario was evaluated at two load points, with a mean file size of 1 megabyte.

- Case 1: offered load = 1 Mbps

- Case 2: offered load = 2 Mbps

For case 1, the FLA algorithm was able to increase the average user data rate by up to approximately 9% while the average cell throughput was increased negligibly by around 2%. But, the cell-edge user throughput was decreased by around 3.6%. For case 2, the FLA algorithm was able to increase the average user data rate and the average cell-throughput by up to 12% while the cell-edge user throughput was increased by up to 7%. But, it was seen that at one of the comparison points, cell-edge user throughput was decreased by approximately 7%.

In general, the performance of the FLA algorithm relative to fixed link adaptation was increased as the randomness of the scenario was increased from FDM scheduler to PFTF scheduler and from full buffer traffic to FTP traffic. This could suggest that the potential to increase the system performance using differentiated link adaptation in LTE downlink, using the FLA algorithm increases when the transmissions instances become more random in time.

It was also seen that the cell-edge user throughput suffered most in the first two simulation scenarios and showed the least improvement in the third scenario when differentiated link adaptation was used. Since cell-edge users are more prone to errors than cell centre users due to weaker signal strength and higher inter-cell interference, it is arguable that by using differentiated link adaptation based on error feedback, the link adaptation margin could end up being too high (more CQI back-off), thus being over-conservative.

Table 5-5: Downlink - FLA algorithm, comparison with fixed link adaptation margin – FTP traffic-PFTF scheduler, mean file size = 1MB, offered load = 1 Mbps/cell

	Combination for highest avg. cell throughput			**Combination for highest Cell-edge user throughput**			**Combination for highest avg. user data rate**			**Best combination**		
	Fixed link adapt. margin	***FLA algo*.**	*% change from fixed margin*	*Fixed link adapt. margin*	***FLA algo*.**	*% change from fixed margin*	*Fixed link adapt. margin*	***FLA algo.***	*% change from fixed margin*	*Fixed link adapt. margin*	***FLA algo*.**	*% change from fixed margin*
Average cell throughput (bps/Hz/cell)	0.3196	**0.3257**	**+1.91**	0.3196	**0.3243**	**+1.47**	0.3179	**0.3243**	**+2.01**	0.3179	**0.3243**	**+2.01**
Cell-edge-user throughput (bps/Hz)	0.0332	**0.0320**	**-3.61**	0.0332	**0.0320**	**-3.61**	0.0325	**0.0320**	**-1.54**	0.0325	**0.0320**	**-1.54**
Average user data rate (Mbps)	4.7254	**5.0239**	**+6.32**	4.7254	**5.1566**	**+9.13**	4.8625	**5.1566**	**+6.05**	4.8625	**5.1566**	**+6.05**

Table 5-6: Downlink - FLA algorithm, comparison with fixed link adaptation margin – FTP traffic-PFTF scheduler, mean file size = 1MB, offered load = 2 Mbps/cell

	Combination for highest avg. cell throughput			**Combination for highest Cell-edge user throughput**			**Combination for highest avg. user data rate**			**Best combination**		
	Fixed link adapt. margin	***FLA algo.***	*% change from fixed margin*	*Fixed link adapt. margin*	***FLA algo.***	*% change from fixed margin*	*Fixed link adapt. margin*	***FLA algo.***	*% change from fixed margin*	*Fixed link adapt. margin*	***FLA algo.***	*% change from fixed margin*
Average cell throughput (bps/Hz/cell)	0.6704	**0.7137**	**+6.46**	0.6376	**0.7128**	**+11.79**	0.6669	**0.7137**	**+7.02**	0.6669	**0.7128**	**+6.88**
Cell-edge-user throughput (bps/Hz)	0.0099	**0.0106**	**+7.07**	0.0118	**0.0118**	**0**	0.0114	**0.0106**	**-7.02**	0.0114	**0.0118**	**+3.51**
Average user data rate (Mbps)	3.7982	**4.1647**	**+9.65**	3.6780	**4.1440**	**+12.67**	3.8283	**4.1647**	**+8.79**	3.8283	**4.1440**	**+8.25**

6. LTE Uplink – Differentiated link adaptation

This chapter presents simulation results for differentiated link adaptation for LTE uplink using FLA algorithm and WLA algorithm. The performance of the algorithms will be compared with each other and with the performance of using a fixed link adaptation margin.

6.1. Simulation parameters

Table 6-1 shows the simulation parameters used to obtain the results in this section. With the exception of the maximum number of transmission attempts and the link adaptation margin, the rest of the parameters are essentially the same as in chapter 4.

The maximum transmission attempts were changed to the default value of 6, to be more realistic. Fixed link adaptation margins for benchmarking with the differentiated link adaptation algorithms were derived through simulations.

Table 6-1: Simulation parameters LTE Uplink - differentiated link adaptation

Environment	Urban Micro-cellular with modified user speeds *(see 3.2.1)*
Channel model	UMi *(see 3.2.2)*
Number of cells	21 cells (7 sites x 3 sectors per site)
Offered load	10 users per cell
Antenna configuration	1 tx X 2 rx
Scheduler	FDM / Channel quality dependent FDM
Traffic model	Full buffer
CQI reporting period	1 ms (1 sub frames) (DRS based)
CQI delay	6 ms (6 sub frames)
Maximum transmission attempts	6
Link adaptation margin	Will be clear from the context
Number of mobile positions	630 (21 cells x 10 users per cell x 3 iterations*)*.

6.2. Simulation results

The performance evaluation was carried out for two different situations. One is full buffer traffic-FDM scheduler and the other is full buffer traffic-Channel quality dependent FDM scheduler.

6.2.1. Full buffer traffic – FDM scheduler

As for the downlink, a series of simulations were run for various fixed link adaptation margins in order to choose the benchmarks for comparison with differentiated link adaptation using FLA and WLA algorithms. Figure 6-1 shows the average cell throughput, cell-edge user throughput and BLER for full buffer traffic-FDM scheduler scenario for various fixed link adaptation margins. Three comparison points were chosen. In this case, all three comparison points, the maximum average cell throughput, maximum cell-edge user throughput and the best combination, are at the link adaptation margin of 0 dB, which means without any CQI adjustment.

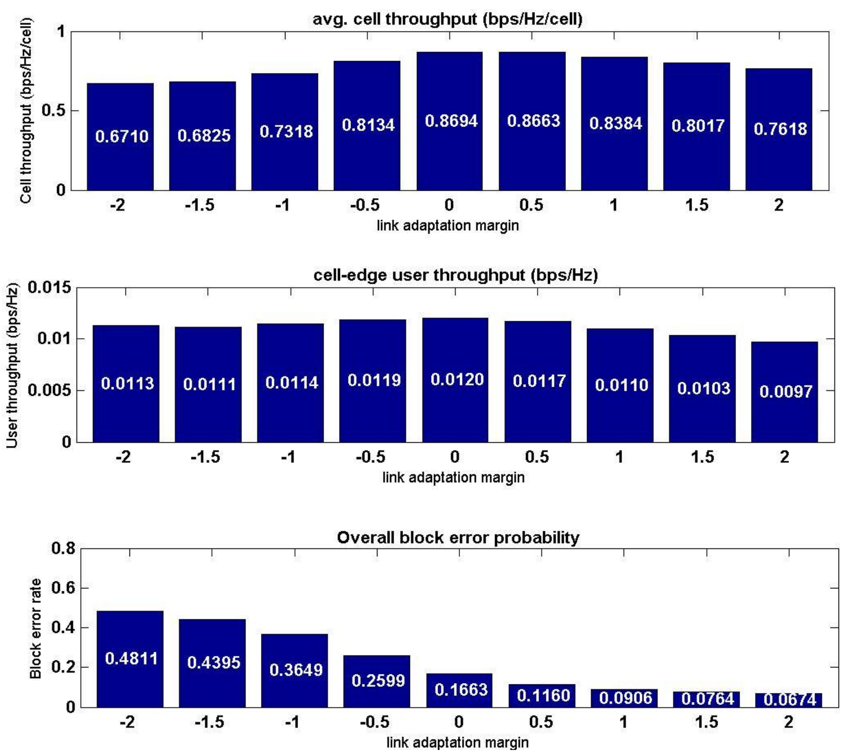

Figure 6-1: Uplink - Avg. cell throughput, cell-edge user throughput and BLER for various fixed link adaptation margins – full buffer traffic-FDM scheduler

Having chosen the benchmarks for performance evaluation, Table 6-2 shows the comparison between the use of a fixed link adaptation margin and differentiated link adaptation using FLA algorithm, in terms of average cell throughput and cell-edge user throughput. As it can be seen in the table, FLA algorithm has resulted in a large degradation in average cell throughput and cell-edge user throughput in all comparison points, including up to more than 15% decrease in average cell-throughput and more than

20% decrease in cell-edge user throughput. The decrease with FLA algorithm was much larger than what was seen in the downlink for full buffer traffic-FDM scheduler scenario. It should be noted that the uplink channel estimation was more accurate compared to that of the downlink as shown in 4.4 and for most of the transmissions, the SINR estimation error was between -1 to 1 dB. Therefore it is possible that when FLA algorithm tries to adjust the CQI values frequently, it actually degrades performance.

Table 6-2: Uplink - FLA algorithm, comparison with fixed link adaptation margin – full buffer traffic-FDM scheduler

	Combination for highest avg. cell throughput			**Combination for highest Cell-edge user throughput**			**Best combination**		
	Fixed link adapt. margin	***FLA algo.***	*% change from fixed margin*	*Fixed link adapt. margin*	***FLA algo.***	*% change from fixed margin*	*Fixed link adapt. margin*	***FLA algo.***	*% change from fixed margin*
Average cell throughput bps/Hz/cell	0.8694	**0.8315**	**-4.36**	0.8694	**0.7325**	**-15.75**	0.8694	**0.7718**	**-11.23**
Cell-edge-user throughput bps/Hz	0.0120	**0.0095**	**-20.83**	0.0120	**0.0111**	**-7.50**	0.0120	**0.0109**	**-9.17**

Table 6-3: Uplink - WLA algorithm, comparison with fixed link adaptation margin – full buffer traffic-FDM scheduler

	Combination for highest avg. cell throughput			**Combination for highest Cell-edge user throughput**			**Best combination**		
	Fixed link adapt. margin	***WLA algo.***	*% change from fixed margin*	*Fixed link adapt. margin*	***WLA algo.***	*% change from fixed margin*	*Fixed link adapt. margin*	***WLA algo.***	*% change from fixed margin*
Average cell throughput bps/Hz/cell	0.8694	**0.8277**	**-4.80**	0.8694	**0.8007**	**-7.90**	0.8694	**0.8007**	**-7.90**
Cell-edge-user throughput bps/Hz	0.0120	**0.0103**	**-14.17**	0.0120	**0.0110**	**-8.33**	0.0120	**0.0110**	**-8.33**

Table 6-3 shows the performance comparison of a fixed link adaptation margin and differentiated link adaptation using WLA algorithm. Similar to FLA algorithm the performance with WLA was worse than with a fixed link adaptation margin. The average cell throughput has decreased as much as up to 8% and cell-edge user throughput has decreased up to 14%.

FLA algorithm and WLA algorithm comparison

It is interesting to note that, unlike in the downlink, the performance of the WLA algorithm was better than the performance of the FLA algorithm. This means, that although neither of the algorithms managed to increase the average cell throughput and cell-edge user throughput, the decrease of performance with WLA is less than that with FLA algorithm. The WLA algorithm, which acts based on the BLER during a window period, is much slower in updating CQI values as compared to FLA algorithm which acts on received ACKs or NACKs for the last transmission. Therefore, given that the channel estimation in the uplink was quite accurate and that most of the SINR estimation errors were below 1 dB, it could be suspected that the slowness of the WLA algorithm makes it better than the FLA algorithm. To verify this statement, the average cell throughput and the cell-edge user throughput of the algorithm was plotted as the window size increases from 5 to 100 frames as shown in Figure 6-2. The window size is shown in the x-axis and the average cell throughput (left plot) and cell-edge user throughput (right plot) are shown in the y-axis. The multiple line graphs on the same plot refer to each combination of LOWerr and HIGHerr parameters. It is clear from the graph that, with few exceptions, the average cell throughput and cell-edge user throughput increases as the window size is increased. Since increasing window size means that the CQI adjustment happens less frequently and in effect becomes more similar to using a fixed link adaptation margin, it is likely that the better performance of the WLA algorithm over FLA algorithm is not due to an effectiveness of the algorithm itself, but rather due to being slower and more similar to a fixed link adaptation margin. The same effect, although less prominent, was present in the downlink as shown before in Figure 5-2.

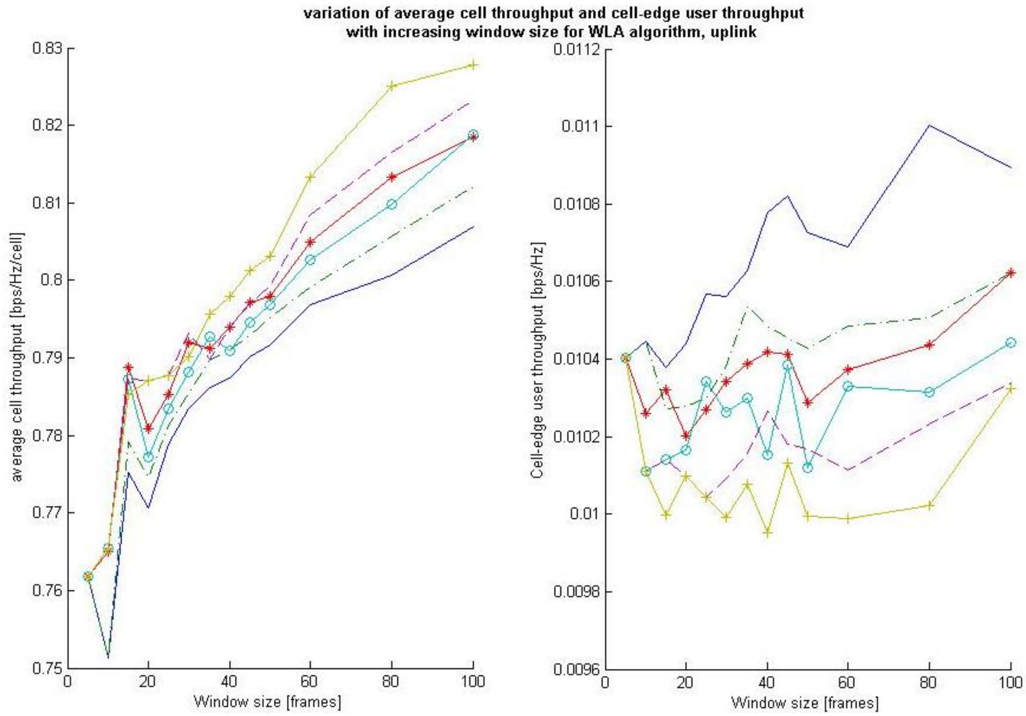

Figure 6-2: WLA algorithm UMi uplink Full buffer traffic - FDM scheduler - variation of avg. cell throughput and cell-edge user throughput with increasing window size

6.2.2. Full buffer traffic – Channel quality dependent FDM scheduler

This section presents results for LTE uplink, full buffer traffic-Channel quality dependent FDM scheduler scenario. Unlike the FDM scheduler, the Channel quality dependent FDM scheduler *(see 2.4.1.2)* uses CQI of individual users for scheduling purpose where all users are scheduled in every frame with equal number of chunks allocated, but the frequencies of the allocated chunks are determined by the CQI of each user. Figure 6-3 shows the average cell throughput, cell-edge user throughput and BLER for various fixed link adaptation margins and the benchmarks for the three comparison points are chosen similar to 6.2.1. The point of highest average cell throughput was found to be at fixed link adaptation margin of 0.5 dB and the point of highest cell-edge user throughput and best combination was found to be at 0 dB.

Table 6-4 shows the performance comparison between fixed link adaptation margin and differentiated link adaptation using FLA algorithm. Similar to full buffer traffic-FDM scheduler, the FLA algorithm has resulted in large degradation in average cell throughput and cell-edge user throughput where average cell throughput decreased by around 9% and cell-edge user throughput by up to 20%.

Similarly, Table 6-5 shows the performance comparison for differentiated link adaptation using WLA algorithm, where performance decreased again compared to that of using a fixed link adaptation margin. The average cell throughput has decreased by up to 3% and cell-edge user throughput by up to approximately 8.5%.

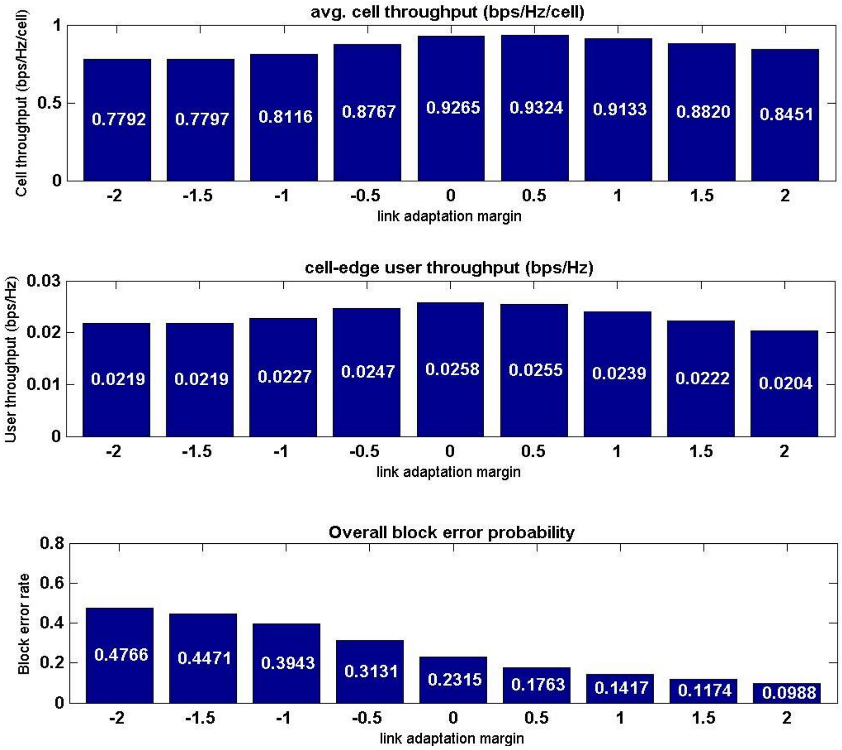

Figure 6-3: Uplink - Avg. cell throughput, cell-edge user throughput and BLER for various fixed link adaptation margins – full buffer traffic-Channel quality dependent FDM scheduler

Table 6-4: Uplink - FLA algorithm, comparison with fixed link adaptation margin – full buffer traffic-Channel quality dependent FDM scheduler

	Combination for highest avg. cell throughput			**Combination for highest Cell-edge user throughput**			**Best combination**		
	Fixed link adapt. margin	***FLA algo.***	*% change from fixed margin*	*Fixed link adapt. margin*	***FLA algo.***	*% change from fixed margin*	*Fixed link adapt. margin*	***FLA algo.***	*% change from fixed margin*
Average cell throughput bps/Hz/cell	0.9324	**0.8593**	**-7.84**	0.9265	**0.8436**	**-8.95**	0.9265	**0.8539**	**-7.84**
Cell-edge-user throughput bps/Hz	0.0255	**0.0204**	**-20.00**	0.0258	**0.0211**	**-18.22**	0.0258	**0.0210**	**-18.60**

Table 6-5: Uplink - WLA algorithm, comparison with fixed link adaptation margin – full buffer traffic- Channel quality dependent FDM scheduler

	Combination for highest avg. cell throughput			**Combination for highest Cell-edge user throughput**			**Best combination**		
	Fixed link adapt. margin	***WLA algo*.**	*% change from fixed margin*	*Fixed link adapt. margin*	***WLA algo.***	*% change from fixed margin*	*Fixed link adapt. margin*	***WLA algo*.**	*% change from fixed margin*
Average cell throughput bps/Hz/cell	0.9324	**0.9097**	**-2.43**	0.9265	**0.8996**	**-2.90**	0.9265	**0.9097**	**-1.81**
Cell-edge-user throughput bps/Hz	0.0255	**0.0236**	**-7.45**	0.0258	**0.0237**	**-8.14**	0.0258	**0.0236**	**-8.53**

FLA algorithm and WLA algorithm comparison

Similar to what was seen for the LTE uplink for full buffer traffic-FDM scheduler, the WLA algorithm performs better than the FLA algorithm for the scenario of full buffer traffic-Channel quality dependent FDM scheduler. Again this could be due to the WLA algorithm being slow to update CQI. This is quite evident from the Figure 6-4, where it is seen that for the WLA algorithm, the average cell throughput and the cell-edge user throughput has increased as the window size increased with only a few exceptions.

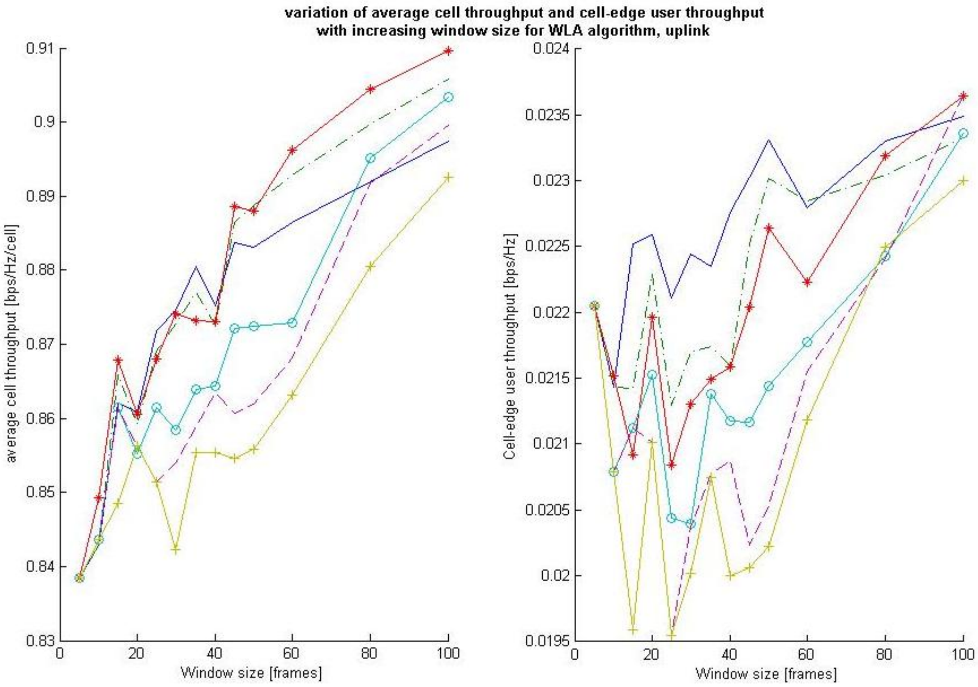

Figure 6-4: WLA algorithm UMi uplink Full buffer traffic – Channel quality dependent FDM scheduler -variation of avg. cell throughput and cell-edge user throughput with increasing window size

6.3. Summary

This chapter presented simulation results for the LTE uplink for the two simulation scenarios of full buffer traffic-FDM scheduler and full buffer traffic-Channel quality dependent FDM scheduler. The performance of differentiated link adaptation using FLA and WLA algorithms in terms of average cell throughput and cell-edge user throughput was compared with the performance of using a fixed link adaptation margin. Also, the two algorithms were compared with each other and the performance of WLA algorithm with increasing window size was shown.

The FLA algorithm resulted in large degradation in average cell throughput and cell-edge user throughput for both scenarios as compared to fixed link adaptation margin. Given that the uplink channel estimation was quite accurate with very low SINR error variance as compared to the downlink and most of the transmissions have SINR error between -1 and 1 dB, as shown in 4.4, it is likely that frequent CQI adjustments are not appropriate for the situation. Therefore, the FLA algorithm suffered from trying to update the CQI values after every transmission. On the other hand the WLA algorithm, which also resulted in large degradation in performance in full buffer traffic-FDM scenario and some degradation in full buffer traffic-Channel quality dependent FDM scenario, performed comparatively better than the FLA algorithm. This is in contrast to what was seen in the downlink. In Figure 6-2 and Figure 6-4, it was shown that the average cell throughput and the cell-edge user throughput for WLA algorithm increased as the window size was increased, which could suggest that the better performance of the WLA algorithm compared to FLA algorithm was simply due to the fact that it is slower and less frequently updates the CQI values.

In conclusion, it can be said that the differentiated link adaptation did not achieve the goal of improving average cell throughput and cell-edge user throughput for LTE uplink for the simulated scenarios, but decreased the performance as compared to what was achieved using a fixed link adaptation margin.

7. Conclusion

The goal of this thesis was to improve the system performance for LTE downlink and uplink by using differentiated link adaptation based on packet error occurrences of each user as feedback. The performance of the two investigated differentiated link adaptation, FLA and WLA, was compared with the best performance that is achievable using a fixed link adaptation margin.

An initial study was carried out as a general analysis for LTE downlink and uplink in order to assess the amount of performance degradation that can be attributable to imperfect CQI, the probability density function of SINR estimation error., and to have an idea on the nature of packet error occurrences, (i.e. if packet errors are mostly concentrated as long clusters or more short term). It was found that the uplink channel estimation which was based on DRS was more accurate with less variance than the channel estimation in the downlink. Similarly, uplink showed less degradation in performance due to imperfect CQI as compared to the downlink. It was also seen that the errors were less likely to occur as clusters.

Then the differentiated link adaptation was applied to LTE downlink for three scenarios, and to LTE uplink for two scenarios. A performance gain was achieved only for the application of FLA algorithm to downlink FTP traffic-PFTF scheduler scenario, which is the most unpredictable in terms of scheduling of users and traffic patterns. Therefore it seemed that the gain in performance by using differentiated link adaptation increases as the short term variations of the system increases. In more uniform scenarios, such as full buffer traffic-FDM scheduler, it was better to use a fixed link adaptation margin than differentiated link adaptation.

In LTE uplink, no performance gain was possible using differentiated link adaptation, instead the performance was worse compared to using a fixed link adaptation margin. As it was seen in chapter 4, the uplink channel estimation was already quite accurate and it is possible that the adjusted link adaptation margin was often applied to a new channel estimate already taking into account the changed channel conditions. Thus the link adaptation loop was in fact working on the same time scale or slower than the DRS based channel estimation.

It was also seen that cell-edge user throughput was the hardest performance metric to improve. Since cell-edge users are more prone to errors than cell centre users, it is possible that by using differentiated link adaptation based on error feedback, the CQI back-off becomes over conservative, thus reducing the throughput.

8. Future work

As an extension to the work carried out in this thesis, following future work will be interesting:

- Extending the FTP traffic simulations that were performed for LTE downlink to include higher load scenarios in order to check if the performance gain achieved will be increased or decreased.
- Simulating other ITU environments such as urban macro-cellular and indoor environments like InH can be of interest.
- Other scheduler-traffic model combinations can be simulated to investigate the behaviour of the algorithms.

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