Master's Thesis

Evovled 3G systems using channel dependent link adaptation for HSDPA

Nida Syed
Kailash Krishnan Surya

Department of Electrical and Information Technology,
Faculty of Engineering, LTH, Lund University, October 2014.
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Nida Syed
Kailash Krishnan Surya

wir12nsy@student.lu.se
wir12ksu@student.lu.se

Ericsson AB
Lindholmspiren 11, 417 56 Göteborg

Advisor: Lars Blomstergren

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Abstract

With the exponential increase in the use of mobile data traffic today, there is a constant need for higher user data speeds. As a result, an increased importance is given to the performance of present day wireless networks. One key problem that arises as a consequence, is to find the most effective way to optimize the radio resources such that the user gets the maximum possible throughput under a given channel condition. To put it in simple words: *How well can you make the radio link adapt to a constantly varying wireless channel?* The problem of link adaptation has been studied in detail and several solutions have been proposed. In evolved 3G networks with High Speed Packet Data Access (HSPA), the quality of the channel is measured by the user equipment (UE) on the downlink channel. This measure is then quantized into a value called the Channel Quality Indicator (CQI) which indicates the size of the transport block and the modulation scheme to be used. The CQI is then reported to the base station on the uplink. A single BLock Error Rate (BLER) target, typically 10%, is maintained throughout. Some of the solutions proposed for the link adaptation problem in HSPA involve adjusting the received CQI value based on different measures like for example: adding the effect of Doppler spread for different speeds.

The objective of this Master Thesis is to conceive a novel algorithm for link adaptation by deciding whether the UE is in one of several known channel types. Each channel type is a combination of three parameters i.e. the channel model, geometry factor and UE speed. A statistical characterization of these channel types are made by the analysis of the statistical properties of a set of CQI reports from the UE. Once the channel types have been characterized, an accurate decision on a particular channel type can be made by analysing a given set of CQI values. Based on studies done at Ericsson prior to the thesis, it was decided that rather than use one BLER target as in the conventional implementation, three or four BLER targets would be used in this thesis implementation such that each channel type would have one optimal BLER target. Since there are thirty-one channel types and three or four BLER targets considered in this Thesis work (also a requirement from Ericsson), several channel types can have the same optimal BLER target.

The incoming CQI value is adjusted based on the difference between the measured BLER and the BLER target that needs to be achieved. This adjusted CQI value indicates the transport block size, modulation and coding scheme that

needs to be used. The results of the tests performed to validate the algorithm at the Ericsson Radio Access Network laboratory for the various simulated channel types show a substantial increase in throughputs of up to 40% for some channel types at the UE. Additional investigations were carried out to test the accuracy of the algorithm in determining channel types with prior knowledge of speed or geometry factor and the resulting effect on the UE throughput. A brief study on filtering the incoming CQI values was made. Filtering of CQI values with an appropriate filtering coefficient would reduce the variations between subsequent CQI values. This in turn could reduce the error caused due to the delay between the CQI measurement and the execution of link adaptation based on that measured CQI value.

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Chapter 1

Introduction

Wireless communication systems have come a long way since the pioneering work started around the beginning of 20th century. Packet Data over cellular systems was introduced in the second half of 1990s, with *General Packet Radio Services* (GPRS) in the Global System for Mobile Communication (GSM) system. Addition of packet data in few other cellular technologies such as the Personal Digital Cellular (PDC) in Japan was also done around this time. In spite of fairly low data rates, it proved to have a good potential for applications over packet data in mobile systems. The introduction of *Universal Mobile Telecommunications System* (UMTS) which supports *Wideband Code Division Multiple Access* (WCDMA) and the higher-bandwidth radio interface of Universal Terrestrial Radio Access (UTRA) paved way for a wide range of possibilities. Release 99, which was the first Third Generation Partnership Project (3GPP) release for UTRA supported a theoretical data rate of up to 384 kbps [1].

1.1 WCDMA Evolution

Evolution of WCDMA started with the upgrade to High-Speed Downlink Packet Data Access (HSDPA) in Release 5 and High-Speed Uplink Packet Data Access (HSUPA) in Release 6 of the 3GPP/WCDMA specifications. HSDPA and HSUPA together referred as HSPA increased packet data performance, significantly reduced round trip times and improved capacity as compared to Release 99. Release 6 also introduced *Multimedia Broadcast Multi-cast Services* (MBMS) for efficient support to the broadcast services in WCDMA. Release 7 and beyond further enhanced the WCDMA capabilities with the support for Multiple Input Multiple Output (MIMO) antenna systems and higher order modulation techniques. This is also referred to as evolved HSPA or HSPA+. Release 8 introduced another important feature: Multi-Carrier Operation. This provided attractive opportunities to the operator in providing higher data rates to the user and also decrease the production costs [2] [3] .

1.2 Wireless Channel

A channel is one of the basic elements of a communications system. It is defined as the physical medium that connects the transmitter and receiver in a communications system. The physical medium could be a copper wire, air, free space etc. *Cf. Background and Preview, [4].*

A wireless channel in the context of WCDMA uses air as the medium linking the transmitter and receiver. The properties of wireless channels are significant as they determine the channel capacity and the behaviour of specific wireless systems. It is therefore essential to study wireless channels and their properties as this knowledge can be applied during system design. This also forms an essential part of this thesis work.

One primary difference between wired channels and wireless channels is that in wireless channels there is multi-path propagation. This means that there are multiple propagation paths between transmitter and receiver. Multi-path propagation happens due to the various propagation mechanisms that govern propagation of electromagnetic waves. In a simple scenario called free space propagation, there is one transmit antenna and one receive antenna in free space. In a real scenario however, there are obstacles known as Interacting Objects (IO) which maybe conducting or dielectric by nature. If the surface of these IOs are smooth, then the waves are reflected and some energy penetrates through the IO which is known as transmission. If the IOs have a rough surface, then most of the waves undergo scattering. Diffraction also takes place around the edges of these IOs. *Cf. Chapter 4, [5].*

The combined effect of these mechanisms cause fluctuations in the received signal strength. On a very short distance scale, those fluctuations in received power that are comparable to one wavelength of the received signal are known as small scale fading. The interference between different multi-path components cause small scale fading. Fluctuations are also observed when the mean power is averaged over ten wavelengths. These fluctuations which happen on a larger scale which correspond to few hundred wavelengths are known as large scale fading. The shadowing effect of large objects in the path between transmitter and receiver causes large scale fading.

Since the channel information information can be extracted from the pattern of the received signal, it is imperative to measure the received signal. In the context of WCDMA, the Channel Quality Indicator (CQI) measures the received signal quality (at the User Equipment (UE)) at constant small intervals of time and reports it to the NodeB. *Cf. Chapter 9, [3]*

1.3 What is Link Adaptation?

A key characteristic of mobile radio communication is the variations in the communication conditions. These variations could be due to: frequency selective fading which will result in rapid and random variations in the channel attenuation or due to shadow fading or due to path loss. All these factors significantly affect the average received signal strength. Interference at the receiver due to transmissions in other cells and by other terminals also significantly impacts the quality of the signal. *Cf. Chapter 7, [3].*

One of the techniques used to handle the rapid variations in the instantaneous channel conditions at the User Equipment (UE), is *Link Adaptation*. Link adaptation strives to adapt to the changes in the instantaneous transmission capacity that the channel conditions offer. This is done through appropriate processing of the data before transmission by varying the transmission parameters such as transmitted power, code rate and modulation of the radio link accordingly. *Cf. Chapter 7, [3].*Link Adaptation can be done in 2 ways i.e. *Dynamic Power Control* and *Dynamic Rate Control*.

1.3.1 Dynamic Power Control

This technique dynamically adjusts the transmit power, P to compensate for the variations in the instantaneous channel conditions. The transmit power is always less than the maximum allowed transmit power P_{max} set for the system. In principle, this technique increases power at the transmitter when the radio link experiences poor radio conditions and vice versa. Consider E_b to be the received energy per information bit and N_0 to be the constant noise power spectral density (W/Hz). By dynamically varying the power in accordance to the channel variations, E_b/N_0 at the receiver remains almost constant. Therefore, the transmit power is in effect inversely proportional to the channel quality. This would mean that the user would get a constant data rate irrespective of the channel variations. This is useful for services such as circuit-switched voice. Hence, in this type of link adaptation, transmit power is the parameter adjusted before transmission. *Cf. Chapter 7, [3].*

1.3.2 Dynamic Rate Control

In this type of link adaptation, the data rate (R) is dynamically adjusted to compensate for the varying channel conditions. In principle, when channel conditions are good, data rate is increased and vice versa. This also implies that the power amplifier always transmits at full power and hence is used more efficiently when compared to dynamic power control where the power is constantly varied. The rate control maintains the $E_b/N_0 \sim P/R$ by varying the data rate. Hence, in this technique, transmit data rate is the transmission parameter adjusted pre-transmission. *Cf. Chapter 7, [3].*

In practice, the data rate is varied by varying the channel code rate and/or the modulation scheme keeping certain resources like power and number of spreading codes. A one user scenario is considered in this thesis. It can be shown that rate control is more efficient than power control [6][7]. In case of good channel conditions, the E_b/N_0 at the receiver is high and the limiting factor is bandwidth. In such conditions higher order modulation schemes such as 64-Quadrature Amplitude Modulation (64 QAM) is used along with a high code rate. In case of poor channel conditions, lower order modulation schemes like Quadrature Phase Shift Keying (QPSK) along with a low code rate is used. Hence, link adaptation by rate control is known as *Adaptive Modulation and Coding* (AMC).

Link adaptation generally works in conjunction with *Channel Dependent Scheduling*. Channel dependent scheduling deals with sharing of radio resources available in the system between users to accomplish efficient resource utilization. However, it is impossible to perfectly adapt the radio link in accordance to these variations because of the following:

- The extremely random variations in the channel conditions.
- The CQI value based on which the link adaptation is to be implemented becomes too old. This is because the channel conditions could have changed since that CQI value was reported.

Hence, a technique called *Hybrid Automatic Repeat-reQuest* (HARQ) is used which requests retransmission of erroneously received data. HARQ can therefore be viewed as a technique used to handle instantaneous variations in the channel post-transmission and complements link adaptation and channel dependent scheduling very well. *Cf. Chapter 7, [3].* In this thesis work, dynamic rate control is the type of link adaptation that is implemented.

1.4 Block Error Rate Targets

The BLock Error Rate (BLER) is defined as the ratio of the number of erroneous blocks to the total number of blocks transmitted. A BLER target indicates the permissible number of erroneous blocks. Hence, a BLER target of 15% means that there should be no more than fifteen erroneous blocks in every hundred blocks transmitted.

The problem that link adaptation attempts to address is that there is an uncertainty in the prediction of the instantaneous transmission capacity on the downlink. In some cases the instantaneous transmission capacity is underestimated and as a result the block of data is transmitted successfully but the entire transmission capacity is not utilized. In other cases the instantaneous transmission capacity is overestimated, the result would be an erroneous transmission giving rise to Block Error.

In the conventional implementation which will be discussed in detail in Section 1.5, a single fixed BLER target of 10% is used. The link is always adapted with a BLER target of 10%. Whereas, in this thesis implementation, three or four BLER targets were used. This was a requirement provided by Ericsson based on their previous studies and work. In this thesis, 'channel type' is used to indicate a combination of the channel model, Geometry Factor and UE speed. The thirty-one channel types that were used in this thesis was also a requirement from Ericsson. The BLER target that was chosen was based on the channel type that was decided by the algorithm. Each channel type was mapped to one BLER target for which throughput was maximum. The reason for having multiple BLER targets is due to the uncertainty in the prediction of the instantaneous transmission capacity. By having larger BLER targets for channel types with high variations (high level of uncertainty), it is possible to transmit larger transport blocks with higher order modulation and coding schemes than when compared to the transport blocks used with a fixed 10% BLER target. However, the probability of error is also higher. Hence, for a higher BLER target setting:

- There is a gain in data rate due to the incorporation of:
  - Larger transport block size/Higher coding rate.
  - Higher order modulation scheme.
- There is a loss in data rate incurred due to:
  - Re-transmission of erroneous blocks.

When the gain in data rate is greater than the loss in data rate, there is an increase in throughput.

1.5 Related work

Link Adaptation processes have not been standardized by 3GPP and it is vendor specific. Numerous investigations have been done in this field and a few of them are discussed here. The conventional implementation uses the CQI value reported to the Node-B to choose an appropriate Modulation and Coding Scheme (MCS) which meets the 10% BLER target in conjunction with Hybrid Automatic Repeat Request (HARQ) [8]. *Cf. Chapter 9, [3].*

In [9], the effect of pre-processing the received CQI report before execution of the link adaptation algorithm at the Node-B was evaluated. Among the three different classes of CQI estimation strategies analysed, it was found that when the User Equipment (UE) speed was high, some processing strategies can provide a better channel estimation than the last received CQI. However, if the UE speed was low, the basic mode outperforms other processing techniques. Hence, knowledge of UE speed was essential for optimal link adaptation.

In [10], two algorithms are proposed to map the instantaneous channel state into an instantaneous effective Signal-to-Noise-Ratio (SNR). The effective SNR was then used to find an estimate of the CQI value. It focuses on better estimation of CQI which leads to better link adaptation.

In [11], an Interference Averaging algorithm was studied, which handles the CQI mismatch problem caused by rapid interference fluctuation in the Link Adaptation process.

The conventional implementation of link adaptation (to which this thesis work was compared) has a single constant BLER target setting of 10%. The incoming CQI values are adjusted appropriately when the measured BLER was lesser than or greater than the BLER target of 10%. (CQI adjustment is further explained in Section 1.6) The CQI value indicates the transport block size, modulation and coding schemes that can be used which is explained in detail in Section 2.2. Hence, by adjusting the CQI value appropriately, the modulation/coding schemes and transport block size indicated by the adjusted CQI value also changes accordingly. This directly affects the UE throughput. *Cf. Chapter 9, [3]*

1.6 Problem Definition

User throughput and efficient management of radio resources will be among the two most important parameters for any mobile communication system. Link adaptation plays a key role in achieving both these objectives. In Section 1.5, an overview was given on the various approaches to the link adaptation problem. Link adaptation in most modern wireless systems such as an Evolved 3G System, adopts dynamic rate control technique. At Ericsson, the implementation of link adaptation involves adjusting the reported CQI value. The CQI indicates the size of the transport block, modulation scheme and coding rate to be used on the downlink [8]. By adjusting the CQI value, the size of the transport block to be transmitted, modulation scheme and coding rate on the downlink is adjusted. And as the size of transport block, modulation scheme and coding rate are changed, so does the data rate or throughput delivered to the UE. CQI adjustment is used in this thesis implementation as well as in the conventional implementation. The impact of implementing link adaptation with three or four BLER target settings was carried out at Ericsson prior to this thesis. In this thesis, *channel type* is used to indicate a combination of the channel model, Geometry Factor and UE speed. The *optimal BLER target* for a particular channel type is always one value out of the three or four BLER target settings. It is possible that in some cases, the choice of BLER target maybe sub-optimal rather than optimal if the actual optimal BLER target for that channel type lies in between these three or four pre-set values. For the purpose of this thesis, *optimal BLER target* refers to the single BLER target among the three or four BLER targets that results in maximum throughput at the UE.

As mentioned in Section 1.4, the problem that link adaptation strives to solve is the uncertainty in the prediction of the instantaneous transmission capacity on the downlink. This uncertainty is due to the following factors:

- Randomly varying wireless channel quality.
- The CQI value becomes too old to use for link adaptation. This may be due to:
  - Reporting Interval
  - Delay which could be due to UE measurement delay, transmission delay on the uplink and processing delay.
- CQI errors which maybe due to UE measurement error or due to error during quantization.

Consider Figure 1.1 which illustrates the uncertainty problem. It shows the received signal quality. A lot of variations are observed in the signal. At instant *t1*, the UE makes a measurement of the channel quality and reports a CQI on the uplink to the NodeB. Consider that the CQI has been processed and a transport block of the size indicated by the CQI has been chosen to be sent on the downlink at instant *t2*. This happens after a delay *(t2-t1)*. At *t1* the CQI measured is 18. The transport block size corresponding to CQI value 18 is chosen. When this transport block is about to be transmitted on the downlink at instant *t2*, the channel has

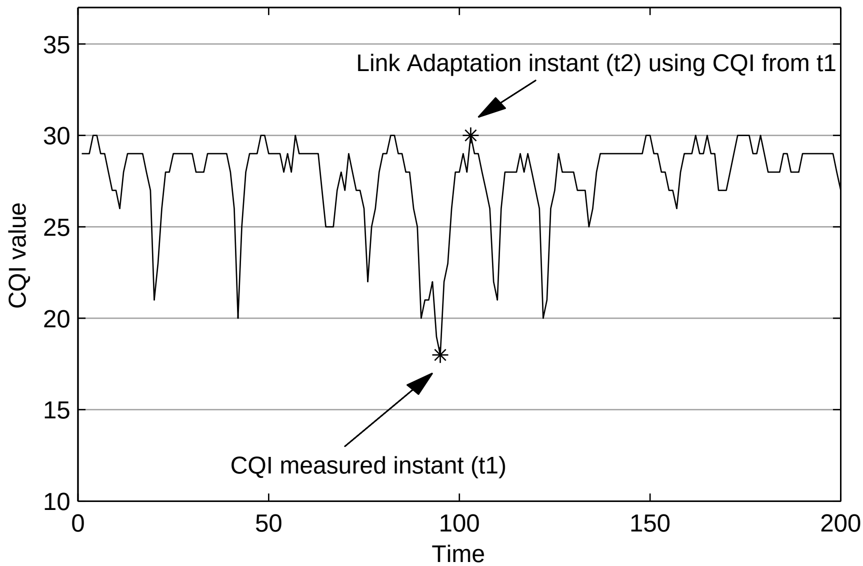

Figure 1.1: Uncertainty due to delay in Link Adaptation

changed. The correct transport block size that should be transmitted at instant *t2* is the transport block size that is indicated by CQI value 30. But that will not be the case and the transport block of size indicated by CQI value 18 will be used. As the CQI value becomes larger, so does the size of the transport block it indicates. Hence in this case, there is an underestimation of the transmission capacity and there is underutilization of the link.

If the opposite was true and the measured value of CQI is greater than the CQI at the instant in which it is to be transmitted on the downlink, there is an overestimation of the transmission capacity and this will lead to erroneous blocks and a larger value of BLER.

A brief investigation was also made to examine if there was a gain in throughput by filtering the incoming CQI values such that variations between consecutive CQI values are reduced. It was assumed that the filtering would reduce the errors caused due to the use of CQI values which are too old for the Link Adaptation which leads to a suboptimal Link Adaptation.

1.7 Approach

The purpose of this thesis work was to develop an algorithm to decide the channel type at the NodeB using the statistical properties of the reported CQIs from the UE. Based on inputs from previous work and studies done by Ericsson, optimal BLER targets are known for each of the channel types that are considered in this thesis. The characterized channel types are mapped to the appropriate BLER target category which results in the maximum possible throughput. In principle, a lot of information about the channel type like the rate of variation, distance of

UE from the NodeB, characteristic fading dips etc. can be extracted from the statistical analysis of the CQI values. Hence, link adaptation using CQI adjustment and multiple BLER targets endeavours to reduce the errors caused due to uncertainty. This in turn should increase the user throughput. In this thesis, a one user scenario was considered such that the single user has a full buffer of data.

The approach to implement link adaptation with CQI adjustment and multiple BLER targets in this thesis was as follows:

- As the first step, the thirty-one known channel types (please refer to Table 3.3) based on channel model, geometry factor and UE speed are simulated in the Ericsson Radio Access Network Laboratory and the CQI values reported every 4 *Transmission Time Intervals* (TTIs)(1 TTI= 2 ms) are extracted from a UE made by a single chipset vendor. The CQI values are obtained for each Channel Type for a period of 60 seconds.
- In the second step, the number of CQI values (window size) over which statistical properties should be calculated was investigated. This window size was determined to be twenty-five CQI values (A requirement from Ericsson was to have a window size less than or equal to twenty-five CQI values). Window size chosen was a trade-off between: *"How fast you can adapt to the channel conditions"* and the accuracy of Channel Type decision.
- In the third step, the various statistical properties that need to be used to explicitly identify each of the thirty-one different channel types were determined. The statistical properties that were finally used were the Mean, Variance, Minimum, Correlation Coefficient, Average Fade Duration (AFD) and Level Crossing Rate (LCR).
- The fourth step included quantifying and uniquely identifying or characterizing each channel type with the statistical measures made. At the end of this process, each channel type could be distinguished from one another by the set of all statistical measures mentioned in the previous step.
- Now that each channel type has been statistically quantified, the fifth step was to develop an algorithm that can accurately determine a single channel type for a given set of twenty-five CQI values.
- The sixth step was to map the different channel types to their appropriate BLER targets based on previous work done by Ericsson.
- The seventh step included validating the developed algorithm in the Ericsson RAN lab to determine the impact of the algorithm on the UE throughput.
- The effect of filtering and impact of having different number of BLER targets was also investigated.

1.8 Limitations

Some of the limitations in the approach taken in this thesis are as follows:

- A single UE scenario is considered. Multiple UE scenario will add more complexity with scheduling, CQI measurements and statistical calculations based on the CQIs received from each UE.
- A limited set of thirty one Channel Types is considered. The channel conditions in a real scenario can lie outside the conditions described by these thirty one channel types.
- In this thesis, emphasis is not laid on the detailed estimation of the computational complexity.

Chapter 2

Evolved 3G Systems

The purpose of this chapter is to introduce to the reader the key concepts and definitions relevant to this thesis work. Emphasis is laid on CQI which is sent in the uplink control signal from the UEs.

2.1 Protocol Architecture

WCDMA like most modern communication systems follows the layered processing architecture where each layer is responsible for a specific radio-access functionality. The Packet Data Convergence Protocol (PDCP) layer is where the user data first enters from the core network. PDCP performs the header compression of the user data and passes it to the next layer. The Radio Link Protocol (RLC) layer handles the IP packets coming from the PDCP and is responsible for segmentation of the IP packets into smaller units known as RLC Protocol Data Units (RLC PDUs) and also the ARQ functionality. *Cf. Chapter 8, [3].*

The RLC, next connects to the Medium Access Control (MAC) layer via the so called *Logical Channels*. The MAC layer can multiplex data from multiple logical logical channels and also determines the Transport Format (instantaneous data rate) of the data sent on to the physical layer. HSDPA introduced a new sub layer in the MAC by the name MAC-hs which is responsible for the functions such the scheduling, link adaptation (rate control) and HARQ. The interface between MAC and the physical layer is built of multiple Transport Channels over which the data is transferred in the form of *transport blocks*. The High-Speed Downlink Shared Channel (HS-DSCH) is the transport channel introduced to support the technologies introduced by HSDPA and is controlled by MAC-hs (MAC - high speed) or MAC-ehs (MAC - enhanced high speed). For an overview of the Logical and Transport channels and also the mappings between them, the reader is referred to [12]. TTI is the time duration over which the MAC layer feeds one or several transport blocks to the physical layer. The size and number of transport blocks can vary between each TTI, which in essence means that the data rate can be varied for each TTI. Release 99 supports TTI lengths of 10, 20, 40 and 80 ms whereas the HSDPA supports a TTI length of 2 ms and HSUPA supports TTI lengths of 2 and 10 ms. *Cf. Chapter 9, [13].* A larger TTI means better time diversity but also increased latency.

The physical layer takes care of the operations such as Cyclic Redundancy

Check (CRC) attachment, encoding, data modulation and spreading. The resulting bit stream is mapped onto a physical channel, digital to analog converted and modulated on to a carrier radio frequency. The PDCP, RLC, MAC and physical layer are controlled and configured by the Radio Resource Control (RRC) protocol. The RRC can provide the requested Quality of Service (QoS) by the core network by appropriately setting the parameters of the RLC, MAC and physical layers. *Cf. Chapter 7, [3]*. In this thesis work, we concentrate on link adaptation in the downlink, i.e HSDPA.

2.2 Channel Quality Indicator

The channel quality indicator (CQI) is an n-bit value sent by the UE to the base-station (NodeB) which gives a measure about the quality of the downlink wireless channel. The value indicates the maximum data rate that can be supported by the UE in the channel conditions at that instant. In specific, the CQI denotes the transport block size, modulation scheme and coding rate and thereby the data rate that can be supported for a given BLER target [8]. The reason for the CQI value not being an exact measure of channel quality is that the receiver implementation varies among different UEs. Hence, it is possible that for the same measure of channel quality(SNR), one UE can support higher data rates than others. In order to have a standard method, the CQI is used to indicate the transport block size, modulation and coding scheme to be used. Each of these n- bit CQI values indicates a particular transport block size, the modulation scheme and the number of channelization codes. Since some of the receivers support only some of the modulation schemes, there are multiple categories of UEs and each has a corresponding table which maps the CQI value to its respective transport block size, modulation scheme and the number of channelization codes. *Cf. Chapter 9, [3]*. For an example of the CQI mapping, the reader is referred to Table 9.2 *Example of CQI reporting for two different UE categories* in [3].

Typically, the received Signal-to-Noise ratio (SNR) is measured by the UE on the downlink physical channel known as Common Pilot Channel (CPICH) [8]. This SNR_{CPICH} is then quantized into a CQI value between zero and thirty. This CQI value is configured in HSPA to be represented by 5 bits and is sent to the NodeB over the High-Speed Dedicated Physical Control Channel (HS-DPCCH). In a MIMO system each stream is represented by a four bit CQI value. *Cf. Chapter 9, [3]*.

The reporting of the CQI values hence calculated can be configured to be 2-160 ms apart. For the CQI values used in this thesis, an interval of 8 ms is configured between the CQI reports which correspond to four TTIs.

2.3 Hybrid ARQ

Although link adaptation counteracts the adverse effects of channel variations to a certain extent, transmission errors due to unpredictable interference sources and receiver noise are hard to adapt to. Hence, techniques such as *Forward Error*

Correction (FEC) and *Automatic Repeat Request* (ARQ) are employed. While the FEC scheme adds redundancy in the transmitted signal, ARQ technique relies on re-transmission of the erroneous received data. The receiver uses an error detecting code, such as the *Cyclic Redundancy Check* to detect the errors in the received packet and notifies the transmitter with an acknowledgement (ACK) for an error free received data packet and a negative acknowledgement (NACK) for an erroneous received data packet. *Cf. Chapter 7, [3].*

Most of the modern day technologies use a combination of FEC and ARQ known as *Hybrid ARQ* (HARQ). In this technique, FEC is used to correct a subset of errors in the received data while ARQ is used to request retransmission of the data which is left uncorrected by FEC. HSDPA uses *HARQ with Soft Combining* where, the erroneously received packets for which retransmissions are requested are retained as they still contain some information. The stored packet is combined with the retransmitted packet, and the decoding is done on this combined packet. In the HARQ scheme, although the set of information bits need to be the same in each retransmission, the coded bits representing the same set of information bits can be different. Based on whether the retransmitted coded bits are identical or not, HARQ can be categorized into *Chase Combining* and *Incremental Redundancy* (IR). Chase combining uses the same coded bits in every retransmission; hence no additional coding gain is obtained. However, the accumulated received E_b/N_0 increases with each retransmission. With IR, multiple sets of coded bits representing the same set of information bits can be sent in each retransmission. IR results in an increased coding gain in addition to increased accumulated E_b/N_0 with each transmission. It can be said that Chase combining is a special case of Incremental redundancy. *Cf. Chapter 9, [3].*

Chapter 3

Channel Types : A Study

An important concept in this thesis was the characterization of various channels. A transmitted signal follows several different paths before arriving at the receiving antenna. An aggregate of all these different paths gives rise to a multi-path radio propagation channel. The resultant signal could be affected by one or several factors such as reflection, diffraction, path loss, relative motion of either the scatterers, transmitter or receiver or all/some of them, slow fading and fast fading. In this thesis, channel type characterization was a critical step in the process of link adaptation. There are a total of thirty-one different channel types that have been considered in thesis (Please refer to Table 3.3). The information extracted from the CQI values can broadly be categorized under three properties i.e. type of channel model, Geometry Factor and Speed. Each of these three properties (Channel model, Geometry Factor and Speed) are discussed in detail in the Sections 3.1, 3.2 and 3.3. The aim was to use the statistical characteristics of the CQI values and accurately determine a channel type based on these three properties.

3.1 Channel models

An important factor of radio propagation in mobile communications is multipath fading and channel time dispersion. The type and extent of fading varies with the propagation environment and the speed of the UE. For wideband technologies (e.g. WCDMA) each signal component becomes significant. Their number, strength and relative (time) delays are important factors that need to be considered. The key parameters considered to describe each of the channel models are delay-spread, path loss, shadow fading, multi-path fading characteristics and the operating radio frequency. Since UMTS is a standard, any models proposed should consider a wide range of environments like large/small cities, rural areas etc. In this thesis, we consider the *Average White Gaussian Noise (AWGN) Environment*, *Outdoor to Indoor and Pedestrian Test Environment* and *Vehicular Test Environment*. Some of the conditions that can be expected from these environments are described in Sections 3.1.1 to 3.1.3.

3.1.1 AWGN Environment

In an AWGN environment, a static channel profile exists with no channel fading, frequency selectivity, dispersion or non-linearity. This means only a single channel tap. A clear Line of Sight (LoS) exists between the UE and the nodeB with the white noise being the only impairment to the communication link. Also, the UE is assumed to be stationary.

3.1.2 Outdoor to Indoor and Pedestrian Environment

Pedestrian users are assumed to be located in streets or inside buildings. Base stations generally have low heights, located outdoors and are also characterized by low transmit powers and small cells. A geometric path loss rule can vary from the R^{-2} (where R is the distance between NodeB and UE) rule in case there is LoS in a canyon like street where there is Fresnel zone clearance. In the case there is no Fresnel zone clearance, the R^{-4} path loss rule is used or if there are obstructions, the R^{-6} path loss rule could also be used. A standard deviation of 10 dB for outdoors and 12 dB for indoors due to log normal shadow fading can be expected. Rayleigh and Rician fading rates depend upon the speed of the UE. However, faster fading due to reflections from moving vehicles can also be observed occasionally [16].

PEDESTRIAN CHANNEL-A	TAP	1	2	3	4
	RELATIVE DELAY (ns)	0	110	190	410
	AVERAGE POWER (dB)	0	-9.7	-19.2	-22.8
	DOPPLER SPECTRUM	Classic	Classic	Classic	Classic

Table 3.1: Delay Spread description for Pedestrian Channel-A

3.1.3 Vehicular Test Environment

This environment is described by larger cells and higher transmit power. A geometric path loss rule of R^{-4} and log-normal shadow fading with a standard deviation of 10 dB can be expected in an urban or suburban environment. Path loss is lower in rural areas with flat terrain and in case of a mountainous terrain a path loss rule of R^{-2} is more appropriate. Rayleigh fading rates depends on speed of the vehicle [16].

For each of these test environments, a channel impulse response model based on the tapped-delay line model is also measured. The tapped-delay line model is

VEHICULAR CHANNEL-A	TAP	1	2	3	4	5	6
	RELATIVE DELAY (ns)	0	310	710	1090	1730	2510
	AVERAGE POWER (dB)	0	-1.0	-9.0	-10.0	-15.0	-20.0
	DOPPLER SPECTRUM	Classic	Classic	Classic	Classic	Classic	Classic

Table 3.2: Delay Spread description for Vehicular Channel-A

described by the time delay with respect to the first tap, the number of taps, average power with respect to the strongest tap and the Doppler spectrum for each tap. The r.m.s. delay spreads are generally small but can be large in rare cases. Each test environment contains two cases i.e. channel-A which describes the low delay spread case and channel-B represents the median delay spread case. Both cases occur frequently. In this thesis we have chosen only channel-A. Table 3.1 and Table 3.2 indicate the delay spread for channel type A in case of a pedestrian environment and a vehicular environment [16].

3.2 Geometry factor

The geometry factor, G, is used mainly on downlink and is defined as the ratio of power from the serving cell base station P_{own} to the sum of the total received power from the neighbouring cells base stations P_{oth} and the thermal noise N. A simple formula for the calculation of G is given below [14]:

$$G = \frac{P_{own}}{P_{oth} + N}. \tag{3.1}$$

For the simulation of G in the Ericsson RAN lab, N was assumed to be equal to zero.

The geometry factor indirectly reflects the distance of the UE from the nodeB. From the above equation it can be said that, for a higher geometry factor, the UE should be closer to the base station where the received power from serving cell is much higher than the received power from neighbouring cells. For low geometry factors, the UE is close to the cell edge and hence the received power form the neighbouring cells becomes significant and the received power from serving cell becomes weaker due to path loss. In this thesis, two cases of Geometry factors were considered for the Pedestrian-A (PA) and Vehicular-A (VA) channel models. A geometry factor of 20 was used to represent a high value of G (or UE close to nodeB) and a geometry factor of 5 was used to represent a low value of G (or UE close to cell-edge).

The influence of geometry factor on the mean value of CQI for a PA channel is illustrated in Figure 3.1. As we can see for higher G, the mean is higher and the mean is lower for lower G.

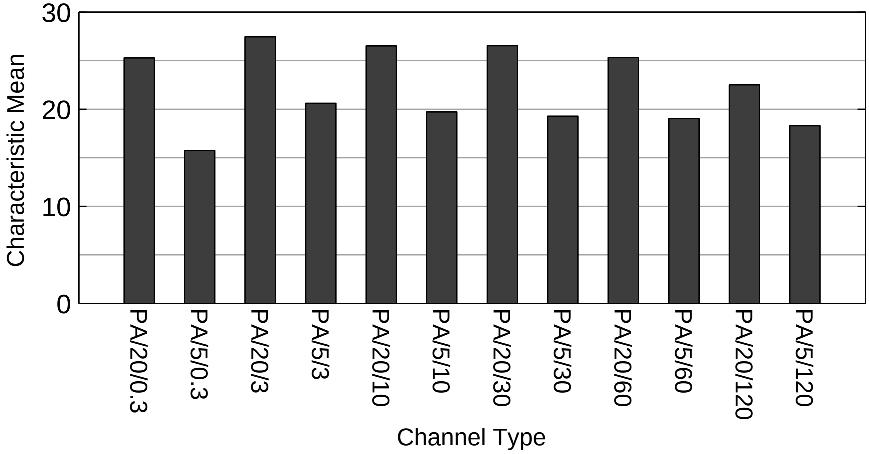

Figure 3.1: Impact of Geometry on the Mean of twenty-five CQI samples of a PA channel

3.3 UE Speed

Another important factor to be taken into account during Link Adaptation is the speed of the UE. Variations in the received signal quality increase with the speed of UE. In this thesis, six different speeds have been considered. Low speeds include 0.3, 3 and 10 km/h. Higher speeds include 30, 60 and 120 km/h. The figures 3.2 and 3.3 illustrate the impact of speed on the CQI trend of a particular channel model for a given geometry.

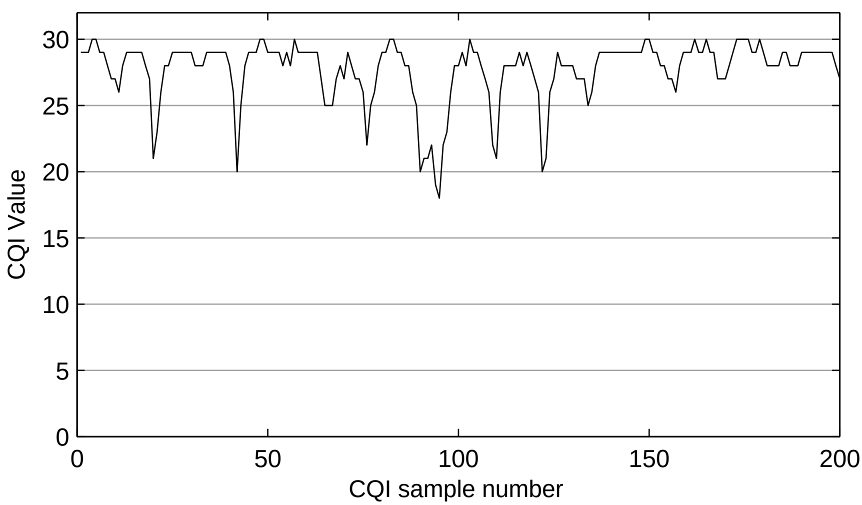

Figure 3.2: CQI trend in a PA/20/3 channel type

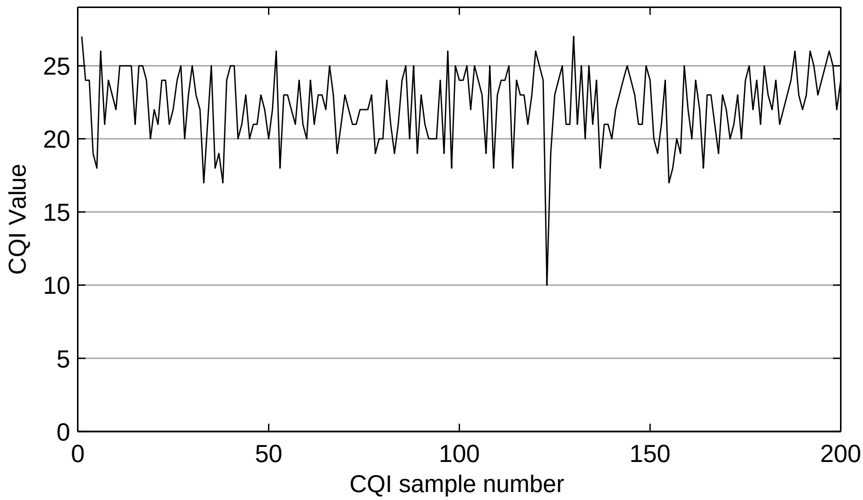

Figure 3.3: CQI trend in a PA/20/120 channel type

3.4 Channel Types and Representation

For the purpose of this Thesis, each channel type was described by the three parameters: Channel Model, Geometry Factor and UE speed. The PA and VA channel models are tested for two geometry factors and a total of six speeds. The geometry factors are chosen such that the effect of high and low geometry factors can be seen. The AWGN channel model was measured for various geometry factors with a step size of five ranging from extremely high geometry factor to extremely low geometry factor. The UE speeds range from the low speed of a pedestrian user to high speed of vehicular user. Each channel can be represented as C/G/S where C stands for the channel model; G stands for geometry factor and S for the UE speed. The Table 3.3 indicates all the thirty-one channels.

Table 3.3: 31 Channel Types considered in this thesis work

Channel Model	Geometry	Speed	Representation
PA	20	0.3	PA/20/0.3
PA	5	0.3	PA/5/0.3
PA	20	3	PA/20/3
PA	5	3	PA/5/3
PA	20	10	PA/20/10
PA	5	10	PA/5/10
PA	20	30	PA/20/30
PA	5	30	PA/5/30
PA	20	60	PA/20/60
PA	5	60	PA/5/60
PA	20	120	PA/20/120
PA	5	120	PA/5/120
VA	20	0.3	VA/20/0.3
VA	5	0.3	VA/5/0.3
VA	20	3	VA/20/3
VA	5	3	VA/5/3
VA	20	10	VA/20/10
VA	5	10	VA/5/10
VA	20	30	VA/20/30
VA	5	30	VA/5/30
VA	20	60	VA/20/60
VA	5	60	VA/5/60
VA	20	120	VA/20/120
VA	5	120	VA/5/120
AWGN	>25	NA	AWGN/>25
AWGN	20	NA	AWGN/20
AWGN	15	NA	AWGN/15
AWGN	10	NA	AWGN/10
AWGN	5	NA	AWGN/5
AWGN	0	NA	AWGN/0
AWGN	-5	NA	AWGN/-5

Chapter 4

CQI: Statistical Analysis

Characterization of the various known channel types based on channel model, geometry factor and UE-speed was central to the problem being addressed by this thesis work. A total of thirty-one channel types need to be parametrized and distinctly differentiated from each other. Statistical analysis of CQI values was the means by which characterization of a channel type was achieved. The various steps include deciding the number of CQI values that need to be considered for statistical analysis, finding those statistical parameters which help in differentiating one channel type from another and finding a unique sequence of these statistical parameters that can accurately distinguish between the thirty-one channel types. The approach to each of these steps is discussed in detail in the following sub-sections.

4.1 Window size

One of the first problems to solve was finding a suitable number of CQIs or *window size* over which a statistical analysis can be made. An investigation was made into finding a window size or the number of CQIs whose statistics characterize the channel type. MATLAB simulations showed that in order to perfectly characterize a channel type (among the set of thirty-one channel types considered in this thesis), the window size had to be in the order of several hundreds of CQIs. In practice however, decisions need to be made about the channel types much faster as it might be constantly varying. But, by employing a small window size, it is possible that the coherence time of some of the channel types might be longer than the window size.

The conclusion from the investigation was that the window size cannot be made too long such that the link adaptation is too slow. At the same time, it should not be too short such that the interval is too small to characterize the channel type or that there is additional processing overhead at the base station. Different window sizes ranging from two-hundred CQI values to ten CQI values were investigated.

In the case of two-hundred CQI values, the interval was deemed too large. As mentioned previously, the time interval between CQI reports is 8 ms. This would mean that a minimum of 1600 ms would be needed for two-hundred CQI values to be reported. Some additional processing and scheduling overhead is added on top of this 1600 ms to calculate the statistical parameters and finally make the changes for the link to adapt accordingly. A period of over 1600 ms is too long resulting in a very slow Link Adaptation process. In the case of ten CQI values, the interval was too small to use some of the statistical parameters like the Average Fade Duration and Level Crossing Rate to define a fade and thereby to characterize the channel type. A window size of twenty-five CQI values corresponding to 200 ms was determined to be not too small or too large.

To characterize each of the thirty-one channel types, a sequence of thousand CQI values was considered for each channel type. All statistical parameters were calculated for a window of twenty-five CQI values and then were averaged over forty such windows (i.e. over the total of thousand CQI values, in steps of twenty-five). This process was repeated for all the thirty-one channel types considered in this thesis. These are the statistics which form the basis for the algorithm development in this thesis.(Read: Mean, Variance, Minimum, Correlation Coefficient, Level Crossing Rate and Average Fade Duration).

4.2 Statistical Parameters

Another key factor for characterizing a channel type was to choose the right statistical parameters. A single statistical parameter cannot distinguish between all the thirty-one channel types but an appropriate combination of statistical parameters can be used to resolve them. When choosing the parameters a few points needed to be considered: Firstly, we needed those parameters which can have as many unique values as possible for different channel types to be able to distinguish between them. Secondly, the parameters also needed to be such that there was no redundancy i.e. the statistical parameters chosen should not be such that they distinguish between the same channel types. For example : If stat A was able to distinguish between twenty-five out of the thirty-one channel types and stat B also distinguishes between the same twenty-five channel types, then stat B would be redundant. Lastly, the number of statistical parameters used must be minimal to avoid adding processing overhead at the base station which would cause delay errors in link adaptation.

The statistical parameters that were investigated are given in the following subsections. It has to be noted that the analysis on the statistical parameters in this thesis has been done on a single chipset vendor. The values of statistics such as Mean of the CQI series varies from vendor to vendor as the calculation of CQI is not clearly defined in the 3GPP standard and the adaptation might be different across the vendors. *Cf. Chapter 6, [15].* An offset correction will be required in order to apply the algorithm developed in this thesis to other chipset vendors.

4.2.1 Mean

The mean is an important statistical parameter in characterizing the channel types. Consider thousand CQI values of a known channel type i.e. with a channel model C, Geometry Factor G and UE speed S. The mean was measured over this Sample Count of N = *1000* CQI values in steps of Window Size, W = *25* for each channel type (C/G/S). The calculation to find the characterized value of mean for each channel type was as follows:

$$\mu_j = (CQI_i + CQI_{i+1} + \ldots + CQI_{i+W-1})/W, \tag{4.1}$$

$$\mu_{C/G/S} = (\mu_0 + \mu_1 + \ldots + \mu_{(N/W)-1})/(N/W), \tag{4.2}$$

where, $j = \{0, 1, \ldots, (N/W) - 1\}$ represents the j^{th} window under consideration and $i = (j * 25)$.

Now $\mu_{C/G/S}$ characterizes the mean of that particular channel type. This set of calculations was carried out for all the thirty-one channel types to characterize their mean. The characterized values of mean were able to clearly distinguish between some channel types. The plot in 4.1 shows the characterized values of mean for all the thirty-one channel types.

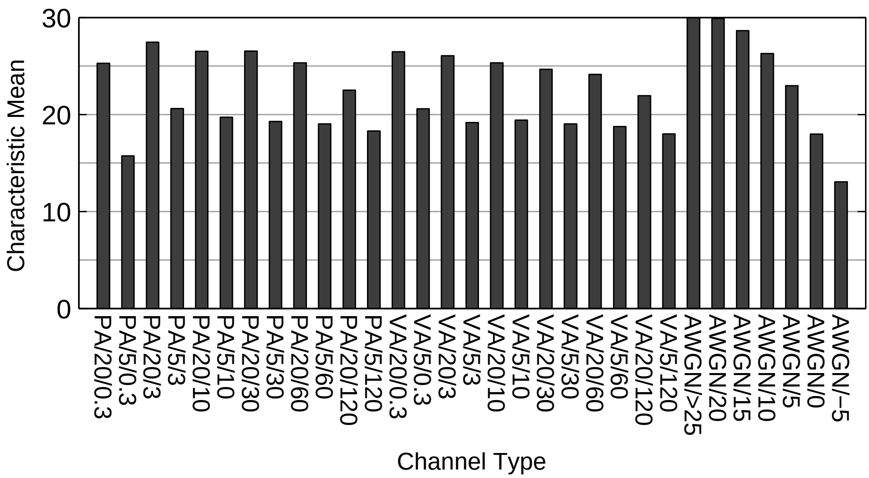

Figure 4.1: Characteristic *Mean* for various Channel Types

From the Figure 4.1, it is clear that some channel types can be clearly distinguished from one another whereas some others cannot be. One of the trends observed from the mean value of each channel type were that there was a significant decrease in mean when the geometry factor was reduced from high to low. There was also a decrease in the mean value with an increase in UE speed except in the case of extremely low speeds of 0.3 km/h and 3 km/h. The conclusion from this investigation was that the mean value was affected more by the geometry factor and to a lesser extent by the UE speeds under consideration. This is reasonable since lower geometry would mean that the UE is further away from the nodeB and the average signal strength(and the mean CQI) would be lower compared to a UE in a higher geometry channel type.

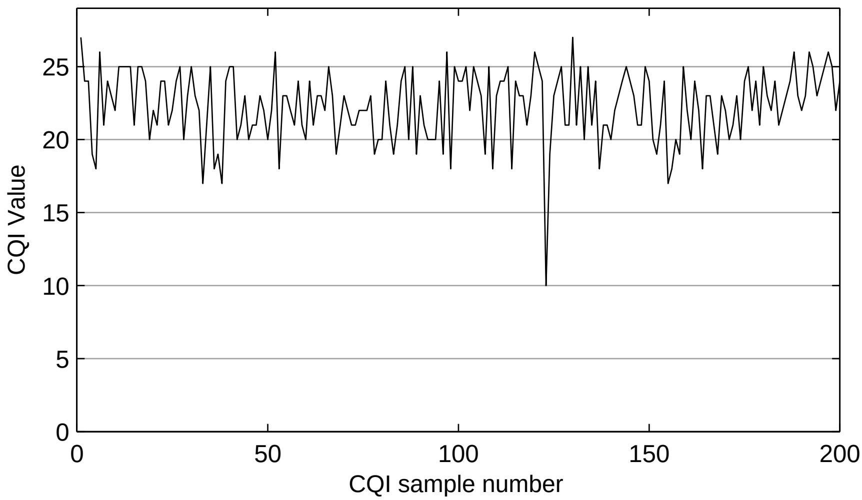

Figure 4.2: CQI trend in a *PA/20/120* channel type

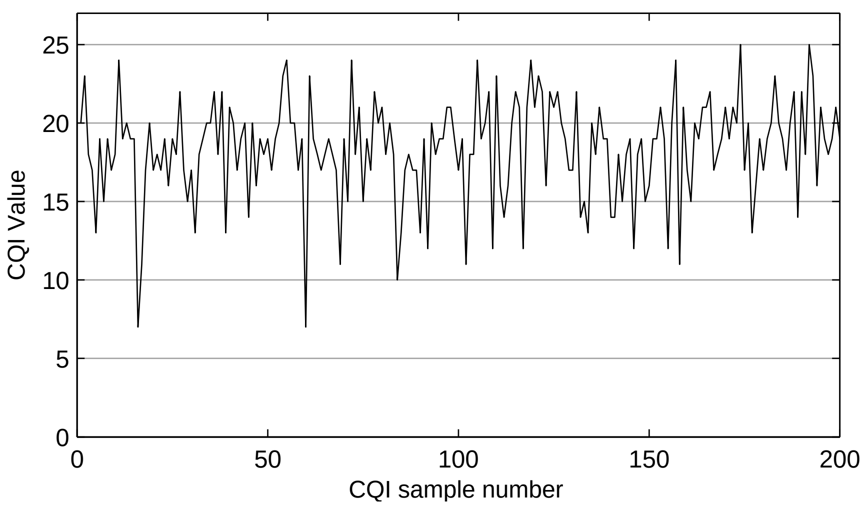

Figure 4.3: CQI trend in a *PA/5/120* channel type

A graphical representation of a set of two-hundred CQI values respectively for few channel types is plotted in Figures 4.2, 4.3, 4.4 and 4.5. Two channel types at low speeds of 10 km/h and two channel types at high speeds of 120 km/h are considered for both high and low geometry and for the same Pedestrian-A channel model. It can be seen that the characteristic mean changes significantly with a change in geometry factor (G of 20 and 5) and keeping the same speed.

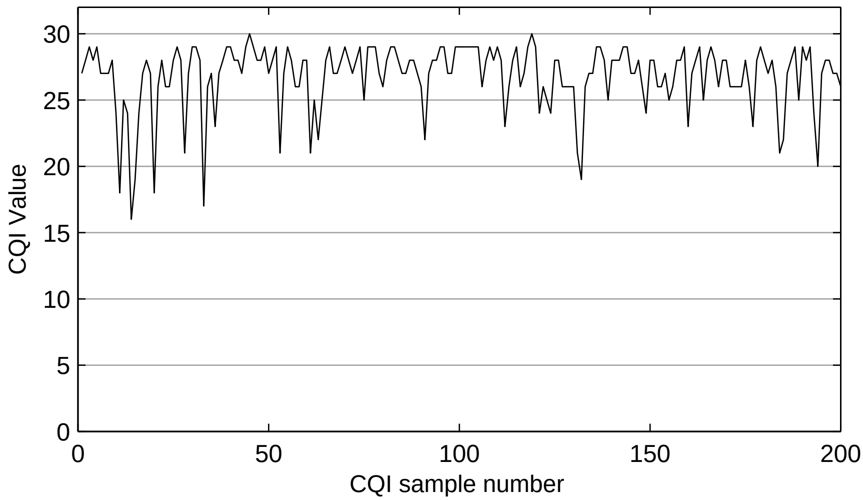

Figure 4.4: CQI trend in a *PA/20/10* channel type

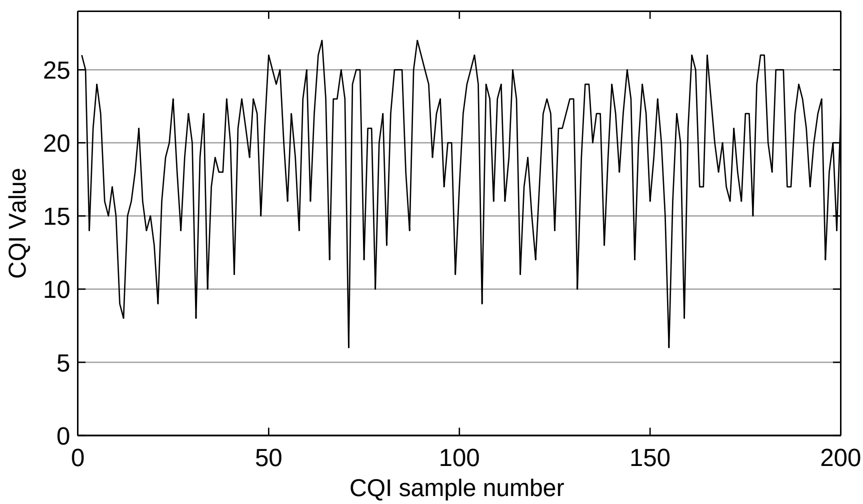

Figure 4.5: CQI trend in a *PA/5/10* channel type

Whereas, the change in characteristic mean with different UE speeds (120 km/h and 10 km/h) is not very significant.

4.2.2 Variance

Variance, another important characteristic in this case, gives the measure of how the channel varies with respect to its mean.The variance, σ^2 is the square of the Standard deviation, σ. The σ is estimated as:

$$\sigma = (\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2)^{1/2}, \tag{4.3}$$

where, n is the number of elements in the sample x.

Similar to the *Mean* calculation, the variance was measured over a Sample Count of N = *1000* CQI values in steps of Window Size, W = *25* for each channel type (C/G/S). The calculation to find the characterized value for each channel type was as follows:

$$\sigma_j^2 = variance(CQI_i, CQI_{i+1}, \ldots, CQI_{i+W-1}), \tag{4.4}$$

$$\sigma_{C/G/S}^2 = (\sigma_0^2 + \sigma_1^2 + \ldots + \sigma_{(N/W)-1}^2)/(N/W), \tag{4.5}$$

where, j = $\{0, 1, \ldots, (N/W) - 1\}$ represents the j^{th} window under consideration and $i = (j * 25)$.

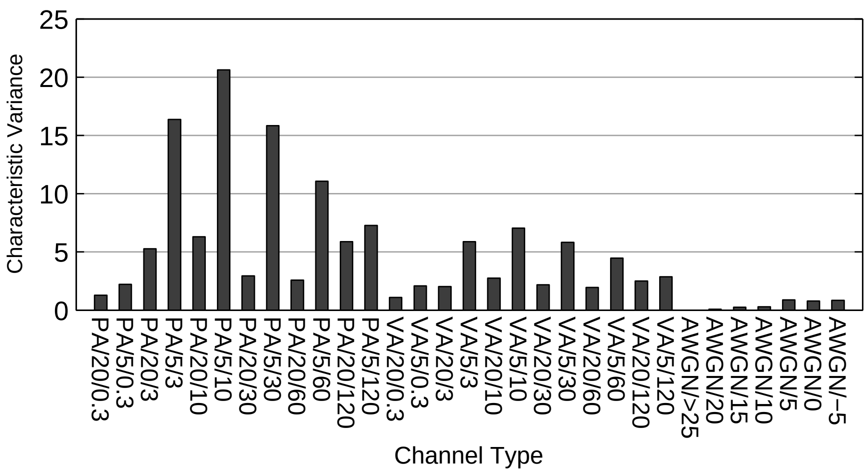

Figure 4.6: Characteristic *Variance* for various Channel Types

$\sigma_{C/G/S}^2$ was considered as the characterized value of variance for the channel type. A different set of channel types are now clearly distinguishable using the variance. As seen from the graph in Figure 4.6, there was again a significant change in variance between channel types with high and low geometry factor. Lower geometry results in high variance and high geometry results in low variance.

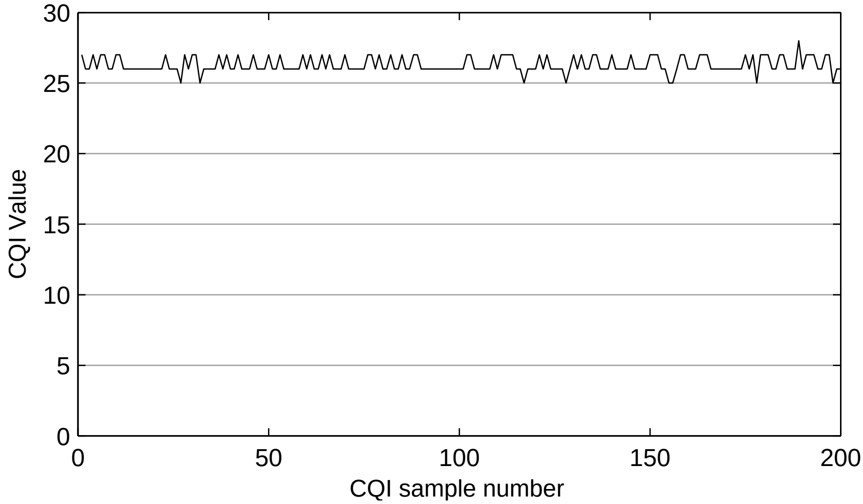

Figure 4.7: CQI trend in an *AWGN/10* channel type

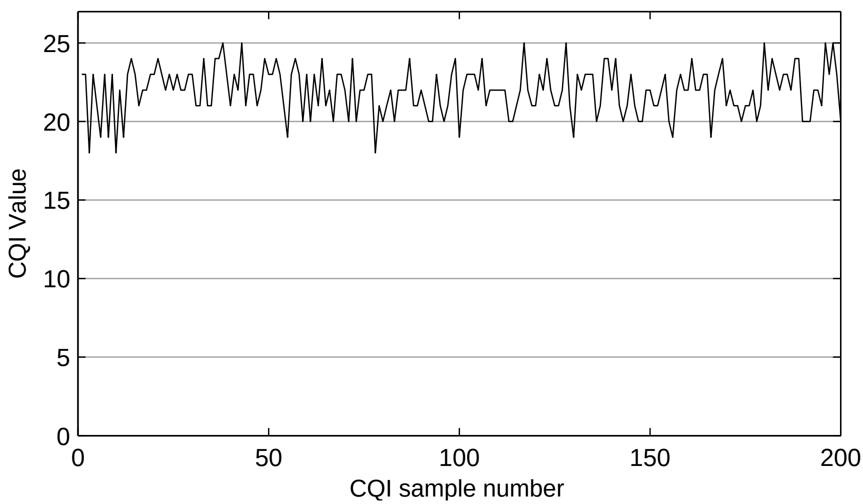

Figure 4.8: CQI trend in a *VA/20/120* channel type

It was observed that out of the thirty-one channel types considered, the PA/5/10 channel type had the maximum variance. Another clear trend with the value of variance was with respect to the channel model. In the case of the AWGN channel model, the value of the variance was low and was between 0 and 1 for all the different geometry factors under consideration. It was also observed that the value of variance especially for the low geometry factors was much higher for the PA channel models than those for VA channel models.

To illustrate the difference graphically, an AWGN /10 (Figure 4.7) channel type and a VA/20/120 (Figure 4.8) channel type are chosen and their respective

CQI values are plotted. As seen from the graphs, there are several deep fades and there are significant variations from the mean in the VA/20/120 channel type when compared to the AWGN/10 channel type. These 2 channels are thereby easy to distinguish using variance.

4.2.3 Minimum

Some channel types are characterized by many fades. The mean might not be able to characterize for example a channel type with few distinct deep fades that might occur once every few windows. The quantities to be calculated in these cases are the maximum and minimum value of the CQIs in a window size. Between finding the maximum or minimum value we chose to use the minimum values as accommodating both parameters would be redundant. The Minimum was measured over the Sample Count of $N = 1000$ CQI values in steps of Window Size, $W = 25$ for each channel type (C/G/S). The calculation to find the characterized value of Minimum for each channel type was as follows:

$$Min_j = minimum(CQI_i, CQI_{i+1}, \ldots, CQI_{i+W-1})/W, \quad (4.6)$$
$$Min_{C/G/S} = (Min_0 + Min_1 + \ldots + Min_{(N/W)-1})/(N/W), \quad (4.7)$$

where, $j = \{0, 1, \ldots, (N/W) - 1\}$ represents the j^{th} window under consideration and $i = (j * 25)$.

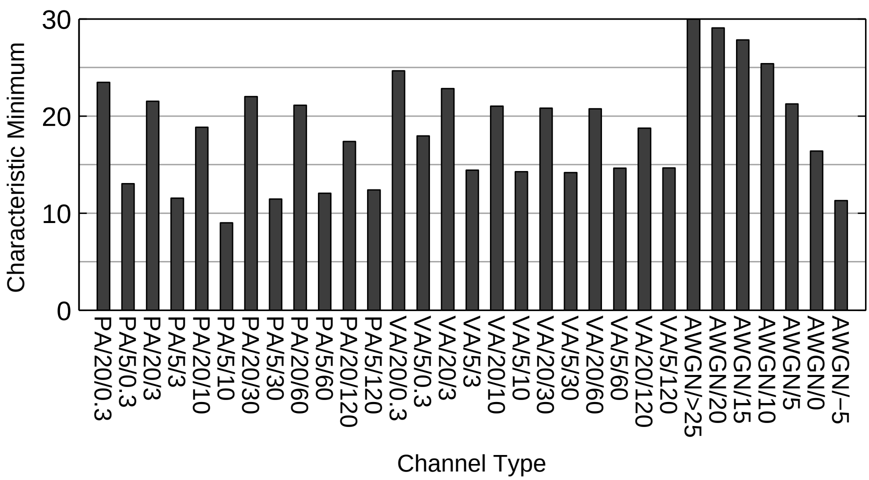

Figure 4.9: Characteristic *Minimum* for various Channel Types

$Min_{C/G/S}$ was the characterized value of minimum for each channel type. The minimum has a similar trend to the trend seen in mean. There was a change in the value of minimum with a change in geometry factor or a change in speed.

A significant change was seen when the geometry factor was changed. The characteristic minimums of channel types with high geometry factor are higher than those with low geometry factor. With respect to speed, there was a change in the value of the minimum; however there was no clear trend.

A PA/20/0.3 (Figure 4.10) and PA/5/0.3 (Figure 4.11) channel types are chosen to highlight the difference in characteristic minimum for different geometries. As can be seen from the plot for PA/5/0.3, characteristic deep fades occur at regular intervals and not so many for PA/20/0.3.

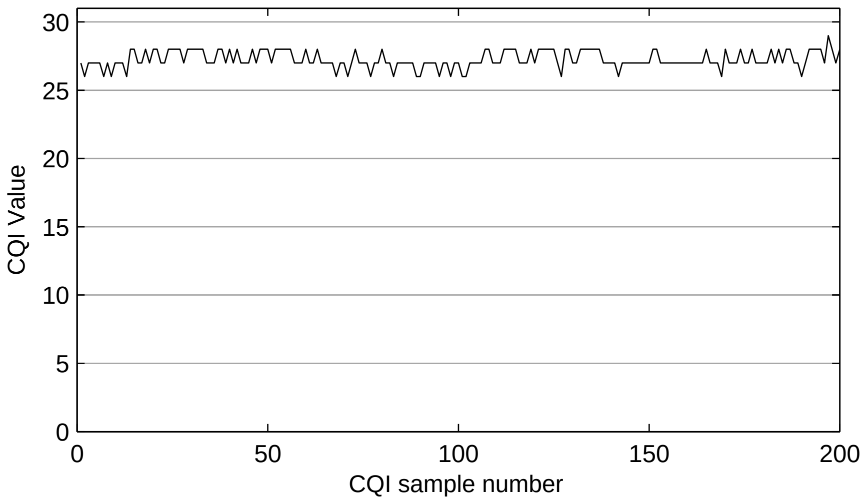

Figure 4.10: CQI trend in a *PA/20/0.3* channel type

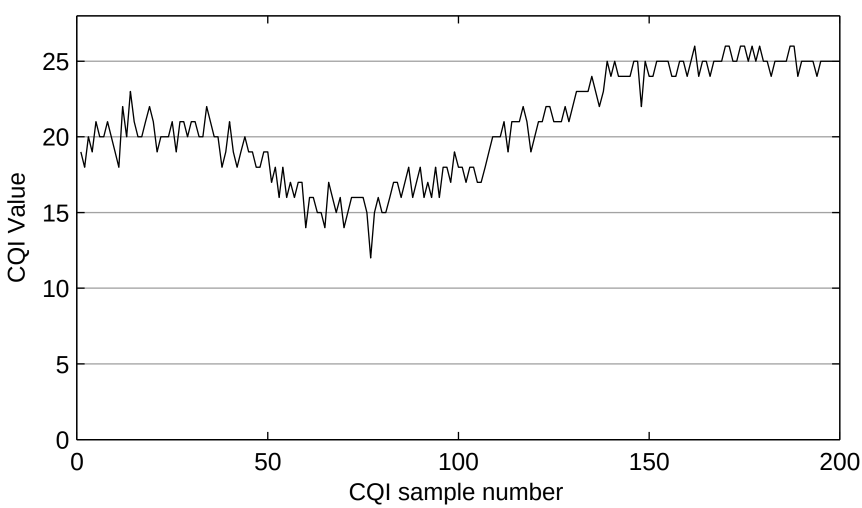

Figure 4.11: CQI trend in a *PA/5/0.3* channel type

4.2.4 Correlation Coefficient

The relation between consecutive CQI values was another important characteristic which needs to be quantified for each channel type. The variance only compares each value with the mean whereas in the calculation of the correlation coefficient, each value was compared to its previous value. The correlation coefficient can vary between -1 and 1. The calculation of the correlation coefficient was as follows:

$corr_{coeff}$ is estimated as:

$$corr_{coeff} = \frac{\sum_{i=1}^{n}(A_i - \bar{A})(B_i - \bar{B})}{\sqrt{\sum_{i=1}^{n}(A_i - \bar{A})^2(B_i - \bar{B})^2}}, \tag{4.8}$$

where n is the length of the number series A and B, $\bar{A}$ = mean(A) and $\bar{B}$ = mean(B).

The Correlation Coefficient was measured over the Sample Count of $N = 1000$ CQI values in steps of Window Size, $W = 25$ for each channel type (C/G/S). The calculation to find the characterized value of Correlation Coefficient for each channel type was as follows:

$$\begin{aligned} Corr_j = corr_{coeff}[(&CQI_i, CQI_{i+1}, \ldots, CQI_{i+W-2}), \\ &(CQI_{i+1}, CQI_{i+2}, \ldots, CQI_{i+W-1})], \end{aligned} \tag{4.9}$$

$$Corr_{C/G/S} = (Corr_0 + Corr_1 + \ldots + Corr_{(N/W)-1})/(N/W), \tag{4.10}$$

where, $j = \{0, 1, \ldots, (N/W) - 1\}$ represents the j^{th} window under consideration and $i = (j * 25)$.

$Corr_{C/G/S}$ was the characterized value of correlation coefficient. There was a change in the value of the correlation coefficient with a change in geometry factor or UE speed. The graph in Figure 4.12 gives the characterized value of the correlation coefficient for all the thirty-one channel types.

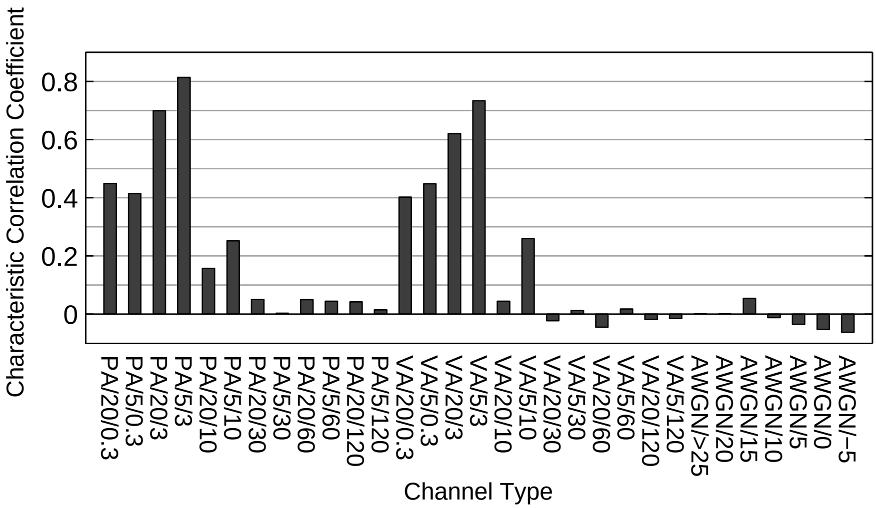

Figure 4.12: Characteristic *Correlation Coefficient* for various Channel Types

The correlation coefficient varies significantly with UE speed. From the trend observed in the graph shown in Figure 4.12, a conclusion can be made that the fade duration was high only for the lower UE speeds. Though there was a change with respect to geometry factor, a clear pattern was not seen.

In the two channel types considered in the Figures 4.13 and 4.14, it is clear that VA/5/3 channel type has a longer coherence time when compared to the VA/5/30 channel type. (For a detailed definition of Coherence time, the reader is referred to Chapter 6 in [5]). Using the correlation coefficient, these channel types can be distinguished easily.

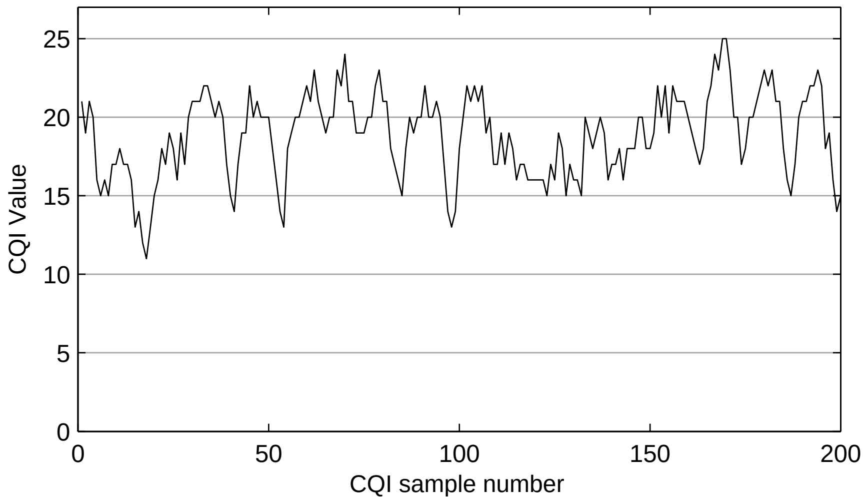

Figure 4.13: CQI trend in a *VA/5/3* channel type

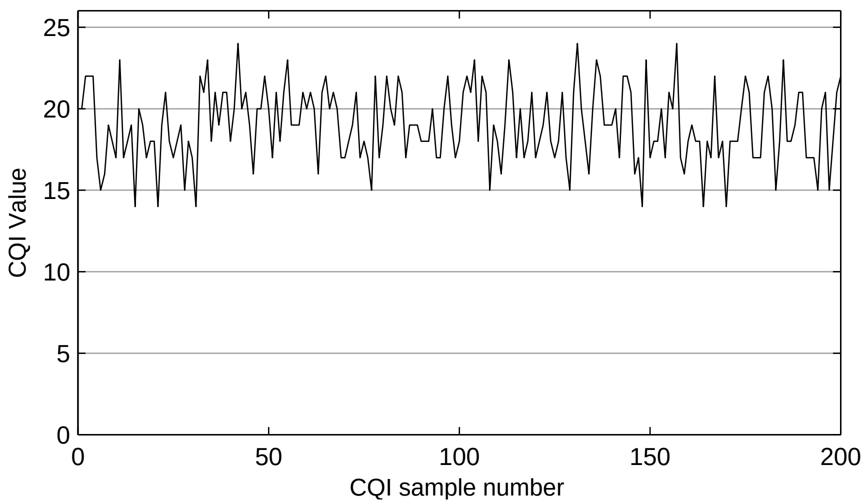

Figure 4.14: CQI trend in a *VA/5/30* channel type

4.2.5 Level Crossing Rate

The LCR was a statistical property used to study the rate at which fading dips occur. The measure depends on the threshold we consider. *Cf. Chapter 5, [5].* As this was being used for all the thirty-one channel types, the threshold considered for defining the fades has to be common. As already seen, different channel types have different values of means and it becomes impossible to choose a generic level or threshold for all the channel types. To overcome this problem, CQI values normalized by their mean are chosen for the LCR calculations. Various thresholds were simulated and tested in MATLAB. The conclusion was that, setting 1 as the threshold works best to differentiate between values of LCR for different channel types. The LCR was also measured over the Sample Count of $N = 1000$ CQI values in steps of Window Size, $W = 25$ for each channel type (C/G/S). The calculation to find the characterized value of LCR for each channel type was as follows:

$$LCR_j = N_j/W, \tag{4.11}$$

$$LCR_{C/G/S} = (LCR_0 + LCR_1 + \ldots + LCR_{(N/W)-1})/(N/W), \tag{4.12}$$

where, $j = \{0, 1, \ldots, (N/W) - 1\}$ represents the j^{th} window under consideration. N_j represents the number of normalized CQI samples less than the threshold (1) in the j^{th} window of twenty-five CQI samples

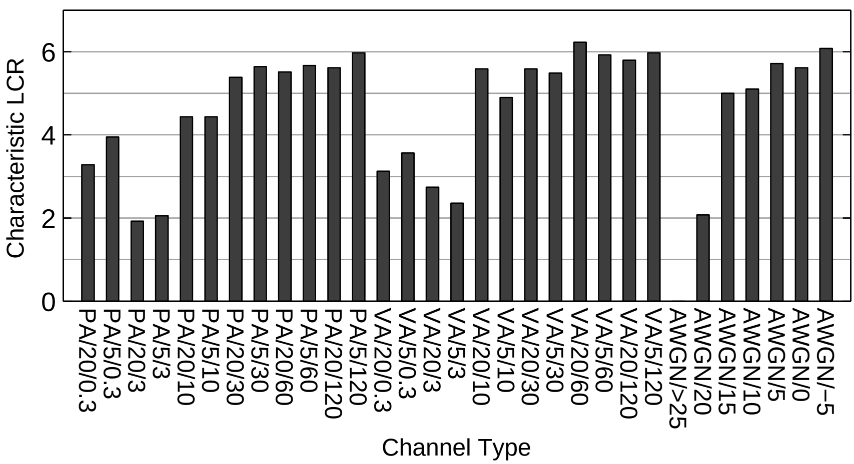

Figure 4.15: Characteristic *LCR* for various Channel Types

The $LCR_{C/G/S}$ was the normalized value of LCR for channel type C/G/S. The LCR varies with both geometry factor and UE speed. The change with geometry factor was small but the change with UE speed was significant.

From the graph in Figure 4.15, the trend observed was that the LCR was high for higher speeds in the PA and VA channel models and was also high for the medium and low geometry factors in the AWGN channel model. A conclusion can be made that the channel variations about the mean increases with an increase in UE speed.

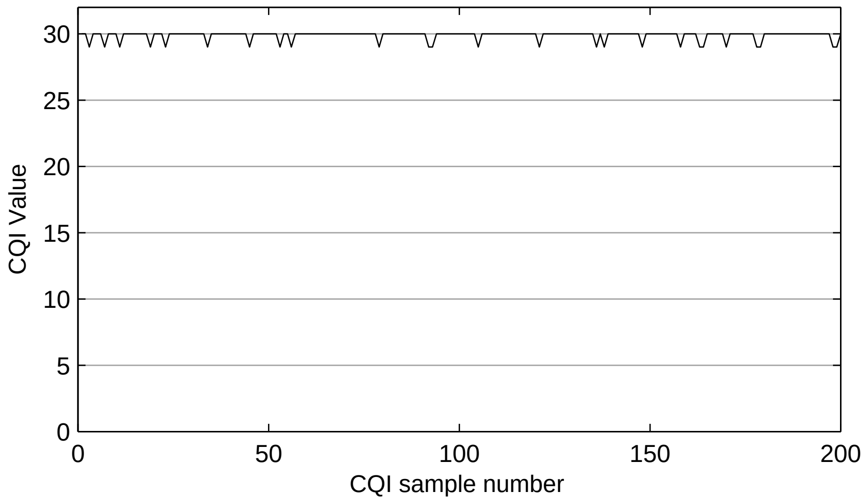

Figure 4.16: CQI trend in an *AWGN/20* channel type

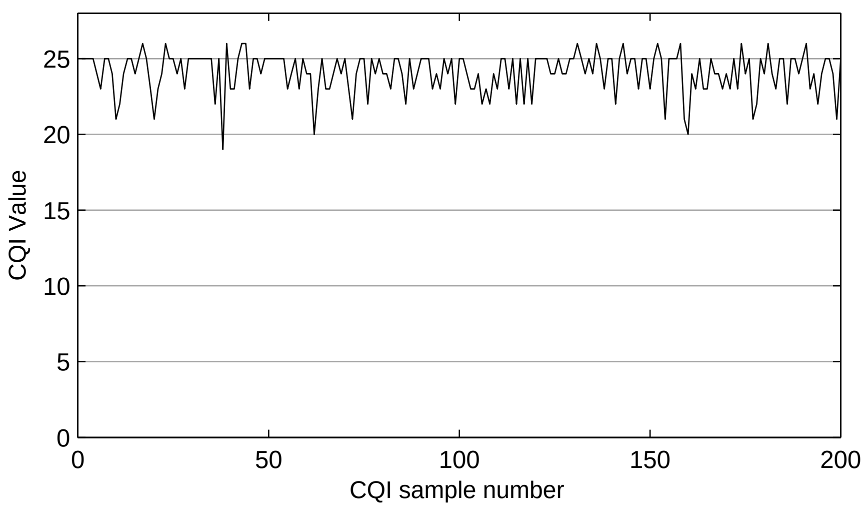

Figure 4.17: CQI trend in a *VA/20/60* channel type

From Figures 4.16 and Figure 4.17, the difference in the LCR between the channel types AWGN/20 and VA/20/60 can be seen clearly.

4.2.6 Average Fade Duration

When the normalized CQI value was less than the defined threshold, it was considered as a fade.The Average Fade Duration (AFD) was a measure of the length of each of these fades in terms of number of CQI values. The threshold was the same as that taken up in the case of LCR i.e. 1, with normalized CQI values as input. Like the calculations for previous statistics, the AFD was measured over the Sample Count of $N = 1000$ CQI values in steps of Window Size, $W = 25$ for each channel type (C/G/S). The calculation to find the characterized value of AFD for each channel type was as follows:

$$AFD_j = mean(f_{1j}, f_{2j}, \ldots, f_{nj})/N_j, \tag{4.13}$$
$$AFD_{C/G/S} = (AFD_0 + AFD_1 + \ldots + AFD_{(N/W)-1})/(N/W), \tag{4.14}$$

where, $j = \{0, 1, \ldots, (N/W) - 1\}$ represents the j^{th} window under consideration. N_j represents the number of normalized CQI samples less than the threshold in the j^{th} window of twenty-five CQI samples.

$AFD_{C/G/S}$ was the characterized value of AFD for channel type C/G/S and is shown in the Figure 4.18.

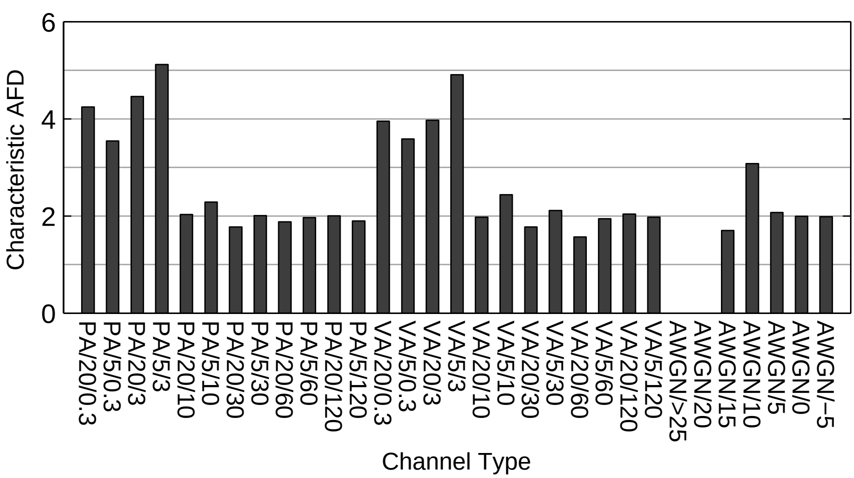

Figure 4.18: Characteristic *AFD* for various Channel Types

From the graph in Figure 4.18, the trend shows that AFD values are high for lower UE speeds compared to the higher speeds. This is natural as a user moving at high speed is more likely to come out of a deep fade faster as compared to a pedestrian user. Another observation was that among the channel types in the AWGN channel model, the AWGN/10 channel type has characteristic fades which are long.

From the Figures 4.19 and 4.20 it can be clearly noticed that fades in the VA/5/0.3 are longer compared to those in the VA/5/120.

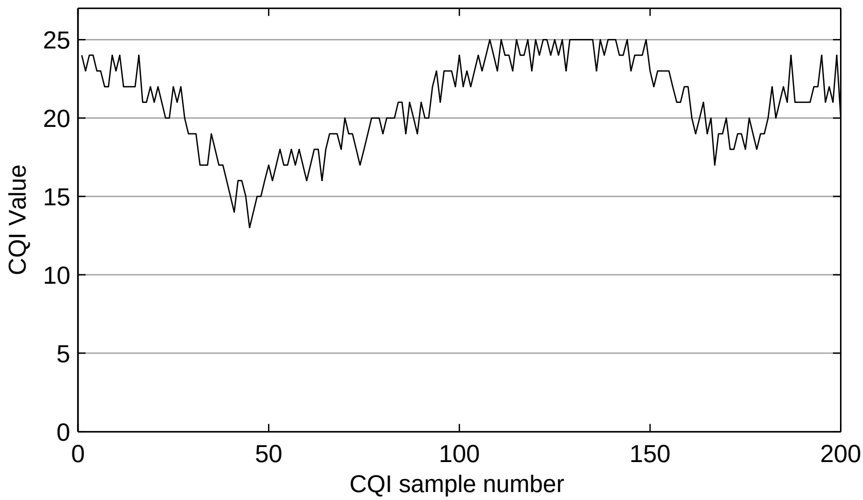

Figure 4.19: CQI trend in a *VA/5/0.3* channel type

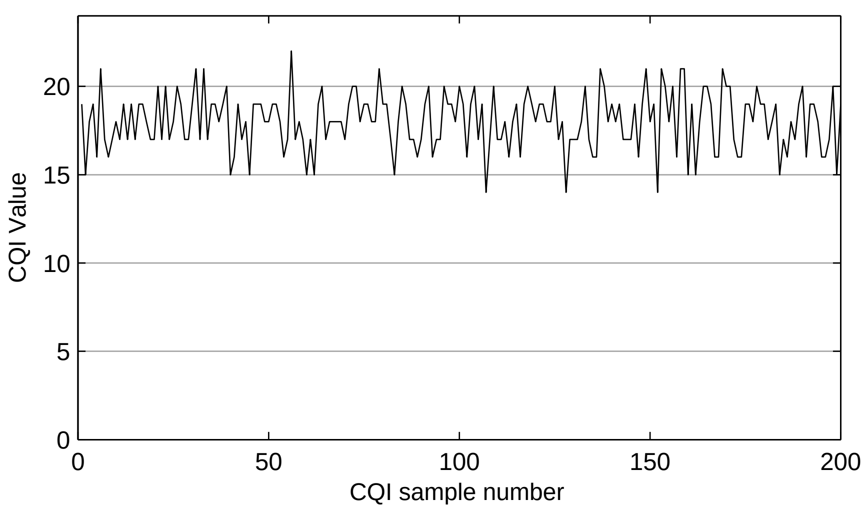

Figure 4.20: CQI trend in a *VA/5/120* channel type

The calculation of LCR and AFD can is further explained in Figures 4.21 and 4.22 for a PA/5/3 and PA/20/3 Channel Type. For the Channel Type PA/5/3, *LCR* = *2* and *AFD* = *(2+8)* ÷ *2* = *5*. For the Channel Type PA/20/3, *LCR* = *2* and *AFD* = *(3+5)* ÷ *2* = *4*.

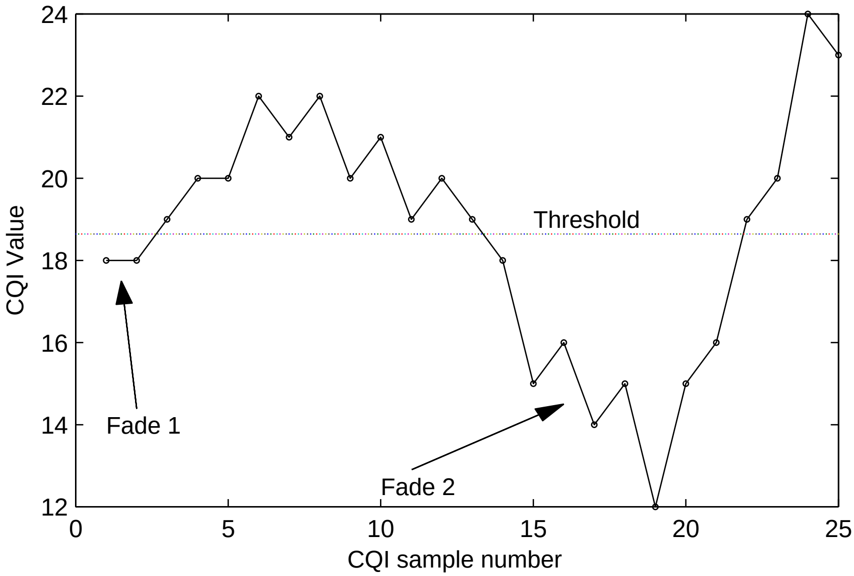

Figure 4.21: AFD and LCR in a PA/5/3 Channel Type

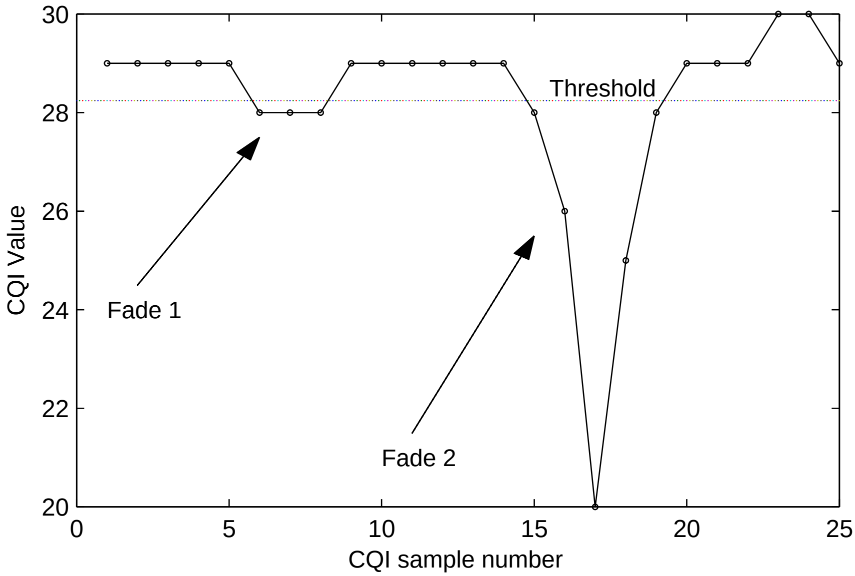

Figure 4.22: AFD and LCR in a PA/20/3 Channel Type

Chapter 5

Channel Type Decision and BLER target Mapping

In this chapter, we explain in detail the algorithm flow and the pre-requisite analysis. As mentioned in Section 4.2, the algorithm developed for this thesis has been tuned to an UE chipset. The same can be optimized to match different UE chipsets by estimating the mean offset for each UE chipset.

5.1 Channel Type Categories under each statistic

In the first step of the pre-requisite analysis, each statistical measure (mean, variance etc.) was calculated for all the thirty-one channel types. Next, for each statistical measure, the channel types with similar values are categorized together. For example, channel types with the characteristic mean value between m1 and m2 are grouped together. This process was carried out for all the six statistical measures. An illustration of the channel type grouping is shown in the Tables 5.1 and 5.2. Description regarding the selection of the thresholds *m1, m2 . . . v1, v2 . . .* is given in Sections 6.1.1 to 6.1.3.

Table 5.1: Channel Type categories under statistic: *Mean*

m1 <= Mean <= m2 Channel Types= { 1, 2, 3 }	m2 < Mean <= m3 Channel Types={ 4, 5, 6 }
m3 < Mean <= m4 Channel Types= { 7, 8, 9 }	m4 < Mean <= m5 Channel Types={ 10, 11, 12 }

Table 5.2: Channel Type categories under statistic: *Variance*

v1 <= Variance <= v2 Channel Types= { 2, 5, 8, 9 }	v2 < Variance <= v3 Channel Types={ 4, 6 }
v3 < Variance <= v4 Channel Types= { 7, 12 }	v4 < Variance < v5 Channel Types={ 1, 3, 10, 11 }

5.2 Link Adaptation using multiple BLER thresholds

The limiting factor in choosing a higher order modulation and coding scheme in a given channel condition is the Error Rate limit or target that is set for the system as mentioned previously in Section 1.4. In most systems, the conventional approach would be to have a fixed error rate threshold of around 10% as mentioned in Section 1.5.

In the case where channel conditions are such that the received CQIs are at a fairly constant level, link adaptation with a fixed BLER target of 10% works well. Not much can be done to further increase throughput within the given system architecture and standards. But in the case where channel conditions are such that the there are huge variations in the CQI and the uncertainty is very high, a fixed BLER target of 10% is not a good setting for delivering high throughput to the UE. To increase throughput multiple BLER target settings which maybe higher than 10% are used.

Consider a system such that three BLER targets X%, Y% and Z% are set where, Z >Y >X. By using a larger BLER target like Z% when the uncertainty in the channel is high, a higher modulation/coding scheme can be used. Effectively with Z% as BLER target, large transport blocks are transmitted on the downlink which are larger than those transmitted with the BLER target at 10%. This comes at the cost of having a higher probability of error. If the gain in throughput due to transmitting larger transport blocks is greater than the loss in throughput due to re-transmitting erroneous blocks, then there is an overall gain in throughput. The same holds true for setting BLER targets at Y% and X% respectively. It is possible that in certain channel types there is a gain in throughput only in Y% and not in Z% as there may be too many re-transmissions when BLER target is Z%. Similarly in some cases X% maybe the optimal BLER target setting. This process of testing the optimal BLER target for each of the thirty-one channel types was carried out at Ericsson prior to this thesis. Hence, each of the thirty-one channel types mapped to one of the X, Y or Z BLER target groups. In this thesis, we analyse an incoming set of CQI values to decide the channel type. The appropriate BLER target corresponding to this channel type is used on the downlink for Link Adaptation as this would lead to an increase in throughput delivered at the UE.

5.2.1 Algorithm

During the process of link adaptation, for each new set of twenty-five CQI values reported by the UE, the various statistics discussed are calculated and based on these statistics we filter out a unique channel type from the channel type categories made earlier. The algorithm flow is further explained in the flowchart given in Figure 5.1. Careful channel type categorization was essential, and thresholds for each channel type category had to be optimized over a number of simulations for each statistic. Based on the MATLAB simulations, the small measurement window size corresponding to twenty-five CQI values does not cause too much of a processing delay, while still being good enough to fairly characterize most of the channel types considered for this thesis (further confirmed by the results obtained from the Ericsson RAN Lab Simulations).

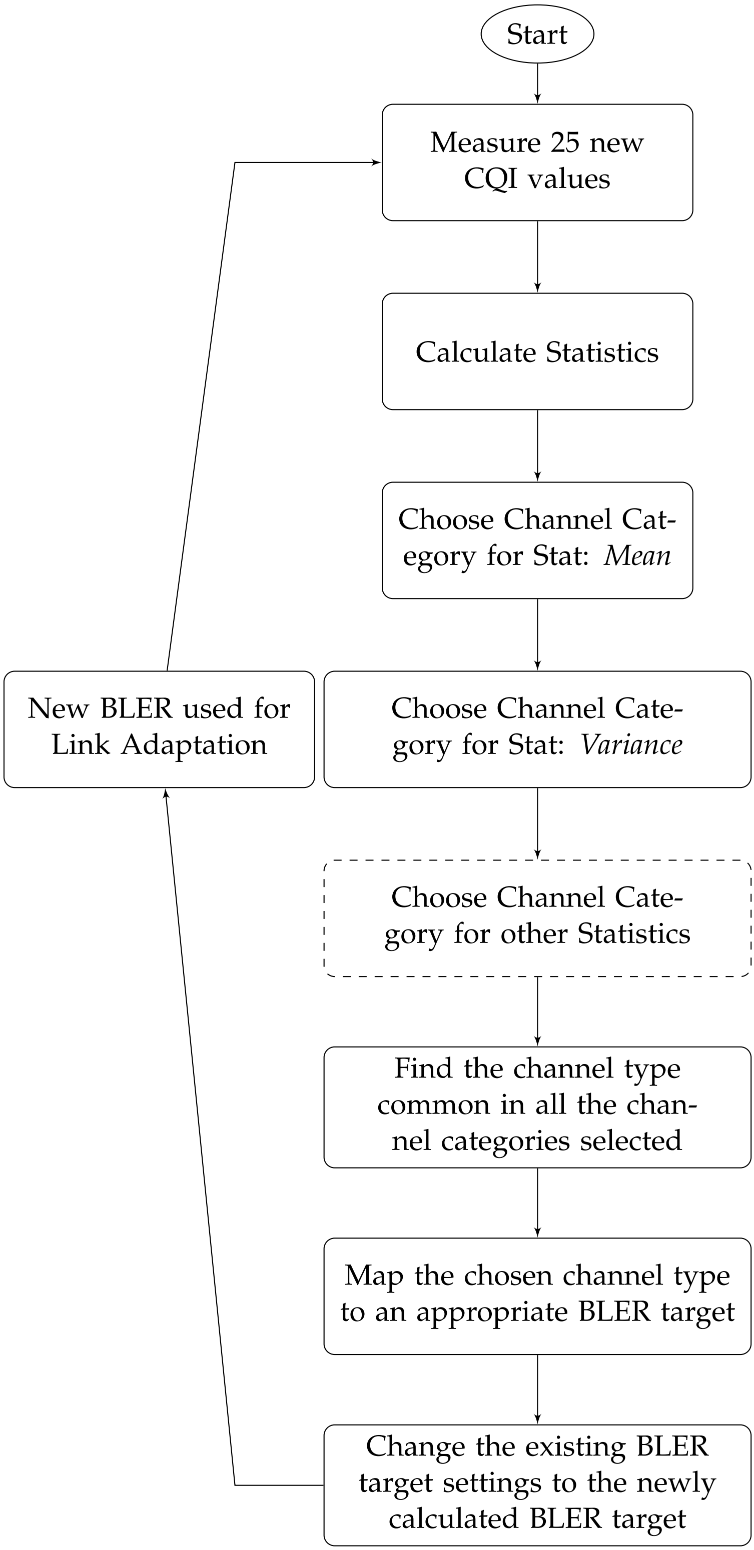

Figure 5.1: Algorithm Flow

Chapter 6

Simulations and Black Module Testing

In this chapter, we describe the simulations done using *MATLAB* and the *Black Module* testing done in the *Ericsson RAN* lab.

6.1 MATLAB simulations

After having carefully implemented the algorithm described in the Figure 5.1 of Section 5.2.1 in MATLAB, the data from log files generated in the Ericsson RAN labs are used as input to the algorithm. The log files contain the series of CQIs reported by the UE in the various channel conditions considered in this thesis.

Various approaches were considered in order to fine tune the algorithm and achieve optimal results, these are described in Subsections 6.1.1 to 6.1.5.

6.1.1 Thresholds fine tuning

The thresholds here refer to the selection of parameters such as *m1,m2 ...v1, v2 ...* described in Table 5.1 and 5.2. During the process of picking out a channel type from the set of channel types under each statistic (refer to Algorithm in Subsection 5.2.1), it was possible that same channel type was not chosen in every window. This was due to the fact that channel type could be different if window size changes. Consider a set of two-thousand CQI values of a particular channel type. The channel type determined for a window size of five-hundred CQIs at the end of the first five-hundred CQI values maybe different to the channel type determined at the end of the second set of five-hundred CQIs. Similarly if a window size of twenty-five CQIs are used on the first five-hundred values, it was possible that among the twenty decisions there could be five or ten different channel types. This was because the channel behavior can be quite different in a small window sizes (200 ms) as compared to its behaviour over a larger window size or over another twenty-five CQIs window. This is illustrated further in Figure 6.1. As we can see, within the duration of one-hundred and twenty-five CQI samples, a VA/20/10 channel type can appear to be a VA/20/60, PA/20/120 or VA/20/3 channel type as well.

Initially, the focus was to choose the right channel type describing the conditions over a period of one minute (At least choose the right 2 out of the 3 channel parameters: C/G/S). But as we can see in Figure 6.1, this may not always be possible as the channel type can vary significantly within a period of one minute. Hence, it was concluded that better performance in terms of data throughputs can be achieved if the objective was to choose the BLER target optimal for the entire one minute duration instead of the individual channel type definitions. A plot of CQIs in Figure 6.1 shows 5 windows of a VA/20/10 channel. The Table 6.1 shows the optimal BLER for the channel types decided in these 5 windows.

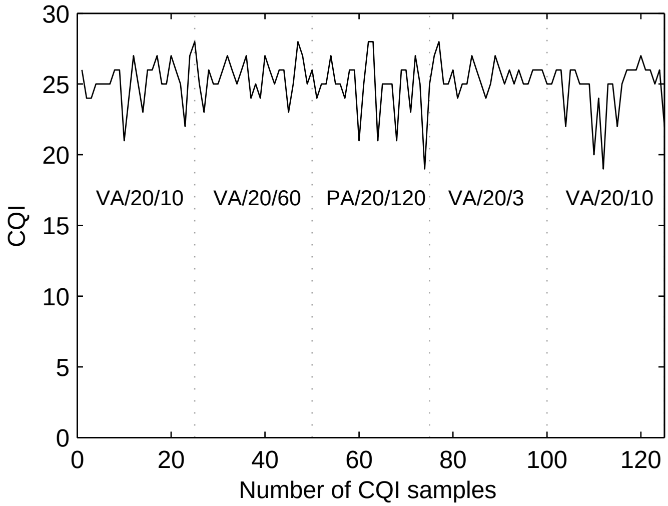

Figure 6.1: CQI trend in *VA/20/10* Channel Type in five windows

Table 6.1: Optimal BLERs for the Channel Types shown in the five windows in Figure 6.1

Channel Type	Optimal BLER
VA/20/10	Z
VA/20/60	Y
PA/20/120	Z
VA/20/3	Y
VA/20/10	Z

The channel type categorization (Table 5.1 and 5.2) was done with the objective to choose the optimal BLER target. This channel type was then mapped to the optimal BLER target obtained by the previous work done at Ericsson. The reason for having two steps, viz. determining a channel type and mapping the channel type to a BLER target was that, the knowledge of channel type decision can prove to be valuable for future studies. A number of tests were done with different threshold settings for the channel type categories and the ones which give the best results in terms of selecting the optimal BLER target were chosen. The results from MATLAB simulations for BLER target selection for different channel types is as shown in Figures 6.2, 6.3 and 6.4.

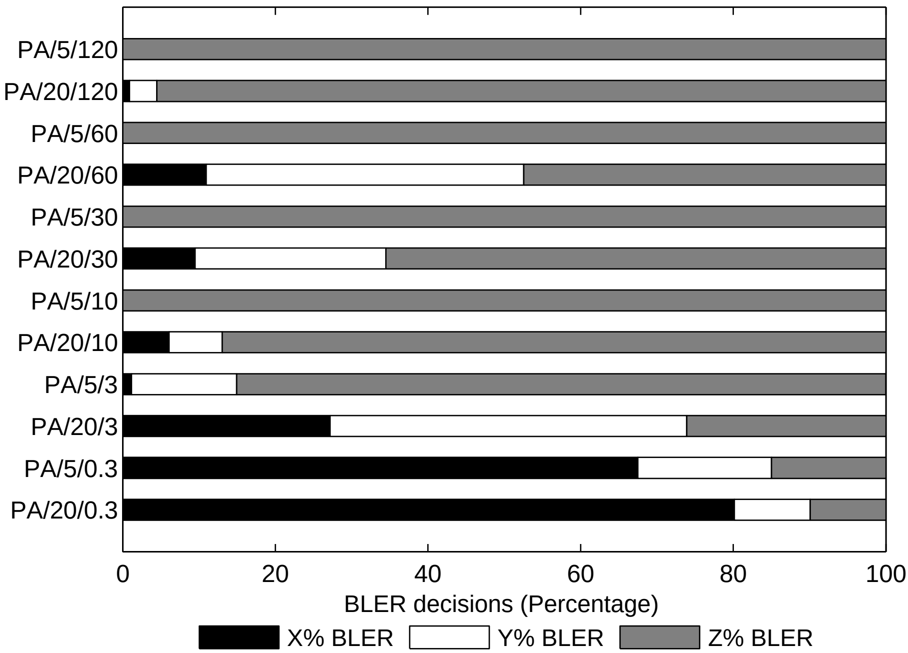

Figure 6.2: BLER Target decisions: PA Channels

In the Figure 6.2, if the Channel Type PA/20/10 is considered, the algorithm developed in this thesis chooses a BLER target of Z% for little greater than 80% of the measurement period. A BLER target of X% is chosen for under 10% of the measurement period.

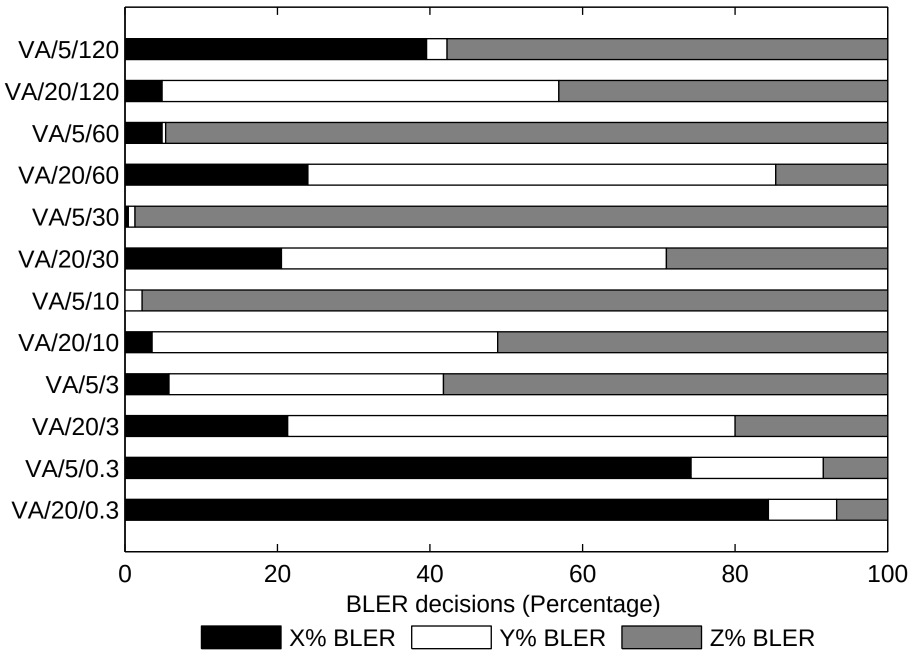

Figure 6.3: BLER Target decisions: VA Channels

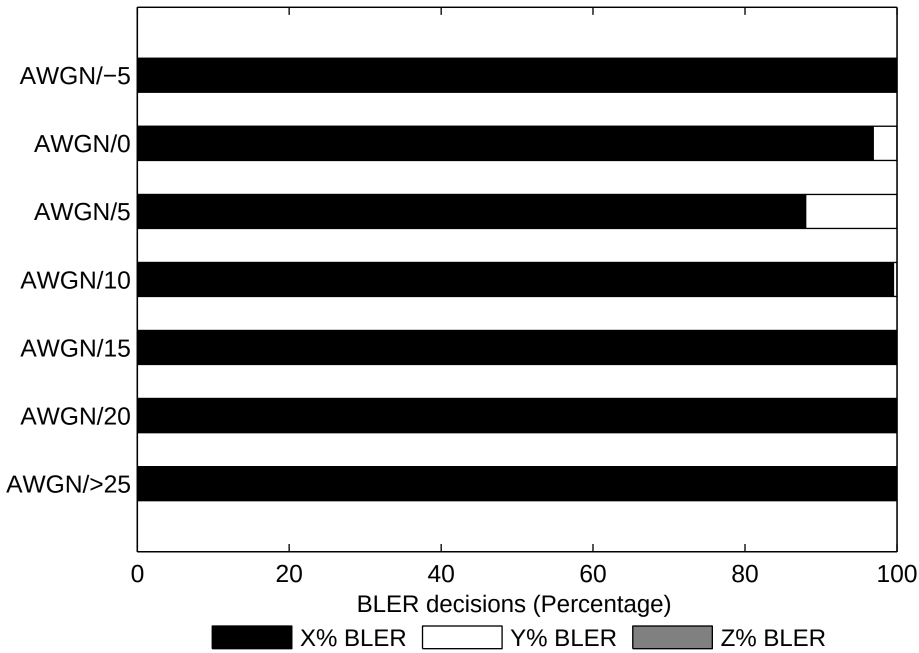

Figure 6.4: BLER Target decisions: AWGN Channels

6.1.2 Thresholds fine tuning :Geometry factor known

Assuming that the Geometry factor of the channel was known at the nodeB, the MATLAB simulations were carried out again. The channel type categories contained channel types with just two parameters, i.e Channel Model and Speed. At the end of the algorithm, before obtaining the optimal BLER target, the known geometry factor was appended to get the complete channel type description.

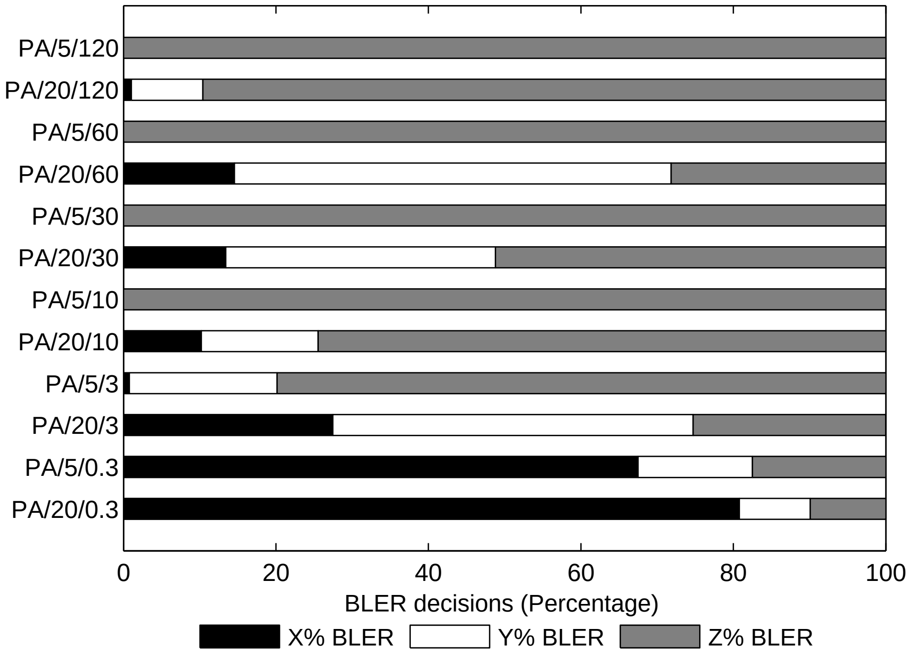

Figure 6.5: BLER Target decisions: PA Channels, Geometry Factor known at the nodeB

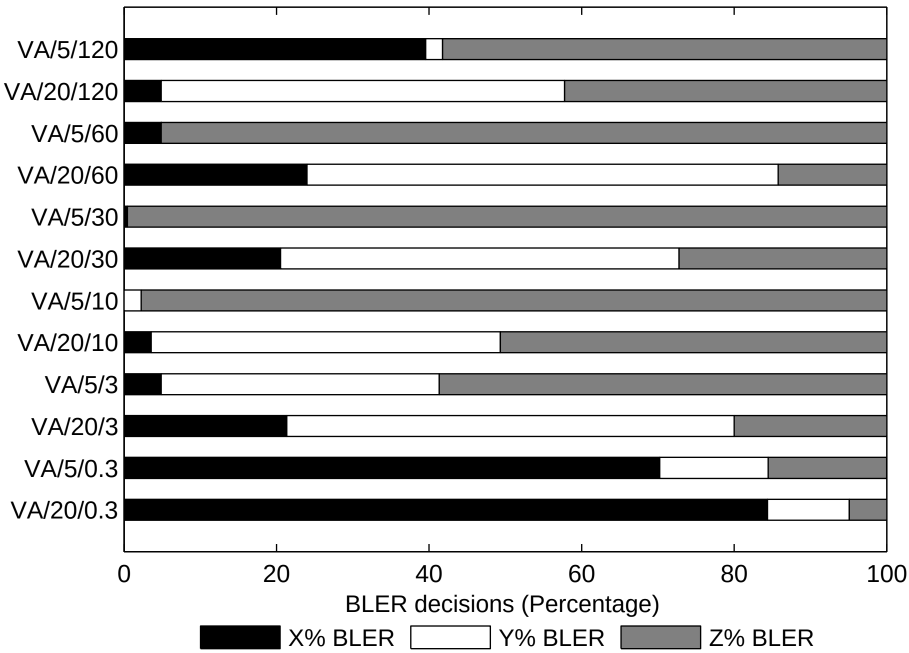

Figure 6.6: BLER Target decisions: VA Channels, Geometry Factor known at the nodeB

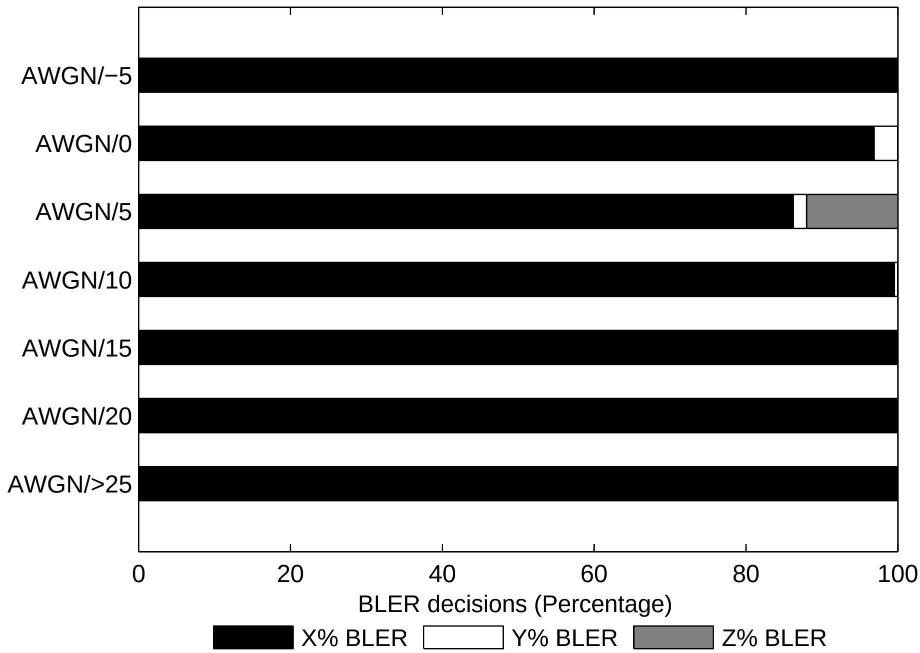

Figure 6.7: BLER Target decisions: AWGN Channels, Geometry Factor known at the nodeB

As shown in Figures 6.5, 6.6 and 6.7, it was found that the knowledge of the Geometry factor gives only a marginal or no improvement in comparison with the approach discussed in Section 6.1.1 in terms of choosing the optimal BLER target.

6.1.3 Thresholds fine tuning: Speed known

Another approach was to study the effect of the UE speed knowledge at the nodeB. With the assumption that the UE speed was known at the nodeB, the algorithm was tuned to have channel type categories as earlier, with the difference that the channel type categories contained channel types with just two parameters, i.e Channel Model and Geometry Factor. At the end of the algorithm, before obtaining the optimal BLER target, the known UE Speed was appended to get the complete channel type description. It was found that, an improvement in choosing the right BLER target was found in the PA and VA channels. In the case of AWGN channels, since the UE speed is zero for all the channel types considered, we can say that the optimal BLER target was chosen 100% of the time.

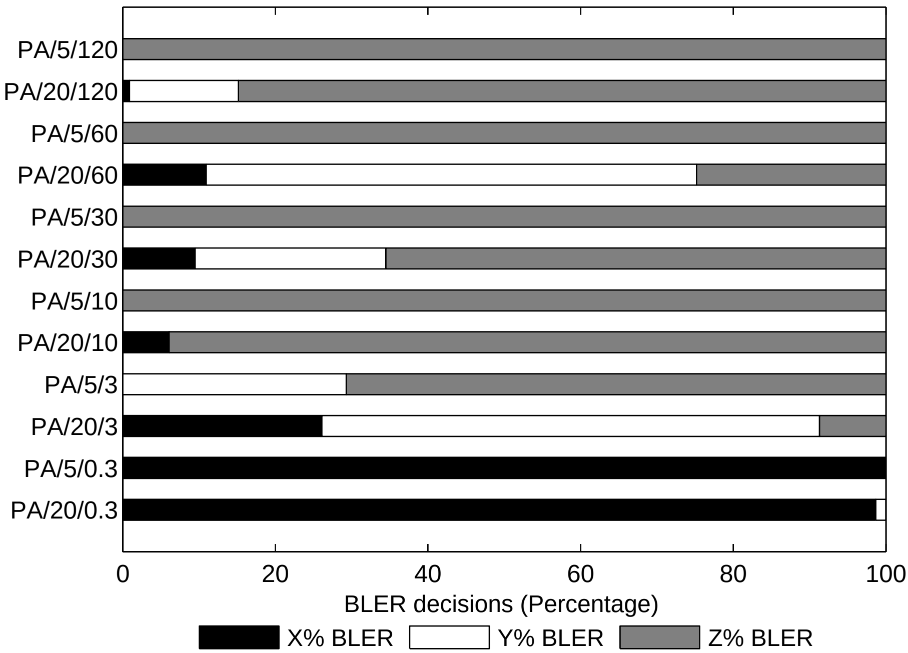

Figure 6.8: BLER Target decisions: PA Channels, UE Speed known at the nodeB

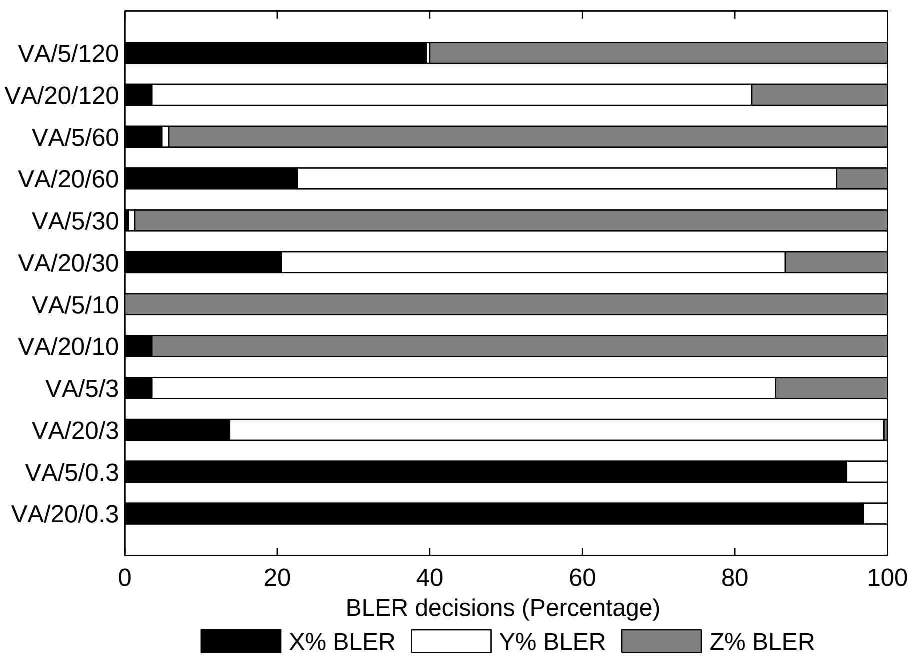

Figure 6.9: BLER Target decisions: VA Channels, UE Speed known at the nodeB

6.1.4 Variable Window Size

Variable window size was another factor that was considered. The effect of having contiguous windows of variable sizes for the channel characterization could be beneficial in certain cases such as VA/20/120 where the channel variations are high. For example, window sizes of ten CQIs can be evaluated in addition to the window size of twenty-five CQI values to study the channel variations in short durations. Also, longer window sizes such as fifty and hundred CQI values can be evaluated to study the channel behaviour over longer durations of time. This would come at the cost of additional complexity, memory requirements and also a more detailed study of the channel behaviour. Hence this approach was reserved for future studies and investigation.

6.1.5 CQI Filtering

In the process of link adaptation, there is a difference between BLER (measured error rate) and the BLER target. In an ideal case the measured error rate should be equal to the BLER target. If it is not equal to the BLER target an attempt is made to reach the BLER target. This is achieved by adding a correction factor to the CQI value which is used in selecting a transport block size (CQI adjustment).

CQI filtering tries to address the problem of uncertainty due to constant and large variations in signal quality of various channel types. An attempt was made to reduce the uncertainty by using filtered CQI values in CQI adjustment and the calculation of MCS. However, it has to be noted that it is the unfiltered CQI values which were used in the statistical calculations such as the Mean,Variance etc. The reported CQI value is filtered with an appropriate filtering coefficient. A study to find a suitable filtering coefficient was made. As previously mentioned, when a channel type has a large uncertainty, a higher BLER target value is chosen. By choosing a larger BLER target, there is a gain in throughput due to the use of larger transport blocks and a loss due to the probability of error being higher. This loss due to higher errors is primarily because of the overestimation of transmission capacity. CQI filtering strives to reduce these errors by filtering the CQI values such that these variations between consecutive values and hence the uncertainty due to these variations are reduced. By having the filtered CQI at a relatively more constant level there might be some loss where the transmission capacity is underestimated but the errors due to overestimation of transmission capacity and hence re-transmission of erroneous blocks are reduced. This could lead to an increase in throughput. The filtering process involved filtering with the appropriate filtering coefficients keeping the same values of BLER targets.

6.2 Black Module Testing

In order to test the data throughputs obtained by the implementation of the algorithm devised, the C language version of it was plugged into the Ericsson Black Module. The Black Module was based on the Ericsson product implementation and consists of the user scheduling block in addition to the CQI measurement and adjustment components and the BLER setting block. Additional functionality was added to it to switch between the algorithm developed in this thesis and the Ericsson product implementation during the lab tests. A test matrix was prepared considering the channel types for which maximum throughputs was expected, as testing for all the thirty-one channels was not possible. The details of the test cases are given in Table 6.2 and 6.3. The measurements were done for a period of 4 minutes for each channel type. It has to be noted that the results obtained from the MATLAB simulations and the RAN lab simulations will not be exactly the same as there is certain amount of randomness involved in the simulation of the the various channel characteristics.

Test Case	Description
TC1.1	Conventional Implementation
TC1.2	Thesis Algo : Channel characterization and 3 BLER target groups
TC1.3	Thesis Algo : Channel characterization and 4 BLER target groups
TC2.1	Filtering (alpha=0.7) with channel characterization and BLER target setting
TC2.2	Filtering (alpha=0.6) with channel characterization and BLER target setting
TC2.3	Filtering (alpha=0.8) with channel characterization and BLER target setting
TC2.4	Filtering (alpha=0.2) with channel characterization and BLER target setting
TC3.1	Filtering (alpha=0.7) with Conventional implementation
TC3.2	Filtering (alpha=0.6) with Conventional implementation
TC3.3	Filtering (alpha=0.8) with Conventional implementation
TC3.4	Filtering (alpha=0.2) with Conventional implementation

Table 6.2: Test Case Description

Channel Model	TC1.1	TC1.2	TC1.3	TC2.1	TC2.2	TC2.3	TC2.4
VA/5/60	X	X	X	X	X	X	X
AWGN/15	X	X	X				
VA/5/30	X	X	X	X	X	X	X
PA/5/3	X	X	X				
PA/5/30	X	X	X	X	X	X	X

Table 6.3: Test Matrix

Chapter 7

Results

The next step after MATLAB simulations (MB) was to validate the algorithm using the Black Module (BM) in the Ericsson RAN lab. Tests were carried out according to the test matrix in Table 6.3. The results for each channel type are described in Sections 7.1 to 7.6. For analysis purposes the first part of the results focus on the BLER target decisions and then the second part focuses on the throughput improvement over the conventional implementation. For a comparison, the BLER target decisions made in the black module are plotted along with the BLER decisions made during the MATLAB simulations. The values of W, X, Y and Z are in terms of percentage.Test cases have been shown once again in Table 7.1 for easy referencing.

Test Case	Description
TC1.1	Conventional Implementation
TC1.2	Thesis Algo : Channel characterization and 3 BLER target groups
TC1.3	Thesis Algo : Channel characterization and 4 BLER target groups
TC2.1	Filtering (alpha=0.7) with channel characterization and BLER target setting
TC2.2	Filtering (alpha=0.6) with channel characterization and BLER target setting
TC2.3	Filtering (alpha=0.8) with channel characterization and BLER target setting
TC2.4	Filtering (alpha=0.2) with channel characterization and BLER target setting
TC3.1	Filtering (alpha=0.7) with Conventional implementation
TC3.2	Filtering (alpha=0.6) with Conventional implementation
TC3.3	Filtering (alpha=0.8) with Conventional implementation
TC3.4	Filtering (alpha=0.2) with Conventional implementation

Table 7.1: Test Case Description

7.1 VA/5/60

7.1.1 BLER target decisions

The optimal BLER target for the VA/5/60 channel type was Y for both the settings i.e. with 3 BLER targets and 4 BLER targets. Figure 7.1 shows the ability of the algorithm to resolve into the right BLER targets.

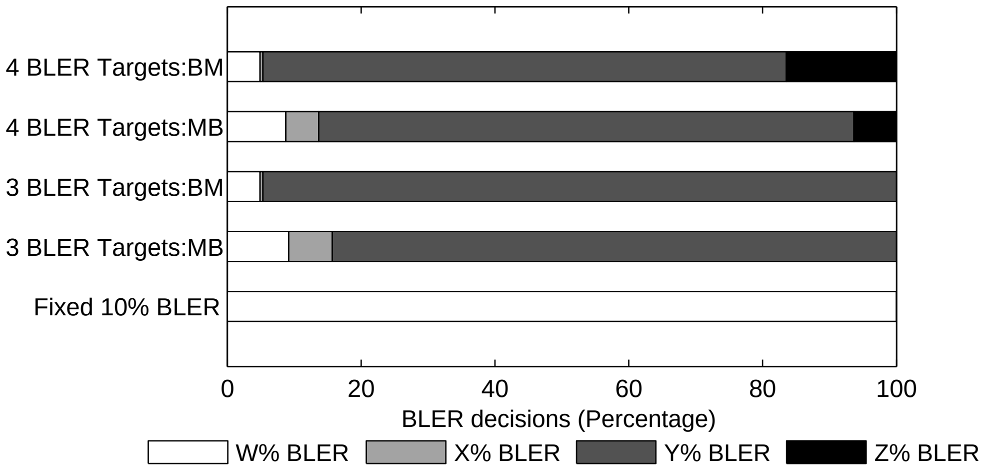

Figure 7.1: BLER Target decisions,VA/5/60

For the 3 BLER targets setting, the MATLAB simulations determined that the algorithm decides the optimal BLER target, Y, 94% of the time. In the black module testing it resolves into the optimal BLER target 84% of the time.

For the 4 BLER targets setting, the algorithm resolves to the optimal BLER target 78% of the time in MATLAB simulations and almost 80% of the time in the case of the black module tests.

7.1.2 Data Throughput

The normalized throughput for the VA/5/60 channel is as shown in the Cumulative Distribution Function (CDF) plot in Figure 7.2. The average throughput for each of three cases i.e. the conventional implementation, the channel type decision algorithm with 3 BLER targets and the channel type decision algorithm with 4 BLER targets was calculated. A throughput increase of 36% was observed over the conventional implementation when the channel type decision algorithm was used with 3 BLER targets or 4 BLER targets.

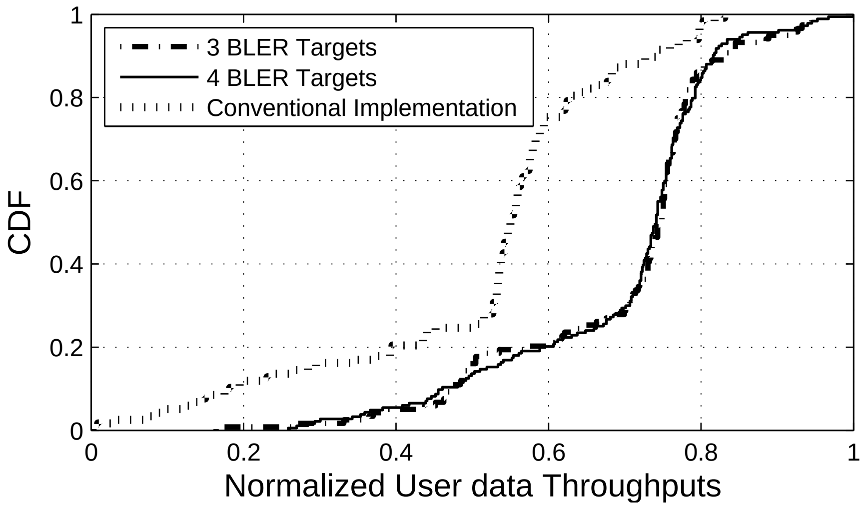

Figure 7.2: Data Throughputs: VA/5/60

7.2 AWGN/15

7.2.1 BLER target decisions

The optimal BLER target for the AWGN/15 channel type was W for both the settings i.e. with 3 BLER targets and 4 BLER targets. Figure 7.3 shows the ability of the algorithm to resolve into the right BLER targets.

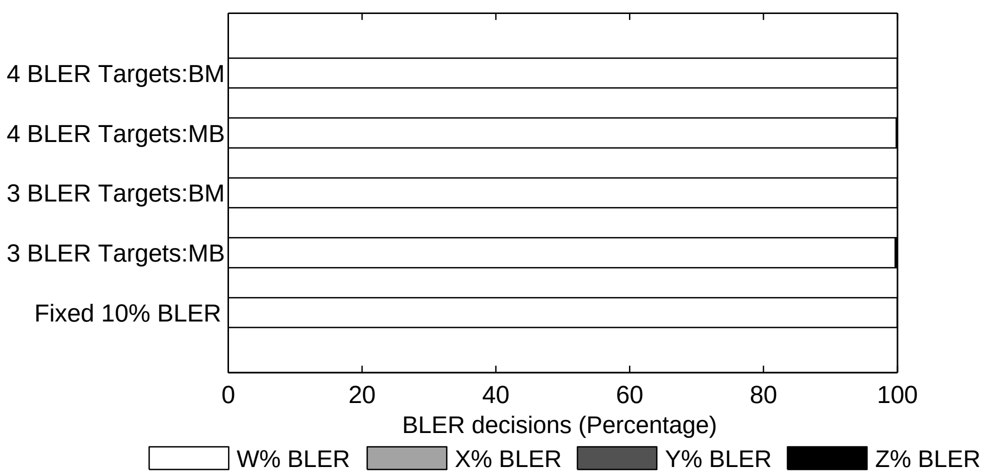

Figure 7.3: BLER Target decisions,AWGN/15

For the 3 BLER target setting, the MATLAB simulations determined that the channel type decision algorithm decides the optimal BLER target, W, 100% of the time. In the black module testing, the number of times the channel type decision algorithm resolves into the optimal BLER target 99% of the time.

For the 4 BLER target setting, the algorithm resolves to the optimal BLER target 100% of the time in MATLAB simulations and almost 99% of the time in the case of the black module tests.

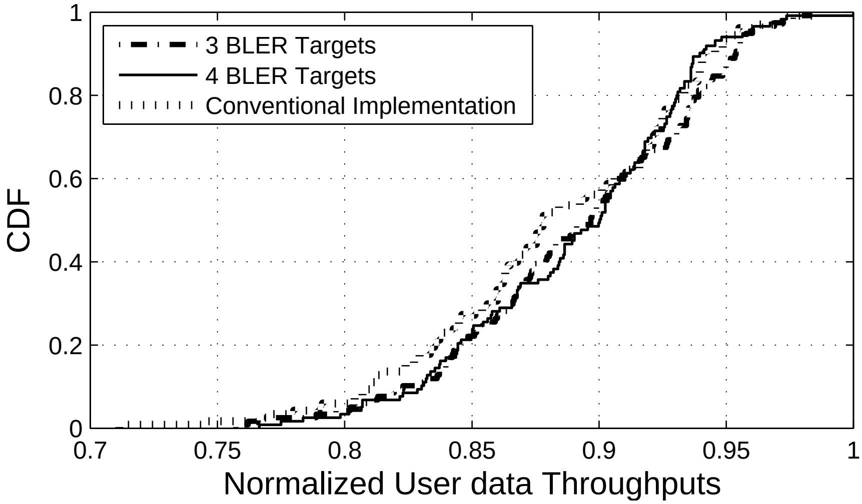

Figure 7.4: Data Throughputs: AWGN/15

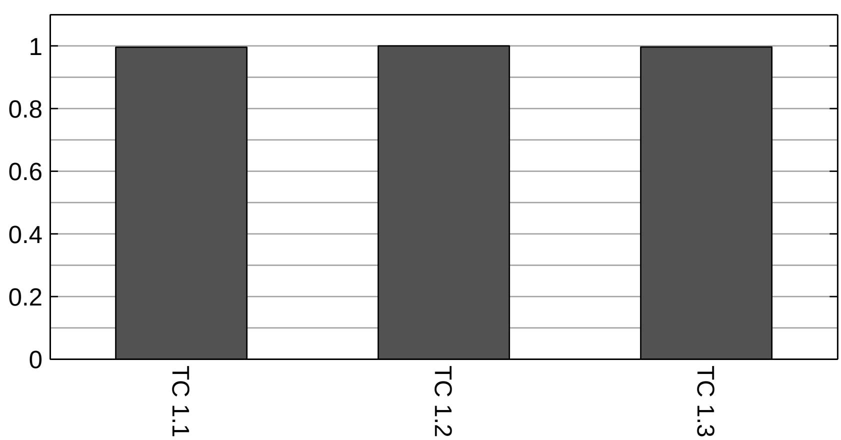

Figure 7.5: Average Data Throughputs: AWGN/15

7.2.2 Throughput

The normalized throughput for the AWGN/15 channel is shown as the cumulative distribution function (CDF) in Figure 7.4. The average throughput for each of three cases i.e. the conventional implementation, the channel type decision algorithm with 3 BLER targets and the channel type decision algorithm with 4 BLER targets was calculated. There was no discernible difference in throughput for the AWGN/15 channel type using the channel type decision algorithm when compared to the conventional implementation.

7.3 VA/5/30

7.3.1 BLER target decisions

The optimal BLER target for the VA/5/30 channel type was Y for both the settings i.e. with 3 BLER targets and 4 BLER targets. Figure 7.6 shows the ability of the algorithm to resolve into the right BLER targets.

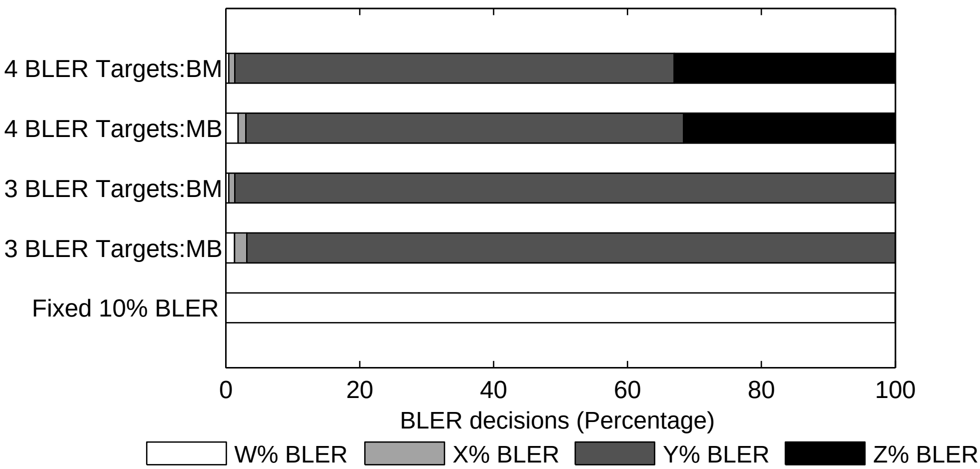

Figure 7.6: BLER Target decisions,VA/5/30

For the 3 BLER target setting, the MATLAB simulations determined that the algorithm decides the optimal BLER target, Y, 98% of the time. In the black module testing it resolves into the optimal BLER target 97% of the time. For the 4 BLER target setting, the algorithm resolves to the optimal BLER target 66% of the time in MATLAB simulations and almost 65% of the time in the case of the black module tests.

7.3.2 Throughput

The normalized throughput for the VA/5/30 channel is as shown as CDF in Figure 4.14. The average throughput for each of three cases i.e. the conventional implementation, the channel type decision algorithm with 3 BLER targets and the channel type decision algorithm with 4 BLER targets was calculated. A throughput increase of 41% was observed over the conventional implementation when the channel type decision algorithm is used with 3 BLER targets and in the case of 4 BLER targets, the increase in the throughput was over 44%. The marginal increase in throughput for the 4 BLER targets case was due to the addition of a higher BLER target. Though Z might not be the optimal BLER target overall for this channel type, it was ideal over some of the windows when the variations are huge. In the case of those windows it is observed that using a bigger transport block size gives more gain even though the number of re-transmissions may become higher. So link adaptation was faster and results in a marginal increase in throughput.

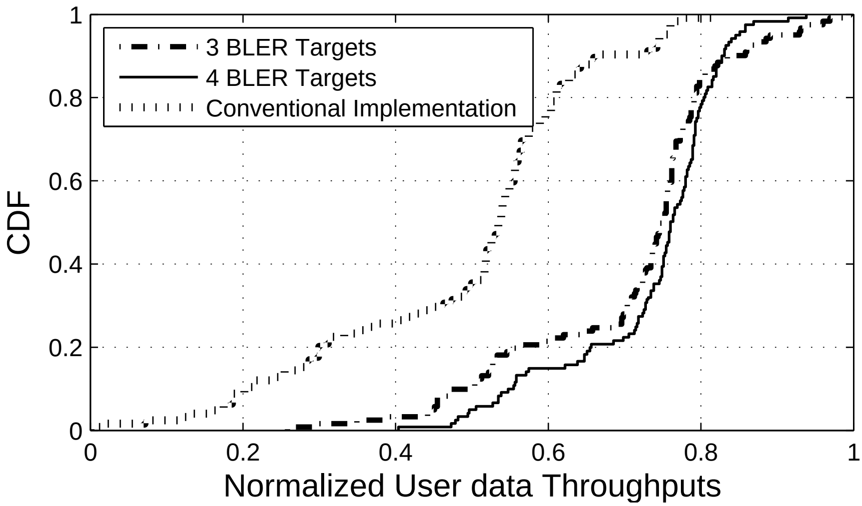

Figure 7.7: Data Throughputs: VA/5/30

7.4 PA/5/3

7.4.1 BLER target decisions

The optimal BLER target for the PA/5/3 channel type was Y for both the settings i.e. with 3 BLER targets and 4 BLER targets. Figure 7.8 shows the ability of the algorithm to resolve into the right BLER targets.

For the 3 BLER target setting, the MATLAB simulations determined that the algorithm decides the optimal BLER target, Y, 85% of the time. In the black module testing it resolves into the optimal BLER target 75% of the time. For the 4 BLER target setting, the algorithm resolves to the optimal BLER target 59% of the time in MATLAB simulations and almost 52% of the time in the case of the black module tests.

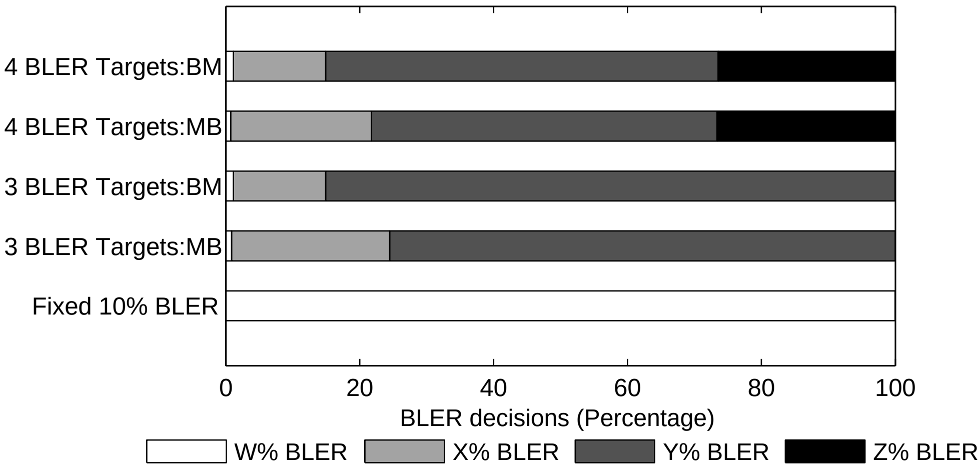

Figure 7.8: BLER Target decisions,PA/5/3

7.4.2 Throughput

The normalized throughput for the PA/5/3 channel was as shown as CDF in Figure 7.9. The average throughput for each of three cases i.e. the conventional implementation, the channel type decision algorithm with 3 BLER targets and the channel type decision algorithm with 4 BLER targets was calculated. A throughput increase of 13% was observed over the conventional implementation when the channel type decision algorithm was used with 3 BLER targets and in the case of 4 BLER targets, the increase in the throughput was over 15%. Again, the marginal increase in throughput for the 4 BLER target case was because of the presence of a higher BLER target, Z, which may not be the optimal BLER target overall for this channel type but was ideal for some windows. This leads to better link adaptation and a slight increase in throughput when compared to the 3 BLER target case.

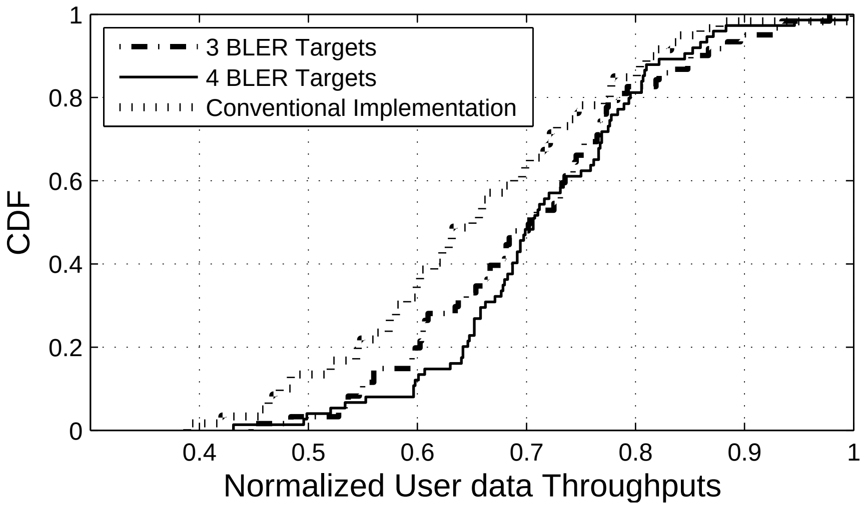

Figure 7.9: Data Throughputs: PA/5/3

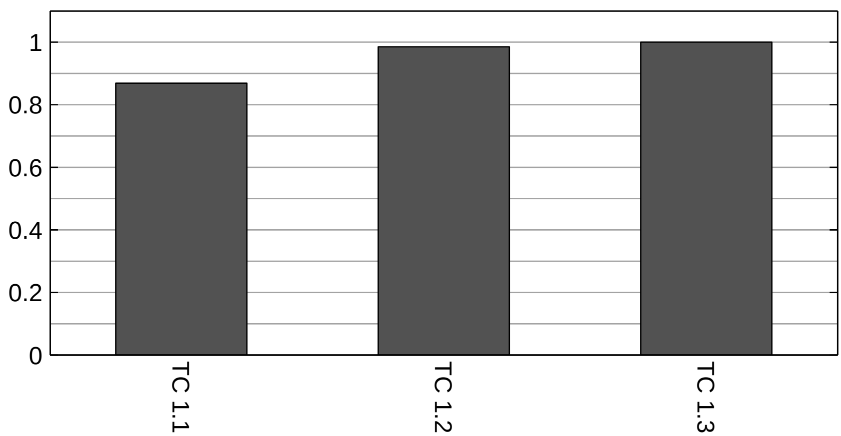

Figure 7.10: Average Data Throughputs: PA/5/3

7.5 PA/5/30

7.5.1 BLER target decisions

The optimal BLER target for the PA/5/30 channel type was Y for 3 BLER targets and Z when 4 BLER targets are considered. Figure 7.11 shows the ability of the algorithm to resolve into the right BLER targets.

For the 3 BLER target setting, the MATLAB simulations determined that the algorithm decides the optimal BLER target, Y, 100% of the time. In the black

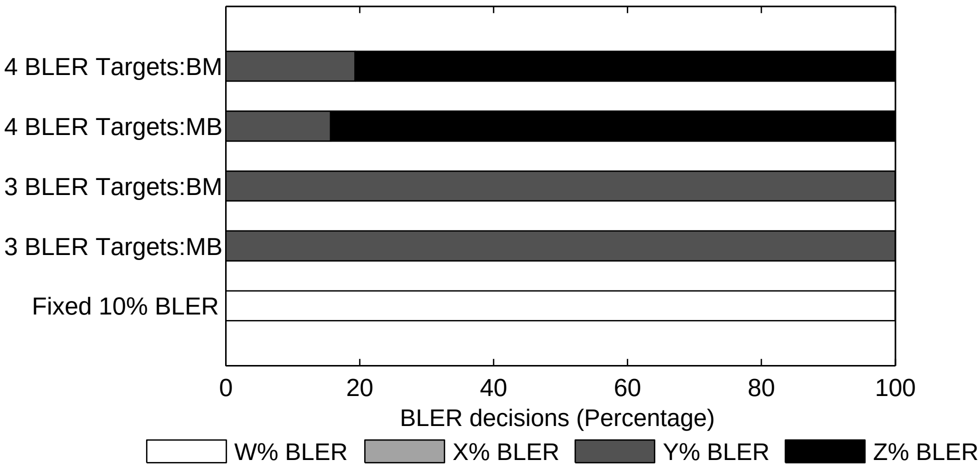

Figure 7.11: BLER Target decisions,PA/5/30

module testing it resolves into the optimal BLER target 100% of the time. For the 4 BLER target setting, the algorithm resolves to the optimal BLER target, Z, 80% of the time in MATLAB simulations and almost 84% of the time in the case of the black module tests.

7.5.2 Throughput

The normalized throughput for the PA/5/30 channel is as CDF in Figure 7.12. The average throughput for each of three cases i.e. the conventional implementation, the channel type decision algorithm with 3 BLER targets and the channel type decision algorithm with 4 BLER targets was calculated. A throughput increase of 35% was observed over the conventional implementation when the channel type decision algorithm is used with 3 BLER targets and in the case of 4 BLER targets, the increase in the throughput was over 49%.

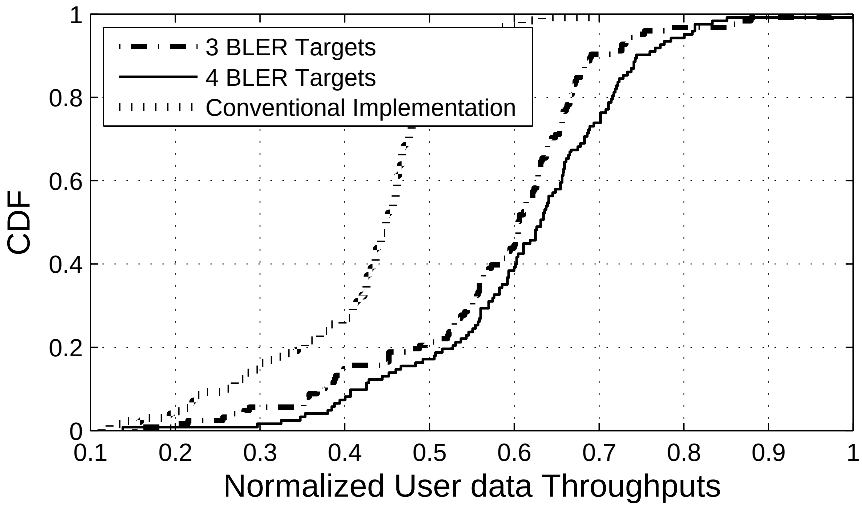

Figure 7.12: Data Throughputs: PA/5/30

7.6 Results of CQI filtering

CQI filtering was tested for the channel types PA/5/30 and VA/5/60. The filtering coefficients used were 0.8,0.7,0.6 and 0.2. Although no significant gain was obtained when filtering was applied in conjunction with this thesis algorithm, a gain was observed when filtering was used with the Ericsson conventional implementation. The average throughputs obtained are as shown in Figures 7.13 to 7.15.

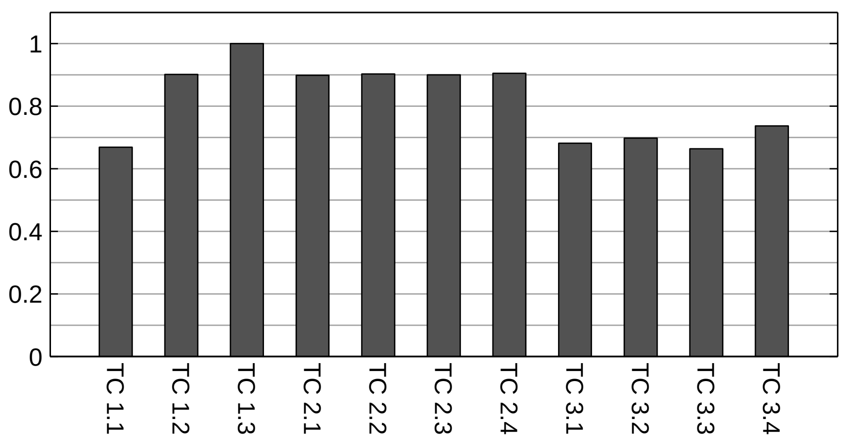

Figure 7.13: Average Data Throughputs: PA/5/30

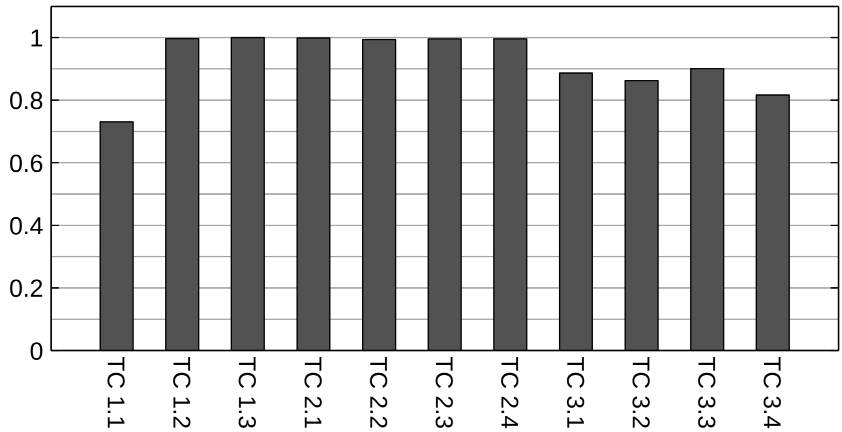

Figure 7.14: Average Data Throughputs: VA/5/60

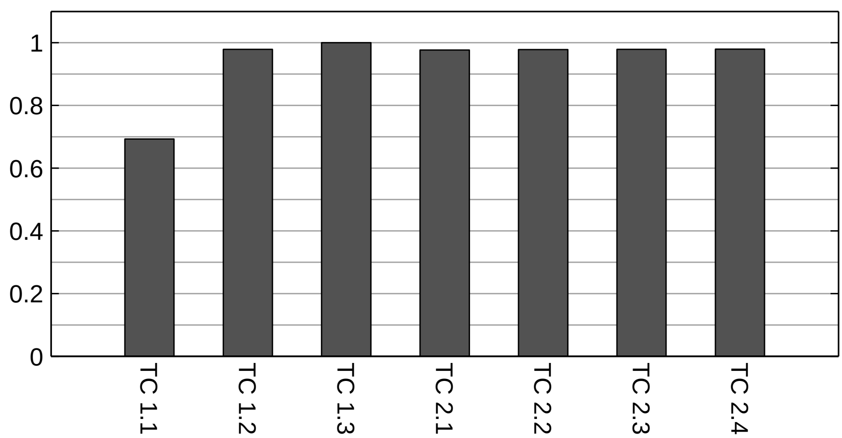

Figure 7.15: Average Data Throughputs: VA/5/30

Chapter 8

Conclusions and Future Work

In this final chapter, the conclusions obtained from the algorithm developed in this thesis work are summarized. The scope for future work is also discussed.

8.1 Conclusions

The algorithm developed in this thesis using statistical analysis of CQI has proved to be fruitful in providing gain in data throughputs compared to the conventional implementation of constant 10% BLER target. This however comes at the expense of processing delays and additional memory requirements. There is room for improvement in terms of processing delays by optimizing the algorithm and the implementable code. Though the uncertainty problem described in Section 1.6 cannot be completely negated, the effect of this uncertainty is reduced.

The important conclusions from this thesis were:

- Maximum gains in throughput were seen in channel types with a high optimal BLER target (Y% or Z%). This means that the uncertainty was high as the channel type was constantly varying. A conclusion was therefore made that the algorithm works well in scenarios where uncertainty was high which was one of the goals of this thesis.
- Another objective of this thesis was to investigate whether there was an increase in throughput with the 4 BLER targets over the 3 BLER targets setting. Apart from one of the test cases, the increase in UE throughput was marginal for the 4 BLER targets setting.
- The impact of the knowledge of Doppler Spread can be further investigated. Simple means of UE Speed estimation such as Level Crossing Rate and Average Fade duration have already been incorporated in the algorithm developed in this thesis. Hence, a significant gain with respect to choosing the right BLER targets cannot be expected with any more additional information about Speed. It has to be noted that the algorithm developed in this works on the combination of the parameters Channel Model (C), Geometry Factor (G) and the UE Speed (S) clubbed together. If additional knowledge of UE speed (obtained from outside the algorithm developed in this thesis) is to be used, then a different approach needs to be taken where the C and G parameters are estimated independently as well.

- CQI Filtering resulted in negligible UE throughput gains. In some cases there was a loss in throughput. As mentioned earlier in section (CQI filtering) this test was only one part of the process. The other part of the process which is discussed in Section 8.2 involves investigation of new values of BLER targets that are more suitable for use after the CQI is filtered. A conclusion can be made that with the existing value of BLER targets, filtering provides only minute gains in UE throughput.

- A window size of 25 CQI values is too small to accurately determine the Channel Type. Hence, importance can be given to selecting the optimal BLER target for the given channel conditions. An observation was made that most channel types with similar statistical properties of CQI have the same optimal BLER target. Hence, it is possible to decide the wrong channel type but still decide on the right BLER target. This will not result in any loss in UE throughput.

8.2 Future Work

In this section we discuss the ideas and aspects which were explored through the course of this thesis work but not implemented in the devised algorithm. Further research and analysis on these aspects can be valuable and may lead to a better and a more robust channel type decision algorithm.

8.2.1 Channel Type Decision for Long Term Users

One of the aspects discussed during the statistical analysis of the CQI was the window size. A window size of twenty-five CQIs or 200 ms was used in this thesis work. However, as mentioned previously the characterization of certain channel types may not be accurate in a window of twenty-five CQIs as the coherence time of the channel type could be longer than twenty-five CQI reports. Having a long window size of several hundreds of CQIs or about a thousand CQIs helps to make accurate channel type decision and thereby to set the optimal BLER target for the given channel type. This can be applied to users who might be streaming a movie or downloading a large data file. Having one window size of thousand CQIs corresponds to about 8 s. This would require the user to be using the data network continuously for more than 8 s. One of the ideas which can be explored is to have two window sizes. Initially a small window size can be used and if the user is downloading a file for longer than say 8s, then a larger window size of thousand CQIs can be used. To monitor whether the channel type changes during the next 8s, the smaller window size can be used and the distribution of BLER target decisions for the smaller window size can be monitored to guide any changes in the channel during the long 8s period. This will however require larger memory requirements to keep track of thousands of CQIs for each user served by the NodeB.

8.2.2 Exploit the history

Another aspect that can be explored is to exploit the channel type decision history or the BLER target history for users previously served by the NodeB. This could help in making link adaptation faster as there is available knowledge of the most probable occurring channel type or the most probable occurring BLER target from the user history stored by the NodeB. In a normal case, at the beginning of the link adaptation process it is assumed that the optimal BLER target is 10% and then adjustments are made to the transport block size accordingly based on the decided channel type and the optimal BLER target for that channel type. With the user history however, the process can be speeded up by assuming the channel type which is most probable to occur based on the user history stored at the NodeB.

8.2.3 Knowledge of Delay Spread

In Section 3.1, a description is given about how a Pedestrian-A, Vehicular-A and an Additive White Gaussian Noise channel models are distinguished. The key factor is the relative delay and the power in each of these delays. Information from the *Rake finger* could be used to determine the relative delays. Along with the statistics of the CQIs used to determine a channel type, the delay information can also be used to determine the channel model and hence increase the accuracy in decision of the channel type. This would lead to accurate BLER target decisions and an increased throughput. Since the uplink frequencies and downlink frequencies are different, a careful analysis should me made while using the delay spread information.

8.2.4 Geometry from Round Trip Time

The geometry factor is a function of both the distance of the UE from the NodeB and the interference. The possibility of measuring the Round Trip Time (RTT) at the NodeB must first be investigated. The round trip time is the time taken for a packet to go from the NodeB to the UE and back. With knowledge of the round trip time and assuming velocity of electromagnetic waves in air, the distance between the UE and the NodeB can be calculated. This would give an accurate indication of the geometry factor. The knowledge of geometry factor can make channel type decision more accurate and hence it helps in making accurate BLER target decisions and in turn leads to a better throughput. The processing time and the load at NodeB also needs to be considered for the accurate estimation of the RTT.

8.2.5 Revised BLER settings with CQI filtering

Another aspect which can be explored is revised BLER target setting when CQI filtering is on. With CQI filtering, the BLER targets which had been set for various channel types can probably be reduced to a certain extent. The optimal reduced BLER targets can be obtained my means of test and trials in the lab environment.

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