Impact Of Transmission Patterns On One-Way Delay In 3G Networks Of Sweden

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Abstract

Over the last few years, there has been a significant rise in the mobile broadband users worldwide. Recently, operators around the world have been improving the 3G networks by providing Dual Carrier-High Speed Packet Access+ (DC-HSPA+) services in both uplink and downlink to the users. However, the delay performance of the operational DC-HSPA+ networks is not focused. Firstly, we investigate and analyze the effect of operator service on One-Way Delay (OWD) and Jitter. Secondly, we investigate the treatment of protocols by 3G network for random packet sizes and random Inter Packet Duration (IPD). Thirdly, we investigate the effect of background load on OWD for packets generated at very low rate. Fourthly, we investigate the impact of constant IPD and streaming. Fifthly, we investigate the effects of shrinking the interval of IPD on OWD in 3G networks. Lastly, we investigate the OWD for Constant-Bit-Rate (CBR) and Variable-Bit-Rate (VBR) transmission patterns.

Firstly, results show that OWD in the DC-HSPA+ networks is lower compared to the OWD in the preceding HSUPA networks and OWD strongly depends on packet-size at lower rates. Secondly, the 3G networks treat User Datagram Protocol (UDP), Transmission Control Protocol (TCP) and Internet Control Message Protocol (ICMP) protocols similarly for random packet size and random IPD. Thirdly, at high rates OWD depends on E-TFCE-DCH Transport Format Combination (ETFC) grants. Thirdly, the results also indicate that background load has a significant impact on the end-to-end OWD. Fourthly, for low rates, OWD depends on packet sizes and for high rates OWD depends on IPD and for higher rates, OWD depends on E-TFC grants. Fifthly, we also observe: Shrinking the interval of IPD does not necessarily improve the OWD performance. Lastly, results also indicate that the VBR pattern has a better OWD performance than the CBR pattern for low transmission rates.

Keywords: Downlink, DC-HSPA+, E-TFCI, HSPA, ICMP, Mobile broadband, One-way Delay, TCP, UDP, Uplink, 3G
Preface

This Master thesis summaries our work and effort within Network Performance Framework Laboratory. The work has been conducted under Department of Telecommunications in Electrical Engineering, School of Computing, at Blekinge Institute of Technology in Sweden.

The Thesis includes four chapters which are briefed as follows:

Chapter-1
Chapter 1 answers:

1. Why is our particular work significant and chosen as our Master Thesis?

2. What did the other researchers in the same field do till now?

3. What particular gap is left unfilled?

Chapter-2
Chapter 2 answers: What have we used for experimentation and How have we done it? It describes the experimental methodology used for our work with emphasis on Traffic Generation, Measurement, Analysis and Visualization.

Chapter-3
Chapter 3 discusses the relevant technical background, which is a prerequisite to understand our analysis of results

Chapter-4
Chapter 4 covers our experimental results and analysis

Chapter-5
Chapter 5 concludes our work and provides ideas on future work

Chapter-6
Chapter 6 includes an informative appendix covering every relevant technical work done
Acknowledgements

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Regards,
Praveen and Vamsi, Sweden
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Acronyms

3GPP 3rd Generation Partnership Project.
CDM Code Division Multiplexing.
Cell-DCH Cell-Dedicated Channel.
Cell-FACH Cell-Forward Access Channel.
Cell-PCH Cell-Paging Channel.
CQI Channel Quality Indicator.
CRC Cyclic Redundancy Check.
DC-HSDPA Dual Carrier-High Speed Downlink Packet Access.
DC-HSPA Dual Carrier-High Speed Packet Access.
DC-HSPA+ Dual Carrier-High Speed Packet Access+.
DCH Dedicated Channel.
DPMI Distributed Passive Measurement Infrastructure.
E-TFCI E-DCH Transport Format Combination Indicator.
EDCH Enhanced Dedicated Transport Channel.
ETFC E-DCH Transport Format Combination.
FACH Forward Link Access Channel.
GGSN Gateway GPRS Support Node.
GPRS General Packet Radio Service.
HARQ Hybrid Automatic Repeat Request.
HSDPA  High Speed Downlink Packet Access.
HSPA  High Speed Packet Access.
HSPA+  High Speed Packet Access+.
HSUPA  High Speed Uplink Packet Access.
ICMP  Internet Control Message Protocol.
IMS  IP Multimdia Subsystem.
IP  Internet Protocol.
IPD  Inter Packet Duration.
IR  Incremental Redundancy.
MAC  Medium Access Control.
MAC-d  Medium Access Control-d.
MAC-e  Medium Access Control-e.
MAC-hs  Medium Access Control-hs.
MArC  Measurement Area Controller.
MIMO  Multiple Input Multiple Output.
OWD  One-Way Delay.
PDCP  Packet Data Convergence Protocol.
PDU  Protocol Data Unit.
POC  Push-to-Talk Over Cellular.
QAM  Quadrature Amplitude Modulation.
QoE  Quality of Experience.
RACH  Random Access Channel.
RLC  Radio Link Control.
RNC  Radio Network Controller.
RTT  Round Trip Time.
**SGSN** Serving GPRS Support Node.

**TCP** Transmission Control Protocol.

**TDM** Time Division Multiplexing.

**TTI** Transmission Time Interval.

**UDP** User Datagram Protocol.

**UE** User Entity.

**UMTS** Universal Mobile Telecommunications System.

**WCDMA** Wideband Code Division Multiple Access.
Introduction
Chapter 1

Introduction

In the recent years, there has been unprecedented growth in the usage of mobile broadband. This has been catalyzed by various factors such as flat rate subscriptions[1], increasing popularity of the plug and play USB dongles and rapidly growing smart-phone segment. As of September 2011, there are over 730 million 3G or Wideband Code Division Multiple Access (WCDMA) subscriptions worldwide [2]. As of June 2011, the number of wireless broadband users in the Organization for Economic Cooperation and Development (OECD) nations exceeded 500 million, with Sweden ranked third with 82.9 percent of its population subscribing to wireless broadband, while South Korea and Finland rank first and second respectively [3]. Furthermore, in Sweden the number of Mobile Broadband Users (MBU) are expected to grow from 2.9 million (2010) to 3.9 million in 2012[4]. In India alone, there were 3.5 million High Speed Packet Access (HSPA) connections by second quarter of 2011 which is not exciting considering its huge population, however projected number of MBU by 2015 is staggering 225.5 million[5]. With increasing number of MBU, there is an increasing trend among the mobile operators to move from flat rate subscriptions to the data based subscriptions to offer higher flexibility to users and for higher profits[6].

As the MBU across the world are increasing and as they are willing to pay for higher Mobile broadband speeds, operators across the world are consistently upgrading the infrastructure used for providing mobile service to the users. As of July 2011, there were 39 commercial operators providing DC-HSPA+ service [2]. The evolving network architectures are flat and IP based with fewer number of network elements. However, the service provided to the end user not only differs from operator to operator, but across the cells of same operator depending on the network configuration and available infrastructure [7] or even possibly on subscription to the user. This could possibly result in co-existence of evolving mobile Radio Access Network (RAN) and their predecessors which in turn effect the user perceived Quality of Experience (QoE) of the service offered by the mobile operators.
In the recent years, there has also been a smartphone revolution which resulted in higher processing powered units with increased storage space and easy to use touch and speech recognition based Graphical User Interface (GUI). The smartphones and tablet PCs, supported by faster mobile networks and users who are willing to pay, further accelerate the development of mobile applications. The majority of mobile traffic generated by these applications consists primarily of UDP, TCP and ICMP datagrams[8]. With this rapid growth there are many applications being developed, from time critical applications like mobile banking to those applications demanding a high QoE like video streaming. These applications generate traffic at different rates, at different intervals, as a single source of traffic or in parallel with other applications under influence of background load. It is very important for application developers to have knowledge on the treatment of how their choice of packet sizes, kind of traffic transmitted and IPD in traffic from their applications is treated by the Mobile Operator’s networks. In this thesis, we conduct end to end measurements on live networks for different operator service, protocols, and different transmission patterns.

1.1 Related Works

In the recent years, there are considerable number of publications on live network measurements. We have used Snowball Literature Search for gathering all relevant articles of research.

In [9], the authors consider ICMP datagrams and use random packet-size and random IPD to prove that the networks are non-deterministic. They use tcpdump[10] to capture packets and conduct RTT and OWD measurements over live HSPA networks in Austria. In this work, authors do not consider the other datagrams like UDP and TCP, and they do not individually investigate the influence of random IP payload size or random IPD. In [11], the authors stress the importance of having random IPD and random packet sizes and conduct Round Trip Time (RTT) and OWD measurements using tcpdump over 3G and 2G networks in Austria, they point out the issues concerning RTT measurement using ICMP ping with constant IPD. [12] reports OWD due to individual components such as User Entity (UE), NodeB, Radio Network Controller (RNC) in High Speed Uplink Packet Access (HSUPA) networks in Austria using large UDP packets. They use Data Acquisition and generation (DAG cards)[13], libpcap[10] depending on the delay due to individual component they are investigating and conclude that the UE has a significant impact on OWD of the packets in the uplink.

The authors show advantages of passive monitoring and analysis of traffic in light of performance optimization in operational 3G networks[14]. In [12, 15], authors use UDP datagrams at lower rates for Constant Bit Rate (CBR) traffic to obtain minimum OWD in the 3G networks and they prove that
packet size has an influence on OWD. The authors use DAG cards with reliable Distributed Passive Measurement Infrastructure (DPMI) and special wiring [16] as they solve clock synchronization problem generally associated with OWD measurements. In [17], authors pump UDP, TCP and ICMP traffic at very low rates and they observe that the 3G networks treat UDP, TCP and ICMP protocols differently. In [18], the author streams UDP datagrams at higher rates for three mobile operators in Sweden, and observes that the 3G networks treat traffic at 128 Kbps in a better manner in uplink and packet size has a pronounced effect than the rate in uplink while in downlink, the rate has pronounced effect than the packet size with networks treating the higher rates in a better manner. The author also observes that the applications streaming with a higher rate must also implement a larger buffer to compensate the jitter. In [19], similar streaming performance for TCP datagrams are considered for mobile operators in Sweden, the authors notice similar observations as in [18]. Interestingly on examination of results in [19], we notice that the throughput offered by the network is not always equal to the rate of generation of the traffic and it differs significantly at higher rates. The authors in [12, 15, 17, 18, 19] use similar measurement methodology and use Huawei E 220 modem [20].

In [21], authors study behavior of delay in WCDMA networks and High Speed Downlink Packet Access (HSDPA) networks in Finland for UDP packets pumped at a constant IPD of 20 ms. They also observe the jitter for CBR traffic and exponential traffic. They conclude that delay performance of HSDPA is superior to WCDMA. They observe a long term dependence, a triangular shaped delay for CBR traffic. Authors in [21] use QoSMET, a software measurement tool. In [22], authors evaluate a live HSDPA network in end users perspective. They compare goodput for UDP and TCP in both WCDMA and HSDPA. They use QoSMET and MOSET for UDP and TCP measurements respectively. They observe that HSDPA and WCDMA goodput correlate well with advertised maximum performance values. In [7], the authors conduct similar live network measurements on live HSPA networks in Finland for UDP and TCP for stationary and mobile cases. They observe that the delay performance of HSPA networks is better than preceding networks. They use QoSMET and MOSET for delay measurements.

In [23], authors present observations about TCP RTT as captured in live traffic of a live operational General Packet Radio Service (GPRS)/ Universal Mobile Telecommunications System (UMTS) network. The authors extract RTT samples from traces collected by passive monitoring using DAG cards at GW interface of one of major service providers in Austria. The authors discuss the various dimensions in RTT variability such as temporal variability caused due to fluctuating radio channel conditions, terminal variability due to terminal capabilities and spatial variability such as radio planning, physical layer settings and buffer provisioning. They observe a strong correlation in GPRS between session size and RTT. In [24], authors show the
high impact latency of a mobile network has on the current mobile networks and ways to reduce the latency. They analyze the current state of HSPA networks in terms of latency. They measure the proportional contribution of RTT due to individual network elements. Their initial analysis showed that UTRAN is the predominant factor in end to end latency. They discuss ways of reducing latencies such as transport network topology optimization and packet scheduling at the schedulers.

1.2 Motivation and Research Questions

This section presents motivations, Research Questions (RQ) and an abstract method to answer the considered RQs.

1.2.1 Impact of Operator service on OWD

As mentioned earlier, operators around the world are upgrading their infrastructure due to increasing number of users and their willingness to pay provided a faster service. However, choice of operator service (HSUPA/HSDPA/DC-HSPA+) affects the spatial variability which is amongst the important dimensions of delay in the mobile networks as explained in [23]. On the basis of our study we noticed that there has not been any work till now that estimates OWD using reliable equipment with focus on accuracy as in [12, 15, 18, 17, 19] and at same time considering the non-deterministic nature of network traffic(random packet sizes and random IPD). We investigate the impact of operator service on OWD in 3G networks.

1. What is the effect of Operator service on OWD/Jitter in 3G networks?
   - Does Operator service affect OWD?
   - Does Operator service affect Jitter?
   - How do the OWD/Jitter measurements help the software developer?

Ans. To answer this question, we generate UDP traffic as chosen by [12, 15] whose IP packet sizes are uniformly distributed to distribute the temporal load of the network. Random IPD is used as specified by RFC 2330 to eliminate correlation between send-time and periodic network behavior. We conduct measurements on four Swedish Mobile operators. IP packet sizes and IPD are uniformly distributed as in [9]. Number of samples generated are 10000 as in [9]. Two of the operators provide us the recently deployed DC-HSPA+ service while the other two operators provided us with HSUPA/HSDPA service. The measurements are carried out using the reliable DAG card based DPMI infrastructure using special wiring. We conducted experiments
in months of June, July, August and September of year 2011 and repeated the experiments in between 6 AM and 6 PM. Service offered by operators is verified by the User Interface (UI) of the modem. We analyze the trace files obtained from our measurement infrastructure and obtain OWD and Jitter. Jitter is quantified using the IPD of IP packets at the receiver, a computer used to receive the sent packets. We plot CDF of IPD at sender, a computer used to generate the traffic, and receiver for the operators. The software developers could use segmentation, if found in the uplink or downlink, or design counter measures if sending and receiving rates are not similar. We verified and validated the tools used in our experiments.

1.2.2 Treatment of protocols by 3G networks

In [17], authors observe that 3G networks provide different treatments to protocols when traffic is pumped at very low rate of one packet per second. We identified two flaws in that work, firstly the traffic is not generated simultaneously. Secondly, authors in [17] do not consider to distribute temporal load of network and they do not use random IPD to eliminate correlation and periodic network behavior. However there is no work that evaluates protocol treatment in 3G networks for random packet sizes and random IPD.

1. Does protocol of selected traffic, namely UDP or TCP or ICMP, affect OWD for random IP packet sizes and IPD?

Ans. We consider similar traffic generation method as in the first RQ, however, we generate 10000 samples for each UDP, TCP and ICMP traffic simultaneously so as to maximize the probability of traffic undergoing similar radio link conditions for a better comparison. We plot the CDFs for OWD in the uplink and the downlink for the various protocols.

1.2.3 Impact of IPD on OWD

Recently, there has been a tremendous increase in the number of applications developed for various smartphones and desktops. These applications generate traffic as standalone applications or under influence of background load. The effect of background-load on OWD was first carried out in [9, 11], however the there were two primary flaws, the authors use two random factors namely packet size and IPD; by doing so, they would not be able to identify the factor responsible for improved performance in the uplink. Secondly, In [9, 11], authors do not find an improvement in the downlink performance. We conduct an experiment considering random packet sizes keeping IPD constant at one second under influence of background load. We
then focus our attention towards applications generating traffic at various rates (without background), we donot consider IPD in this case. We then investigate the effects of IPD on OWD in the uplink or downlink. The experiment funnels towards streaming at high rates in the mobile networks. As there has been no work to determine factors that determine OWD in the uplink and downlink, The aim of this research question is to investigate factors affecting delay at lower and higher rates in 3G networks.

1. Does IPD (constant IPD) of generated traffic have an effect on OWD (Uplink and Downlink)? Does background load have an effect when application generates traffic that has a very low constant IPD of 1 second?

**Ans.** To answer this RQ, we continue to distribute the temporal load to the network by choosing random packet sizes. But, we generate the traffic with a constant IPD so that we could investigate the impact of IPD. We keep the IPD constant for the chosen IPDs and also investigate the impact of background load of 50 Kbps on an low rate application generating traffic with constant IPD. We plot the CDF of OWD for either of the cases. We extend our investigation by conducting the streaming experiments for higher data rates and reason the observations. We use UDP traffic and retain the measurement methodology as used for the first research question.

1.2.4 Shrinking interval of IPD

A variable bit-rate application (similar to one chosen by [9]) is considered, and its IPD is gradually shrunk towards a constant IPD (equal to average of uniformly distributed IPD initially considered) with aim to observe the OWD treatment of traffic by mobile network.

1. Does shrinking the uniformly distributed IPD, maintaining a constant mean have an effect on OWD when packet sizes are random in 3G networks?

**Ans.** We conduct an experiment where we shrink the interval of the IPD across the upper and lower limits considering the base IPD as chosen in [9] to compare the OWD when the VBR applications generate traffic with same mean IPD but different intervals over 3G networks. We plot the CDF of OWD in the uplink and downlink. We generate UDP traffic and retain the measurement methodology used in the first research question.
1.2.5 OWD in CBR versus OWD in VBR

In [12, 15], the authors conduct experiments at one packet per second and observe WCDMA and HSDPA dependent upon the IP payload sizes. However, there is no work that compares the OWD in CBR and VBR at constant IPD of one second.

1. What is impact of traffic generation pattern on OWD when comparing the random vs CBR pattern?

Ans. To answer this research question, we generate the 50 samples for each packet size and increment the packet size by four at a constant rate of one packet per second. For VBR, we generate UDP packets with random IP packet sizes and constant rate of one packet per second. We compare the median OWD for the CBR and VBR traffic. We reason the discrepancies if any. We use UDP traffic and retain the measurement methodology as used in the first research question.

1.3 Research Methodology

While conducting the thesis, we utilize the existing research methods in a controlled manner. This section briefly describes our research methodology.

1. Literature Study: We have used Snowball Literature Search for the literature survey conducted in our thesis. It primarily consisted of research papers. [25], a Ph.D dissertation is used as a reference framework for this thesis. Two books, [26] and [27] are used to as primary references as they provided the experience and knowledge of the experts who worked on designing the mobile access technology. The study helped us to design our experiments and reason our findings. White papers were also studied as they are updated and provide specific knowledge such as [28], which provides knowledge on user plane and control plane latencies. The authors discuss the latency of call setup from idle mode in WCDMA network and HSPA network and show that call setup time could be reduced by signalling using HSPA channels. They also compare HSPA to LTE. In [29], authors explain the benefits of Dual Cell HSDPA, a RAN and discuss its future evolution. [30], a patent discusses an invention of allocating ETFC based on power consumption of Enhanced Dedicated Channel using acknowledgement or negative acknowledgement and a Channel Quality Indicator (CQI).

2. We design and implement our experimental environment which includes the hardware setup and software configurations. We have a set of commands (dagpps - checking pulse synchronization; dagthree
CHAPTER 1. INTRODUCTION

- DAG status; ntpd - NTP daemon; mii-tool, ethtool - setting link speeds, auto negotiation and so on) to check the configuration of our hardware.

3. After implementing the design we verify it. If the implemented design failed to meet the specification, we adapt accordingly. For example, we have verified traffic generator using the CDF plots of IPD at the sender and we verify the analysis tool using manual calculations. Our goal is to create a controlled environment providing us a high scope of repeatability.

4. We repeat the experiment till we prove our hypothesis and produce reliable results, till we are sure if measurement is an aberration or a result. Runs of our experiment depend upon the time taken for a single run and the resources needed to conduct the experiment. In our thesis, repeatability of the experiment is ensured by collecting the seeds for the experiments conducted, storing the logs of IP address allocated to the UE / Gateway(GW), by considering the climatic conditions which could affect the instantaneous radio link conditions.

5. Experiments are repeated at different times to ensure that results are not due to a particular time of the day, to make our experimental results more general.

6. We critically assess our findings to previous works. In this case, we do not compare the numerical results directly, however conclusions drawn can be questioned like in the case of [12], one could question if the measured OWD is true only at one packet per second and not in general(due to multiple delay lines) , at different rates etc. So we question/support the conclusions of previous works.

1.4 Contribution

In this thesis, we conduct measurements to discuss the effect of operator service on OWD, the effect of IPD, the effect of shrinking the interval of IPD on OWD using reliable hardware based measurement infrastructure. We also compare the two transmission methods: the CBR and the Variable Bit Rate(VBR). We develop an ICMP generator, modify the existing generators (UDP and TCP) to enable random payload sizes and random IPD. We also developed an analyzer, that could be used to analyze delay and losses for UDP, TCP and ICMP traces. The experiments were conducted on four major Swedish Mobile Operators: Telenor[31], Telia[32], Tele2[33] and Tre[34]. So the results presented in the thesis can be used by the operators for service optimization.
Experimental Methodology
Chapter 2

Experimental Methodology

Our thesis has been implemented in accordance with the Network Performance Framework [25, p. 27] guidelines. This chapter briefly describes the methodology followed during our work. The implementation details: Four modules namely the Traffic Generation, Measurement, Analysis and Visualization are described below.

2.1 Traffic Generation

The goal of traffic generation is to generate traffic streams according to the desired specification, or at least as close as possible[25, p. 75]. For this purpose, traffic generators are used for generating UDP, TCP and ICMP packets. Traffic generation is primarily carried out using random Internet Protocol (IP) packet-size and random IPD, which are governed by uniform distribution. We have developed a single-stream ICMP traffic generator which operates on raw sockets. The developed traffic generator is a C++ program implemented without a receiver feedback. We have also modified the existing UDP and TCP generators to fit to our use: to facilitate random payload-sizes and random IPD governed by a distribution. These scripts use an application layer header with multiple fields, out of which four significant fields are in common with every traffic generator: A field for separating experiments (Experiment ID), a field for separating experiment runs (Run ID), a field for denoting operator- uplink/downlink-protocol (Key ID) and a field to identify packets within an experiment (Sequence Number). Based on these four fields, we can uniquely identify each datagram generated by the traffic generator, thus avoiding any ambiguities associated with hashing[15].

Figure 2.1 shows a clear and simple schematic representation of the developed traffic generators and the flow of the events is self explanatory in algorithmic form. Our traffic generators operate on raw sockets. Linear Congruential Generators (LCG)[35] are used to generate the random numbers used in the sleep() and send() functions. The tool uses Wait() which is
CHAPTER 2. EXPERIMENTAL METHODOLOGY

Figure 2.1: Algorithm for Traffic Generator
implemented using `while (CurrentTime is less than DesiredTime) loop`, as this does not pause the process execution unlike the `sleep()` or `nanosleep()` function, whose accuracy is in direct relation to the Operating-system’s interrupt handling. Nevertheless, the operating system could still interrupt maximum processes to allow another process to execute and this can cause uncontrolled delay[25, p. 98–99]. A brief validation report of the developed and the modified generators is presented in Appendix B.

### 2.2 Measurement

One of the primary goals of our thesis is to carry out high-quality research measurements. In a Core network, collection of large scale traces is cost-effective and also all network phenomena may not be observed[14]. So in order to fulfill this, we opt a passive traffic measurement and analysis scheme. We chose to perform our experiments and collect measurements using a dedicated measurement-hardware with timestamp accuracy[16] rather than using a measurement-software such as Tcpdump which is chosen by authors: Fabini et al. in [9]. This choice has been made on the basis of performance evaluation conducted in [25, p. 131–164]. Application layer measurements can be inaccurate due to influence of protocol stacks and differ significantly from the lower-layer measurements[36]. Therefore, rather on operating on unreliable application-layer measurements we rely on lower-layer measurements by utilizing a reliable infrastructure: DPMI[37] for collection of link-level traces. The PDUs are collected using the DPMI at the lower layers, so as to minimize the impact of the system and the network stacks. The Measurement Points (MPs) are used for timestamping of sending times and receiving times so as to measure overall sending and receiving times of packet. They are equipped with Endace DAG 3.5E[38] cards, synchronized to GPS via a Endace TDS 2[39], yielding a timestamp accuracy of 60 ns in DAG cards[25]. The use of GPS is recommended method to obtain highest accuracy from the DAG cards[40]. The both MPs are clock-synchronized to a local Network Time Protocol (NTP)[41] Server (`time.bth.se`).

### 2.3 Analysis

Task-specific analysis is carried out during our thesis. Figure 2.2 shows analysis procedure for experimental results obtained. The link-level packet traces collected by the MP are stored locally in binary format of capture files (`.cap`). These `cap` files are not human-readable, so we utilize a software that uses the `Libcap library` utilities to convert it to a text file. The obtained text file is then processed using the Perl Analyzer developed during our thesis. This Perl Analyzer utilizes the special data included in the PDU payload: Experimental ID (E), Run ID (R), Key ID (K), Sequence Number (S) and
IP ID in the IP header as a unique Hash-key identifier. Our Analyzer avoids the ambiguity generally associated with packet-hashing used by [42] in their work. An IP identifier is also chosen as a unique identifier as the PDUs are retransmitted in TCP, while the E, R, K, S would read same for original packet and retransmitted packet and we may obtain erroneous result when either of them arrive to destination. This software accurately calculates the One-way Delay (OWD) associated with segmented packets and packet-loss statistics. In it, Math:: Bigfloat library is used to handle the variables that hold high resolution delay.

![Figure 2.2: Analysis Procedure for Experimental Results](image)
2.3.1 One Way Delay (OWD)

The uplink or downlink OWD, of a packet having a sequence number $S$, is calculated by subtracting the timestamp of packet at the Sender or Receiver by one of the DAG interfaces ($d0x$) with the timestamp of the same packet at the Receiver by the other DAG interface ($d0y$) in the same Measurement Point MP. Delay $(D)$ is the delay in uplink or downlink. $T$ denotes Timestamp. This is given by below equation:

$$Delay(D) = T(S, \text{Receiver or Sender}, d0x) - T(S, \text{Sender or Receiver}, d0y)$$  \hspace{1cm} (2.1)

2.3.2 Loss

Loss is represented as ratio of number of packets lost ($L$) to the total number of packets sent ($N$) by the Sender. Here $L$ implies difference of packet count at Sender and packet count at the Receiver. The number of packets lost is the difference in the number of packets received by the Receiver and the number of packets that are generated from the Sender. This is quoted in an equation as:

$$Loss = L/N$$  \hspace{1cm} (2.2)

2.3.3 Inter Packet Duration (IPD)

IPD is time between the arrival or departure of packets at Receiver or Sender respectively for two successive packets. IPD is calculated as:

$$IPD = T(\text{Receiver / Sender}, (i+1)) - T(\text{Receiver / Sender}, (i))$$  \hspace{1cm} (2.3)

2.4 Visualization

The obtained statistics are then plotted offline and visualized using Matlab 7[43]. A choice of this software made easy to handle and process data and is known to be very stable. A previous version of Matlab (Vers 6.5) could not handle timestamps since 1970, with accuracy of less than 10 microseconds[25, p. 89]. Some of the plots obtained in our thesis include: Minimum OWD, Mean OWD, Median OWD, Percentile CDF and so on. Observations in [25, p. 89] could not pose a significant problem considering the timescales considered in our thesis is minimum of 300 seconds in duration and the IPD considered are few hundreds of micro-seconds. The minimum resolution used in our thesis is 90 micro seconds, used for sampling the CDF of OWD in the section of Gateway analysis.
2.5 Experimental Setup

To evaluate OWD in the Swedish mobile networks, we used the Experimental Setup shown in Figure 2.3. Here, the Sender transmits traffic to the Receiver. This is done via a Gateway (further referred as GW) Vololink VA 126[44], a convergent wireless terminal, connected to the Sender. We utilize a special wiring scheme as in [25] to ensure that the packets are time-stamped by the same clock, thus it is subjected to same skew or drift, if present. During uplink or downlink, the packets initially originate at the Sender or Receiver. They are transmitted along the RAN or BTH network using the GW or 10 Mbps ethernet, then passes through the Mobile Operator’s core network or Swedish University Network(SUNET). The packets then transit through the SUNET or operator core-network before navigating through the BTH or RAN. The traffic finally arrives to the Receiver or Sender. In Figure 2.3, two Wiretaps are placed in between Sender and Receiver: One in between Sender and GW and the other is placed just in front of and contact with the Receiver. These wiretaps are also connected to MPs. The MPs are equipped with Endace network monitoring DAG 3.5E[38] cards, synchronized to GPS via a Endace TDS 2[39], yielding a timestamp accuracy of 60 ns in DAG cards[25]. The both MPs are also clock-synchronized to a local Network Time Protocol (NTP)[41] Server (time.bth.se). The monitoring ports in the wiretap feed the packets into DPMI[37] enabled MPs with local storage for further processing. Here, the MP filters the packets according to the rules set in Measurement Area Controller (MArC). The Sender, the Receiver and Measurement Points use Dell OptiPlex 740[45] using AMD Athlon 64X2 Dual-core processors. The Receiver and Measurement Points use Crux 2.3 Operating system with Linux Kernel 2.6.20.3. The Sender uses Graphical User Interface (GUI) based Ubuntu 10.0[4] with Linux Kernel 2.6.32.21 so as to support web-interface to configure GW.

![Figure 2.3: Experimental Setup to estimate OWD](image-url)
2.5.1 A Special Wiring Scheme

In order to calculate delay (refer Section of Analysis), timestamps at Sender and Receiver systems are required with high level of uncompromising accuracy. For this, the clocks of MPs must be perfectly synchronized. Few of the available solutions for this are: linking up to NTP or GPS. Generally, NTP synchronizes clocks in order of 10-20 ms for WAN and less than 1 ms for LAN while GPS (using Endace TDS 2) synchronizes clocks of MPs in order of 60 ns[25]. However in real time experimentation scenario, usage of two different DAG cards (one near Sender end and other near Receiver end) may lead to minor inaccuracy in recording timestamps. To avoid this problem, a single DAG card must be used for experiment. In order to facilitate this, a special wiring scheme is introduced to help operate on single DAG card during experimentation.

The experiment-setup hardware (Figure 2.3) is connected by a special wiring scheme as elucidated in Figure 2.4. The Wiretap 1 (further referred as WT 1) is connected to Sender and Wiretap 2 (further referred as WT 2) to Receiver end. Let us assume a packet $P$ travels from Sender to Receiver via WT 1 and WT 2 as shown in figure. While it traverses, WT 1 replicates $P$ and passes it DAG 0 on interface 0. Now, DAG 0 assigns Timestamp $T\text{(sen)}$ to $P$. Packet $P$ finally reaches Receiver at WT 2 after passing through all intermediate components. Now, WT 2 replicates $P$ and sends it to DAG 0 on interface 1. Here, DAG 0 assigns Timestamp $T\text{(rec)}$ to $P$. Hence, the experienced OWD is calculated by the difference of $T\text{(rec)}$ and $T\text{(sen)}$. This same method is applicable when packets travel from Receiver to Sender too. Hence in this way highly accurate timestamps are captured in our work.
2.5.2 Delay Constituents

In Figure 2.3, the cumulative OWD of the packets is due to delay encountered in the GW, RAN, core-network of the operator, SUNET and BTH network. Out of these, the delay due to RAN and the Mobile operator’s core network could not be ascertained as they require specialized equipment and permissions to conduct measurements at the Mobile Operator’s core network. However, we can estimate the delay due to traversal in the internet, which comprises of BTH and SUNET too, by using an ICMP ping from the receiver to every operator exchange. Traceroute\cite{46} is a diagnostic computer tool that can be used to notify the path traversed by transmitted packets. Details of the path undertaken by the packets for the mobile operators considered in our thesis is provided in the Appendix E. The Average Round Trip TimeRTT obtained for a packet of 32 bytes is 14.7 ms, 21 ms, 21.9 ms and 14.7 ms for Telenor\cite{31}, Telia\cite{32}, Tele2\cite{33} and Tre\cite{34} operators respectively (as on August 15, 2011). For a 1450 byte ICMP payload, we registered RTT of 17.9 ms, 24.1 ms, 24.2 ms and 17.9 ms respectively for the Mobile Operators mentioned above. The links in this case are symmetric. Through this experiment we note that the contribution for the delay due to internet is quite significant, this is very much unlikely with the observations of author Dr. Arlos in his works: \cite{12} and \cite{15}.

2.5.3 Experimental Procedure

Considering the various steps involved in traffic generation, measurement and analysis, it is not feasible to carry out the experimentation and analysis process manually. So we develop a method to automate the whole process of our experiment. We have developed a control-script which does the process of automation and is first required to start running on Central XPS system before every other hardware or software tool starts. This script takes the ultimate authority to monitor the whole experimental run to execute in a sequential flow.

A neat experimental procedure is briefly explained in Figure 2.5. Here, we utilize multiple servers-single client architecture to automate the experimentation. The messages are exchanged and parsed through TCP sockets to enable the feeding of command line parameters needed to drive the scripts. Firstly, the TCP client in the Central XPS System, depending on the scenario of uplink or downlink, it flushes and starts the required MP. Secondly, TCP client, depending on the uplink or downlink, passes the required command line arguments to start the Server on Receiver or Sender. Thirdly, the TCP client, depending on the uplink or downlink, passes the appropriate command line arguments to the Sender or Receiver to start the Traffic generators. The experiment is now in the phase of running. The traffic flows from Sender or Receiver (depending on uplink or downlink) into networks
Figure 2.5: Experimental Procedure
(explained in section of Experiment Setup) and finally arrive at end system (Receiver or Sender system). Meanwhile, while passing through the Wiretaps at Sender or Receiver, the MP intercepts the traffic and does its job of timestamping sending and receiving times of the passing traffic with help of DAG cards and special wiring (refer Section of Wiring Scheme). After transmission of last packet from Traffic Generator, the cap file stored in the local storage of MP is moved to Central XPS system. Then this cap file is converted into human-readable text format with help of Libcap library utilities (refer Section 2.3). This link-level trace file is used for our analysis of OWD and packet-loss. Finally, the control script drives the Perl Analyzer tool (validation of tool is given in Appendix D) to analyze the traces and obtain the required statistics. After completion of this whole process of experiment, next run or experiment is prepared to be iterated in similar manner.

2.5.4 Delay due to Gateway

![Experimental Setup to estimate: Delay due to Gateway](image)

To estimate the delay due to GW, we conducted an experiment where we directly connected the WAN port in GW to the Wiretap at the Receiver (WT 2), see Figure 2.6, the WAN port is connected to wiretap at the Receiver using a one meter long ethernet cable. UDP packets whose packet sizes are random are sent from the Sender to Receiver at a random IPD. The payload sizes and IPD are uniformly distributed between [32 1450] and [50 500] ms respectively. We estimate the OWD, after the DAG cards capture the sent traffic and after analyzing the trace. The median of OWD due to GW can be approximated by equation on the basis of linear fit, where $L$ is the IP packet size and the delay expressed is in ms. Figure 2.7(a) is the plot of minimum, median and maximum OWD of the UDP packets through GW while Figure 2.7(b) denotes CDF of the OWD. The OWD increases increases as a function...
of packet-size as expected[47]. A linearly increasing CDF plot, considering a uniform distribution shows that the delay increases linearly as a function of the packet size.

\[ \Delta_1(L) = 8.295e - 4.1L + 0.2764 \quad (2.4) \]

2.5.5 Delay due to Internet

The delay due to Internet (\(\Delta_4\)) can be estimated using the experimental setup in Figure 2.8. In Figure 2.8, we send ICMP traffic having random packet sizes generated at random IPD from the receiver to the Operator exchange. The ICMP Request and Reply packets are captured by the DAG cards and the trace files are analyzed as mentioned in earlier section. From our vantage point of the internet, we have the SUNET with optical multi gigabit networks between the receiver and the operator exchange. The IP address of the operator exchange is obtained through \texttt{traceroute}[46] command from the Receiver to the GW. The payload sizes and IPD are uniformly distributed between [32 1450] and [50 500] ms respectively. This traffic can be classified as VBR traffic.

Figure 2.9 plots minimum OWD as a function of packet size (IP). Interestingly, we notice that packet size has an affect on RTT due to internet.
However the effect is negligible compared with the effect of the 3G network (chapter-4). Figure. 2.10 is plot of CDF of RTT for the four operators. In either of these figures we observe that, \( \Delta_4 \) is higher in case of Operator-3 than the other operators. We also estimate \( \Delta_4 \) using ping at one packet per second, from the receiver to the operator exchange, this time for 10000 samples of constant payload sizes: 32 bytes and 1450 bytes. This traffic can be classified as CBR traffic. Table. 2.1 and Table. 2.2 summarize the average and minimum RTT to the four operators for payload sizes considered. OWD is approximately half the RTT considering the high capacity links in the SUNET and BTH.

The result in Figure. 2.9 agree with the results indicated by [47], where packet sizes do not have a significant impact when the capacity of links are high due to low serialization. However, Table. 2.1 and Table. 2.2 indicate a considerable impact of packet size on RTT using ping using CBR traffic at low rates.
CHAPTER 2. EXPERIMENTAL METHODOLOGY

Figure 2.9: Minimum RTT (Delay due to Internet)

Table 2.2: Minimum RTT to Operator’s Exchange

<table>
<thead>
<tr>
<th>Operator</th>
<th>32 Bytes</th>
<th>1450 Bytes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operator-1</td>
<td>12.7 ms</td>
<td>17.9 ms</td>
</tr>
<tr>
<td>Operator-2</td>
<td>12.7 ms</td>
<td>16.1 ms</td>
</tr>
<tr>
<td>Operator-3</td>
<td>20.0 ms</td>
<td>22.8 ms</td>
</tr>
<tr>
<td>Operator-4</td>
<td>12.7 ms</td>
<td>16.1 ms</td>
</tr>
</tbody>
</table>
Figure 2.10: CDF of RTT (Delay due to Internet)
Technical Background
Chapter 3

Technical Background

Mobile operators all over the world have been offering wide range of data services to the customers, but the process of data transfer from the traffic-generating applications through the mobile network is not widely known to the developers who create applications. It would be interesting and informative for developers to know how the packets are treated in theory and in practice during the data exchange though a mobile network. By scope of this knowledge, applications may be designed efficiently to make maximum possible use of the mobile network. This section briefly explains theory behind the data transfer process and the parameters that may possibly affect the OWD in the mobile networks. This chapter is purely based on the literature study conducted during our thesis. This section gives only an abstract but required overview which is a prerequisite to understand our experimental results.

First section provides an overview of prominent changes in releases of the 3rd Generation Partnership Project (3GPP)[48]. Releases from 3GPP Release 6[49] to the currently deployed 3GPP Release 8[50] are considered as relevant to our thesis work for the reason that each of the Swedish Mobile Operator (considered) follows one of the mentioned releases. The second section gives an overview of user scheduling, link adaptation and Hybrid Automatic Repeat Request (HARQ) process, to gain insight on how the core network’s parameters affect OWD in uplink and downlink. The third section gives an overview of the data transfer process in the uplink and the downlink. The last section in this chapter gives an overview of packet scheduling, the channel states of the UE and the ETFC selection process to know the priority given to traffic inside core network of the Operator. In essence, this chapter gives a complete overview on how a Mobile Operator’s core network treats traffic originating from the UE(s).
3.1 Overview of 3GPP Releases 6, Release 7 and Release 8

The 3GPP[48] standards aim for a continuous and improved usage of the available bandwidth spectrum. The fundamental goal of mobile broadband is to offer higher data rates with reduced latency in the mobile networks[51]. A brief overview of 3GPP Release 6[49], 3GPP Release 7[52] and 3GPP Release 8[50] is described below as the mobile operators considered in our thesis implement these standards. 3GPP release 9 and evolution is not described as they are not yet implemented commercially on a large scale (as on July, 2011) and are beyond the scope of our thesis. This section specifies only the significant improvements which are introduced in mentioned 3GPP releases but not a complete overview of the releases. Figure 3.1 gives an overview of the improved architecture in the three releases considered[27, p. 451].

3.1.1 3GPP Release 6

The key new feature introduced is the HSUPA for the WCDMA[26, p. 391]. It has four network elements in the user and control plane: Base Station, RNC, Serving GPRS Support Node (SGSN) and Gateway GPRS Support Node (GGSN)[26, p. 451]. This version also introduced enhancements to the IP Multimedia Subsystem (IMS) such as Push-to-Talk Over Cellular (POC)[53].

3.1.2 3GPP Release 7

This version introduced features such as Higher Order Modulation, 2 X 2 Multiple Input Multiple Output (MIMO) and one tunnel between RAN and
CHAPTER 3. TECHNICAL BACKGROUND

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GGSN[27]. This is a very significant release as it also introduces a flat architecture with all the RNC functionality in the node B, this significantly lowers the latency in mobile networks[26, p. 431]. High Speed Packet Access+ (HSPA+) is introduced in 3GPP Release 7 and further developed in subsequent releases[27].

3.1.3 3GPP Release 8

The 42 Mbps downlink capability is achieved by combining 64 Quadrature Amplitude Modulation (QAM) and doubling the bandwidth using dual carriers (2 X 5 MHz = 10 MHz) and is known as DC-HSPA+. This capability was introduced in 3GPP Release 8 which also standardized 42 Mbps capability by combining 2 X 2 MIMO and 64 QAM in a single 5 MHz carrier[1].

3.2 Scheduling, Link Adaptation and Hybrid ARQ

There are several parameters that affect the OWD and data transfer process during the uplink and downlink in the current UMTS networks. The most important parameters being: Scheduling, Link adaptation and HARQ mechanism[27]. Channel Dependent Scheduling is responsible for sharing of resources available in the communication system to achieve efficient utilization by considering the time-specific radio-channel conditions for scheduling decisions. Link adaptation is responsible for setting up transmission parameters of a radio link to handle variations of the radio link quality. Both the Channel Dependent Scheduling and Link Adaptation try to exploit the channel variations through appropriate processing prior to the transmission of data. But loss and corruption are possible in a radio system, so HARQ requests for retransmission of erroneously received data packets.

In HSDPA, downlink multiplexing is a combination of Code Division Multiplexing (CDM) and Time Division Multiplexing (TDM). In the downlink, Link Adaptation is based on the rate control as it is generally preferred[27, p. 11–62]. Rate control is adjusted by changing the modulation scheme and the channel coding rate. For each Transmission Time Interval (TTI), the rate control mechanism in the scheduler selects, for the scheduled user(s), the transport format(s) and the channelization-code resources to use. The transport format consists of the modulation scheme and the transport block size[27, p. 151]. The higher order modulation, which is used in the downlink, trades power efficiency for the bandwidth efficiency. It is used to provide higher data rates in few situations. Downlink primarily features high speed shared channels for data transmission.

In the uplink, the power resource is distributed across the various users in a communication system. A similar channel dependent scheduling is used as in the downlink, except that it is taken care not to cause excessive interference in the inter or intra cell when the channel conditions are favorable. The
enhanced uplink, which features a shorter TTI than its predecessors, also features Higher Order Modulation from 3GPP Release 7[52]. The enhanced uplink uses enhanced dedicated channels for data transmission. The E-TFC selection is responsible for selecting the transport format of the Enhanced Dedicated Transport Channel (EDCH) in the uplink while the Medium Access Control-e (MAC-e) multiplexing is handled autonomously by the UE. Hence, while the scheduler handles the resource allocation between the UEs, the E-TFC selection controls resource allocation between the flows within the UE. Each ETFC has an associated power offset. The data rate is directly proportional to the power offset. The E-TFC is selected on the basis of available data, serving grant and the available power for the transmission. The UE selects the E-TFC by maximizing the amount of data that can be transmitted given the power constraint and the scheduling grant[27, p. 202–203].

The HARQ performs retransmissions originating at the Medium Access Control (MAC) layer but is known to discard the erroneously received packets. However, we must note that these corrupted packets could possibly consist of partially useful information. So, the present mobile communication systems use HARQ with soft combining. Soft combining is implemented using the Incremental Redundancy (IR) or the chase combining. In the uplink, only HARQ combined with IR is used. Implementation of the IR is generic compared to the chase combining. The HARQ protocol uses multiple stop-and-wait HARQ processes so as to allow continuous transmission[27, p. 227]. With Release 7 supporting MIMO, for each stream, the physical layer HARQ processing and the use of multiple HARQ processes are identical to the single stream case. The acknowledgments for HARQ are sent per stream.

3.3 Packet Data Flow

In the downlink, the Packet Data Convergence Protocol (PDCP) performs the optional IP header compression[26, p. 6]. The output from the PDCP protocol is fed to the Radio Link Control (RLC) protocol entity[53]. After possible concatenation, the RLC Protocol Data Unit (PDU)(s) are segmented into smaller blocks of 40 bytes each(until 3GPP Release 6) and variable sizes (from 3GPP Release 7). An RLC PDU comprises of a data segment and RLC header. Logical channel multiplexing is performed in Medium Access Control-d (MAC-d). In the Medium Access Control-hs (MAC-hs), a number of MAC-d PDUs, possibly of variable size are assembled and a MAC-hs header is attached to form one transport block, subsequently coded and transmitted by the physical layer[27, p. 158–159]. The data flow in the uplink is similar to that of the downlink, except that MAC-e layer is featured instead of MAC-hs layer. The physical layer processing in
the uplink and downlink have several similarities. It involves a Cyclic Redundancy Check (CRC) attachment, coding, rate matching of the HARQ, physical channel segmentation followed by interleaving and modulation. This is then followed by spreading and scrambling.

The Dual Carrier-High Speed Packet Access (DC-HSPA) which is included in the 3GPP Release 8 of UMTS uses similar data transmission techniques as above, except that it uses dual carriers. It doubles the user data rate if the number of users are low because a single user can utilize two parallel frequencies. When the system load increases, the probability of a single user acquiring the full capacity of both the frequencies decreases. But even at a high load Dual Carrier-High Speed Downlink Packet Access (DC-HSDPA) provides capacity benefits compared to two single carriers. Because of the Channel Quality Indicator (CQI) on both the carriers, the Node B’s packet scheduler can transmit packets on the frequency that is not faded[26, p. 459].

### 3.4 E-TFCI

![Diagram of E-TFCI selection process](image)

E-DCH Transport Format Combination Indicator (E-TFCI) contains information about transport block set size. In HSUPA, E-TFCI selection is done by UE to determine the quantity of data to be packed in each of the transport blocks, which are interleaved by specific TTI, prior to packet data transmission.

Figure 3.2 represents a simple schematic representation of process of communication involved in E-TFCI selection between UE and Base Station.
(further referred as BS). In HSUPA, when a UE needs to transmit data into network, it requests BS for higher data rates using uplink signalling (1). Then the Packet Scheduler in BS determines the TFCs that are allowed for usage depending on current resources and number of users (2). The Packet Scheduler in BS responds to each UE with maximum-permissible TFC level (3). Now, the UE selects the ETFC depending on data to transmit, available power and permissible TFC range (4). After E-TFCI is selected, packet data transmission takes place (5).

3.5 User-Specific Packet Scheduling and E-TFC Selection

The Packet Scheduler is generally located in the RNC. The UE uses the common channels namely the Random Access Channel (RACH) in the uplink and the Forward Link Access Channel (FACH) in the downlink as the common channels. Either of these channels is capable of carrying the signaling data and the user data. The UE can also use a bi-directional Dedicated Channel (DCH) which support higher bit rates. Extensions to the above channels are made possible in the HSPA evolution to support higher bit rates. The enhanced FACH and RACH channels optimize the power consumption and prevent the UE to switch to the power hungry Cell-Dedicated Channel (Cell-DCH) state. A UE which is in Cell-Paging Channel (Cell-PCH) is moved to Cell-Forward Access Channel (Cell-FACH) state and then to Cell-DCH state[26, p. 437]. Figure 3.3[26, p. 270] explains a typical ETFC selection process.
Figure 3.3: Algorithm for Selecting Transport Channels and their Bit Rates
Experiments and Analysis
Chapter 4
Experiments and Analysis

In this chapter, a brief overview of the experimental aims, objectives, method, measurement results, observations and conclusions are presented. Limitations of our results are discussed on experiment basis. The first few packets are not considered as they undergo abnormally high delays due to the setting up of the Dedicated channel (DCH) [26]. Extreme delays experienced by few packets irrespective of the Operator are not considered as, they could be due to various reasons such as short outage of service followed by restoration of service after short span, before soft memory of the UE is cleared during transmission of a segmented IP packet, or the fluctuating radio channel conditions. In this case, IP packet undergoes a higher delay for which Operator or underlying radio technology could not be blamed.

4.1 Impact of Operator-Service on OWD in 3G networks

Aim
To study the impact of the service provided by the Operator on OWD in 3G networks.

Objectives
1. To compare the OWD for DC-HSPA+/HSUPA networks in the uplink and DC-HSPA+/HSDPA networks in the downlink.
2. To compare Jitter for DC-HSPA+/HSUPA networks in the uplink and DC-HSPA+/HSDPA networks in the downlink.

Method
To observe the impact of Operator-service on OWD in 3G networks, we send traffic from sender to receiver using GW through the 3G network and mea-
sure the OWD. We use SIM cards in the GW to enable us 3G access. We subscribe to four Swedish public mobile Operators, of which two of the Operators provide us DC-HSPA+ service and the two other Operators provide us HSUPA/HSDPA service. The services are verified using the User interface of the GW (refer Appendix A). Experimental methodology and analysis procedure are described in chapter 2. We plot the OWD of IP packets as a function of their packet sizes and plot the corresponding CDF plots for the Operators considered. Jitter is plotted as a CDF of IPD at the Sender and Receiver.

Traffic Generation

UDP packets are considered as they are used in [12, 15, 18]. Packet sizes and IPD are uniformly distributed as in [9] to distribute the temporal load of network and eliminate co-relation between send-time and periodic network behavior respectively. Packet sizes are uniformly distributed between [32 1450] and the IPD are uniformly distributed between [50 500] ms.

Measurement Results and Observations

This section is divided into two parts, the Uplink and Downlink. In each section, results and observations are presented.

OWD Measurement Results (Uplink)

Figure 4.1 describes the plot of OWD as a function of IP packet size and Table 4.1 summarizes the results in Figure 4.1, which is a summary of width of transport blocks observed on the basis of linear fit. Width of the transport blocks identified can be mapped to ETFC-I combinations, as a width of transport block translates to a single ETFC. The identified delay lines show the segmentation of UDP packets by the UE as it is transmitted into the 3G network. We observe that packet sizes within the observed staircase are treated similarly. Software developers, who make mobile applications can exploit the segmentation by choosing packet sizes as multiples of step sizes identified to obtain the best treatment by the Operator. As observed from our vantage point, observation presented above holds true irrespective of the operating service.

<table>
<thead>
<tr>
<th>Operator</th>
<th>Width of Transport Block Observed</th>
<th>TFC’s Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operator-1</td>
<td>80</td>
<td>1</td>
</tr>
<tr>
<td>Operator-2</td>
<td>40,160,640</td>
<td>3</td>
</tr>
<tr>
<td>Operator-3</td>
<td>40,160,640</td>
<td>3</td>
</tr>
<tr>
<td>Operator-4</td>
<td>40,120</td>
<td>2</td>
</tr>
</tbody>
</table>
In Figure 4.2, we plot the CDF of OWD for the four Operators in the uplink. Table 4.2 summarizes the important observations in Figure 4.2 presenting the % of packets received at the receiver considering a threshold OWD in the uplink. The results in Table 4.2 indicate that the Operators using DC-HSPA+ networks provide lower OWD for UDP packets. The difference in OWD could also be due to several reasons such as differences in the core network, difference in the softwares used at NodeB etc. However, we suspect that a combination of RAN and a possible bypass of SGSN at the Operator’s core network to be reason behind the reduced OWD observed for the Operators providing DC-HSPA+ service.

Table 4.2: Percentage of packets received considering a threshold delay

<table>
<thead>
<tr>
<th>Delay (ms)</th>
<th>Operator-1</th>
<th>Operator-2</th>
<th>Operator-3</th>
<th>Operator-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 50 ms</td>
<td>48.9%</td>
<td>9.5%</td>
<td>11.3%</td>
<td>45%</td>
</tr>
<tr>
<td>&lt; 100 ms</td>
<td>99.4%</td>
<td>40.5%</td>
<td>42.8%</td>
<td>99.8%</td>
</tr>
<tr>
<td>&lt; 150 ms</td>
<td>99.7%</td>
<td>76.5%</td>
<td>76.5%</td>
<td>99.9%</td>
</tr>
<tr>
<td>&lt; 200 ms</td>
<td>99.8%</td>
<td>94.4%</td>
<td>94.3%</td>
<td>99.9%</td>
</tr>
</tbody>
</table>
Jitter in DC-HSPA+/HSUPA Networks (Uplink)

Figure 4.3 presents the CDF of IPD at the sender and receiver in case of uplink. The plot of CDF of IPD at the sender can be seen as verification of traffic generation process, a straight line having a constant slope could be observed for all the four Operators. Strangely, we observe that the CDF of IPD at the receiver for Operators providing us a DC-HSPA+ service is found to be following the CDF of the IPD at the sender, however the minimum IPD observed is around 0 ms indicating packets arriving immediately after each other. In case of Operators providing us a HSUPA service, we observe the CDF of IPD at the receiver to be indicating a stair-case of width 10 ms possibly indicating Transmission Time Interval (TTI). Table 4.3 summarizes the observations in Figure 4.3, presenting the % of packets arriving at the receiver considering a threshold IPD. We also observe that the CDF of IPD at the receiver intersect the CDF of IPD at the sender, at 51.2% and 51.9% corresponding to Operator-2 and Operator-3 respectively. From Figure 4.3 and Table 4.3 we can conclude that the Operators providing us DC-HSPA+ service has superior Jitter performance.
Table 4.3: Percentage of packets received considering a threshold IPD (up-link)

<table>
<thead>
<tr>
<th>IPD (ms)</th>
<th>Operator-1</th>
<th>Operator-2</th>
<th>Operator-3</th>
<th>Operator-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 50 ms</td>
<td>2.1%</td>
<td>10.4%</td>
<td>10.1%</td>
<td>2.8%</td>
</tr>
<tr>
<td>&lt; 500 ms</td>
<td>98%</td>
<td>90.9%</td>
<td>90.3%</td>
<td>97.5%</td>
</tr>
</tbody>
</table>

**OWD Measurement Results (Downlink)**

Figure 4.4 describes the plot of OWD as a function of IP packet size and Table 4.4 summarizes the results in Figure 4.4, which is a summary of number of delay lines observed on the basis of linear fit. The identified delay lines do not show severe segmentation of UDP packets by the NodeB as observed in uplink, as they are received through the 3G network. We observe that packet sizes within the observed delay line are treated similarly. Our experimental results show that packets at best undergo delay as indicated by delay lines, however additional parameters such as queuing and link breakage conditions could effect the delay faced by an IP packet. The major observation that could be made out of this experiment is that the size of packet has a very small effect on the end to end delays measured.

In Figure 4.5 we plot the CDF of OWD for the four Operators in the
Figure 4.4: Plot of OWD as a function of Packet size for the four Operators (downlink)

downlink. Table 4.5 summarizes the important observations in Figure 4.5 presenting the percentage of packets received at the sender considering a threshold OWD in the uplink. The results in Table 4.5 indicate that the Operators using DC-HSPA+ networks have a greater % of packets arriving at the sender below 30 ms, however the CDF curves for Operators providing HSDPA service are steeper. 99.9% of packets arrive at the sender for all the Operators below 60 ms. The difference in OWD initially could also be due to several reasons such as differences in the core network, difference in the softwares used at NodeB etc. However, we suspect that RAN could be significant reason behind the initial lower OWD observed for the Operators providing DC-HSPA+ service [26].

Table 4.4: Delay lines observed in downlink

<table>
<thead>
<tr>
<th>Operator</th>
<th>No. of delay lines observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operator-1</td>
<td>2</td>
</tr>
<tr>
<td>Operator-2</td>
<td>2</td>
</tr>
<tr>
<td>Operator-3</td>
<td>2</td>
</tr>
<tr>
<td>Operator-4</td>
<td>3</td>
</tr>
</tbody>
</table>
CHAPTER 4. EXPERIMENTS AND ANALYSIS

Figure 4.5: CDF of OWD in downlink for Operators considered

Table 4.5: Percentage of packets received considering a threshold delay

<table>
<thead>
<tr>
<th>Delay (ms)</th>
<th>Operator-1</th>
<th>Operator-2</th>
<th>Operator-3</th>
<th>Operator-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 30 ms</td>
<td>10%</td>
<td>1%</td>
<td>2.8%</td>
<td>40%</td>
</tr>
<tr>
<td>&lt; 40 ms</td>
<td>68%</td>
<td>83%</td>
<td>83.8%</td>
<td>89%</td>
</tr>
<tr>
<td>&lt; 50 ms</td>
<td>98.3%</td>
<td>98.8%</td>
<td>99.8%</td>
<td>96%</td>
</tr>
<tr>
<td>&lt; 60 ms</td>
<td>99.9%</td>
<td>99.9%</td>
<td>99.9%</td>
<td>99.9%</td>
</tr>
</tbody>
</table>

Jitter in DC-HSPA+/HSUPA networks (Downlink)

Figure 4.6 presents the CDF of IPD at the sender and receiver in case of downlink. The plot of CDF of IPD at the receiver can be seen as verification of traffic generation process, a straight line having a constant slope could be observed for all the four Operators. We observe that the CDF of IPD at the sender for Operators providing us a DC-HSPA+/HSDPA service is found to be following the CDF of the IPD at the receiver, however the minimum IPD observed is around 0 ms indicating packets arriving immediately after each other. In case of Operator-1, we observe the CDF of IPD at the sender to be indicating a stair-case of width 10 ms possibly indicating TTI of NodeB. Table 4.6 summarizes the observations in Figure 4.6, presenting the percentage of packets arriving at the sender considering a threshold
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IPD. From Figure 4.6 and Table 4.6 we can conclude that the Jitter performance of Operators providing us a HSDPA service is slightly better than the Operators providing us a DC-HSPA+ service.

![Figure 4.6: CDF of IPD for operators considered (downlink)](image)

Table 4.6: Percentage of packets received considering a threshold IPD (downlink)

<table>
<thead>
<tr>
<th>IPD (ms)</th>
<th>Operator-1</th>
<th>Operator-2</th>
<th>Operator-3</th>
<th>Operator-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 50 ms</td>
<td>1.5 %</td>
<td>0.5 %</td>
<td>0.7 %</td>
<td>1.6 %</td>
</tr>
<tr>
<td>&lt; 500 ms</td>
<td>99.4 %</td>
<td>99.7 %</td>
<td>99.7 %</td>
<td>99 %</td>
</tr>
</tbody>
</table>

Conclusions

We conducted experiments in the uplink and downlink for the 3G Operators considered for variable packet size and variable IPD as in [9] using UDP packets. In the uplink we observed segmentation of packets irrespective of Operator and observed clusters of packets undergoing delay in stair case pattern. Delay lines were identified using linear fit and were mapped to the transport block sizes that could be possibly used in the transmission. We observe that OWD and Jitter performance of DC-HSPA+ networks is
better compared to HSUPA networks in the uplink. In the downlink we identified delay lines through a linear fit and estimated jitter using IPD. In the downlink, unlike the uplink, we observe similar OWD performance of DC-HSPA+ and HSDPA networks. HSDPA networks slightly performing better than DC-HSPA+ networks, however the difference is small.

Limitations
The results presented above were performed from single location and experiments were not conducted when for a moving user. Also, the results presented above were that of a single traffic generation method.

Additional results
Additional results are provided in the Appendix A for UDP, TCP and ICMP packets for the experiments conducted in April, May and June. In this case, Operator-2 and Operator-3 provided us HSPA service, while Operator-1 and Operator-4 provided DC-HSPA+ service.

4.2 Treatment of protocols by 3G networks for random packet-size and random IPD

Aim
To compare the OWD in 3G networks for UDP, TCP and ICMP protocols for random packet-size and random IPD in 3G networks.

Objectives
1. To compare the OWD for UDP, TCP and ICMP protocols for DC-HSPA+/HSUPA networks in the uplink and DC-HSPA+/HSDPA networks in the downlink.

Method
To observe the treatment of protocols in 3G networks, we generate 10000 samples for each UDP, TCP and ICMP traffic simultaneously so as to maximize the probability of the generated traffic undergoing similar radio link conditions for a better comparison. The experiments are conducted on the four swedish mobile Operators (Operator-1 and Operator-4) of which two provide us DC-HSPA+ service while other two Operators (Operator-2 and Operator-3) provide us HSUPA/HSDPA service. The three traffic generators are started simultaneously in the uplink from the sender, however in downlink we only start the UDP and TCP generators in the receiver while
we start the ICMP generator at the sender to collect the ICMP reply packets in MP. We collect ICMP reply packets in downlink as we cannot port forward the ICMP packets from the GW to the sender. CDF plots of OWD are plotted in the uplink and downlink. Median plots and OWD plots as a function of time are provided in the Appendix H.

Our method would result in a better comparison as the packets of considered protocols when generated simultaneously, undergo similar conditions in case of link failure or outage.

Traffic Generation

UDP, TCP and ICMP packets are considered in this experiment as used in [17]. Packet sizes and IPD are uniformly distributed as in [9] to distribute the temporal load of network and eliminate co-relation between sendtime and periodic network behaviour respectively. Packet sizes are uniformly distributed between IP packet sizes of [72 1460] and the IPD are uniformly distributed between [50 500] ms.

Measurement Results and Observations

![Figure 4.7: CDF of OWD for considered protocols (uplink)
Table 4.7: Percentage of IP packets received considering a threshold delay (uplink)

<table>
<thead>
<tr>
<th>Delay (ms)</th>
<th>Operator-1</th>
<th>Operator-2</th>
<th>Operator-3</th>
<th>Operator-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 50 ms</td>
<td>48.2%</td>
<td>40.5%</td>
<td>36.1%</td>
<td>81.4%</td>
</tr>
<tr>
<td>&lt; 100 ms</td>
<td>99.2%</td>
<td>94.5%</td>
<td>94.3%</td>
<td>99%</td>
</tr>
<tr>
<td>&lt; 150 ms</td>
<td>99.7%</td>
<td>97.1%</td>
<td>96.6%</td>
<td>99.4%</td>
</tr>
<tr>
<td>&lt; 200 ms</td>
<td>99.8%</td>
<td>98.8%</td>
<td>98.3%</td>
<td>99.6%</td>
</tr>
</tbody>
</table>

Table 4.8: Percentage of packets received considering a threshold delay

<table>
<thead>
<tr>
<th>Delay (ms)</th>
<th>Operator-1</th>
<th>Operator-2</th>
<th>Operator-3</th>
<th>Operator-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 50 ms</td>
<td>70.7%</td>
<td>99.2%</td>
<td>95.2%</td>
<td>94.7%</td>
</tr>
<tr>
<td>&lt; 60 ms</td>
<td>97%</td>
<td>99.7%</td>
<td>99.6%</td>
<td>97.9%</td>
</tr>
</tbody>
</table>

Figure 4.7 and Figure 4.8 present the plot of CDF of OWD for UDP, TCP and ICMP packets in uplink and downlink direction. We observe that CDFs follow each other irrespective of the Operator and the direction. Table 4.7 summarizes the Figure 4.7 while Table 4.8 summarizes the Figure 4.8. The observation of this experiment is contradictory to the experimental findings of [17] as they observe that ICMP packets undergo lower OWD compared to the TCP and UDP packets. This could be because, in [17], the authors generate traffic one at a time, this could possibly result in packets having different link conditions. The traffic generation method used in [17] is very low rate CBR traffic generated at one packet per second, this could result in Operator providing WCDMA, and at one packet per second, ICMP traffic has higher visibility to NodeB due to bi-directional traffic in the uplink and downlink, which could result in NodeB offering comparitively better resources to ICMP traffic compared to TCP traffic and UDP traffic. In our case, as we conduct our experiments using random packet sizes and random IPD, by doing so, we have a higher probability of operating in the dedicated channel, and by generating the traffic simultaneously, we increase the instantaneous load generated by us forcing the Operator to provide us a better service.

Conclusions

We observe that 3G networks treat UDP, TCP and ICMP protocols in similar manner in uplink and downlink irrespective of the Operator. This could be due to generating traffic simultaneously which increases the instantaneous load perceived by the 3G networks and ensures we get the HSDPA/HSUPA/DC-HSPA+ service thereby overcoming the advantage ICMP traffic has at low rates.
Figure 4.8: CDF of OWD for considered protocols (downlink)

Limitations
This experiment as mentioned earlier was conducted for stationary sender and receiver, while we do not conduct experiments when the sender and receiver are mobile. Secondly, our method cannot be directly used to measure OWD for ICMP packets in downlink due to absence of port forwarding in the GW. Thirdly, our experimental measurements reflect the measurements from a single location.

4.3 Effect of Background-Load, IPD and Rates on OWD in 3G networks

Aim
To study the impact of Background Load (BL), constant IPDs and rates on OWD in 3G networks

Objective
1. To compare OWD experienced by packets of applications generating traffic at low rate of one packet per second with and without BL
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in HSUPA/DC-HSPA+ networks in uplink and HSDPA/DC-HSPA+ networks in downlink.

2. To compare the OWD for applications generating traffic at constant IPD in HSUPA/DC-HSPA+ networks in uplink and HSDPA/DC-HSPA+ networks in downlink.

3. To compare the OWD for applications generating CBR traffic at higher rates in HSUPA/DC-HSPA+ networks in uplink and HSDPA/DC-HSPA+ networks in Sweden.

**Method**

To compare the OWD experienced by packets of applications generating traffic at a rate of one packet per second with and without background load, we generate 10000 UDP packets whose packet sizes are uniformly distributed with a constant IPD of one packet per second. The BL of 50 Kbps is generated using UDP packets generated in parallel on another port. These packets are sent from sender to the receiver using the 3G networks, and OWD is measured as described in Chapter 2. We plot the OWD as a function of packet size to observe the mapping of OWD to delay lines identified in Section 1. We also plot the minimum OWD and median OWD as a function of packet size to observe the impact BL has on a delay of low traffic rate generating application. We plot the CDF to observe the overall effect of background load on OWD.

To compare the OWD for applications generating traffic at constant IPD, we consider 10000 samples of UDP traffic generated at constant IPD. The packets are sent from the sender to the receiver and measure OWD as described in Chapter 2. We plot the CDF of OWD in the uplink and the downlink.

To compare the OWD for applications generating CBR traffic at high rates, we generate traffic with constant packet size and constant IPD as in Table H.2 for five minutes into the 3G networks. While conducting the experiments, we conduct the experiments only once as they involve considerable data usage. The subscriptions to the Operators for Operator-1, Operator-2 and Operator-4 are unlimited flat rate subscriptions, while subscription to Operator-3 is data limited. Operator-2, Operator-3 and Operator-4 support over 6 Mbps in the downlink and over 1 Mbps in the uplink, while Operator-1 supports 1 Mbps in the downlink and over 256 Kbps in the uplink (verified [54]). We plot the median delays as a function of rates in the uplink and downlink.
Traffic Generation

While studying the effect of background load on OWD, we generate UDP packets whose IP packet sizes are uniformly distributed between [60 1478]. IPD considered is 1000 ms. The BL is generated using UDP packets having a constant payload size of 100 bytes and IPD of 15.625 ms as chosen in [9].

While studying the effect of constant IPD we generate UDP packets whose IP packet sizes are uniformly distributed between [60 1478]. Four IPD are considered for each Operator, they are 50 ms, 275 ms, 500 ms and 1000 ms.

While studying the effect of rates on OWD, we increases the packet sizes in steps of 100 bytes. The rates considered are 64 Kbps, 128 Kbps, 256 Kbps, 512 Kbps, 1024 Kbps, 2048 Kbps and 4096 Kbps for Operator-2, Operator-3 and Operator-4 in the downlink. In the uplink, we consider 64 Kbps, 128 Kbps, 256 Kbps, 512 Kbps and 1024 Kbps in the uplink for the above Operators. For Operator-1 we consider upto 1024 Kbps in the downlink and upto 256 Kbps in the uplink. The detailed configurations of packet sizes and IPD are provided in tables in the Appendix I.

Measurement Results and Observations

This section is divided into three sub-sections. The first sub-section discusses the effect of BL, while the second sub-section discusses the effect of constant IPD while the third sub-section discusses the effect of rates on OWD.

Background-load - Uplink

Table 4.9: Percentage of packets received considering a threshold delay (with and without BL)

<table>
<thead>
<tr>
<th>Delay (ms)</th>
<th>Operator-1</th>
<th>Operator-2</th>
<th>Operator-3</th>
<th>Operator-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 50 ms</td>
<td>41.5 %</td>
<td>3.8 %</td>
<td>0.9 %</td>
<td>33.7 %</td>
</tr>
<tr>
<td>&lt; 50 ms (BL)</td>
<td>50.3 %</td>
<td>22.8 %</td>
<td>26.5 %</td>
<td>92 %</td>
</tr>
<tr>
<td>&lt; 75 ms</td>
<td>88 %</td>
<td>5.7 %</td>
<td>6.6 %</td>
<td>81 %</td>
</tr>
<tr>
<td>&lt; 75 ms (BL)</td>
<td>94.4 %</td>
<td>76.2 %</td>
<td>82.9 %</td>
<td>99.3 %</td>
</tr>
<tr>
<td>&lt; 100 ms</td>
<td>99 %</td>
<td>13.3 %</td>
<td>13.3 %</td>
<td>97.9 %</td>
</tr>
<tr>
<td>&lt; 100 ms (BL)</td>
<td>99.1 %</td>
<td>91.7 %</td>
<td>93.4 %</td>
<td>99.6 %</td>
</tr>
</tbody>
</table>

The median OWD of the traffic sent is plotted in Figure 4.9, we observe that median delays of each case map to different delay lines with the median of packets with BL mapping to the low-delay line identified in the earlier sections while the packets without the BL map to highest delay line identified in earlier section. In Figure 4.10, we plot the CDF of OWD and observe that the performance of packets with BL would benefit the OWD experienced.
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Figure 4.9: Median OWD in uplink (with and without BL)

Figure 4.10: CDF of OWD in uplink (with and without BL)
by packets generated by low rate applications. Table 4.9 summarizes the important observations for the considered Operators.

The observations could possibly be due to NodeB perceiving higher loads emanating from the sender, thereby providing the sender higher bandwidth channel for uplink transmission. This has an affect on TFC and modulation schemes used by the GW (UE) to transmit the packets over 3G networks resulting in lower OWD. In the case of one packet per second with out BL, there could be few packets that could have been transmitted using WCDMA which further increases the delay and could deteriorates the performance of the application.

**Background-load- Downlink**

In Figure 4.11, we plot the median of OWD as a function of packet size in the downlink. For all the Operators, we observe that most of packets with out the BL undergo a higher delay while the packets with BL undergo a lower delay. Interestingly in Figure 4.11 for Operator-1, we note that shift from lower delay line to the upper delay line happens for a relatively smaller packet size for packets without background load. In Figure 4.12, we plot the CDF of OWD in the downlink and observe that for all the Operators, performance of packets with BL would benefit the OWD experienced by packets generated by low rate applications. Table 4.10 describes the observations in Figure 4.12.

The observations could possibly be due to NodeB perceiving higher loads emanating from the sender, thereby providing the receiver higher bandwidth channel for downlink transmission. This has an affect on TFC and modulation schemes used by the NodeB to transmit the packets over 3G networks resulting in lower OWD. In the case of one packet per second with out BL, there could be few packets that could have been transmitted using WCDMA which further increases the delay and could deteriorates the performance of the application.

<table>
<thead>
<tr>
<th>Delay (ms)</th>
<th>Operator-1</th>
<th>Operator-2</th>
<th>Operator-3</th>
<th>Operator-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 40 ms</td>
<td>1.6 %</td>
<td>84 %</td>
<td>80 %</td>
<td>86.5 %</td>
</tr>
<tr>
<td>&lt; 40 ms (BL)</td>
<td>1.6 %</td>
<td>78.7 %</td>
<td>78.7 %</td>
<td>86.5 %</td>
</tr>
<tr>
<td>&lt; 50 ms</td>
<td>47 %</td>
<td>92.3 %</td>
<td>92.5 %</td>
<td>93.3 %</td>
</tr>
<tr>
<td>&lt; 50 ms (BL)</td>
<td>66.9 %</td>
<td>99 %</td>
<td>99 %</td>
<td>99.5 %</td>
</tr>
</tbody>
</table>
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Figure 4.11: Median OWD in Downlink (with and without BL)

Figure 4.12: CDF of OWD in the downlink (with and without BL)
OWD for Constant IPD

In Figure 4.13, we plot the CDF for chosen IPD in the uplink. We observe for all the Operators that the OWD of packets with 50 ms IPD, map to the lower base delay lines while the packets with 1000 ms and 500 ms map to the higher base delay lines. This is due to the ETFC grants awarded by the Node B to the GW. The difference is not so pronounced for Operator-1 while in the case of Operator-2 and Operator-3, we observe that the packets with IPD of 275 ms are spread across the lower and higher delay lines. In the case of Operator-4, we observe that packets with IPD 275 ms receive similar treatment as packets with IPD of 1000 ms and 500 ms. For all the Operators, we observe that packets with IPD 50 ms receive the best treatment.

In the case of downlink in Figure 4.14, we observe similar OWD for the packets with IPD of 50 ms, 275 ms and 500 ms for all the Operators and the OWD is lower than packets with IPD of 1000 ms. In all the cases, packets generated with 50 ms IPD has lower OWD than packets generated at a higher IPD. Operator-4 shows a clear distinction for packets generated at 50 ms IPD. The observations indicate a strong affect of rate on OWD for UDP packets in the uplink and downlink of 3G networks.

OWD at higher rates

The experiments were conducted during the late May and in the month of June. Figure 4.15 and Figure 4.17 plots the minimum OWD for the UDP packets sent at different rates in the uplink and the downlink respectively. In the uplink and downlink, the measurement results indicate that at higher rates, the grants by the NodeB takes precedence over the sending rates. This could be due to the power control mechanisms employed by the NodeB on the GW in the uplink and the bandwidth sharing and scheduling mechanisms by the NodeB in the downlink [26]. Figure 4.16 and Figure 4.18 show the OWD plot for CBR traffic for 128 Kbps and explains the possible reason behind the irregularities in plot of minimum OWD as a function of packet size, which is expected to be a straight line. It could be quite possible that during the five minutes of experiment, the packet could undergo a delay corresponding to higher delay line due to scheduling/power control by the NodeB. In case of Operator-1 in the downlink in Figure 4.17, as we approached the maximum rate provided by the Operator, we observed abnormally high delays for all the packets. This could be due to rate-control mechanisms employed by the Operator. We could not complete the results for Operator-3 as we exceeded the data limit set to us and in the next month, the Operator changed the service provided.
Figure 4.13: CDF of OWD for Constant IPD (uplink)

Figure 4.14: CDF of OWD for Constant IPD (downlink)
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Figure 4.15: Minimum OWD- CBR Streaming (uplink)

Figure 4.16: OWD for CBR Streaming (uplink)
CHAPTER 4. EXPERIMENTS AND ANALYSIS

Figure 4.17: Minimum OWD- CBR Streaming (downlink)

Figure 4.18: OWD for CBR Streaming (downlink)
Conclusions

We observe that the instantaneous load perceived by the NodeB has a significant impact on the OWD. In case of an application generating traffic at very low rate, its packets would have a lower OWD in the presence of BL emanating from the same source. However if the BL is increased as in this case to greater than 50 Kbps, packets could not possibly experience a lower OWD as the current OWD obtained with BL already corresponds to low OWD lines identified in the earlier section.

In case of constant IPD, we observe that traffic sources having a lower IPD would have lower OWD, however the OWD could not be lower than the low delay lines identified in the earlier sections.

In case of CBR traffic at higher rates, we observed that rates do not have a significant impact on minimum and median OWD (Refer Appendix J), however the grants provided the Operator have a significant role in the observed OWD during the stipulated experimental time. The grants are dependent on the number of active users in the cell, available bandwidth and scheduling mechanisms at the NodeB.

Limitations

The limitations are similar to those mentioned in the previous section. Additionally, CBR experiments were performed only for a single run. Experiments could not be repeated due to change in service by the Operator.

4.4 OWD Comparison for Varying IPD

Aim

To compare OWD experienced by packets of applications generating traffic at random IPD in 3G networks.

Objective

To compare OWD experienced by packets of applications generating traffic whose packet sizes are uniformly distributed and their IPD, uniformly distributed and having a constant mean.

Method

To compare the OWD for traffic having random IPD with a constant mean, we generate 10000 UDP packets whose packet sizes are uniformly distributed and their IPD uniformly distributed over a constant mean. We consider [50 500] ms IPD as chosen in [9] and gradually shrink the interval to the mean and compare the OWD of UDP packets in 3G networks. These packets
are sent from sender to the receiver using the 3G networks and OWD is measured as described in Chapter 2. We plot the CDF for both OWD and standard deviation of OWD measured for the four Operators we consider.

Traffic Generation

We generate UDP packets whose IP packet sizes are uniformly distributed between [60 1478]. Four IPD are considered for each Operator, they are [50 500] ms, [150 400] ms, [250 300] ms and 275 ms. We refer to these four cases as transmission schemes.

Measurement Results and Observations

This section is divided into two sub-sections: uplink and the downlink measurements. Each subsection discusses the CDF for OWD and the Standard deviation for the OWD.

OWD Measurement Results(Uplink)

Figure 4.19 presents the CDF of OWD in the uplink for the four transmission schemes considered. We observe for the Operator-2 and Operator-3, that the traffic generated with IPD of [50 500] ms gets a better treatment compared to rest of the transmission schemes, while traffic generated with IPD of 275 ms constant IPD undergoes a higher OWD. This could be due to higher ETFC-I grant allocation in case of transmission of two larger packets within smaller IPD which could have possibly triggered NodeB due to higher instantaneous rate produced due to this transmission scheme (refer Figure. x.y in chapter 3). As the higher grants are retained before reverting to a lower grant, this could result in smaller packets obtaining a better treatment and bigger packets undergo segments of larger sizes which would benefit the overall OWD performance of the application. The instantaneous rate that triggers the NodeB depends upon the network settings. The Operator-1 and Operator-4 do not show a distinct behavior as Operator-2 and Operator-3.

Figure 4.20 plots the CDF of standard deviations of packet sizes in the uplink, we observe that for Operator-2 and Operator-3, the CDF of standard deviations are in the order of their OWD behavior, however for Operator-4 in the opposite order of observations in Operator-2 and Operator-3. This observation is strange and this observation could be due to more number of packets being transmitted using a single ETFC-I in operator-4.

OWD Measurement Results(Downlink)

Figure 4.21 presents the CDF of OWD in the uplink for the four transmission schemes considered. We observe for the Operator-3 and Operator-4,
Figure 4.19: CDF of OWD for shrinking IPD (uplink)

Figure 4.20: CDF of standard deviations for shrinking IPD (uplink)
that the traffic generated with IPD of \([50 \ 500]\) ms gets a better treatment compared to rest of the transmission schemes, while traffic generated with IPD of \(275\) ms constant IPD undergoes a higher OWD. These observations could be due to similar reasons as stated in the uplink. Operator-1 and Operator-2 do not show a distinct difference in the OWD performance.

Figure 4.22 plots the CDF of standard deviations of packet sizes in the uplink, we observe that for Operator-1 and Operator-2, the CDF of standard deviations are similar for the selected transmission patterns, however for Operator-4 we observe that traffic generated with IPD of \([250 \ 300]\) ms and \(275\) ms are treated better than traffic with IPD of \([50 \ 500]\) ms and \([150 \ 400]\) ms. This could be due to more number of packets being transmitted using a single ETFC-I. In Operator-3, we observe that CDF of standard deviation are in the order of their OWD CDF for different transmission patterns.

**Conclusions**

We observe that random IPD has an affect on OWD. Packets of applications generating traffic with spread IPD (with a constant mean) and higher variance are more likely to undergo lower OWD than packets of applications generating a constant IPD. This is due to the triggering of higher ETFC-I grant when two larger packets are transmitted within a smaller IPD (in case of pattern with IPD having higher variance), this would inturn benefit the smaller packets due to retaining of higher ETFC-I grant till NodeB senses a lower instantaneous rate.

We also observe that packets could be transmitted using a single TFC resulting in lower variation of standard deviation (in case of operator-4).

The results of this experiment could hypothesize that packets of application generating traffic with constant packet size with IPD (constant mean, higher variance) would undergo lower OWD than packets of an applications generating traffic with constant packet size and IPD (constant mean, lower variance).

**Limitations**

The limitations for the experimental results are similar to those stated in Section 1, Additionally, the experiments must be carried out with a fixed IP address, as change of IP address by the operator could make the results incomparable. technically, link conditions could also impact comparison, however the threat is not severe on basis of experimental runs conducted.
CHAPTER 4. EXPERIMENTS AND ANALYSIS

Figure 4.21: CDF of OWD for shrinking IPD (downlink)

Figure 4.22: CDF of standard deviation for shrinking IPD (downlink)
4.5 OWD Comparison for Constant-Bit-Rate (CBR) versus Variable-Bit-Rate (VBR)

Aim
To compare the OWD for CBR and VBR traffic generating patterns.

Objective
To compare OWD experienced by packets of applications generating traffic whose packet sizes and IPD are constant, to the applications generating traffic with random packet sizes and constant IPD.

Method
To compare the OWD for packets of applications generating traffic with constant constant packet size and constant IPD to the applications generating traffic with random packet sizes and constant IPD: we generate 50 UDP packets of a constant packet size starting at minimum packet size in case of random packet sizes case, at one packet per second. We then wait for 5 seconds before generating another stream of 50 packets with packet size incremented by four. Packet size is incremented in small step sizes till the maximum packet size as in random packet size case, as to not miss the possible segmentation which would be visible if small step sizes are chosen. We wait for 5 seconds as to let go the higher ETFC-I grant if granted to the previous packet size. We plot the minimum OWD as a function of packet size and CDF of OWD and for the four Operators we consider in both the uplink and downlink. The obtained OWD is then compared to OWD obtained for packets transmitted with random packet size and constant IPD of one second.

Traffic Generation
We generate UDP packets whose IP packet sizes are uniformly distributed between [60, 1478] at one packet per second. In the CBR case, UDP packet sizes are generated in steps of four between [60, 1476] at one packet per second.

Measurement Results and Observations
This section is divided into two parts, the uplink and the downlink. Each section discusses the minimum OWD and CDF of OWD for the CBR and VBR traffic in the 3G mobile networks.
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OWD Measurement Results (Uplink)

Figure 4.23 plots minimum OWD as a function of packet size in the uplink. We observe that for Operator-1 in general that, the minimum OWD of the packets generated using CBR pattern to be similar to the minimum OWD of packets generated using VBR. In case of VBR, we observe a spread of the minimum OWD across delay lines identified in Section 1 as the packets follow a random transmission pattern and the spread is haphazard. On the contrast, for packets following CBR pattern of generating packets, we observe that in case of packets of sizes 212 to 252 bytes, 540 to 568 bytes, 640 to 732 bytes and few samples from 780 to 956 bytes have a higher base delay line than the rest of plot, this is possibly due to impact of ETFC-I grants, as we know that the grants can be withdrawn on instantaneous conditions such as radio links and instantaneous cell loads. Few packets also undergo a lower delay than the base delay obtained indicating a higher capacity. Operator-1 possibly uses enhanced RACH in the uplink [26]. We could come to this conclusion as we do not observe packets with high end to end delays as it was observed in [12]. This operator probably uses E-DCH as transport channel and E-DPDCH as the physical channel [26] for smaller packets as well. In the case of Operator-2 and Operator-3, we observe OWD as a function of packet size to follow a stair case, this could be due to the packets transmitted using the WCDMA, the width of the stair case is approximately 40 Bytes. This could be mapped to using RACH as the transport channel and PRACH as the physical channel [26]. There is a complete transition from Cell-FACH to Cell-DCH mode at 216 bytes, though few samples below packet sizes of 216 undergo transmission in Cell-DCH mode. The state/mode of the GW (UE) is verified by monitoring the state of the GW in the sender as we know that cell-DCH state is available in the HSPDA/HSUPA/DC-HSPE while RACH/FACH is available in WCDMA [26]. We also observe that the IP packets of sizes 350 to 600 undergo chaotic behavior as we observe a shift of ETFC-I grants. We could make this observation on the basis of OWD plotted as a function of packet size (refer Appendix J). A spread of minimum delays is experienced which could possibly be due to random transmission patterns. For Operator-4, we observe a similar stair case behavior for packets upto 216 bytes. This observation is due to the same reasons as in case Operator-2 and Operator-4. For the rest of the IP packets, the minimum OWD is similar to the one obtained for random packet sizes. We observe a similar spread of minimum OWD for random payload sizes due to the same reason as above. We observe the cell-DCH state for most of the packets in the uplink when random packet size is chosen , as the E-DCH is maintained, this is extremely beneficial as when a small packet follows a larger packet, the smaller packet which is actually meant to have a higher OWD obtains a better treatment, because it retains the grant of the previous packet, an aggregate effect of this behavior is observed when the IP packet size is
randomly chosen.

In Figure 4.24, we plot the CDF of OWD for the CBR and the VBR cases and observe that Operator-2, Operator-3 and Operator-4 treat VBR traffic better in the uplink. However, Operator-1 doesn't show significant improvement in treatment of the VBR traffic in the uplink.

**OWD Measurement Results (Downlink)**

In Figure 4.25, we plot the OWD as a function of packet size in the downlink. We observe that for Operator-1, there is a seamless transition from cell-FACH mode to cell-DCH mode at 76 bytes. This behavior could not just be due to the IP packet sizes, but could possibly be due to the time taken for the seamless transition: which can at times be larger or smaller than what we experienced now. We experience an increase in OWD for IP packets exceeding size of 800 bytes for either of the packets following a random transmission pattern and the CBR pattern. For the Operator-2 and Operator-3, we observe that there is a complete transition from cell-FACH mode to cell-DCH mode at 256 bytes. We observe that, after the allocation of the E-DCH, the plot of Minimum OWD is almost flat, and it follows the minimum OWD obtained by choosing the random packet sizes. For Operator-4, we observe the transition from cell-FACH state to cell-DCH state at packet size of 440 bytes, and at 500 bytes we observe an abnormal jump in the OWD as observe a higher OWD for either of the packets following different transmission methods. We observe a majority of packets to be received in cell-DCH state due to same reason as in uplink. A smaller packet could be transmitted using a higher ETFC-I grant obtained after two larger packets are received by the GW (UE). This effect is aggregated when the packets are randomly received.

In Figure 4.26, we plot the CDF of OWD for the CBR and the VBR cases and observe that Operator-2, Operator-3 and Operator-4 treat VBR traffic better in the downlink. However, Operator-1 does not show significant improvement in treatment of the VBR traffic in the downlink.

**Conclusions and Discussion**

We observe that operators in exception of Operator-1, provide Cell-DCH to a UE in the uplink and downlink on the basis of packet size, however this experiment proves that the instantaneous rate of transmission or reception of packets govern the switch from the Cell-FACH to Cell-DCH state.

This may seem unfair at the outlook, however most of the devices that utilize mobile broadband run on battery, which is power constrained. By maintaining cell-DCH state, the power consumption of the UE increases which drains the battery as power consumption in cell-DCH is twice as that of power consumption in cell-FACH[55]. Since most of the applications
CHAPTER 4. EXPERIMENTS AND ANALYSIS

Figure 4.23: Minimum OWD for CBR vs VBR (uplink)

Figure 4.24: CDF of OWD CBR vs VBR (uplink)
Figure 4.25: Minimum OWD for CBR vs VBR (downlink)

Figure 4.26: CDF of OWD CBR vs VBR (downlink)
generate a low amount of background traffic, by maintaining cell-DCH state, we risk the possibility of losing the UE power. So we consider this a fair trade off for the mobile devices. However we would like to add that users using a dedicated gateway such as VA126, which runs on AC power is not power constrained and this could be unfair for static users who would like to use mobile broadband as a substitute for fixed wired connections. With more users switching to the mobile broadband as a replacement for the fixed connections, this is an interesting problem for the mobile operators to decide. Another advantage of cell-FACH state is that it takes less time taken to set up a bi-directional dedicated channel [26].

Limitations

The measurement results in this section have limitations similar to those of Section. 1 in results.
Conclusions and Future work
Chapter 5

Conclusions and Future work

This chapter is comprised of two sections. Section 5.1 summarizes the results presented in this thesis work. Section 5.2 presents our future work.

5.1 Conclusion

We summarize our thesis by briefly answering our research questions on the basis of our experimental results.

1. What is effect of operator service (HSUPA/HSDPA/DC-HSPA+) on OWD (Uplink and Downlink) in 3G networks?
   • Is there a difference in observed OWD on the basis of operator-service provided by operator?
   • What is impact of operator-service on Jitter?

   Ans. Firstly, operator service has an impact on OWD in 3G networks. It has got a greater impact in the uplink than the downlink. On the basis of experimental results, the DC-HSPA+ service is superior to HSUPA service in the uplink as the packets undergo lower OWD and a better jitter performance, however the DC-HSPA+ service does not have a clear advantage in the downlink over HSDPA. We estimate jitter on the basis of IPD at the sender and receiver. We also observed that the uplink and the downlink are asymmetric in the recently deployed DC-HSPA+ networks and end to end latency has dropped significantly compared to the previously recorded live network measurement results in Sweden. The software developers may in fact use the segmentation of IP packets by the RLC to reduce latency in the generated application traffic. This could be done by choosing packet sizes equal to the width of the stair case patterns observed.
2. Does protocol of selected traffic namely UDP/TCP and ICMP have an affect on OWD for random IP packet sizes and Inter-Packet Durations (IPD)?

**Ans.** The protocol of the IP packets do not have an effect on the OWD when the load is temporally distributed. We observe that 3G networks treat UDP, TCP and ICMP protocols in similar manner in uplink and downlink irrespective of the Operator (section 4.2). This could be due to generating traffic simultaneously which increases the instantaneous load perceived by the 3G networks and ensures we get the HSDPA/HSUPA/DC-HSPA+ service thereby overcoming the advantage ICMP traffic has at low rates.

3. Does Inter-Packet Duration (IPD) (Constant) of generated traffic have an effect on OWD (Uplink and Downlink)? Does background load have an effect when application generates traffic that has a very low constant IPD of 1 second?

**Ans.** Yes, the IPD (constant) of generated traffic has an affect on OWD of UDP packets in 3G networks. On the basis of measurement results (section 4.3), we observed that the packets having lower IPD have significantly lower OWD. A similar experiment was conducted and we observed that packets pumped at lower rate having BL undergo lower end to end delay. This observation enables us to conclude that the instantaneous load perceived by the NodeB has a significant impact on the OWD. We also conducted streaming experiments at higher rates and observed that ETFC-I grants have a very significant impact on the OWD when we stream data at higher rates.

4. Does shrinking the uniformly distributed IPD, maintaining a constant mean have an effect on OWD when packet sizes are random in 3G networks?

**Ans.** Yes, Shrinking an uniformly distributed IPD has an affect on OWD. Packets of applications generating traffic with spread IPD (with a constant mean) and higher variance are more likely to undergo lower OWD than packets of applications generating a constant IPD. This is due to the triggering of higher ETFC-I grant when two larger packets are transmitted within a smaller IPD (in case of pattern with IPD having higher variance), this would intern benefit the smaller packets due to retaining of higher ETFC-I grant till NodeB senses a lower instantaneous rate. We also observe that packets could be transmitted using a single TFC resulting in lower variation of standard deviation (in case of operator-4).
5. What is impact of traffic generation pattern on OWD when comparing the random vs CBR pattern?

**Ans.** Traffic generation pattern has a significant impact on OWD at low rates due to majority of smaller packets being transmitted using WCDMA in the FACH/RACH and E-FACH/E-RACH, while the packets transmitted using the random packet sizes use the enhanced dedicated channels for their transport. This results in the VBR traffic undergoing a lower cumulative OWD compared to CBR traffic. However, this has a trade-off where the power levels of the battery drain when the UE is in cell-DCH mode. Since most of the applications generate a low amount of background traffic, by maintaining cell-DCH state, we risk the possibility of losing the UE power. So we consider this a fair trade off for the mobile devices. However we would like to add that users using a dedicated gateway such as VA126, which runs on AC power which is not power constrained and this could be unfair for static users who would like to use mobile broadband as a substitute for fixed wired connections. With more users switching to the mobile broadband as a replacement for the fixed connections, this is an interesting problem for the mobile operators to decide.

We conclude our thesis as: By observing that packet size has a significant impact on OWD at low rates while the instantaneous rate has a significant impact on the OWD at high rates. However, it is the ETFC grants that dictate the OWD at higher rates.

### 5.2 Future work

The current work only aims to study the impact of the packet size and rate on the user perceived OWD. This work can be extended in many ways. Firstly, Quality of Service (QoS) provided by the operators can possibly be investigated by varying the Type Of Service (TOS) field in the IP of the generated traffic. For this task, there is a need for UDP and TCP generators based on raw sockets having the functionality of existing traffic generators. Impact of port numbers used for sending and receiving the traffic have not been fully investigated, though the initial drive tests do not show a perceivable difference in the OWD when port numbers are changed. However, it would be interesting to consider the impact of combination of the protocol and TOS field in the network layer coupled with the port numbers. The impact of transmission patterns at the higher rates is yet to be investigated. The packet sizes and IPD considered for majority in this thesis are uniformly distributed; it would be interesting to consider the statistical nature of the traffic. The existing traffic generators are also capable of generating IP traf-
fic with IPD which is exponentially distributed. Considering the quantum of work done in this thesis, we could not characterize the losses in the DC-HSPA+/HSPA+ networks. Traffic generated in this thesis is artificial. It would be interesting to measure the OWD at the application level on the live DC-HSPA+/HSPA networks. The CBR measurements presented in the thesis are not repeated for significant number of times, an exhaustive study on streaming performance could be conducted on the DC-HSPA+ networks. In this thesis, we could measure metrics such as Delay, Loss and Jitter, and a lot of focus was on user perceived OWD. But, we would also like to add that considering the relatively shorter span for conducting this thesis, we could not establish relationships between the user perceived OWD, Loss and Jitter on the user perceived Quality of Experience (QoE) [56]. In this thesis, we only considered the perception of a static user. There is a need to consider the perception of mobile broadband by a true mobile user who needs a suitable test-bed for conducting quality assured research measurements.
Appendix
Appendix A

A.1 Operator Services

This section shows the screen-shots of the user interface of the VA126 GW. The screen shots show the service being offered by the operators. Figure A.1 shows the DC-HSPA+ service of Telenor, Figure A.2 shows the HSPA service of Telia, Figure A.3 shows the HSPA service of Tele2 and lastly Figure A.4 shows the DC-HSPA+ service of Tre.

In the Figure A.2 and Figure A.3 we notice that the service shares the same RAN from the numeric location, cell Identification(ID).
Figure A.1: DC-HSPA+ Service of Operator-1
## Network Status

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<thead>
<tr>
<th>State</th>
<th>Connected (refresh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IP Address</td>
<td>90.237.139.247</td>
</tr>
<tr>
<td>Subnet Mask</td>
<td>255.255.255.255</td>
</tr>
<tr>
<td>Primary DNS</td>
<td>195.67.199.27</td>
</tr>
<tr>
<td>Secondary DNS</td>
<td>195.67.199.28</td>
</tr>
<tr>
<td>MTU</td>
<td>1500</td>
</tr>
</tbody>
</table>

## Traffic Statistics

| RX Packets | 75  |
| RX Bytes   | 10750 |
| TX Packets | 84  |
| TX Bytes   | 8763 |

## Connection Profiles

<table>
<thead>
<tr>
<th>Active Profile</th>
<th>Telia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Profile Selection</td>
<td>Telia</td>
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</tbody>
</table>

## Module

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<tr>
<th>IMSI</th>
<th>240016010035526</th>
</tr>
</thead>
<tbody>
<tr>
<td>IMEI</td>
<td>351829040026806</td>
</tr>
<tr>
<td>Firmware</td>
<td>N1_1_1_7AP</td>
</tr>
</tbody>
</table>

## Network

<table>
<thead>
<tr>
<th>Network State</th>
<th>Registered HSDPA/HSUPA (WCDMA 2100)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Network Operator</td>
<td>Telia</td>
</tr>
<tr>
<td>Service Provider</td>
<td>Telia</td>
</tr>
<tr>
<td>Received Signal Strength</td>
<td>-75 dBm</td>
</tr>
<tr>
<td>Numeric Location, Cell ID</td>
<td>0041, 0041512E</td>
</tr>
</tbody>
</table>

Figure A.2: HSDPA/HSUPA Service of Operator-2
### Network Status

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</tr>
<tr>
<td>Subnet Mask:</td>
<td>255.255.255.255</td>
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<tr>
<td>Primary DNS:</td>
<td>130.244.127.161</td>
</tr>
<tr>
<td>Secondary DNS</td>
<td>130.244.127.169</td>
</tr>
<tr>
<td>MTU:</td>
<td>1500</td>
</tr>
</tbody>
</table>

### Traffic Statistics

| RX Packets: | 244     |
| RX Bytes:   | 268091  |
| TX Packets: | 303     |
| TX Bytes:   | 340151  |

### Connection Profiles

- **Active Profile**: Tele2
- **Profile Selection**
  - Tele2
  - Activate
  - Edit
  - Delete
  - Add...

### Module

- **IMSI**: 240070501556177
- **IMEI**: 351829040026806
- **Firmware**: N1_3_1_7AP

### Network

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</thead>
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</tr>
<tr>
<td>Service Provider:</td>
<td>Tele2</td>
</tr>
<tr>
<td>Received Signal Strength:</td>
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</tr>
<tr>
<td>Numeric Location, Cell ID:</td>
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Figure A.3: HSDPA/HSUPA Service of Operator-3
### Network Status

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<th>Value</th>
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<td>IP Address</td>
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<tr>
<td>Subnet Mask</td>
<td>255.255.255.255</td>
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<tr>
<td>Primary DNS</td>
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<tr>
<td>Secondary DNS</td>
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<tr>
<td>MTU</td>
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</tr>
</tbody>
</table>

### Traffic Statistics

<table>
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<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>RX Packets</td>
<td>74</td>
</tr>
<tr>
<td>RX Bytes</td>
<td>63739</td>
</tr>
<tr>
<td>TX Packets</td>
<td>85</td>
</tr>
<tr>
<td>TX Bytes</td>
<td>65238</td>
</tr>
</tbody>
</table>

### Connection Profiles

- **Active Profile:** Three
- **Profile Selection:** Three

### Module

- **IMSI:** 240020002700682
- **IMEI:** 351829040026806
- **Firmware:** N1_1_1_7AP

### Network

- **Network State:** Registered DC-HSPA+ (WCDMA 2100)
- **Network Operator:** 3
- **Service Provider:** 3
- **Received Signal Strength:** -63 dBm
- **Numeric Location, Cell ID:** 75FA, 0123E4D3

---

Figure A.4: DC-HSPA+ Service of Operator-4
Appendix B

B.1 Traffic Generator Validation

This section presents the validation of the traffic generator. Uplink measurements are used to validate the traffic generator. We chose a traffic generator to check the packet size and IPD distributions. It must be noted that the traffic generator has a significant impact on measurement process as in [22].

B.1.1 Plot of CDF of Packet-sizes

Figure B.1 presents the plot of percentile and CDF for the uniformly distributed IP packet sizes. Packet sizes are distributed between 60 and 1478 bytes.

B.1.2 Plot of Histogram CDF of Inter-arrival gaps

Figure B.2 presents the plot of percentile and CDF plot of IPD. In the first subplot, the IPD is uniformly distributed between 50 and 500 ms. In the second subplot, the IPD is uniformly distributed between 150 and 400 ms. In the third subplot, the IPD is uniformly distributed between 250 and 300 ms. In the fourth subplot, we use a constant IPD of 275 ms.
Figure B.1: Plot of percentile and CDF for uniformly distributed IP packet-sizes
Figure B.2: Plot of percentile and CDF plot of IPD
Appendix C

C.1 DPMI Validation

The same experimental setup is built with 10 meter wire between sender and receiver. And the values in the graphs are compared with L/0.5C, where L is length of wire and C is velocity of light. There is no significant difference. We see approximately 60 ns and 120 ns. The 120ns delay line is due to missing the clock pulse.

Figure C.1: DPMI validation
Appendix D

D.1 Perl Analyzer Tool Validation

D.1.1 Sample Trace file


D.1.2 Output of analyzer (OWD)

Read as Sequence number, time stamp at receiver, time stamp at sender, OWD, packet size, IP-ID

3 1313834964.550067961250 1313834964.585754454250 0.035686493 1397
0

4 1313834965.549944460500 1313834965.585923969750 0.03597950925 11754DF
0

D.1.3 Output of Analyzer(Loss)

Number of packets sent from 194.47.148.30 to 192.168.0.5 with 90.237.171.38 as Gateway: 10019

Number of packets received from 194.47.148.30 to 192.168.0.5 with 90.237.171.38 as Gateway: 10015

Packet delivery ratio is 0.9996007585587383970456133346641381375387
D.1.4 Error Verification

\[ 1313834964.585754454250 - 1313834964.550067961250 = 0.035686493 \]
\[ 1313834965.585923969750 - 1313834965.549944460500 = 0.03597950925 \]
Loss = \( \frac{10015}{10019} = 0.9996007... \)
Error : nill until six decimal places
Ability to reproduce time stamps: Yes.
So this tool is valid to be used in this thesis.
Appendix E

E.1 Extended Gateway Evaluation

Figure E.1: Extended Gateway Evaluation-shrinking interval CDF
Figure E.2: Extended Gateway Evaluation-CBR

Figure E.3: Extended Gateway Evaluation-Constant IPD
Figure E.4: Extended Gateway Evaluation-constant IPD CDF

Figure E.5: Extended Gateway Evaluation-shrinking interval
Appendix F

F.1 Operator Traces

This section shows the traceroute of the four operators considered in our thesis. These results were collected on 15 August 2011. We also present the RTT for the Ping request/reply messages to the operator exchanges from the receiver to estimate the delay due to the SUNET and the BTH networks. The ICMP payload sizes of 50 bytes to 1450 bytes as in [9] is considered to present the RTT statistics. A '*' indicates a failed DNS query in the traceroute. Standard traceroute [46] and ping commands are used for these statistics.

F.1.1 Operator-1

Traceroute

Tracing route to comfer.tek.bth.se [194.47.148.30] over a maximum of 30 hops:
1 2 ms 1 ms 1 ms 192.168.0.1
2 63 ms 59 ms 217.174.64.73
3 147 ms 89 ms 69 ms u93.dialup.net.vodafone.se [217.174.68.93]
4 77 ms 59 ms ti3004d300-ge2-0-2.ti.telenor.net [146.172.106.229]
5 87 ms 59 ms ti3004c310-ae8-0.ti.telenor.net [146.172.99.41]
6 55 ms 59 ms ti3004b300-ae0-0.ti.telenor.net [146.172.105.42]
7 68 ms 69 ms 139 ms c2sth-ge-5-1-0.sunet.se [195.69.117.19]
8 57 ms 59 ms ti1tug-ae0-v1.sunet.se [130.242.83.38]
9 58 ms 59 ms m1tug-ae0-v1.sunet.se [130.242.83.42]
10 78 ms 79 ms 79 ms ls-bth-br2.sunet.se [193.11.0.106]
11 78 ms 79 ms 79 ms bthred-ge-0-25.net.bth.se [194.47.128.250]
12 77 ms 81 ms 81 ms kna-vss-vl18.net.bth.se [194.47.128.78]
13 95 ms 79 ms 79 ms comfer.tek.bth.se [194.47.148.30]
Trace complete.
RTT

RTT for 32 Byte ICMP payload (60 byte IP packet size)
PING 195.69.117.19 (195.69.117.19) 32(60) bytes of data.
— 195.69.117.19 ping statistics —
10000 packets transmitted, 10000 received, 0% packet loss, time 9999665 ms
rtt min/avg/max/mdev = 12.656/14.771/87.865/6.329 ms

RTT for 1450 Byte ICMP payload (1478 IP packet size)
PING 195.69.117.19 (195.69.117.19) 1450(1478) bytes of data.
— 195.69.117.19 ping statistics —
10000 packets transmitted, 10000 received, 0% packet loss, time 9998997 ms
rtt min/avg/max/mdev = 16.077/17.885/100.539/7.856 ms

F.1.2 Operator-2

Traceroute

Tracing route to confer.tek.bth.se [194.47.148.30]
over a maximum of 30 hops:
1 1 ms 1 ms 2 ms 192.168.0.1
2 278 ms 55 ms 62 ms 10.9.15.146
3 * * * Request timed out.
4 251 ms 289 ms 349 ms 90-229-40-108.link.se.telia.net [90.229.40.108]
5 258 ms 319 ms 329 ms g-ra-td2-link.se.telia.net [81.228.78.192]
6 268 ms 299 ms 299 ms g-br-c5-link.se.telia.net [81.228.93.52]
7 267 ms 309 ms 299 ms fre-c5-link.se.telia.net [81.228.74.103]
8 257 ms 309 ms 369 ms fre-peer3-link.se.telia.net [81.228.94.13]
9 297 ms 309 ms 309 ms sunet.se.telia.net [195.67.220.150]
10 267 ms 319 ms 309 ms m1fre-a1-v1.sunet.se [130.242.83.45]
11 279 ms 319 ms 319 ms m1tug-a1-v1.sunet.se [130.242.83.49]
12 * 278 ms 319 ms ls-bth-br2.sunet.se [193.11.0.106]
13 257 ms 319 ms * bthred-ge-0-25.net.bth.se [194.47.128.250]
14 277 ms 329 ms 349 ms kna-vss-vl18.net.bth.se [194.47.128.78]
15 278 ms 308 ms 329 ms confer.tek.bth.se [194.47.148.30]
Trace complete.

RTT

RTT for 32 Byte ICMP payload (60 byte IP packet size)
PING 195.67.220.150 (195.67.220.150) 32(60) bytes of data.
— 195.67.220.150 ping statistics —
10000 packets transmitted, 10000 received, 0% packet loss, time 9999597 ms
rtt min/avg/max/mdev = 12.656/21.046/197.818/21.858 ms

a.2.2 RTT for 1450 Byte ICMP payload (1478 IP packet size)
PING 195.67.220.150 (195.67.220.150) 1450(1478) bytes of data.
APPENDIX F

F.1.3 Operator-3

Traceroute

Tracing route to comfer.tek.bth.se [194.47.148.30]
over a maximum of 30 hops:
1  2 ms 1 ms 1 ms 192.168.0.1
2  258 ms 309 ms 319 ms bck3-cggsn-1.vlan100.tele2.net [130.244.235.33]
3  298 ms 310 ms 298 ms bck3-vpe-1.tengigabiteth9-4s500.tele2.net [130.244.192.9]
4  * 334 ms 339 ms bck-pe-1.tengigabiteth1-3.tele2.net [130.244.194.225]
5  248 ms 299 ms 309 ms bck-core-1.tengigabiteth13-0-0.tele2.net [130.244.52.101]
6  279 ms 399 ms 378 ms netnod-ix-ge-b-gbg-1500.sunet.se [194.68.130.19]
7  257 ms 329 ms 339 ms t1tug-ge-0-2-0.sunet.se [130.242.83.109]
8  288 ms 315 ms 339 ms m1tug-a0-v1.sunet.se [130.242.83.42]
9  299 ms 319 ms 339 ms ls-bth-br2.sunet.se [193.11.0.106]
10 339 ms * 272 ms bthred-ge-0-25.net.bth.se [194.47.128.250]
11 99 ms 107 ms 101 ms kna-vss-vl18.net.bth.se [194.47.128.78]
12 98 ms 109 ms 109 ms comfer.tek.bth.se [194.47.148.30]
Trace complete.

RTT

RTT for 32 Byte ICMP payload (60 byte IP packet size)
PING 194.68.130.19 (194.68.130.19) 32(60) bytes of data.
— 194.68.130.19 ping statistics —
10000 packets transmitted, 10000 received, 0% packet loss, time 9999907ms
rtt min/avg/max/mdev = 20.042/21.853/86.892/6.049 ms

RTT for 1450 Byte ICMP payload (1478 IP packet size)
PING 194.68.130.19 (194.68.130.19) 1450(1478) bytes of data.
— 194.68.130.19 ping statistics —
10000 packets transmitted, 10000 received, 0% packet loss, time 19997342ms
rtt min/avg/max/mdev = 22.826/24.247/84.548/5.318 ms

F.1.4 Operator-4

Traceroute

Tracing route to comfer.tek.bth.se [194.47.148.30]
over a maximum of 30 hops:
1  2 ms 1 ms 1 ms 192.168.0.1
2  294 ms 378 ms 329 ms 10.66.37.50
3  40 ms 41 ms 39 ms 10.66.37.53
RTT

RTT for 32 Byte ICMP payload (60 byte IP packet size)
PING 194.68.123.19 (194.68.123.19) 32(60) bytes of data.
  — 194.68.123.19 ping statistics —
  10000 packets transmitted, 10000 received, 0% packet loss, time 9999340ms
  rtt min/avg/max/mdev = 12.652/14.670/69.475/5.413 ms
a.2.2 RTT for 1450 Byte ICMP payload (1478 IP packet size)
PING 194.68.123.19 (194.68.123.19) 1450(1478) bytes of data.
  — 194.68.123.19 ping statistics —
  10000 packets transmitted, 10000 received, 0% packet loss, time 9999009ms
  rtt min/avg/max/mdev = 16.092/17.849/87.796/5.753 ms
Appendix G

G.1 Fabini Experiment

Figure G.1: Histogram CDF Plot of OWD in uplink for TCP
Figure G.2: CDF of IPD for TCP in Uplink
Figure G.3: Histogram CDF Plot of OWD in downlink for TCP

Figure G.4: CDF of IPD for TCP in Downlink
Figure G.5: Histogram CDF Plot of OWD in Uplink for ICMP

Figure G.6: CDF of IPD for ICMP in Uplink
Figure G.7: Histogram CDF Plot of OWD in Downlink for ICMP

Figure G.8: CDF of IPD for ICMP in Downlink
Figure G.9: Histogram CDF Plot of OWD in Uplink for UDP

Figure G.10: CDF of IPD for UDP in Uplink
Figure G.11: Histogram CDF Plot of OWD in Downlink for UDP

Figure G.12: CDF of IPD for UDP in Downlink
Appendix H

H.1 Protocol Experiment

Figure H.1: Protocols OWD in Uplink
Figure H.2: Protocols Median OWD in Uplink
Figure H.3: Protocols OWD in Downlink

Figure H.4: Protocols Median OWD in Downlink


Appendix I

I.1 Streaming Experiment

Table I.1: Required Number of Packets: Streaming experiment

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Figure I.1: CBR Streaming Uplink

Figure I.2: CBR Streaming Downlink
Table I.2: Required Inter Packet Duration: Streaming experiment

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Appendix J

J.1 Constant Bit-rate versus Variable Bit-rate

Figure J.1: Median OWD of CBR versus VBR in Uplink
Figure J.2: OWD Plot of CBR versus VBR in Uplink
Figure J.3: Plot of OWD for CBR versus VBR in downlink

Figure J.4: Plot of Median OWD for CBR versus VBR in downlink
Bibliography


