Measuring the QoS Characteristics of Operational 3G Mobile Broadband Networks

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***Abstract*—Today, many smart phones and tablets have multiple interfaces (i.e. WLAN and 3G). These multiple interfaces can be utilized simultaneously by a multi-path transport protocol to provide bandwidth aggregation or reliability. However, in order to design efficient multi-path scheduling and congestion control strategies, it is crucial to understand the behaviour and properties of the underlying paths first. WLAN links have already been studied extensively in the literature. Therefore, in this paper, we focus on Mobile Broadband (MBB) networks that are in use today. We utilized NORNET EDGE nodes that are connected to up to five different 3G ISPs (UMTS and CDMA2000), hence, providing a realistic view on the QoS characteristics that are experienced by end-users of these MBB networks. We present QoS characteristics (e.g. bandwidth, delay and loss) and discuss our observations. Our results shed light on what a multi-path transport endpoint has to expect – and to efficiently cope with – when using today's MBB networks as transport paths.**

I. INTRODUCTION

The Transmission Control Protocol (TCP) and the User Datagram Protocol (UDP) are the Transport Layer protocols for most services being deployed in the Internet of today. Being designed more than three decades ago, they make the assumption that end hosts are just connected to a single Internet Service Provider (ISP). However, this is not the case any more for many current end hosts. For example, almost every smart phone provides at least 3G (third generation of mobile telecommunications technology) and IEEE 802.11 WLAN connectivity. With more advanced transport protocols – like Multi-Path TCP (MPTCP, [1]) or Concurrent Multipath Transfer for the Stream Control Transmission Protocol (CMT-SCTP, [2]) – it is possible to utilize multiple paths in the networks *simultaneously*. This feature is denoted as multi-path transport.

Currently, multi-path transport is mainly used for data centre traffic [3], i.e. for transferring large amounts of data among data centres as quickly as possible. In data centre networks, however, the quality of service (QoS) characteristics – like bandwidth, delay, and loss rate – of different paths over fibre networks are quite similar. The challenge [4] of scheduling data over multiple paths is to also work effectively when these parameters highly differ. In Mobile Broadband (MBB) networks, QoS does not only depend on the link capacity and on cross traffic, but also on short-scale channel variation, mobility, radio resources as well as the configurations made by the MBB ISPs.

QoS characteristics of wireless networks have been of interest since the 90's. The authors in [5] studied IEEE 802.11 WLAN and discussed the transport protocol performance in such networks. In [6], the authors studied TCP performance in 3G networks and specifically considered the rate and delay variations. In [7], a measurement study was carried out to explore the interaction between the MAC layer in Code Division Multiple Access (CDMA) and TCP with different congestion control mechanisms. In [8], the authors target applications with different QoS requirements in CDMA networks. They studied different TCP performance parameters, e.g., throughput, round-trip times and loss rates, and they introduce the potential of bandwidth estimation to achieve application QoS. Similarly, Tan et.al. focused on extensive measurements in operational 3G networks to assess temporal and spatial network characteristics and evaluated the TCP performance impact on the Application Layer [9]. They focused on video and voice call applications, since these have strict QoS requirements. In [10], a system-level overview is provided about performance increase and limitations that can be achieved with *3G long-term evolution*, i.e., the evolution of 3G systems to what is nowadays named as 4G or, analogically, LTE. While all these studies shed light on the QoS in MBB networks, none of these studies had thoroughly investigated bandwidth, delay and loss for multiple network providers and for multiple MBB technologies. Furthermore, none of these studies considered multiple network operators at the same time, hence, took the effect of the network configuration into account.

There have also been studies that investigate the performance of MPTCP in operational wireless networks from IEEE 802.11 public access points to 3G-CDMA2000 and 4G LTE networks [11]. They focused on throughput performance and the effect of multi-path transmission in the congestion control. While it is important to see how multi-path protocols work in real operational networks, in order to design useful multi-path scheduling and congestion control strategies, it is crucial to understand the behaviour and properties of the underlying paths first. Particularly, it is necessary to know what kind of QoS characteristics to expect from the *real* MBB networks that are in use today.

In this paper, we take the initial step to analyze the QoS characteristics of different MBB networks. We have therefore utilized the NORNET EDGE platform [12]–[14]. NORNET EDGE has deployed MBB research nodes being distributed all over the country of Norway. These nodes are connected to up to five different 3G ISPs: four Universal Mobile Telecommunications System (UMTS) networks and one CDMA2000 network. This setup therefore provides a realistic view on the QoS characteristics that are experienced by end-users of these MBB networks. We will present QoS characteristics (i.e. bandwidth, delay and loss), and discuss our observations. The results of our work can then, as a step of future work, be utilized as a baseline scenario of what a multi-path transport endpoint has to expect – and to efficiently cope with – when

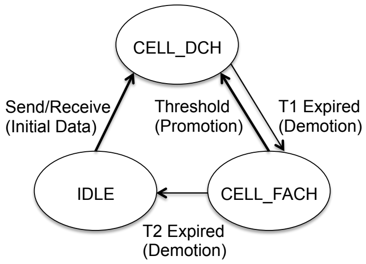


Figure 1. Example of 3G-UMTS RRC State Machine

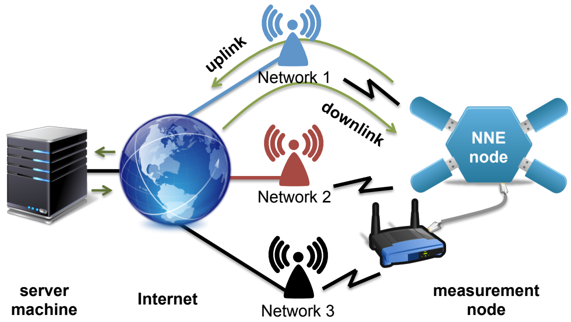


Figure 2. Measurement Setup Overview

using today's MBB networks as transport paths.

The rest of this paper is structured as follows: Section II provides some background on 3G MBB networks. Section III discusses our methods and the measurement setup. In Section IV, we discuss our results and the implications to multipath transport over MBB networks. The conclusion is provided in Section V.

II. Background on 3G Networks

A. 3G Network Standards

UMTS and CDMA2000 are two different standards enabling 3G MBB networks. While 3GPP[1] is the standardization body for UMTS, 3GPP2[2] is for CDMA2000. 3G-UMTS has mainly two subsystems: The universal terrestrial radio access network (UTRAN) and the core network (CN). The UTRAN consists of user equipments (UEs), base stations (NodeBs) and radio network controllers (RNC), which enable UEs to connect to the CN. The RNC keeps track of each UE's radio resource control (RRC) state and it is in charge of UEs state transitions. In Subsection II-B, RRC-state machine of 3G-UMTS will be described in detail.

In 3G-CDMA2000, the radio access network is composed of different elements, even though they are similar in number and functionality. For instance, UEs RRC is similar to 3G-UMTS networks [15], [16]. CDMA2000 1xEV-DO (Evolution-Data Optimized) Rev.A network standard is a subsequent stage of the CDMA2000 family of standards.

Current 3G-UMTS supports maximum theoretical data rates up to 21 Mbit/s and 11 Mbit/s in downlink and uplink if High Speed Packet Access (HSPA+) is available. 3G-CDMA2000 1xEV-DO Rev.A supports 3.1 Mbit/s and 1.2 Mbit/s in down- and uplink, whereas Rev.B supports 4.9 Mbit/s and 1.8 Mbit/s in down- and uplink [15], [16]. These values are per carrier and 2 to 3 carriers are typically bundled in operational networks.

B. 3G Radio Resource State Machine

At any particular time, UEs are in idle or connected mode. While connected, each RNC keeps track of the UEs state on its NodeBs and each UE is assigned a RRC-state. There are typically three RRC-states [15], [17]: IDLE or DISCONNECTED, forward access channel (CELL_FACH), and dedicated channel (CELL_DCH). CELL_FACH is a low-bandwidth shared channel [15] whereas CELL_DCH is a dedicated channel where high-bandwidth data transmissions take place. RRC state transitions are configurable and controlled by two timers and one data rate threshold as illustrated in Figure 1.

State promotions are performed when the data threshold is exceeded and state demotions are controlled by timeouts, e.g., T1 and T2 [18]. When data arrives, the RRC-state transition can be to either CELL_FACH or CELL_DCH, depending on the RRC configuration [18], [19]. CELL_DCH are limited per NodeB and dedicated to a single UE.

Similarly, in 3G-CDMA2000, RRC is tracked by the packet data serving node (PDSN) and it is typically composed of INACTIVE, ACTIVE and DORMANT states [16]. An additional CONTROL HOLD MODE, between ACTIVE and DORMANT states, may exist in some configurations to reduce delay. In DORMANT mode there is no data transfer, no signalling between UE and base station, although the packet data service registration is kept.

III. Methodology

In the following, we describe the measurement setup and the methodology we follow during the measurements.

A. Experimental Setup

The experiments are carried out on NorNet Edge[3] [12]–[14], a programmable testbed for measurements and network research. The NorNet Edge testbed is composed of customized single-board measurement nodes.

The measurement nodes are connected to multiple MBB providers[4]: four 3G-UMTS operators using identical USB 3G modems, and one 3G-CDMA2000 1xEV-DO Rev.A network connected to the node over USB. The 3G-UMTS modems support HSPA+ and have a theoretical data rate of up to 21.6 Mbit/s and 5.8 Mbit/s in downlink and uplink. The 3G-CDMA2000 standalone modem supports a theoretical data rate of 9.3 Mbit/s and 3.1 Mbit/s in downlink and uplink. Figure 2 shows an overview of the measurement setup.

The measurement nodes are geographically distributed over the Oslo region of Norway; their locations are presented in Figure 3. Particularly, these locations represent different traffic densities. For example, some of the nodes are in urban areas while other nodes are in rural areas and one node is located in a part of the region with many office buildings.

B. Measurement Procedure and Collected Data

MBB networks are stateful and they reserve resources for each connection, as we discussed in Section II. Therefore, the QoS parameters not only depend on the total capacity

[1]3GPP: http://www.3gpp.org.
[2]3GPP2: http://www.3gpp2.org.
[3]NorNet: https://www.nntb.no/.
[4]We keep the mobile broadband provider names anonymized.

Figure 3. The Locations of the Measurement Nodes in Oslo, Norway

and the cross traffic, but also on the scheduling and resource allocation in the network. In our experiments, considering most of the traffic is transmitted in the active states, we focus on CELL_DCH for 3G-UMTS and ACTIVE in 3G-CDMA2000 [19]. We measure the QoS parameters between our MBB measurement nodes and a central server that sits on a well-provisioned research network at Simula. We assume that the MBB radio link will be the bottleneck, hence, the measured parameter will be used to characterize the MBB links. During the measurement, along with data, the RRC state of the connection for UMTS connections is also recorded at the measurement node. This information is extracted from the modem using LIBQCDM[5] and LIBQMI[6] libraries that communicate with modems equipped with QUALCOMM chipsets. We used the RRC state information to double check that all the data transmissions occur in CELL_DCH state.

Each measurement sample at each measurement location was collected both in uplink and downlink during workdays (Monday to Friday), between August and October of 2013. We waited a random period of time in between consecutive measurements in order to return to idle state, hence, provide independent measurement samples.

The QoS parameters that are considered in this paper are: throughput, delay and loss. For the throughput measurements, 1500 byte UDP packets are sent back-to-back from the measurement node (3G modem) to the server (uplink) and then from the server to the measurement node (downlink). We focus on UDP throughput rather than TCP, since we want to observe the absolute throughput that is achievable by the MBB networks without considering protocol-specific effects such as congestion control. For the delay and loss measurements, the client sends 100 packets of 1500 bytes every 1 second, and the server replies them back to the client upon arrival. On both sides, delay is measured: one-way (uplink and downlink) and RTT. From this data set, we then extract the loss.

[5]LIBQCDM: http://cgit.freedesktop.org/ModemManager/.
[6]LIBQMI: http://cgit.freedesktop.org/libqmi.

IV. Evaluation

In the following, we present the experimental results of our measurements. We first focus on the throughput and show how the achievable throughput in a MBB connection varies over time and discuss how long throughput should be measured to get stable results. We further discuss and compare the throughput characteristics of different MBB providers. We then observe the delay and loss characteristics of MBB networks.

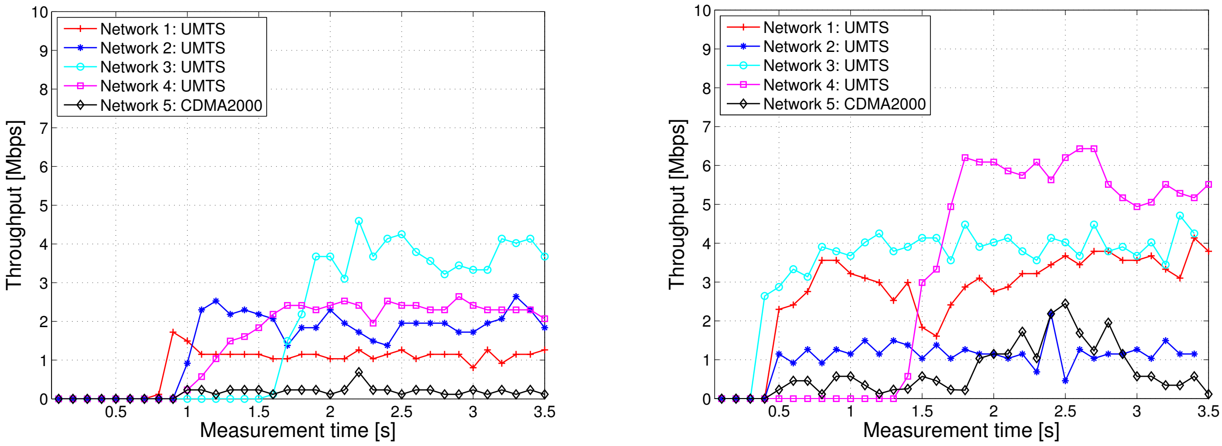
A. *Characterizing MBB Throughput*

We first investigate how throughput changes over time. Although we are mainly interested in the throughput in the active state, it is also interesting to observe how different network providers handle state transitions. In order to observe this effect, we measure the throughput in fine granularity from the beginning of the transmission. In Figure 4, we pick one sample measurement and illustrate how throughput varies in time among different providers. We observe that the throughput is significantly lower for the first few seconds of the measurement duration due to the context establishment and channel acquisition (as described in Subsection II-B). Furthermore, the state establishment times change from one operator to the other even though they use similar technologies. Hence, it takes a different time span for each operator to start the transmission of the data. This underlines the importance of taking radio resource transition into account when characterizing the bandwidth in MBB networks. The throughput characteristics need to be measured at CELL_DCH state for 3G-UMTS and ACTIVE state for 3G-CDMA2000, since it is the state where the data transmission occurs. Figure 4 shows that this process normally takes 1 to 2 seconds, depending on the operator. Therefore, while evaluating the stability and variance of the throughput, we discard the first two seconds of each measurement sample in order to account for the channel acquisition time.

1) Stability of the Observed Throughput: Next, we investigate the stability of the observed throughput over each measurement sample. Each measurement has a duration of 15 seconds out of which the two first seconds are discarded due to the initial RRC state transition phase. Hence, we calculate the mean and variance of throughput for the remaining 13 seconds. We then compute the variation coefficient, which is defined as the ratio of the standard deviation σ to the mean μ:

$$c_v = \frac{\sigma}{\mu}$$

Figure 5 shows the cumulative distribution function (CDF) for the variation coefficient c_v across over 350 measurements for uplink and downlink. Note that the x-axis is limited to 1. The tail, which represents less than 0.25% of the data, is ignored. We observe that the standard deviation stays relatively low relative to the mean. In uplink, c_v lies within 0.1 to 0.4 in 90% of the measurements in the 3G-UMTS networks and in 70% of the measurements in the 3G-CDMA2000 network. c_v is slightly higher in the downlink direction, but still



(a) Uplink (b) Downlink

Figure 4. Throughput over Single Measurement Sample

below 0.4 in 90% of the measurements for all five networks. This relatively low variability indicates that the throughput is reasonably stable.

2) Throughput Variance: Each of the measurements runs for 15 seconds. Such a test is, however, quite intrusive and involves sending a significant amount of data through the network. Therefore, it is interesting to investigate if the same result can be achieved with a shorter measurement duration. This is particularly of interest for MBB, since active measurements in such networks are costly, and short measurements could be performed more frequently to accurately capture short-term changes of path characteristics.

Figure 6 shows the measured throughput in uplink and downlink as a box plot for each network. The x-axis denotes the duration of the measurement. While the measurement was run from time-scales of 1 up to 10 seconds, only 1, 2 and 10 seconds are shown. A duration of 2 seconds means that we consider only 2 seconds of the measurement after channel acquisition. Similarly, a duration of 10 seconds means that we consider 10 seconds of the same measurement after channel acquisition. The values shown in Figure 6 are the mean, quartiles (boxes), and min/max values (whiskers) across all 350 measurements for each network. We observe that the values for duration for 2 seconds and 10 seconds are very similar which illustrates that after the RRC state transition phase, 2 seconds is enough to observe a stable throughput.

Note that subscriptions used for one of the provider (Network 1: UMTS) limits the download speeds to 3 Mbit/s in downlink. This is becoming a common practice in MBBs in densely populated areas. It is still interesting to observe how such bandwidth throttling positively influenced the stability of the achieved throughput indicated in Figure 6.

B. One-Way Delays and Round Trip Times

For the one-way delay measurements, we rely on the precision of the Network Time Protocol (NTP) and the methodology in [20]. Before each measurement, NTP is resynchronized both on client and server. NTP does not guarantee better accuracy than 10 to 20 ms in the wide area, which is comparable to uplink or downlink delays of 20 ms [20]. Although one-way delay values are relevant, we are most interested in its spread rather than their absolute values.

Table I
One-Way Delay and Round-Trip-Time Median

Network	**1**	**2**	**3**	**4**	**5**
Uplink (in s)	0.0453	0.0335	0.0698	0.0643	0.1575
Downlink (in s)	0.0289	0.0319	0.0581	0.0292	0.0289
RTT (in s)	0.0768	0.0665	0.1291	0.0961	0.1920

Table II
Packet Loss Percentage

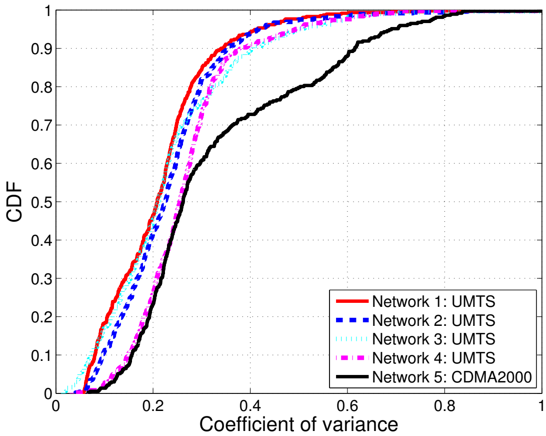
Network	**1**	**2**	**3**	**4**	**5**
Uplink loss (in %)	0.035	0.066	0.031	0.025	0.024
Downlink loss (in %)	0.262	0.306	0.371	0.251	0.052

We present the CCDF (complementary CDF) across all 350 measurements for one-way (uplink and downlink) and RTT delays for each network in Figure 7. All measurement samples were collected when the 3G-UMTS are in CELL_DCH and ACTIVE state for 3G-CDMA2000. We try to identify which direction (uplink or downlink) contributes more to the total delay. We observe that uplink contributes mostly to the total delay compared to the downlink. Furthermore, 3G-CDMA2000 RTT values are observed to be higher compared to 3G-UMTS. At times, we observe that some of the lost packets have subsequent packet numbers and arrive in bursts due to, we believe, short glitches in packet processing/delivery in the network.

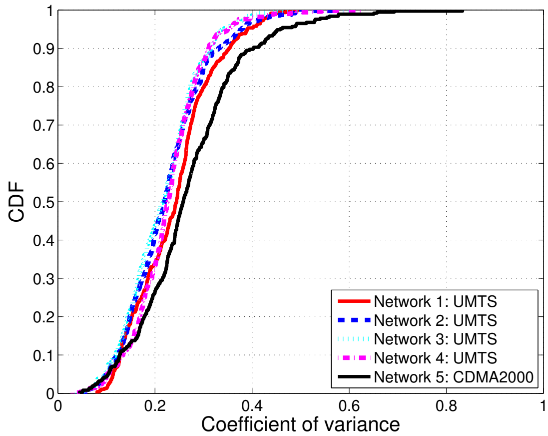
In Table I, we present the median delay values for all network operators. We observe that, with almost no exception, uplink delay counts more to RTT compared to downlink. Note that the one-way values (uplink and downlink) also have the NTP imprecision in each of the samples.

C. Packet Losses

We analyze loss across different measurements and compute the average packet loss rate for downlink and uplink. In Table II, we illustrate the average packet loss rate for each operator across all 350 measurements. We discard the first

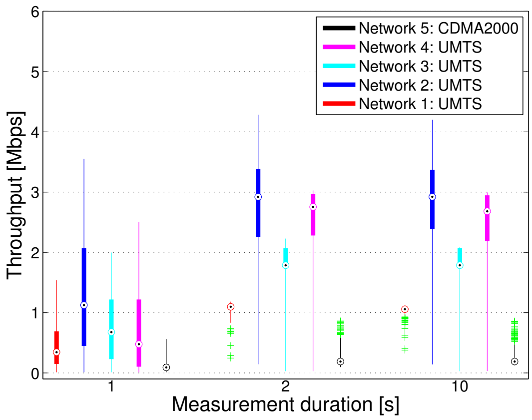


(a) Uplink

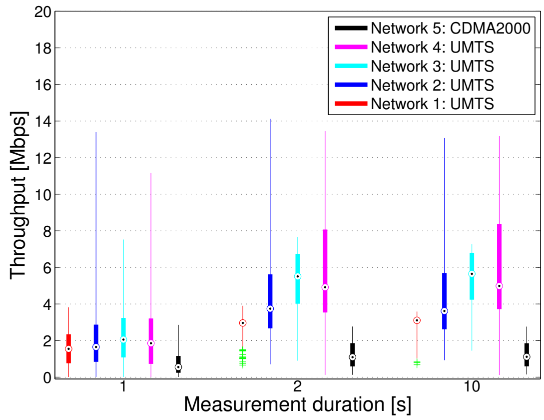


(b) Downlink

Figure 5. CDF of the Variation Coefficient c_v



(a) Uplink



(b) Downlink

Figure 6. Throughput at Different Time-Scales

three packets to guarantee that only DCH is considered. We observe that the uplink has slightly less packet losses compared to the downlink. We also investigate the packet losses within the single measurements and observe that all packets have – as expected – on the average a similar probability of getting lost.

D. Discussion

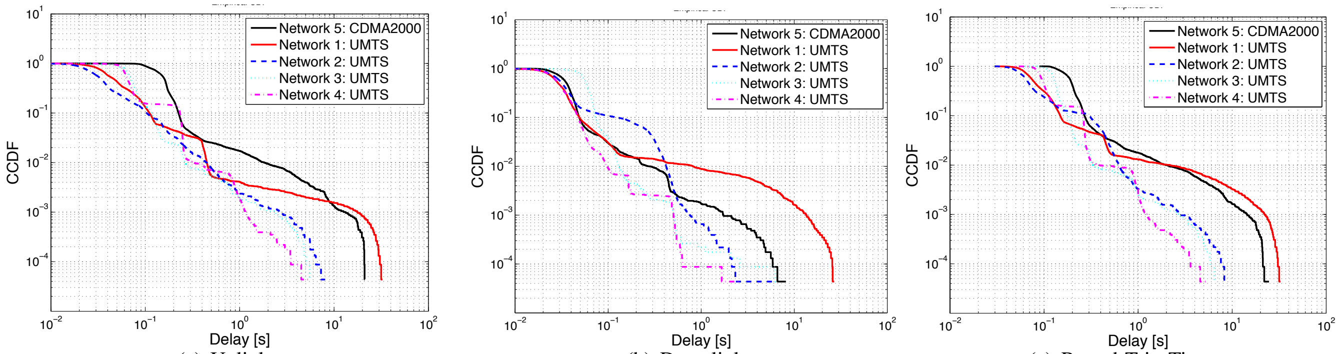
In this work we characterized different networks, at different locations, regarding their bandwidth, delay (uplink, downlink and RTT) and packet loss. We believe our results are of significant importance for multi-path data transmission, and, in particular, for improving multi-path transport performance.

The bandwidth characteristics shown in Subsection IV-A illustrate bandwidth asymmetries in uplink and downlink. Despite the asymmetry, after entering DCH, throughput remains relatively stable in both directions. This is also confirmed by looking at the throughput variance at different time-scales. Delay in uplink and downlink is shown to be reasonably stable in the range of few tens of milliseconds. We also identified that uplink delay contributes more to the round trip time. Finally, packet loss is shown to be relatively low both in uplink and downlink after discarding the first few packets due to channel acquisition.

These insights have significant potential to be used for throughput, delay or loss based link stability estimation. One possible application, in the context of multi-path data transmission, could be to classify paths based on current bandwidth, delay and loss characteristics, and to assign them to different applications with different QoS requirements, as e.g. in [21]. It can further be used to dynamically select paths to fulfill the Application Layer QoS requirements and for multi-path congestion control [22].

V. Conclusion

In this paper, we studied the QoS characteristics of operational 3G-UMTS and 3G-CDMA2000 1xEV-DO Rev.A networks in Oslo, Norway. In terms of throughput, we show



(a) Uplink (b) Downlink (c) Round-Trip Time

Figure 7. One-way Delay (Up- and Downlink) and Round-Trip-Time

that even though the underlying technology is the same, different operators have very different bandwidth characteristics. Despite these differences, we observed that after the initial state transition phase, the throughput becomes stable within around 2 seconds. Furthermore, we show that the delay in uplink and downlink is stable and that the uplink delay contributes more to the round trip time. Finally, packet loss is shown to be relatively low (both, in uplink and downlink), and on the average lower in the uplink compared to the downlink.

Our future work on QoS characteristics in MBB networks includes the comparison of pedestrian or vehicular mobility to the static scenario and the method presented in this paper against other less-predictable network traffic patterns, e.g., congested scenarios or weekend traffic. Another subject of our ongoing research is to investigate TCP and the influence of congestion control mechanisms on the QoS. Finally, we are also transferring our obtained insights into improvements for multi-path transport, e.g. for scheduling of data onto paths as well as for multi-path congestion control, particularly for the CMT-SCTP and MPTCP protocols. We are then going to evaluate these improvements in the NorNet testbed as well.

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