Social Benchmarking of QoS & QoE in Cellular Data Networks

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***Abstract*—We developed a benchmarking tool called *NetBench* to measure the quality of service (QoS) and quality of experience (QoE) in cellular data networks and to share them among users of the tool. This tool has a user interface that displays the summarized QoS and QoE on a map to motivate users to share their QoS and QoE. We have been continuously collecting QoS related metrics and a QoE related metric from this tool. We characterize the QoS and QoE of three cellular data network carriers (one is a CDMA2000 operator and the others are UMTS/W-CDMA operators supporting HSDPA/HSUPA) in Japan from the collected data for eight months. We demonstrate that round trip time (RTT) among other QoS related metrics such as signal strength and packet loss rate is one of the metrics that explains the performance of TCP throughput. We also demonstrate that the packet loss rate and RTT of the QoS related metrics affects the QoE. These overall results of QoS and QoE indicate that the characteristics of QoE is explained by QoS, especially by RTT.**

***Index Terms*—Cellular data network, 3G, quality of service, quality of experience**

I. Introduction

Cellular data networks have been globally deployed, and the traffic volume in the cellular data networks is dramatically increasing [1]. Therefore, the cellular data networks are an essential component of the Internet. Understanding the quality of service (QoS) and quality of experience (QoE) in the cellular data networks is crucial for network design and traffic engineering as well as performance evaluation. From the viewpoint of subscribers of the cellular data networks, it is also important to know the actual service level from QoS and QoE because the cellular data network service is a best effort service, and consequently the actual service level is often very different from the nominal service level announced by cellular carriers. However, it is not easy to compare such metrics over multiple operators though each likely has them as internal data.

We developed a social benchmarking tool called *NetBench* for smartphones to measure both the QoS and QoE in cellular data networks and to share them among the users of the tool [2]. From this tool, we have been collecting QoS related metrics such as TCP throughput, signal strength, ICMP packet loss rate, and round trip time (RTT) based on the active measurement approach, and a QoE related metric that is user's vote (*good* or *bad*).

In this paper, we introduce the developed tool and then present the characteristics of the QoS and QoE of three cellular data network carriers (one is a CDMA2000 operator and the others are UMTS/W-CDMA operators supporting HSDPA/HSUPA) in Japan from the collected data for eight months. As for the QoS related metrics, we demonstrate that the RTT is one of the metrics that explains the TCP throughput. We observe less correlation between signal strength, ICMP packet loss rate, and TCP throughput for each carrier. On the other hand, the correlation between RTT and TCP throughput is stronger than any correlations between TCP throughput and other metrics for every carrier. In particular, we observe a strong correlation between RTT and TCP throughput for one carrier using UMTS/W-CDMA. As for the QoE related metric, we demonstrate that the RTT and the packet loss rate mainly affect the QoE. We show that the characteristics of QoE is explained by QoS, especially by RTT, from these overall results.

The contributions of this paper are twofold: 1) We developed a social benchmarking tool to measure QoS and QoE. 2) We show the characteristics of the QoS and QoE and their correlation in cellular data networks from the data collected from the developed tool.

II. Related Works

The QoS and QoE analysis in the cellular data networks has not been well researched in prior works. Halepovic et al. [3] and Williamson et al. [4] focused on the user mobility such as cell changes in a cellular data network and they modeled the temporal characteristics of the user mobility from their measurement in CDMA2000 network. However, they do not analyze the performance at the actual service level of the cellular data network.

Romirer-Maierhofer et al. [5] reported their TCP RTT measurement results in GPRS/EDGE and UMTS/HSxPA networks. Balasubramanian et al. [6] measured the QoS such as TCP/UDP throughput and packet loss rate in 3G and WiFi networks. However, they have not focused on the QoE of users and the correlation between QoS and QoE.

Huang et al. [7] measured the high-level performance of smartphones such as pervasive Web browsing while taking into account the differences of the hardware and software of devices. The high-level performance on which they focus is similar to the QoE, but they do not analyze the correlation between low-level QoS such as throughputs and QoE.

Joel et al. [8] analyzed the performance of cellular and 802.11 WiFi networks at metropolitan areas using a large scale dataset obtained at a throughput measurement site. Their approach is similar to ours in terms of using crowd-sourced data. However, the have not collected the QoE of users and analyzed the correlation between QoS and QoE.

Shafiq et al. [9] modeled the characteristics of Internet traffic of cellular devices by analyzing the flow level traffic data collected at cellular data network carrier's core network. Xu et al. [10] have also focused on the cellular data network carriers' wired network infrastructure, and analyzed the characteristics of routing in the carrier's network. However, their focus is carrier's core network only, and consequently, they could not achieve to analyze the characteristics and correlation between the QoS and QoE through wireless and wired networks of cellular data networks.

Jin et al. [11] has developed a smartphone application to collect troubles of cellular data networks from mobile customers. Their approach is similar to our QoE collection, but they do not analyze the characteristics and correlation between the QoS and QoE.

The QoE has gained great interest and characterizing the correlation between QoS and QoE become increasingly important. Schatz et al. [12] focus on both the QoS and QoE. They conducted lab and field trials to measure the QoS and end-user QoE. Their focus is similar to ours, but their trials do not highlight the correlation between the low-level QoS related metrics such as RTT and QoE.

III. Preliminary

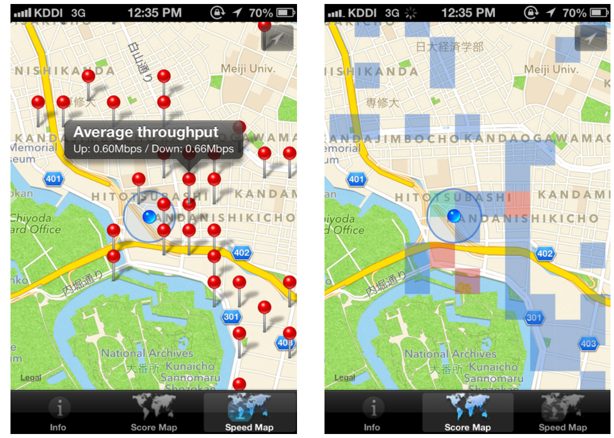
A. Social benchmarking tool

We developed a social benchmarking tool *NetBench* [2] for iPhones and iPads [13] supporting iOS version 5 or later to measure the QoS and QoE in cellular data networks and to share them among the users of the tool at the user interface on the device and the Web site. This tool supports two measurements: 1) QoS and 2) QoE.

The former, QoS measurement, is implemented as the active measurement. It first sends 21 ICMP echo request packets to a measurement server in Tokyo and receives ICMP echo reply packets with 3 second timeout to measure the ICMP packet loss rate and the minimum, median, and maximum RTT. Next, it measures the average download throughput from the measurement server for 10 seconds using TCP with an unprivileged port number. Likewise, it then measures the average upload throughput to the measurement server for 10 seconds using TCP with an unprivileged port number. At the end of this procedure, it records the signal strength[1], and geolocation information of the device.

The latter, QoE measurement, is the combination of user's vote and active measurement. Users can choose either *+1 (good)* or *-1 (bad)* at the graphical user interface of the developed tool according to their feelings (i.e., QoE). After a user chooses the alternative of *good* or *bad*, it records the signal strength and geolocation information. It then sends 10 ICMP echo request packets to a measurement server and receives ICMP echo reply packets with 3 second timeout to measure the ICMP packet loss rate and the minimum, median, and maximum RTT.

[1]The unit of signal strength is unknown but it is the value as is obtained through iOS's API.



(a) QoS (b) QoE

Fig. 1. Screenshots of the user interface to browse shared QoS/QoE posts

TABLE I
The breakdown of the QoS and QoE posts by carrier

Carrier	QoS	QoE +1 (good)	QoE -1 (bad)
KDDI	791	419	63
Softbank	316	22	18
docomo	173	3	3
Others	5	3	2
WiFi	158	45	27

The posts from the users of the same carrier are shared through the user at the user interface of the tool on a device. We present the screenshots in Fig. 1. Figure 1(a) is the screenshot showing the QoS that places pins with the average throughputs on the map. Figure 1(b) is the screenshot showing the QoE that places tiles with the average QoE score in the Hue color space from red (bad) to blue (good) on the map. Similarly, shared posts from users of each carrier can be browsed at the Web interface. These interfaces motivate users to share their QoS and QoE with other users.

B. Collected Data

We obtained 1443 (shared) posts of QoS and 605 posts of QoE in eight months (from mid-March to mid-November, 2012). The breakdown of the QoS and QoE posts by carrier is shown in TABLE I. The majority of the posts are from three carriers in Japan, and consequently, we focus on these three carriers excluding measurements and posts using WiFi in this paper. Note that KDDI is CDMA2000 operator, and Softbank and docomo are UMTS/W-CDMA operators supporting HSDPA/HSUPA.

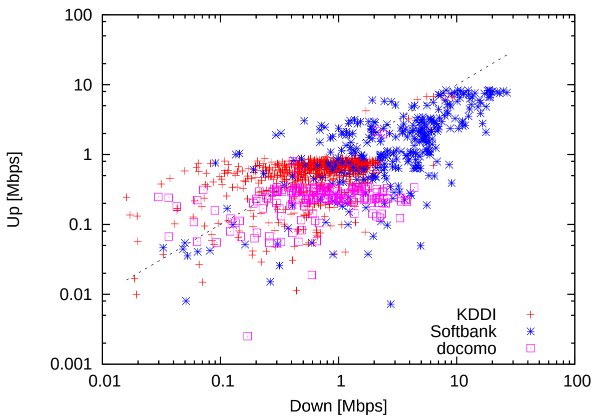


Fig. 2. TCP download versus upload throughputs

IV. Analysis Results

A. Quality of Service

We focus on the QoS related metrics and analyze the correlations between these metrics in this subsection.

We first present a scatter plot of the average TCP download throughput versus the average TCP upload throughput in Fig. 2. We expected a strong positive correlation between the download and upload throughputs because the wireless radio path environment is almost equal. However, the actual correlations between the download and upload throughputs are not much strong, as the correlation coefficients between the download and upload throughputs with the logarithmic scale of KDDI, Softbank, and docomo are 0.510, 0.675, and 0.341, respectively. This is because the download links are likely more congested than the upload links, and consequently, the download throughput is dispersed more than the upload throughput. Another insight from Fig. 2 is that the correlation coefficients of KDDI and docomo are relatively smaller than Softbank. A plausible reason of this is the difference of the configuration and traffic engineering policy of carriers; KDDI and docomo seem to limit the maximum speed to keep fairness while the configuration of Softbank is based on best effort.

We then show scatter plots of the signal strength versus average TCP download/upload throughput in Fig. 3. Here, we exclude the results of docomo from this figure because the API fails to obtain the signal strength through the operating system when it uses a SIM card of docomo. We note that we cannot directly compare the signal strength values between KDDI and Softbank because they use different 3G standards. The signal strength is commonly used to indicate the QoS and displayed on the user interface of devices. However, Fig. 3 shows that the signal strength does not affect the throughput. We confirm very small positive correlation between the signal strength and the average TCP download/upload throughput at KDDI; the correlation coefficients between the signal strength and the average TCP download/upload throughput with the logarithmic scale are 0.031 and 0.137, respectively.

Figure 4 shows the correlation between the ICMP packet loss rate and the average TCP download/upload throughput with the logarithmic scale. It is commonly known that packet loss results in remarkable TCP performance degradation due to retransmission and a shrink of the sliding window. However, this result shows that packet loss does not cause remarkable TCP performance degradation. We discuss the reason of this result here; in the developed tool, we setup the timeout in the ICMP packet loss measurement to 3 seconds, meaning that packets exceeding 3 seconds of RTT are counted as packet loss. Therefore, most of the packets that are detected as packet loss are not actually dropped but properly delivered between smartphones and the Internet by being buffered at smartphones or intermediate devices in cellular data networks for several seconds. We observe negative correlation between the packet loss rate and the average TCP download/upload throughput with the logarithmic scale. Two reasons can be given for this correlation: 1) actual packet drops cause the lower throughput, and 2) larger RTT of packets results in lower throughput.

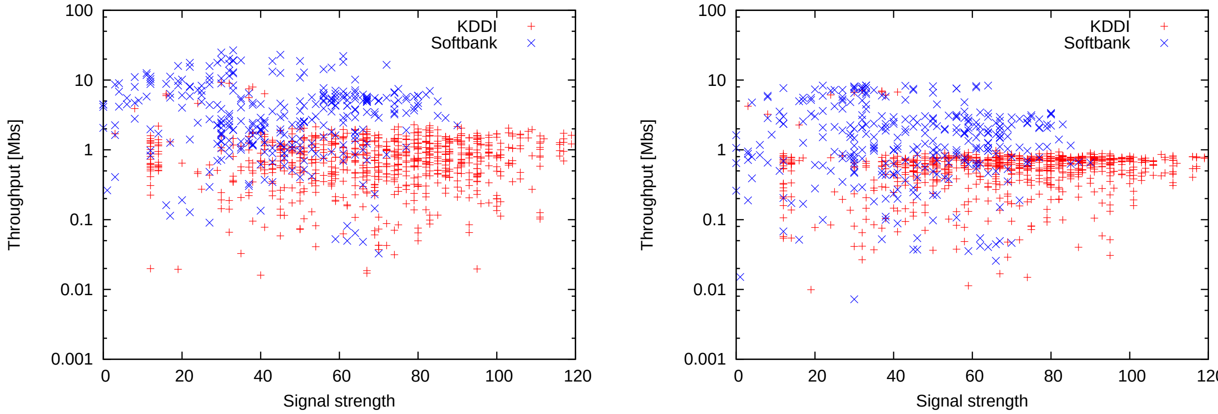
Figure 5 presents the absolute correlation between the median of ICMP RTT with the logarithmic scale and the average TCP download/upload throughput with the logarithmic scale. We find that the correlation between RTT and TCP throughput is stronger than any correlations between the average TCP download/upload throughput and other metrics described above for every carrier. In particular, we observe a strong negative correlation between the median of RTT and the average TCP download/upload throughput with the logarithmic scale for Softbank; the correlation coefficients for download and upload are -0.507 and -0.601, respectively.

We summarize the correlation coefficients between the QoS related metrics in Fig. 6. These matrices demonstrate that the RTT is one of the metrics that explains the performance of TCP throughput most especially in one operator. The signal strength that is displayed to smartphone users as a quality indicator has small correlation with the other metrics. The ICMP high packet loss rate does not result in the noticeable throughput degradation, but this is because most of packets counted as packet loss are detected as being dropped due to timeout and they are properly delivered explained above.

B. Quality of Experience

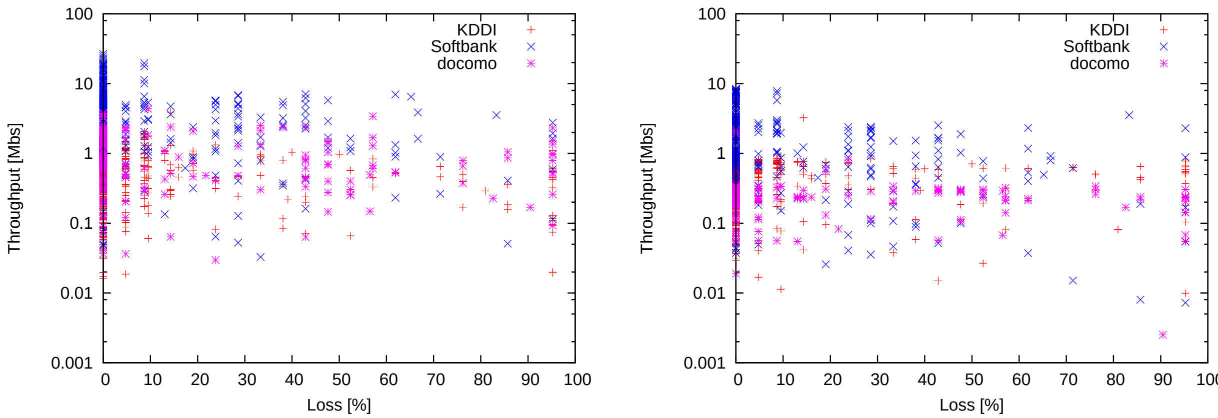
In this subsection, we analyze the QoE posts and then discuss the characteristics between the QoS and QoE.

The probability density function (PDF) and complementary cumulative distribution function (CCDF) of the median RTT by QoE are presented in Fig. 7. This figure shows that users experience bad quality in the cellular data networks at larger RTT. Specifically, 200 milliseconds for the median RTT is the borderline where users experience bad quality. The RTT has a correlation with the TCP throughput as shown in Section IV-A, but we do not observe a shrink of the TCP download/upload throughput around at 200 milliseconds of the median RTT (Fig. 5). Therefore, the RTT is the dominant QoS parameter that affects the QoE. Since the major carrier for the QoE posts is KDDI as shown in TABLE I, we next focus on the KDDI. In Fig. 5, the points of KDDI are concentrated less



(a) Download (b) Upload

Fig. 3. Signal strength versus TCP download/upload throughput



(a) Download (b) Upload

Fig. 4. Packet loss rate versus TCP download/upload throughput

than 200 milliseconds of the median RTT and the shrink of the TCP download/upload throughput cannot be observed as well. This implies that the median RTT becomes less than 200 milliseconds at the stable network environment that brings a good QoE to users, but the throughput does not significantly affect the QoE.

Figure 8 shows the CCDF of packet loss rate by QoE. As shown in Section IV-A, the packet loss rate is highly correlated with the RTT due to the timeout of the measurement. Therefore, the packet loss rate as well as the RTT affects the QoE. Note that the timeout of the ICMP packet loss measurement in QoE is set to the same value, 3 seconds, as that in QoS. Therefore, as described in the QoS result, packets that are detected as packet loss shall not be actually dropped but properly delivered between smartphones and the Internet by being buffered at smartphones or intermediate devices in cellular data networks for several seconds. To support this result, we will also evaluate the TCP packet loss rate as well as the ICMP packet loss rate in the future experiments as discussed in Section V.

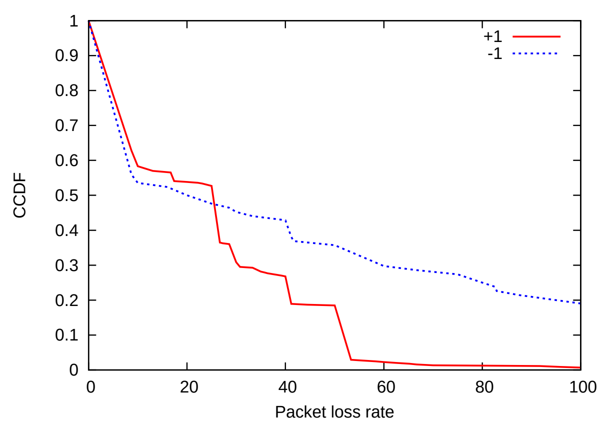
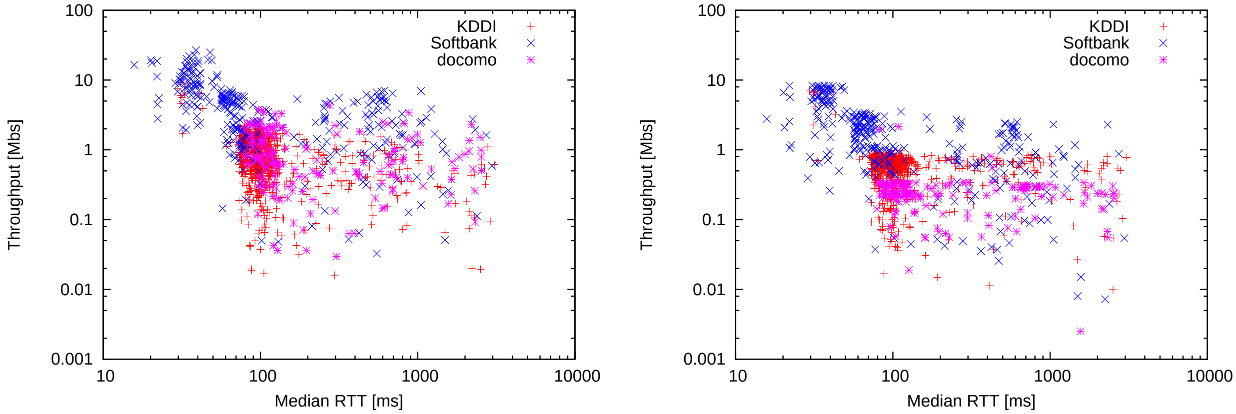


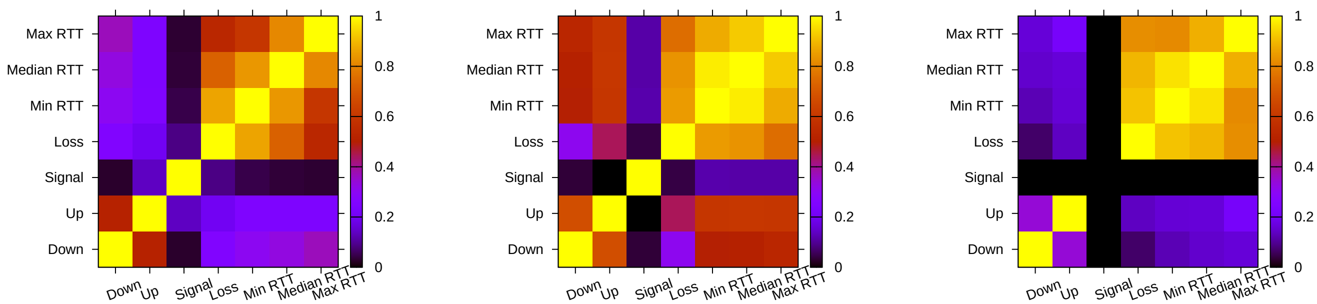
Fig. 8. CCDF of packet loss rate by QoE

We do not measure the correlation between the QoE and throughput in this paper, but the results shown above demonstrate that the RTT is the dominant QoS parameter that affects



(a) Download (b) Upload

Fig. 5. The median of RTT versus TCP download/upload throughput



(a) KDDI (b) Softbank (c) docomo

Fig. 6. The absolute values of correlation coefficients between the QoS related metrics

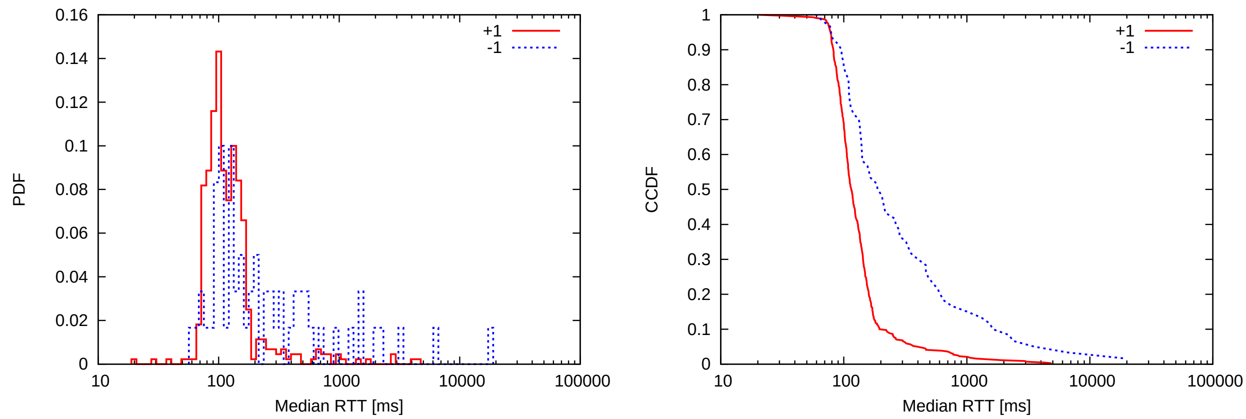
the QoE. Note that the throughput is correlated with the RTT, and consequently, the correlation between the QoE and the throughput is also conceivable.

V. Discussion

Differences of hardwares and operating systems: In this paper, we do not take into account the differences of hardwares and operating systems. We confirm that few differences of operating systems exist because the developed tool only support iOS version 5 or later. As for the hardwares, we admit that differences of hardwares shall affect the QoS as pointed out in Ref. [7]. However, we could not collect enough number of samples for various hardwares in this paper and our QoS measurement is not a heavy task consuming the CPU resource although the QoE shall be affected by hardware spec, so we do not take into account the difference of hardwares. We are developing the tool for another platform (Android [14]). We will evaluate the QoS and QoE for different hardwares and operating systems in future.

Collected metrics: We have collected TCP throughput, signal strength, ICMP packet loss rate, and ICMP RTT for QoS related metrics, and user's vote (*good* or *bad*) for a QoE related metric. Collecting the QoE related metric is a step forward to understand the relationships between QoS and QoE. However, we have not collected other considerable and possibly significant QoS related metrics such TCP packet loss rate, TCP RTT, and DNS lookup delay. In this paper, we have used ICMP RTT and ICMP packet loss rate instead of TCP RTT and TCP packet loss rate although it is known that ICMP might not be good to explain the RTT and packet loss rate for data packets (e.g., TCP packets) due to low priority configuration for ICMP packets. This is because of the difficulty of collecting TCP RTT and packet loss rate on smartphones due to their API restrictions. However, the metrics based on ICMP still indicate coarse grained view of the network status as shown in Fig. 4, Fig. 5, and Fig. 7. We started the experiment with the small number of metrics that are easy to be implemented to show that collecting the QoS and QoE related metrics are significant to understand the QoS and QoE. We plan to collect other metrics in the future version of the developed tool to discuss more detailed characteristics between the QoS and QoE.

Middleboxes: It is well known that some middleboxes such as carrier grade NAT gateways, accelerators, and transparent Web proxy servers are usually deployed in cellular data networks [15]. In this paper, we use unprivileged ports (above 1023) for TCP throughput measurements to avoid the interception of transparent Web proxy servers. Likewise, we



(a) PDF (b) CCDF

Fig. 7. PDF and CCDF of the median RTT by QoE

do not use TCP RTT and packet loss rate but ICMP RTT and packet loss rate to ignore TCP accelerators. However, we can consider that the QoE is affected by the acceleration mechanisms of these middleboxes. We will evaluate the impact of these middleboxes by measuring application-level (e.g., HTTP) goodputs and TCP RTT and packet loss rate as well.

Use of time and geolocation data: We have collected time and geolocation information with the QoS and QoE posts, but we have not analyzed the time and geolocation data in this paper because the number of samples is not enough to statistically analyze the QoS and QoE by hour and geolocation at the moment. We think the QoS and QoE vary by hour, and the geolocation data have the potential to shed light on the QoS and QoE at the congested environment in a metropolitan area. We will analyze time and geolocation data when we can obtain enough number of samples.

VI. Conclusion

We developed a social benchmarking tool for smartphones to measure the QoS and QoE in cellular data networks and share them among the users of the tool. In this paper, we presented the characteristics of the QoS and QoE of three cellular data network carriers (one is a CDMA2000 operator and the others are UMTS/W-CDMA operators supporting HSDPA/HSUPA) in Japan from the collected data. We demonstrated that RTT, rather than other QoS related metrics such as signal strength and packet loss rate, was one of the metrics that explains the performance of TCP throughput. We also demonstrated that the packet loss rate and RTT of the QoS related metrics affected the QoE. We showed that the characteristics of QoE was explained by QoS, especially by RTT, from these overall results.

Unfortunately, the number of available posts for QoE was currently limited. So, we will improve the user interface of the tool to attract users and collect more QoS and QoE posts. We also plan to add some metrics related to QoS such as TCP RTT, TCP packet loss rate, HTTP goodput, UDP throughput, and delay in DNS.

Acknowledgment

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