On the Statistics of QoS Parameters over Heterogeneous Networks*

A. Botta, A. Pescapé, and G. Ventre

Universitá degli Studi di Napoli, "Federico II"
Via Claudio 21, Napoli, Italy {a.botta, pescape, giorgio}@unina.it

Abstract. Offering real services with a specific Quality of Service (QoS) guarantee over heterogeneous networks is very challenging. To make it feasible a complete and robust real performance assessment of these scenarios is of paramount importance. This paper deals with a performance evaluation and measurement of a number of heterogeneous end-to-end (e2e) paths taking into account a wide range of statistics. An active measurement approach of UDP QoS parameters has been adopted for the studying of (i) proprieties we called concise statistics (mean, standard deviation, inter quantile range, minimum, maximum, and median) and (ii) detailed statistics (Probability Density Function, Auto Correlation Function, Entropy, and log-log Complementary Cumulative Distribution Function). Used tools and traces are publicly available at www.grid.unina.it/Traffic/.

Keywords: Monitoring and measurement systems, End-to-end QoS.

1 Introduction

The perceived quality of *Internet applications* is primarily determined by parameters like packet loss, delay, jitter, throughput, and available bandwidth. For this purpose, several reference documents containing constraints regarding these parameters have been defined [1], [2], [3], and research have focused on the effects of these parameters on real time traffic (i.e. telephony)[4]. Understanding the statistics of QoS parameters is important (i) for the appropriate design of network algorithms (routing, flow control, streaming, ...), (ii) for the evaluation of network capability to support new value-added services (i.e. telephony, games), (iii) for the study of network performance, (iv) for developing algorithms to detect anomalies (attacks, misconfigurations, ...) and, finally, (v) for the definition of Service Level Agreements (SLAs). In literature there are a lot of works focused on the analysis of QoS parameters and more specifically on the delay (both One Way Delay (OWD) and Round Trip Time (RTT)) over backbone networks [5], [6], [7], [8], [9]. It is our opinion that with rapidly expanding core and backbone networks, performance parameters such as delay, jitter, bandwidth, and loss get

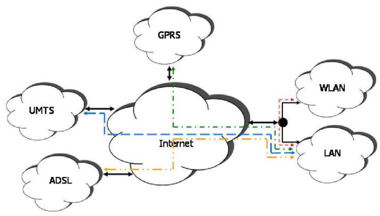
* This work has been partially supported by the MIUR in the framework of the PRIN 2004 Quasar Project and by the E-Next European project.

increasingly dominated by access networks. Thus the focus changes from observing performance in the network core to the communicating hosts and their access networks. To the best of our knowledge, as for the performance study, in literature a number of interesting works are present. Unfortunately, they are characterized by the use of a classical approach devoted to determine just the first order statistics of the considered QoS parameters. To fulfill this gap, in this work we present some results regarding both the "*concise statistics*" (mean, standard deviation, inter quantile range, minimum, maximum, and median) and "*detailed statistics*" (Probability Density Function, Auto Correlation Function, Entropy, and log-log Complementary Cumulative Distribution Function) of the considered QoS parameters. More precisely we present such combined statistical analysis of delay, jitter, and throughput. The rest of the paper is organized as follows. In Section 2 motivations, related works, and the reference framework which our work is based on, are presented. The experimental setup where our work has been carried out is presented in Section 3. Section 4 shows the results of the QoS parameter analysis over some selected e2e paths. In Section 5 a short discussion on obtained results is presented. Finally, Section 6 provides some concluding remarks and issues for future research.

2 Motivation and Related Works

In [5] the authors measure the e2e delay of fixed paths demonstrating that about 84% present typical histograms having a Gamma-like shape with heavy tail. The authors of [7] present an analysis of the delay distributions of the SPRINT IP backbone. They find that the main contributing factor in network delay is the speed of light and the jitter is extremely low. In [9] and in [8] the authors measure and analyze the single-hop packet delay through operational routers in a backbone IP network. They find that it is long tailed and fits a Weibull distribution with the scale parameter, a = 0.5, and the shape parameter, b = 0.58 to 0.6 (or b=0.6 to 0.82). Authors of [10] present results related to packet delay and loss for IP data traversing the University of Auckland Internet access path. The paper contains a complete analysis but there is no indication of statistical proprieties of the considered variables. In [11] the authors present a jitter analysis obtained with the RIPE NCC Test Traffic Measurement setup among several measurement point located all over the world. In [12] the authors present evidence that the packet round trip delays exhibit Long Range Dependence (LRD) showing that the complementary probability distribution of packet round trip delays decays more slowly than exponential rate. In [13] the authors study the delay characteristics of ADSL service in Korea. They measure traffic delays path by path across the whole network, to locate the bottleneck of the delay. Also, they study the relationship between delay and packet size, and between delay and network utilization. [14] presents an analysis of the Self-similarity of Internet Packet Delay. Over some selected fixed paths they find evidence that the degree of self-similarity for a round-trip path in the Internet may be correlated with the packet loss observed on that path. This result has been achieved using tools like

Table 1. Abstraction of the Experimental Test-bed and Considered Paths



e2e path	Protocol	OSs	Devices
GPRS-to-Ethernet	UDP	Windows XP-to-Linux	Laptop-to-Workstation
UMTS-to-Ethernet	UDP	Windows XP-to-Linux	Laptop-to-Workstation
ADSL-to-Ethernet	UDP	Linux-to-Linux	PC-to-Workstation
Ethernet-to-GPRS	UDP	Linux-to-Windows XP	Workstation-to-Laptop
Ethernet-to-ADSL	UDP	Linux-to-Linux	Workstation-to-Desktop PC
Ethernet-to-WLAN	UDP	Linux-to-Windows XP	Workstation-to-Laptop

variance-time plot, R/S analysis, periodogram analysis, and Whittle's estimator. As shown, there exist several qualified tools and methodologies for characterizing network behavior from e2e measurements. As for the statistical approach, the works present in literature are focused on QoS parameters analysis over backbone networks and they perform a statistical analysis just in terms of CDFs and PDFs (sometimes along with the percentiles analysis). Other times they take into account the analysis of the Long Range Dependence (LRD). To the best of our knowledge, our approach extends the results present in literature in that we consider a more general framework in terms of both statistical approach and heterogeneous network scenarios (i.e. composed of a large mix of variables regarding the considered end-user device, operating systems, access networks technologies (Ethernet, ADSL, WLAN 802.11b, GPRS, and UMTS)). More precisely, **(i)** we present a complete evaluation, from the application point of view, of heterogeneous e2e paths in terms of a wide range of QoS parameters (throughput, delay, jitter); **(ii)** we focus our attention on a novel vision of the e2e path (a path including the communicating peers and their operating systems); therefore we take into account several factors like Operating Systems, End-Users' Device, Network Technologies and relationships among them; **(iii)** we present a more complete statistical approach, including the study of the probability distributions, the tail analysis, the entropy measure, and the LRD analysis. This permits to highlight some behavior hidden applying just a concise statistical approach. **(iv)** we made publicly available the used tools and data traces at [23].

3 Test-beds, Tools, and Measurement Approach

3.1 Test-bed and Data Traces

We performed our experiments over the real test-bed described in [15]. It is composed of a number of heterogeneous wireless/wired networks which simplified abstraction is depicted in Table 1. Over such test-bed several configurations have been taken into account, indeed, the experiments have been performed by varying a number of configuration parameters like operating system, end user device, access network, transport protocol, and traffic condition. By combining all these variables we obtained about 350 different network conditions. The measurement stage has been performed in the time period between December 2003 and November 2004, in the day hours between 9:00 am and 6:00 pm. In that

Table 2. Throughput[Kbps]

e2e Path	Min	Max	Avg	StDev	IQR	Med
GPRS-to-Ethernet	0	40.96	18.44	6.913	0	20.48
UMTS-to-Ethernet	0	327.6	52.31	47.92	20.48	61.44
ADSL-to-Ethernet	122.8	245.8	204.6	6.924	0	204.8
Ethernet-to-GPRS	0	61.44	39.56	16.60	0	40.96
Ethernet-to-ADSL	20.48	348.2	204.5	15.01	0	204.8
Ethernet-to-WLAN	184.3	225.3	204.7	3.934	0	204.8

Table 3. Jitter [s]

e2e Path	Min	Max	Avg	StDev	IQR	Med
GPRS-to-Ethernet	0.048	5.048	0.179	0.531	0.003	0.090
UMTS-to-Ethernet	0	1.768	0.054	0.171	0.02	0.03
ADSL-to-Ethernet	0	0.089	$7{\cdot}10^{-4}$	0.002	$3{\cdot}10^{-4}$	$7{\cdot}10^{-4}$
Ethernet-to-GPRS	0	0.518	0.055	0.076	0.066	0.047
Ethernet-to-ADSL	0	0.034	$6{\cdot}10^{-3}$	0.001	$4{\cdot}10^{-4}$	$3{\cdot}10^{-4}$
Ethernet-to-WLAN	0	0.023	$7{\cdot}10^{-4}$	0.001	$7{\cdot}10^{-4}$	$5{\cdot}10^{-4}$

time, over $34GB$ of traffic traces have been collected. Such traces have been previously inspected and sanitized in order to detect and remove samples affected by errors. Also, we would like to underline that the used GPRS and UMTS connections have been provided by two of the principal Italian Telecom Operators. Such connections are the same provided to all their customers, for this reason, the reported performance are exactly the same a user would experience. To highlight the features of the proposed statistical approach, as an example, we consider six e2e paths. The characteristics of the analyzed scenarios are presented in Table 1. TCP results have also been obtained, but in this work we focus on the UDP ones. It is worth noting that ICMP has not been used in our experiments because (i) it is handled by the routers differently from UDP/TCP and (ii) we are interested in the behavior of QoS parameters of application traffic (based on TCP and UDP).

3.2 Measurement Approach

As for the active measurement procedure we used our tool called Distributed Internet Traffic Generator (D-ITG) [23]. By combining different pairs of PS (Packet Size) and IDT (Inter Departure Time) D-ITG generates a multitude of traffic patterns. In this way we generate controlled synthetic traffic that is - at the same time - realistic. Also, in order to draw a reference curve for the parameter statistics, in this paper we consider only a UDP Constant Bitrate (CBR) traffic profile generated with constant PS and constant IDT. We would like to underline that our experiments have been carried out by using three traffic conditions namely *Low*, *Medium*, and *High Traffic* [24]. For each of them a number of PS have been used. Due to the nominal bandwidth of some of the used wireless connections (i.e. GPRS and UMTS), we consider here, only *Low Traffic* condition using IDT equal to $1/100s$ and PS equal to $256Bytes$ (thanks to this choice we have a maximum theoretical bit rate equal to $204.8Kbps$). To point out the e2e communication differences, we show the behavior of throughput, jitter, and Round Trip Time measured over UDP connections. We do not present the packet loss because, in this traffic condition, in the scenarios including WLAN and ADSL, it was always equal to 0. The jitter samples have been calculated by using the definition given in [25]. Finally, it is worth noting that presented results have been averaged on several tests in order to minimize the effect of random

Table 4. RTT [s]

Path	Min	Max	Avg	StDev	IQR	Med
GPRS-to-Ethernet	6.309	17.11	10.95	3.92	6.311	12.69
UMTS-to-Ethernet	1.535	4.182	2.551	0.573	0.543	2.494
ADSL-to-Ethernet	0.042	0.638	0.277	0.130	0.070	0.260
Ethernet-to-GPRS	0.801	14.31	10.15	3.017	3.040	11.26
Ethernet-to-ADSL	0.044	0.200	0.095	0.014	0.019	0.100
Ethernet-to-WLAN	$3 \cdot 10^{-4}$	0.135	0.084	0.02	0.002	0.090

Table 5. Jitter and RTT Entropy [bit]

E2E path	GPRS-to-Eth	UMTS-to-Eth	ADSL-to-Eth	Eth-to-GPRS	Eth-to-ADSL	Eth-to-WLAN
Jitter	3.978	3.258	0.465	6.079	0.628	0.910
RTT	4.399	6.406	2.976	8.504	2.562	1.571

error on measures. In the following the mean values across 20 test repetitions are reported.

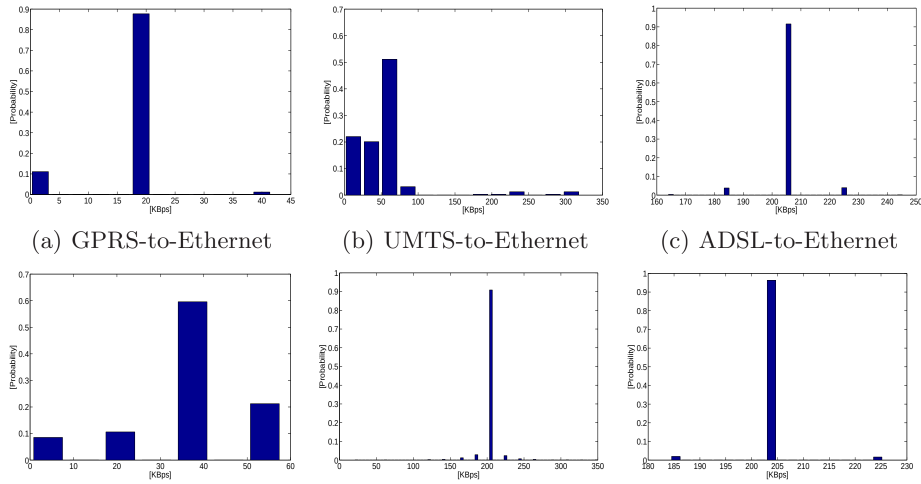
3.3 Statistical Methodology

By integrating established and well-known tools, found in different works, we have set up a methodology and provided a statistical analysis of the collected samples. Along with the evaluation of mean, standard deviation, inter quantile range, maximum, minimum values we adopted tools as distribution estimation, study of the tails, auto-correlation function, and entropy measure. In Section 4 the motivations to select each of these tools are present. Statistical software tools as well as the data traces used in this paper are freely available at [23].

4 Analysis of QoS parameters

4.1 Concise Statistical Analysis

Tables 2, 3, and 4 present the results of the concise statistical analysis. More precisely, for each considered path, they contain the minimum, the maximum, the average, and the median values of throughput, jitter and round trip time. Also, they contain the standard deviation and the inter quantile range (IQR) of the same parameters. The used IQR is defined as the difference between the $75th$ and $25th$ percentiles. Average and standard deviation are more useful when analyzed along with minimum and maximum values. Moreover the IQR and median are better estimators for skewed distributions (e.g. Figure 2(c)), than respectively the standard deviation and the average value, because they are less influenced by extreme samples. As for the throughput, Table 2 shows that, as expected, in the configurations including GPRS and UMTS connections, the minimum, average, and median values of throughput are lower than the corresponding values of the other configurations. Also, the standard deviation looks very similar for very different configurations. Despite this, such result can be related to very different situations and misleading if not observed together with the average values (see GPRS/ADSL-to-Ethernet). It is also interesting to note that in the UMTS-to-Ethernet configuration we achieved a standard deviation very close to the mean value. This implies that the average is not representative of the sample values. Indeed, the samples achieved very different values from each other. Moreover, in this case, we observe a mean value quite different from the median. As for the jitter, Table 3 shows that, also for this parameter, the GPRS/UMTS based configurations achieved the worst performance (higher jitter values). Indeed, they present higher maximum, average, median, and standard deviation values. In Section 5 a possible explanation of such behavior is present. The RTT values presented in Table 4 confirm such behavior. Indeed, all the values are higher for the samples collected by using GPRS and UMTS connections. It is worth noting that in the case of Ethernet-to-GPRS and GPRS-to-Ethernet the average values and the median values are quite different. This is not true in the case of other paths. This behavior is amplified in the case of throughput.



(a) GPRS-to-Ethernet (b) UMTS-to-Ethernet (c) ADSL-to-Ethernet

(d) Ethernet-to-GPRS (e) Ethernet-to-ADSL (f) Ethernet-to-WLAN

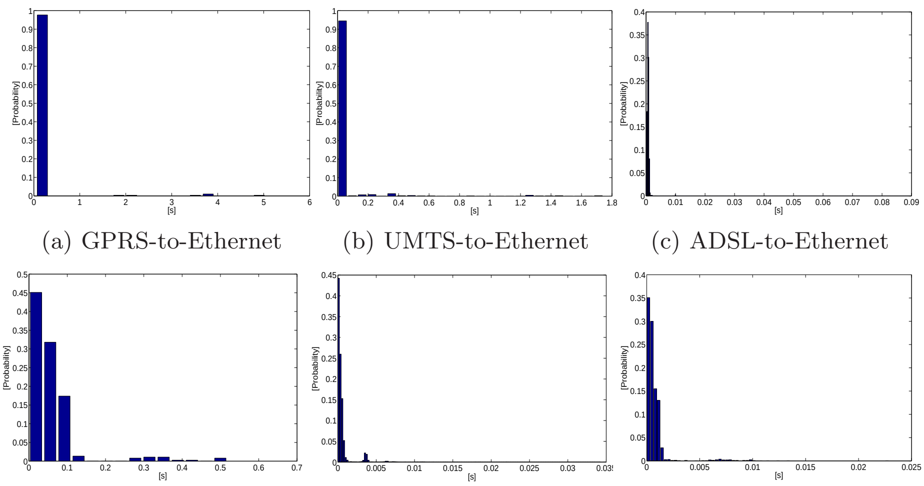
Fig. 1. PDF of UDP throughput

4.2 Detailed Statistical Analysis

In this Section, applying the methodology presented in Section 3.3, we show our results on Probability Density Functions (PDFs) of QoS parameters as well as some results regarding the Auto Correlation Function (ACF), the Entropy measure, and the tail analysis. We used the Entropy to concisely quantify the randomness of the considered parameters, and the ACF to study the temporal relationships among the samples. Finally, due to the fact that the distribution's behavior in its upper tail can be crucially important we provide also the tail analysis. The throughput samples have been collected evaluating the average throughput on fixed size time intervals ($100ms$) while for RTT and jitter, each packet represents one sample. Also, to plot the PDFs of all the considered parameters, we used the bin width suggested by the Scott Rule [21].

Probability Density Functions: ***Throughput*** In Figure 1 the PDFs of the throughput samples are depicted. Figure 1 shows that (i) in the GPRS-to-Ethernet case (Fig 1(a)) the main part (87%) of the samples achieved the median value ($20.48Kbps$) while more than 10% was $0Kbps$; (ii) in the UMTS-to-Ethernet scenario the samples are spread over the interval $[0, 350]Kbps$; (iii) in the ADSL-to-Ethernet case the median value ($204.8Kbps$) has been obtained by more than 90% of the samples; (iv) in the Ethernet-to-GPRS case (Fig 1(d)) the samples are multi-modally distributed over 4 values (0, 20.48, 40.96, and $61.44Kbps$); (v) in the Ethernet-to-ADSL scenario even if more than 90% of the samples attained the median value ($204.8Kbps$), the remaining ones range from 20.48 to $348.2Kbps$; (vi) in the Ethernet-to-WLAN case the samples are even more concentrated around their median value ($204.8Kbps$).

Jitter In Figure 2 the PDFs of the jitter samples are depicted. As shown, the distributions look similar in the shape, indeed, they present the sample majority close to 0 even if a not negligible upper tail is noticed. However, the sample values of the configurations including GPRS/UMTS differ of about 1 order of magnitude from the other configurations. Indeed, in the GPRS-to-Ethernet, Ethernet-to-GPRS, and UMTS-to-Ethernet cases the samples are mainly distributed (95% of samples) over the interval $[0, 0.15]s$. Instead, in the other cases, the 95% of the samples present values less than $0.015s$. It is interesting to note that the uplink of GPRS and ADSL connections present quite different sample values from the downlink. Such result is due to the asymmetry of these connections. It can be used in a classification framework.

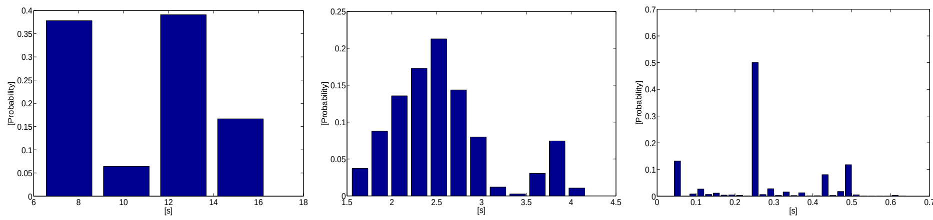


(a) GPRS-to-Ethernet (b) UMTS-to-Ethernet (c) ADSL-to-Ethernet

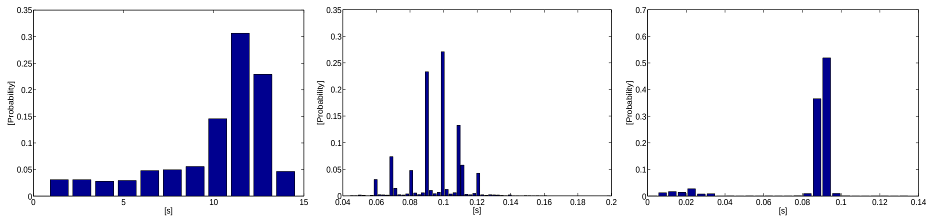
(d) Ethernet-to-GPRS (e) Ethernet-to-ADSL (f) Ethernet-to-WLAN

Fig. 2. PDF of UDP Jitter

Delay (RTT) In Figure 3 the PDFs of the RTT samples are sketched. In contrast with the jitter here the distributions are very different from each other. Indeed, the GPRS-to-Ethernet samples are multi-modally distributed around 4 values (6.5, 10, 12.5, and $17s$). In the UMTS-to-Ethernet case the distribution is bimodal with the modes not strictly separated. In the ADSL-to-Ethernet configuration the samples are spread all over the $[0.05, 0.7]s$ interval with a concentration (the 50% of the samples) around their median value ($0.26s$). Ethernet-to-GPRS samples are close to their median value ($11.26s$) and a heavy lower tail is present. The Ethernet-to-ADSL configuration presents samples that are mainly distributed over the interval $[0.04, 0.2s]$, and, in the mainly populated interval ($[0.06, 0.12]s$), spikes are present at multiple of $0.01s$. Finally, the Ethernet-to-WLAN samples are bimodally distributed around $0.02s$ and $0.09s$.



(a) GPRS-to-Ethernet (b) UMTS-to-Ethernet (c) ADSL-to-Ethernet

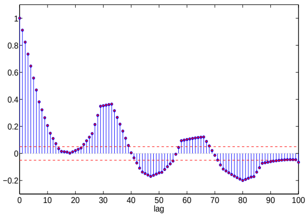


(d) Ethernet-to-GPRS (e) Ethernet-to-ADSL (f) Ethernet-to-WLAN

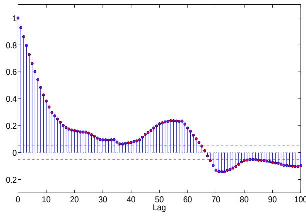
Fig. 3. PDF of UDP RTT

Other statistics: ***ACF*** To understand the sample statistical dependence, in Figure 4 the ACF of the UDP RTT samples as a function of sample distance (called *lag*) is sketched. As the traces are related to synthetic CBR traffic the more the ACF values approach 0 the more uncorrelation among packet arrival times has been introduced by the e2e path. As we can see the $ACF(1)$ values is higher than 0.9 for all the considered configurations. Also, the configurations that include GPRS and UMTS connections present more uncorrelation among samples. Indeed, for such configurations the autocorrelation plot decays more rapidly than in the other cases. Such behavior proves that the GPRS and UMTS connections introduce uncorrelated randomness in packet arrival process. In the case of GPRS and UMTS at sender side, the ACF shows an oscillating behavior. This is due some periodicities in the RTT sequences. Our preliminary analysis shows that such behavior is related to the packet loss trend [22].

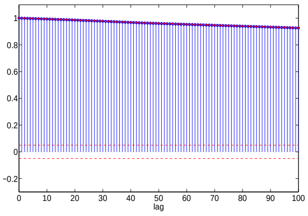
Entropy In order to better understand the variability of collected samples we have also evaluated the entropy of the traces. For the sake of comparing entropy values of different configurations, when estimating such parameter, we



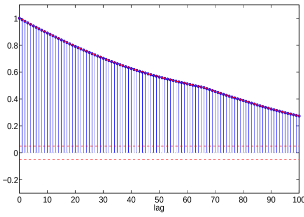
(a) GPRS-to-Ethernet



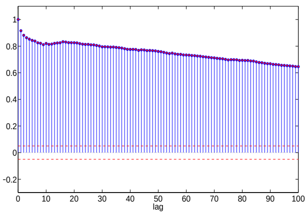
(b) UMTS-to-Ethernet



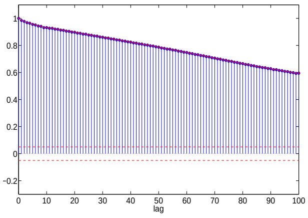
(c) ADSL-to-Ethernet



(d) Ethernet-to-GPRS



(e) Ethernet-to-ADSL



(f) Ethernet-to-WLAN

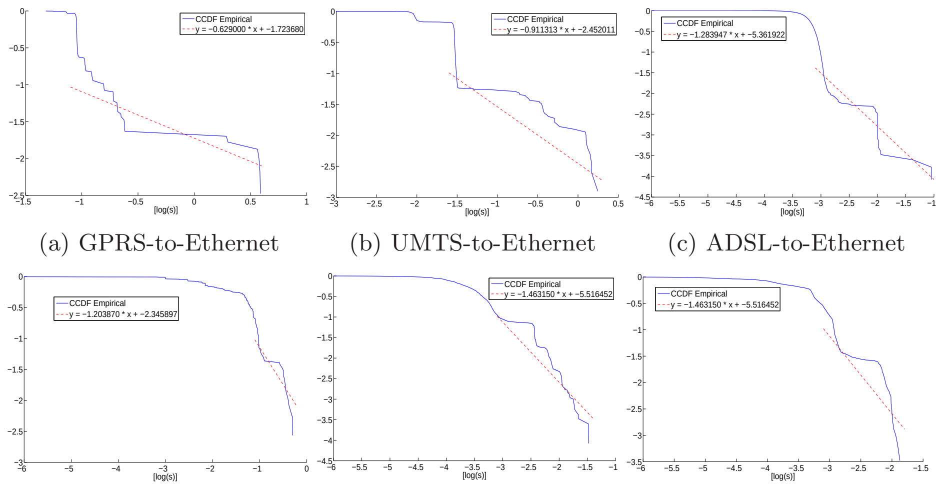
Fig. 4. ACF of UDP RTT

used the same bin size for all the configurations instead of the Scott rule one. Indeed, the Scott rule provides a bin size that varies with the samples number and values. Therefore for the RTT we used a bin width equal to $0.01s$ while for the jitter equal to $0.001s$. Table 5 presents entropy values calculated for the jitter and RTT samples. Such Table shows that the entropy values obtained on the GPRS-to-Ethernet, Ethernet-to-GPRS, and UMTS-to-Ethernet paths are always higher than that achieved on the other configurations. Furthermore, the reported values prove that the randomness introduced by GPRS and UMTS connections influences both the delay and its variations (jitter). It is also interesting to note that when the GPRS is used at sender side both RTT and jitter entropy values are much higher with respect to the other direction of the communication.

Tail analysis In order to analyze the tail behavior we sketch the plot of the complementary CDF (CCDF) in logarithmic scales. In Figure 5 the CCDF of the jitter samples is depicted. In such Figure it has also been reported a line that allows us to evaluate the slope of the upper tail. With such plot it becomes clear that the jitter presents a heavy tail behavior for all the analyzed configuration. In Figure 6 the CCDF of RTT samples is sketched using logarithmic scales. In contrast to the previous parameter, in the RTT distribution there is no evidence of a heavy tail behavior. Indeed, for all the considered configurations the sample distributions decay to zero with an over-exponential rate.

5 Discussion

For GPRS and ADSL based configurations we have observed a relevant difference on the collected statistics depending on the communication direction. In particular, the PDFs, ACFs, and entropy values of RTT samples collected inject-



(a) GPRS-to-Ethernet (b) UMTS-to-Ethernet (c) ADSL-to-Ethernet

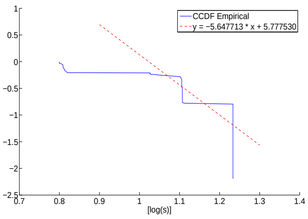
(d) Ethernet-to-GPRS (e) Ethernet-to-ADSL (f) Ethernet-to-WLAN

Fig. 5. Log Log CCDF of UDP jitter

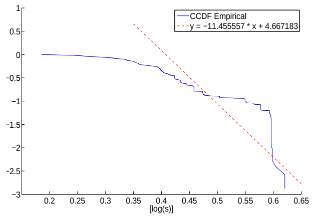
ing traffic in the uplink direction, are different from the ones related to the other direction. This behavior is partially hidden applying just a concise statistical approach. Also, a similar consideration can be done for the jitter and throughput samples. As a general consideration, we can state that there is a clear impact of the connection bandwidth on all the presented parameters. As an example, if we look at the RTT and jitter entropy of GPRS based configurations, we observe much higher values when the GPRS is present at receiver side. This behavior can be probably justified considering that, in this case, the packets are queued in some segment of the e2e path close to the receiver side. This is suitable with the low capacity of the GPRS access network. In the opposite case, with the GPRS at sender side, just the allowed packets traverse the e2e path and the randomness is lower than the previous one.

Presented results have shown evidence that the jitter presents a heavy tailed behavior, indeed, its CCDF decays with a rate lower than the exponential one. By the observation of the ACFs, we have noticed that RTT shows, in most cases, a LRD behavior. While, just for GPRS/UMTS based connections, the ACF also presents some periodicities.

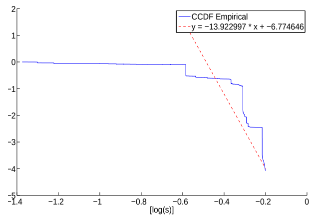
As for the comparison between wireline and wireless connections, we have observed that RTT samples collected on GPRS and UMTS based configurations present the lowest values of correlation and the highest entropy values. A higher entropy value has been observed in both RTT and jitter samples. This behavior is probably due to the fact that to transmit IP packets on a cellular network, a number of architecture elements have to be traversed before to reach the Internet. Each of these elements has its own protocol stack and gateway to the Internet. Furthermore, cellular networks have been designed to mainly transport voice traffic at $64Kbps$. Therefore, at higher bit rate, they introduce considerable latency in IP packet transmission. Also, they contribute to increase delay vari-



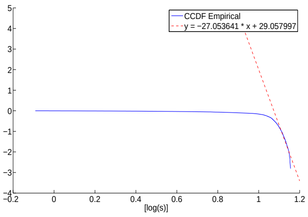
(a) GPRS-to-Ethernet



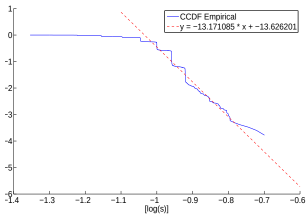
(b) UMTS-to-Ethernet



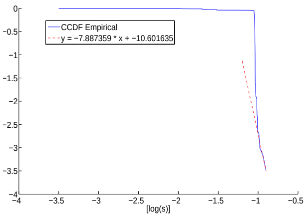
(c) ADSL-to-Ethernet



(d) Ethernet-to-GPRS



(e) Ethernet-to-ADSL



(f) Ethernet-to-WLAN

Fig. 6. Log Log CCDF of UDP RTT

ation (jitter) values as already been remarked in Section 4.1. Further analysis aiming to fully understand the driving phenomena at the base of the measured results are the subject of our ongoing work.

6 Conclusions

In this paper we presented some results of our empirical performance study of a number of e2e heterogeneous paths. Tools and traces used in this work are freely and publicly available at [23].

A number of tests conducted on our real test-bed yielded important proprieties of throughput, delay, and jitter in terms of both concise (minimum, maximum, average, median, standard deviation, and IQR values) and detailed (PDF, ACF, entropy, and tail analysis) statistics. Thanks to this combined approach, several behaviors - hidden applying just a concise statistics - have been analyzed. Among them we can summarize the following: (i) we have analyzed the impact of network path bandwidth on RTT and jitter and the difference between such parameters distributions for uplink and downlink traffic; (ii) the jitter presents evidences of heavy tail; (iii) the ACF analysis of the RTT reveals LRD in all cases except the GPRS/UMTS path where we found a periodic behavior; (iv) we found the highest values of entropy (of both jitter and RTT) in the case of path containing GPRS and UMTS connections. Preliminary results have shown that the considered parameters, collected at the edge of the network, present a behavior different from the ones collected on the backbone (according to the results presented in the cited works).

Currently, we are using statistics presented in this work in a e2e path classification framework.

References

1. ITU-T SG16, “One-way Transmission Time”, Recommendation G.114
2. ITU-T SG13, “Network Performance Objectives for IP-Based Services”, Y.1541
3. ITU-T SG12, “The E-model, a computational model for use in transmission planning”, Recommendation G.107
4. L. Zheng, L. Zhang, D. Xu, “Characteristics of network delay and delay jitter and its effect on voice over IP (VoIP)”, ICC 2001, V. 1, June 01 pp.122–126.
5. C.J. Bovy, H.T. Mertodimedjo, G. Hooghiemstra, H. Uijterwaal and P. Van Mieghem, “Analysis of End-to-end Delay Measurements in Internet”, PAM 02
6. B.-Y. Choi, S. Moon, Z.-L. Zhang, K. Papagiannaki, C. Diot, “Analysis of point-to-point packet delay in an operational network”, INFOCOM 04, V. 23, no. 1, March 04 pp. 1798-1808
7. C. Fraleigh et al. , “Packet-level traffic measurements from the sprint IP backbone”, IEEE Network, vol. 17, no. 6, Nov 03 pp. 6-16
8. K. Papagiannaki, S. Moon, C. Fraleigh, P. Thiran, C. Diot, “Measurement and analysis of single-hop delay on an IP backbone network”, Journal on Selected Areas in Communications,V. 21, no. 6, Aug 03 pp. 908-921
9. K. Papagiannaki, S. Moon, C. Fraleigh, P. Thiran, F. Tobagi, C. Diot, “Analysis of measured single-hop delay from an operational backbone network”, INFOCOM 02, V. 21, no. 1, June 02 pp. 535-544
10. K. Mochalski, J.Micheel, S.Donnelly, “Packet Delay and Loss at the Auckland Internet Access Path”, PAM 02
11. M.Alves et al. , “New Measurements with the RIPE NCC Test Traffic Measurements Setup”, PAM 02
12. Q. Li, D. L. Mills, “On the long-range dependence of packet round-trip Delays in Internet”, ICC 98, pp. 1185-1191
13. K. C. Kang, K. Nam, D. J. Jeon, S. Y. Kim, “Delay Characteristics of High-Speed Internet Access Network: One Case Study”, APNOMS 03
14. M.S. Borella, S. Uludag, G.B. Brewster, I. Sidhu, “Self-similarity of Internet packet delay”, ICC 97 V. 1, June 97 pp. 513–517
15. A. Botta, D. Emma, A. Pescapé, G. Ventre,“Systematic Performance Modeling and Characterization of Heterogeneous IP Networks”, IEEE ICPADS 05 PMW2MNC Workshop. V. 2, pp. 120-124 - July 05, Fukuoka (Japan)
16. M. Crovella, M.S. Taqqu, “Estimating the Heavy Tail Index from Scaling Properties”. In Methodology and Computing in Applied Probability, V. 1 No. 1 (99).
17. M. Crovella, “Network Traffic Modeling”. Tutorial at SIGCOMM 04.
18. T.M.Cover, J.A.Thomas, “Elements of information theory”, J. Wiley and sons, 91
19. C. Shannon, “A Mathematical Theory of Communication” Bell Systems Technical Journal, 47:143157, 48.
20. M. Lelarge, Z. Liu, C.H. Xia,“Asymptotic Tail Distribution of End-to-End Delay in Networks of Queues with Self-Similar Cross Traffic”, INFOCOM 04.
21. D.W.Scott, “On optimal and data-based histograms”, Biometrika 66, pp.605-610
22. G. Iannello, F. Palmieri, A. Pescapé, P. Salvo Rossi, “End-to-End Packet-Channel Bayesian Model applied to Heterogeneous Wireless Networks”, Globecom 2005
23. `http://www.grid.unina.it/Traffic`
24. G. Iannello, A. Pescapé, G. Ventre, L. Vollero, Measuring Quality of Service parameters over heterogeneous IP networks, International Conference on Networking (ICN 2005), LNCS 3421, pp. 718727, 2005.- April 2005, Reunion Island
25. C. Demichelis, P. Chimento, IP Packet Delay Variation Metric for IP Performance Metrics (IPPM), RFC 3393, November 2002