Analysis of Throughput Performance Statistics for Benchmarking LTE Networks

V. Buenestado, J. M. Ruiz-Avilés, M. Toril, S. Luna-Ramírez, and A. Mendo

***Abstract*—In this letter, a comprehensive analysis of throughput performance statistics in a live LTE network is presented. The analysis shows the relationship between several widely accepted throughput performance indicators, i.e., the user throughput, the cell throughput, and the radio link throughput, and how these indicators are related to signal quality statistics. The analysis is performed on a per-cell and per-connection basis. For this purpose, throughput and signal quality statistics are collected from network performance counters and call traces in cells of a live LTE system. Results show that all throughput measures are strongly affected by chatty applications dominating current LTE networks due to the last transmission time interval transmissions and the outer loop link adaptation mechanism.**

***Index Terms*—LTE, throughput, CQI, live cellular network.**

I. Introduction

A key process in cellular network operation is the assessment of any newly added network feature. For this purpose, the metrics used to assess network performance must reflect user experience accurately. Poorly selected key performance indicators can be difficult to interpret, and reaching their target levels may have little impact on user experience and overall network efficiency. To avoid this, mobile operators are changing their way of verifying their networks, substituting network-centric performance indicators by user-centric service performance indicators [1]. In the same direction, 3rd Generation Partnership Project (3GPP) has defined five classes of service performance indicators, namely service availability, accessibility, retainability, mobility and integrity [2].

Average user throughput is currently used by operators to check the integrity of data services in all radio access technologies, while user-centric indicators become available [2]. In addition, average cell throughput is used to estimate the maximum cell capacity for network dimensioning [3]. LTE throughput performance has been reported in the literature based on simulation tools [4] or field tests [5]. However, our first tests of automatic coverage-capacity network optimization algorithms [2] in live LTE systems have shown that user throughput is hardly affected by these algorithms, even if lower-level performance indicators, such as signal-to-interference ratios or channel quality indicators, vary significantly. Large improvements in connection quality statistics should lead to the use of more efficient modulation schemes due to the Adaptive Modulation and Coding (AMC) algorithm in the base station. This should translate into larger throughput figures, which was not the case. Thus, a deeper analysis of throughput statistics is needed for live LTE networks.

In this work, a comprehensive analysis of several widely accepted throughput network performance indicators in LTE is presented, based on counters and call traces of a live network. The aim is to understand how throughput performance indicators differ and how much they are correlated with signal quality indicators. Section II outlines the considered throughput performance indicators. Section III describes the live scenario where statistics are collected. Section IV shows the results of the analysis and Section V summarizes the conclusions of the study.

II. Definitions

This section describes the indicators used in the analysis, which are generated from Performance Management (PM) counters in the network management system. All the considered throughput performance indicators are defined in [2] and are implemented by most vendors. The following definitions are valid for DownLink (DL) and UpLink (UL) channels.

A. Average User Throughput

Average user throughput is measured as

$$AvgUeThp = \frac{TotPDCPVolDataExclLastTTIs}{TotEffectiveTimeExclLastTTIs} \; [kbps], \tag{1}$$

where $TotPDCPVolDataExclLastTTIs$ is the total Packet Data Convergence Protocol (PDCP) Service Data Unit (SDU) volume transferred per cell and Reporting Output Period (ROP), excluding data transferred in the Time Transmission Intervals (TTI) emptying the buffer (referred to as 'last TTIs'), and $TotEffectiveTimeExclLastTTIs$ is the time used to send the information excluding last TTIs [2]. Both $TotPDCPVolDataExclLastTTIs$ and $TotEffectiveTimeExclLastTTIs$ are aggregated measurements of all users in a cell. Last TTIs are excluded to remove TTIs that are not fully utilized so as to achieve a throughput measure independent of file size [2].

B. Average Cell Throughput

Average cell throughput is defined as

$$AvgCellThp = \frac{TotPDCPVolData}{ActiveSchedTime} \; [kbps], \tag{2}$$

Manuscript received February 5, 2014; accepted July 7, 2014. Date of publication July 16, 2014; date of current version September 8, 2014. This work was supported in part by the Spanish Ministry of Economy and Competitiveness under Grant TIN2012-36455, by Optimi Ericsson, by Agencia IDEA (Consejería de Ciencia, Innovación y Empresa, Junta de Andalucía) under Ref. 59288, and by FEDER. The associate editor coordinating the review of this paper and approving it for publication was S. Vural.

V. Buenestado, J. M. Ruiz-Avilés, M. Toril, and S. Luna-Ramírez are with the Department of Communications Engineering, University of Málaga, 29071 Málaga, Spain (e-mail: vbg@ic.uma.es; jmruiz@ic.uma.es; mtoril@ic.uma.es; sluna@ic.uma.es).

A. Mendo is with the Business Unit Network Operations Support System Product Development Unit Department, Ericsson, 29590 Málaga, Spain (e-mail: adriano.mendo@ericsson.com).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LCOMM.2014.2337876

where $TotPDCPVolData$ is the total PDCP SDU data volume transferred in a cell and ROP considering all TTIs, and $ActiveSchedTime$ is the scheduler activity time. $ActiveSchedTime$ is incremented by 1 ms in every TTI with data to be scheduled. Therefore, $AvgCellThp$ is the aggregated user throughput in a cell when resources are being scheduled.

C. Average Radio Link Throughput

Average radio link throughput indicates the spectral efficiency in a cell, as

$$AvgRadioThp = \frac{TotSuccVolData}{TotResourcesForTr} \left[\frac{kb}{RE}\right], \quad (3)$$

where $TotSuccVolData$ is the total successfully transmitted Medium Access Control (MAC) Protocol Data Unit (PDU) data volume, and $TotResourcesForTr$ is the number of Resource Elements (RE) used for transmission. RE is the smallest assigned resource unit, consisting of one subcarrier (15 kHz) for a duration of one OFDM symbol [4]. $TotSuccVolData$ is incremented when a transmission is acknowledged on Hybrid Automatic Repeat reQuest (HARQ) level and $TotResourcesForTr$ is incremented when HARQ feedback for a transmission is received, regardless of the feedback received. Thus, $AvgRadioThp$ indicates the average data volume transmitted per RE, as a measure of spectral efficiency.

D. Traffic

Traffic is the total user data volume in a period, as

$$Traffic = \frac{TotPDCPVolData}{PeriodDuration} \, [kbps], \quad (4)$$

where $TotPDCPVolData$ is the transferred PDCP SDU data volume and $PeriodDuration$ is the measurement period. $TotPDCPVolData$ is the same statistic used in $AvgCellThp$ and $PeriodDuration$ is the ROP. $Traffic$ indicates the average cell throughput including periods where the scheduler is inactive.

E. Average Number of Users

Two indicators are used to measure the average number of users in one cell, namely

$$AvgNoUeperTTIinROP = \frac{TotNoActiveUsers}{PeriodDuration}, \quad (5)$$

$$AvgNoUeperTTIinSchedAct = \frac{TotNoActiveUsers}{ActiveSchedTime}, \quad (6)$$

where $TotNoActiveUsers$ is the sum of number of active users per TTI across the whole period of time $PeriodDuration$, and $ActiveSchedTime$ is the scheduler activity time during this period. The main difference between them is that (6) only takes into account TTIs with active users.

III. Scenario

This section describes the main features of the live LTE network used for data collection.

TABLE I
SCHEDULING PERFORMANCE STATISTICS

	Downlink	Uplink
Perc. data transmitted in last TTIs [%]	13.80	47.26
Perc. of underused TTIs (last TTIs) [%]	38.10	89.06
Avg. data vol. in last TTIs [kb]	2.05	0.11
Avg. data vol. in other TTIs [kb]	7.91	1.02
Avg. scheduler activity ratio [%]	15.14	14.68
Avg. no. active users per TTI in ROP	0.20	0.32
Avg. no. active users per TTI in scheduler activity	1.35	2.16
Avg. number of active TTIs per connection	239	932

A. Analysis Set Up

The considered urban area consists of 234 LTE cells, of which 129 use a first carrier at 734 MHz with 10 MHz bandwidth and the other 105 use a second carrier at 2.132 GHz with 5 MHz bandwidth. The above-described throughput performance indicators were collected during 2 days on a cell and hourly basis, obtaining a total of 11 232 samples. Thus, ROP is one hour. Moreover, measurement events of 60 000 calls were processed to allow a more detailed analysis based on call traces. Both data sets comprise DL and UL measurements.

B. Preliminary Analysis

Table I presents relevant scheduling performance statistics for the UL and DL. It is observed that, currently, almost half of the data transmitted in UL is sent in a last TTI. Likewise, 90% of TTIs in UL are last TTIs. From this data, it can be deduced that UL traffic consists of very small data bursts. The comparison of the average data volume transmitted in last TTIs against that of the rest of TTIs, shows that the former is significantly lower (2.05 kb against 7.91 kb for DL, and 0.11 kb against 1.02 kb for UL). This is clear evidence of the inefficiency of last TTI transmissions due to insufficient amount of data in the buffer to fill assigned REs in these TTIs. It is also observed that both UL and DL schedulers have the same activity ratio (i.e., activity time/ROP). Nonetheless, the average number of users per TTI in UL is 60% larger than in DL, both per ROP and per scheduler activity.

Since most UL data transmissions take place in last TTIs (i.e., 90% of total TTIs), and last TTIs are not considered in some of the throughput indicators in Section II, the analysis in the following section is focused on DL.

IV. Throughput Performance Analysis

The following paragraphs compare the different throughput performance indicators. The analysis is first carried out based on PM counters, and is later extended to call traces.

A. Counter Based Analysis

Fig. 1(a)–(c) show the relationship between the different throughput performance indicators based on hourly measurements. In particular, Fig. 1(a) shows the correlation between $DL\ AvgUeThp$ and $DL\ Traffic$. In the x-axis, $DLAvgUeThp$ has been multiplied by $DL\ AvgNoUeperTTIinROP$ to have an estimate of the total traffic (without last TTIs) per ROP. It is observed that both indicators are strongly correlated, since the determination coefficient is very large (i.e., $R^2 = 0.96$). However, the slope of the regression line is not 1, but

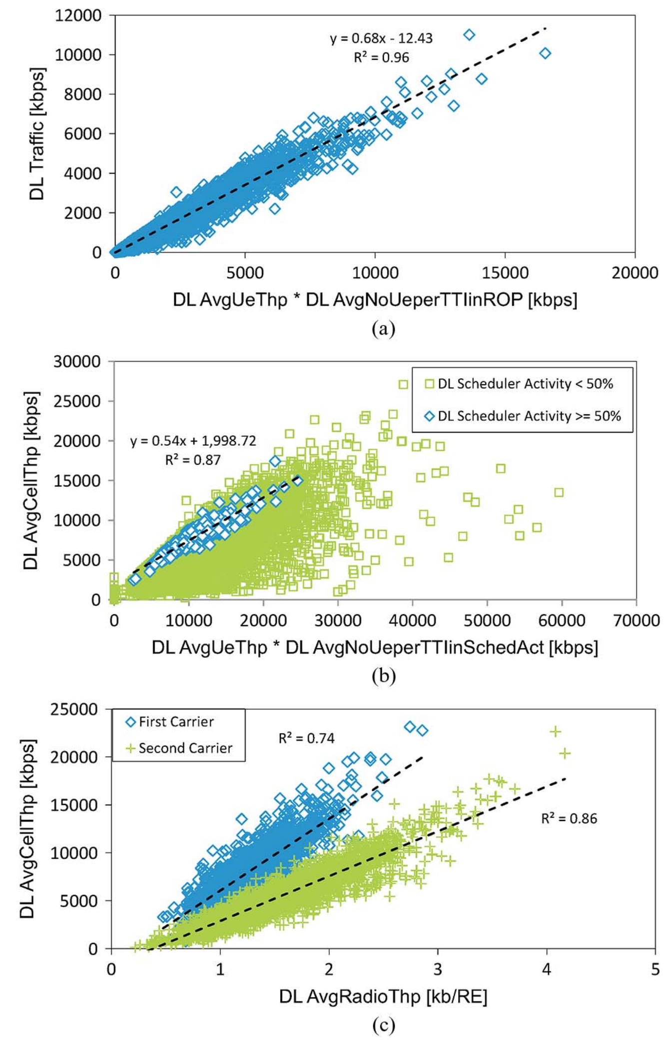

Fig. 1. Correlation between throughput performance indicators from counters.

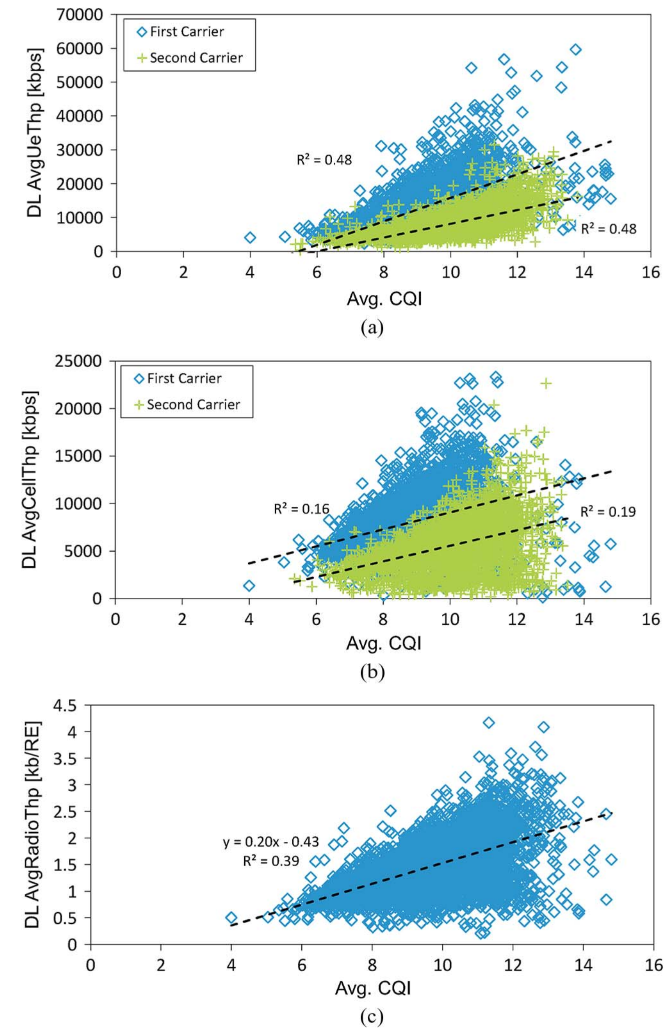

Fig. 2. Correlation of throughput performance indicators with connection quality from counters. (a) DL AvgUeThp. (b) DL AvgCellThp. (c) DL AvgRadioThp.

0.68. A theoretical analysis shows that such a slope is the ratio between the percentage of time and percentage data of non last TTIs, whose values are shown in Table I (i.e., $(1-0.381)/(1-0.138)=0.71$). From the figure, it can be concluded that $DL\ AvgUeThp$ and $DLTraffic$ provide similar information.

Fig. 1(b) compares $DL\ AvgUeThp$ and $DL\ AvgCellThp$. In this case, $DL\ AvgUeThp$ has been multiplied by $DL\ AvgNoUeperTTIinSchedAct$ to have an estimate of the total traffic (including last TTIs) divided by the scheduler activity period. It is observed that the correlation between both indicators is not so strong. A closer analysis shows that the lack of correlation is due to samples with low scheduler activity ratio, where the total traffic volume including last TTIs may not be correlated with the traffic volume without last TTIs. To confirm this, a regression line has been drawn for hours with scheduler activity period larger than 50% (i.e., 30 minutes per hour), represented by diamonds in the figure, resulting in $R^2=0.87$. This observation points out that $AvgCellThp$ must be handled with care when scheduler activity is small.

Fig. 1(c) shows the correlation between $DL\ AvgRadioThp$ and $DL\ AvgCellThp$, broken down by carrier frequency. It is observed that both indicators have a good correlation in both carriers ($R^2=0.74$ and $R^2=0.86$, respectively). The different slopes are due to the different bandwidths in each carrier (i.e., 10 MHz vs. 5 MHz), which makes that, for the same $DL\ AvgRadioThp$, $DL\ AvgCellThp$ in the second carrier is half that of the first carrier. From the figure, it is deduced that $DL\ AvgRadioThp$ and $DL\ AvgCellThp$ provide similar information when evaluated per carrier.

Having understood the differences between throughput performance indicators, the analysis is now focused on their relationship with connection quality indicators. Fig. 2(a)–(c) depict the correlation of average CQI with $DL\ AvgUeThp$, $DL\ AvgCellThp$ and $DL\ AvgRadioThp$, respectively. In Fig. 2(a) and (b), points have been grouped per carrier, since the same average CQI value (corresponding to a specific AMC scheme) would lead to different $AvgUeThp$ and $AvgCellThp$ for different system bandwidths. This is not the case for $DL\ AvgRadioThp$, as the latter is normalized by the occupied bandwidth. The figures show that the correlation between average CQI and any of the throughput performance indicators is not as strong as expected. Specifically, $R^2=0.48$, 0.19 and 0.39 for $DL\ AvgUeThp$, $DL\ AvgCellThp$ and $DL\ AvgRadioThp$, respectively. From these results, it might wrongly be concluded that a good radio signal quality does not have a direct impact on user data rates, cell capacity or network

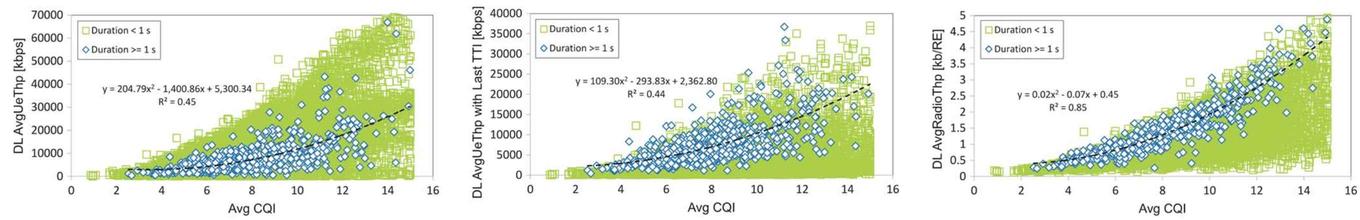

Fig. 3. Correlation of throughput and connection quality in call traces. (a) DL AvgUeThp (without last TTI). (b) DL AvgUeThp (with last TTI). (c) DL AvgRadioThp.

spectral efficiency. Such a weak correlation is not due to last TTI transmissions, since it affects all throughput indicators. This observation is the reason for the analysis based on call traces described next.

B. Trace Based Analysis

To check the relationship between throughput performance and CQI in a connection level, three throughput performance indicators, equivalent to those in eq. (1), (2), and (3), are defined on a connection basis. Note that all variables in eq. (1), (2), and (3) can be defined per connection, except the scheduler activity time, $ActiveSchedTime$, in eq. (2), which is a cell-level indicator. If $ActiveSchedTime$ is substituted by the total effective time per connection including last TTIs, (2) is converted into average user throughput including last TTIs per connection, which is the closest approximation to cell throughput in a connection level.

Fig. 3(a)–(c) shows the correlation between the defined throughput performance indicators and the average CQI experienced in the connection. Each point in the figures represents one connection. Samples are classified into short and long connections. Long connections are those with more than 1000 scheduled TTIs (i.e., 1 s of effective time). The aim of separating long calls is to isolate those connections where the impact of the modulation ramp-up caused by Outer Loop Link Adaptation (OLLA) is minimum [6]. In the figures, it is seen that, for short connections, the correlation between the three throughput statistics and average CQI is very low. This is due to the fact that short connections do not reach the steady state of OLLA, causing that the modulation ramp-up is not long enough to compensate the conservative initial settings for OLLA defined by operators. Although correlation increases for long connections in all throughput indicators, it is still low for average user throughput with and without last TTIs, which show $R^2 = 0.44$ and 0.45, respectively. A strong correlation is only observed for radio link throughput, for which $R^2 = 0.85$. It is thus confirmed that improving average CQI has a positive impact on all throughput indicators. However, it is clear that OLLA has a strong impact on all throughput performance statistics.

V. Conclusion

To assess a cellular network, an operator must combine different throughput performance indicators to check user date rates, network capacity and spectral efficiency. In this paper, several throughput performance indicators have been analyzed based on measurements of a live LTE network. Results have put into evidence the impact of last TTI transmissions and OLLA on throughput statistics. A preliminary analysis of traffic statistics has shown the large share of last TTI transmissions originated by chatty applications dominating recently deployed LTE networks. Then, the analysis of counters has shown that averages of user throughput, cell throughput and radio link throughput may not be correlated in hours with low scheduler activity due to last TTI transmissions. Moreover, the analysis has pointed out the weak correlation of all throughput indicators with average CQI. The analysis of call traces has proved that such a weak correlation is partly due to OLLA in short connections. Not shown is the fact that the analysis has been repeated for other scenarios and ROPs, leading to the same conclusions. This situation might change when data hungry applications become popular. The analysis can be extended to delay and quality-of-experience statistics, which better reflect the quality of audiovisual media services, once these statistics are available on a service basis.

References

[1] P. Brooks and B. Hestnes, "User measures of quality of experience: Why being objective and quantitative is important," *IEEE Network*, vol. 24, no. 2, pp. 8–13, Mar./Apr. 2010.

[2] "Key Performance Indicators (KPI) for Evolved Universal Terrestrial Radio Access Network (E UTRAN): Definitions," TS 32.450, Jun. 2010, Version 9.1.0 Release 9.

[3] V. Wille, M. Toril, and S. Luna, "Estimating pole capacity in a live HSDPA network," *IEEE Commun. Lett.*, vol. 17, no. 16, pp. 1260–1263, Jun. 2013.

[4] H. Holma and A. Toskala, *LTE for UMTS: Evolution to LTE Advanced*. Hoboken, NJ, USA: Wiley, 2011.

[5] M. Wylie Green and T. Svensson, "Throughput, capacity, handover and latency performance in a 3GPP LTE FDD field trial," in *Proc. IEEE GLOBECOM*, Dec. 2010, pp. 1–6.

[6] K. Aho, O. Alanen, and J. Kaikkonen, "CQI reporting imperfections and their consequences in LTE networks," in *Proc. 10th ICN*, Jan. 2011, pp. 241–245.