On the impact of network load on CQI reporting and Link Adaptation in LTE systems

Igor A. Tomić, Milutin S. Davidović, Dejan D. Drajić, and Predrag Ivaniš

***Abstract*—Data payload in mobile networks is persistently increasing, which puts a lot of pressure to Mobile Operators to seek for solutions that will deliver cheaper bit per second. Network performance modelling is important discipline in process of technology strategy definition, evaluation of different solutions/scenarios and finally design and planning of Long Term Evolution (LTE) systems. One of the key prerequisites for successful performance modelling process and prediction of user experience with growing network load is to understand impact of traffic increase on link adaptation. In this paper correlation between network load, measured as *Physical Resource Block* (PRB) utilization, and Link adaptation, measured with reported *Channel Quality Indicator* (CQI) is analyzed. Analysis is done based on performance measurements from mature commercial LTE network with several frequency layers deployed. Impact of network load increase on link adaptation performance was assessed. Performance of different frequency bands were observed separately, analysis was conducted for low band (bellow 1 GHz) and mid band (in range between 1 GHz and 6 GHz). Furthermore, analysis was segmented for different topologies in terms of network density – from urban to rural. Finally, impact of user mobility and spatial distribution of terminals, variations during working days and weekends were investigated.**

***Index Terms*—LTE, Performance modelling, CQI, Network load, PRB utilization, Link adaptation, Spectral efficiency.**

I. Introduction

IN the last few years mobile operators were facing increase of data payload and growing network load as a major challenge in a mission to secure required user experience, that is mainly defined and measured as target downlink throughput or latency [1]. Fourth and fifth generation (4G and 5G) of mobile communication systems are based on *Orthogonal Frequency Division Multiple Access* (OFDMA) technique which enables flexible radio resource allocation [2], [3]. The most common answer from mobile operators has been the investment in spectrum expansions and deployment of additional frequency layers in carrier aggregation scenario.

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However, as spectrum assets are limited and scarce resources, price per Hz was increasing even dramatically on spectral auctions over last ten years, mainly due to growing demand which is lately present on all meridians around the globe [4]. In such circumstances, spectral efficiency is important more than ever [5], [6] and mobile operators are looking for spectral efficiency improvements to the largest possible extent.

The main driver for spectral efficiency is link adaptation, and its performance in OFDMA based systems is mainly driven by interference which is reflected in reported CQI based on *User Equipment* (UE) channel quality estimation and related measurements. With growing traffic, mainly for data services, but also speech and IoT [6], and higher network utilization observed, increase of intra-system interference is logically expected.

This paper investigates impact of growing network load on CQI reporting. In chapter II, theoretical considerations will be elaborated, while in chapter III impact of network load and correlation with CQI degradation will be investigated. Chapter IV will further analyze correlations for different network density, followed by deep dive to network performance signatures during working days and weekends in chapter V. Finally, paper will be concluded with overview of findings, proposal for future work and list of references.

II. Theoretical background

Link adaptation is the ability of radio communication systems to adapt the modulation scheme and the coding rate of the error correction according to the conditions that user expects and quality of the radio link. Algorithm will secure that a high-level efficient modulation scheme and a small amount of error correction is used when conditions of the radio link are good. Link adaptation happens in a downlink scheduler located in base station, which needs to know radio channel for each UE. The estimation of radio channel state and selection of optimal transmission scheme may be achieved through closed loop measurements, presented at Fig. 1, performed by UE on channels transmitted by base stations (*Cell reference Signal* – CRS in LTE) or reciprocity based on measurements conducted by base stations on signal transmitted by UE (*Sounding Reference Signal* – SRS), which is mainly applicable for Time Division Duplex (TDD) systems with good uplink-downlink channel reciprocity. In Frequency Division Duplex (FDD) systems closed loop channel estimation is used, where 3GPP standard requests each UE to perform *Channel State Information* (CSI) reporting that carries necessary information on a radio signal [8].

CSI reporting may be periodic and aperiodic. Periodic reporting is carried either by *Physical Uplink Control Channel* (PUCCH) or *Physical Uplink Shared Channel*

(PUSCH) when user data on *Dedicated Control Channel* (DCCH) and *Dedicated Traffic Channel* (DTCH) needs to be transmitted at the same time with L1/L2 control signaling. Periodicity is configured by a higher *Radio Resource Control* (RRC) layer. Aperiodic reporting is used mostly for *Random Access Channel* (RACH) procedure, where handovers or losses of synchronization are common reasons. Aperiodic reporting also happens when eNodeB schedules specific *Physical Downlink Control Channel* (PDCCH) *Downlink Control Indicator* (DCI) format 0 together with CQI request field set to 1, demanding uplink grant for UE data together with an aperiodic CQI report.

CSI consists of three major components: *Channel Quality Indicator* (CQI), *Precoding Matrix Index* (PMI) and *Rank Indicator* (RI). The focus of this paper is behavior of CQI, which implicitly indicates a suitable link adaptation and downlink transmission data rate, i.e. the highest *Modulation and Coding Scheme* (MCS) value at which the UE will be able to properly demodulate and decode the downlink data at target *Block Error Rate* (BLER) of 10%.

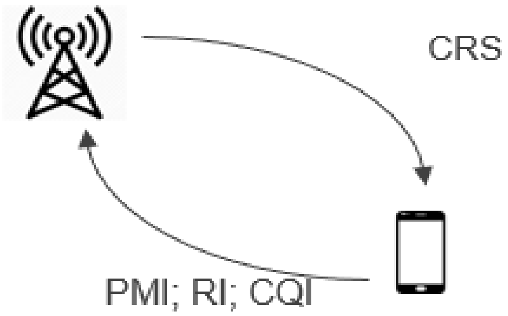

Fig. 1. Channel estimation based on Closed loop measurements, typical for LTE FDD systems

TABLE I
4-BIT CQI TABLE UP TO 64QAM MODULATION

CQI Index	Modulation	Code rate ×1024	efficiency
0	*Out of order*		
1	QPSK	78	0.1523
2	QPSK	120	0.2344
3	QPSK	193	0.3770
4	QPSK	308	0.6016
5	QPSK	449	0.8770
6	QPSK	602	1.1758
7	16QAM	378	1.4766
8	16QAM	490	1.9141
9	16QAM	616	2.4063
10	64QAM	466	2.7305
11	64QAM	567	3.3223
12	64QAM	666	3.9023
13	64QAM	772	4.5234
14	64QAM	873	5.1152
15	64QAM	948	5.5547

CQI calculation is not precisely defined by 3GPP standard and UE or chipset manufacturers have freedom to design algorithm and do implementation that will maximize accuracy and performance of link adaptation. However, calculations are typically based on measurements of *Signal-to-Interference plus Noise Ratio* (SINR), which are mapped to 16 discrete CQI values between 0 and 15, where index 15 indicates the best channel quality and index 1 indicates the poorest channel quality. Expected link adaptation - the mapping between CQI and modulation scheme and transport block size is defined by 3GPP [8], with two mapping tables defined for different UE capability. Table 1 is used for UEs supporting modulation up to 64QAM, while Table 2 is used for UEs supporting modulation up to 256QAM.

TABLE 2
4-BIT CQI TABLE UP TO 256QAM MODULATION

CQI Index	Modulation	Code rate ×1024	efficiency
0	*Out of order*		
1	QPSK	78	0.1523
2	QPSK	193	0.3770
3	QPSK	449	0.8770
4	16QAM	378	1.4766
5	16QAM	490	1.9141
6	16QAM	616	2.4063
7	64QAM	466	2.7305
8	64QAM	567	3.3223
9	64QAM	666	3.9023
10	64QAM	772	4.5234
11	64QAM	873	5.1152
12	256QAM	711	5.5547
13	256QAM	797	6.2266
14	256QAM	885	6.9141
15	256QAM	948	7.4063

CQI indicator is one of the main drivers for performance of LTE system, as it will determine link adaptation in terms of selected modulation, transmitted bits per symbol, coding and efficiency. Furthermore, there is a strong correlation observed between CQI and probability to have Rank higher than 1 and use more layers in *Multiple Input Multiple Output* (MIMO) system, which is often referred to as MIMO utilization [1]. Hence, lower CQI reported will cause additional negative impact on spectral efficiency, through worse spatial multiplexing performance.

III. CQI REPORTING AND NETWORK LOAD

Performance management data, including relevant counters and performance indicators, have been collected from commercial network that operates in two frequency bands: Band 12 - 700 MHz (operating DL frequency: 729 – 746 MHz) and Band 2 – PCS 1900 MHz (operating DL frequency: 1930–1990 MHz). Analysis is focused on average reported CQI and network load measured as average PRB utilization. Data was collected for period of ten days with cell resolution, where aggregation and averaging were performed afterwards on hourly level.

Fig. 2 presents correlation between average reported CQI and PRB utilization for two operating frequency bands, where first observation is a very good level of correlation between average CQI and network load, for both frequency bands, with correlation coefficient of 0.8173 for Band 2 and 0.9357 for Band 12. Network load is not evenly distributed, where for Band 12, average PRB utilization spans up to 45% during busy hour, while maximum measured PRB utilization for Band 2 is 20%.

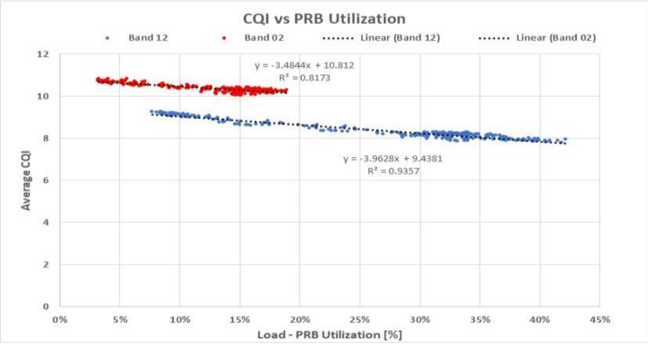

Fig. 2. Average reported CQI vs PRB utilization, LTE Bands 2 and 12

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Some final remarks are that average CQI for same level of network load is higher on Band 2. This can be explained with lower operating frequency of Band 12(700 MHz vs 1900 MHz), which means that radio waves have better propagation in Band 12 and system is more sensitive on inter-cell interference. The difference between two curves in average reported CQI for same level of network load is quite significant – approximately 1.5.

From observation discussed in this chapter, it can be concluded that CQI reporting process in LTE network is driven mainly by inter-cell interference, with strong correlation with network load, and greater sensitivity for lower frequency bands.

IV. CQI Reporting and Network Density

Logical next step in analysis is to evaluate impact of network density in terms of number of deployed base stations and average Inter-Site Distance (ISD).

Network topology was analyzed with deep dive to geographical position of base stations, where sites were segmented to high and low network density area with following criteria:

- High network density area: if criteria more than three neighboring sites within radius of 1.2 km is met
- Low network density area: if criteria less than two neighboring sites within radius of 1.2 km is met

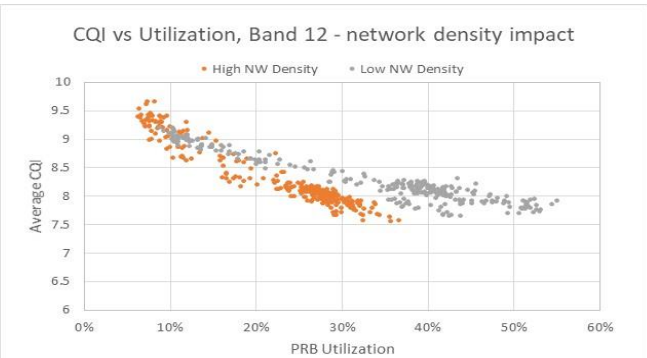

Fig. 3. CQI vs PRB Utilization, Network density impact, Band 12

Fig. 3 presents correlation between average CQI and PRB utilization, for two group of sites – belonging to high and low network density area, with operating frequency in Band 12. Similar analysis is done for Band 2, and results are presented on Fig. 4.

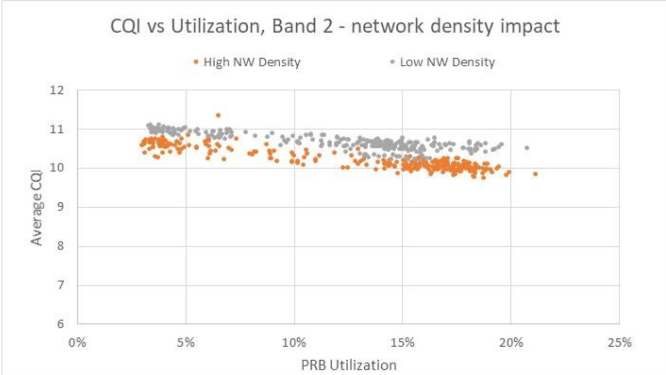

Fig. 4. CQI vs PRB Utilization, Network density impact, Band 2

The first observation is that base stations in high density areas are more affected with growing load, and lower reported CQI may be expected for same level of PRB utilization. Also, it is interesting to notice that impact of network density on correlation of interest is different for two observed frequency bands. While for Band 2 (Fig. 4) two curves are parallel, only shifted by approximately 0.5, in case of Band 12 (Fig. 3) steeper curve and higher relative drop may be expected in high density areas. For PRB utilization increase from 10% to 30%, in high density area average CQI reported value will drop from 9 to 8, while in low density area drop will be less severe, from 9 to 8.5.

V. CQI Reporting and User Distribution

After network load impact analysis, operating frequency band and network density on CQI reporting, another interesting aspect to consider is behavior of users in terms of their mobility and spatial distribution. One way to assess impact of mobility is to segment data for workdays – Monday to Friday, and weekends – Saturday to Sunday, as mobility patterns are clearly different.

As already noted in the Chapter I, good correlation is present in both Band 12 and Band 2 and it remained similar after the segmentation of the data sample to workdays and weekends.

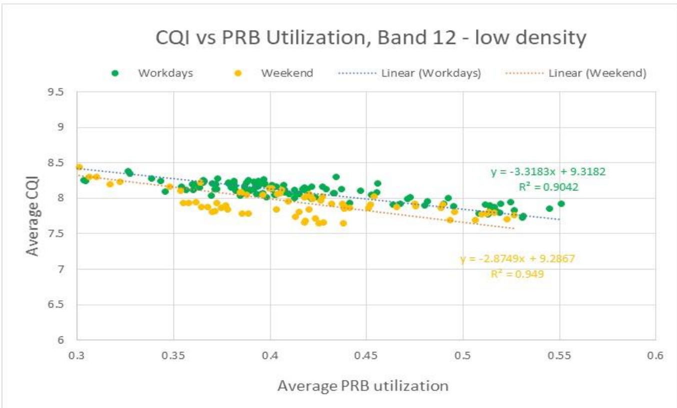

Fig. 5. CQI vs PRB Utilization, User Distribution Impact, Low density area, Band 12

However, there is a trend of having slightly lower CQI as well as the bigger deviation of reported CQI during the weekend.

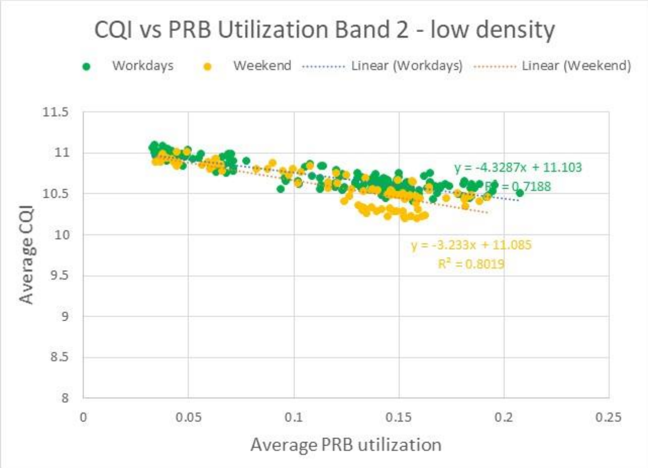

Fig. 6. CQI vs PRB Utilization, User Distribution Impact, Low density area, Band 2

This phenomenon is more noticeable in the low-density areas, especially in the range of higher PRB utilization in the observed sample (Fig. 5 and Fig. 6). The drop of 0.1-0.2 in average reported CQI during the weekend could be observed. In this case, another interesting phenomenon of having larger spam/deviation or even two trends of reported CQI for the same load circumstances could be observed. This could be due to different activity patterns of the users in some hours during the weekend in these areas, but further investigation (i.e. machine learning based) need to be conducted to drive some more specific conclusions.

On the other hand, looking at the high-density areas (Fig. 7 and Fig. 8), the impact of the day of the week on the CQI vs PRB utilization correlation is neglectable, most probably due to the reason that there is not much difference in user mobility and spatial distribution patterns in more dense areas of the network.

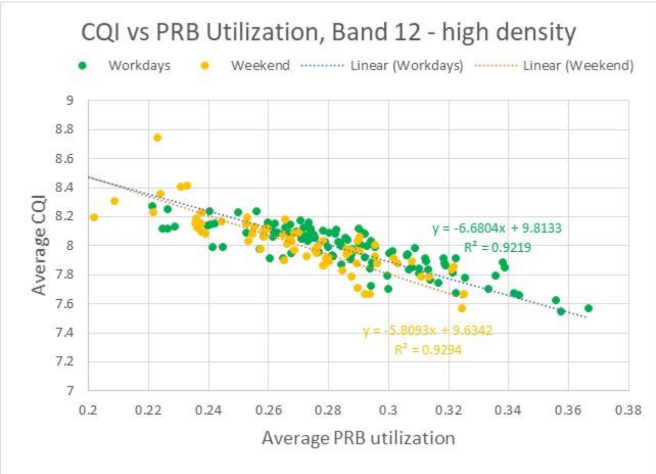

Fig. 7. CQI vs PRB Utilization, User Distribution Impact, High density area, Band 12

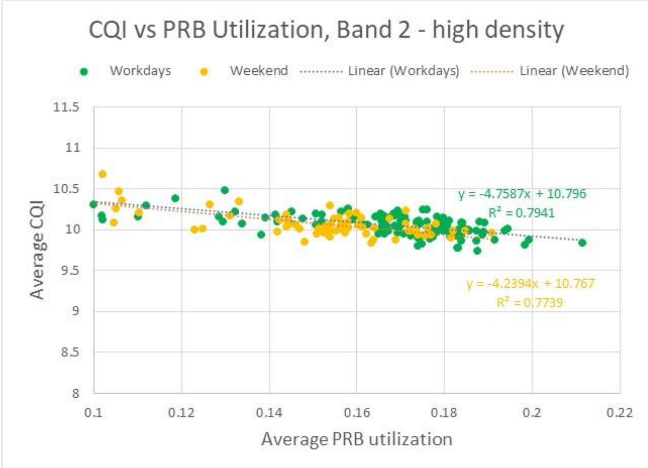

Fig. 8. CQI vs PRB Utilization, User Distribution Impact, High density area, Band 2

VI. Conclusion

Link adaptation is one of the main drivers for performance of OFDMA based mobile communication systems, such as LTE and NR. In this paper, the impact of network load on CQI reporting was analyzed and strong level of correlation was observed. Greater sensitivity for lower frequency bands was proven, which was in line with expectations, having in mind better propagation at lower frequencies causing more inter-cell interference. Furthermore, the areas with higher network density showed to be more affected with growing load and CQI degradation drop with steeper trend. Finally, impact of user mobility and traffic distribution is also evident, where different patterns were recognized during workdays and weekends.

Future work concerns deeper analysis of particular patterns through implementation of artificial intelligence and machine learning (AI/ML) techniques, and further correlation with spatial multiplexing performance in MIMO.

References

[1] I.Tomić, Đ.Lukić, M. Davidović, D. Drajić, and P. Ivaniš, "Statistical analysis of CQI reporting and MIMO utilization for downlink scheduling in live LTE mobile network", *Telfor Journal 2020*, vol. 12, iss. 1, pp. 8-12

[2] C. Cox, *An Introduction to LTE, 2nd edition*, John Wiley & The Sons Ltd, Chichester 2014.

[3] N. Gospić, I. Tomić, D. Popović and D. Bogojević, *"Razvoj mobilnih telekomunikacija, od GSM do LTE,"* Univerzitet u Beogradu, Saobraćajni fakultet, Beograd 2010.

[4] Spectrum Navigator, Q1 2021 New insights and trends to watch, GSMA, May 2021, https://www.gsma.com/spectrum/wp-content/uploads/2021/03/Spectrum-Navigator-Q1-2021.pdf

[5] M.Davidović, S.Bjekovic and I.Tomic, "On the impact of network load on LTE network downlink performance", *IcETRAN conference 2015*, Srebrno Jezero 2015.

[6] I.A.Tomić, M.S.Davidović and S.M.Bjeković, "On the downlink capacity of LTE cell," *23rd Telecommunications Forum TELFOR 2015*, pp. 181-185, Belgrade 2015.

[7] M. Davidović, I. Tomić, D. Drajić, and Z. Čiča, "On the Impact of NB-IoT on LTE MBB Downlink Performance," *TELFOR Journal*, Vol.11, No.1, pp. 20-24, Belgrade 2019.

[8] "*Evolved Universal Terrestrial Radio Access (E-UTRA); Physical Layer Procedures," 3GPP TS 36.213 15.7.0*, September 2019.