On the Role of Downlink Control Information in the Provision of QoS for NRT Services in LTE

David González G, Mario Garcia-Lozano, Silvia Ruiz, Joan Olmos
Universitat Politècnica de Catalunya. Department of Signal Theory and Communications
Escola d'Enginyeria de Telecomunicació i Aeroespacial (EETAC).
C/ Esteve Terradas, 7. 08860, Castelldefels, Barcelona, Spain
Email: david.gonzalez.gonzalez@upc.edu

***Abstract*—The provision of Quality of Service (QoS) to users of LTE networks depends to a large degree on the choice of an appropriate scheduling algorithm able to meet the requirements of mobile operators. Dynamic packet scheduling has been recognized as a key approach to maximize the utility of OFDMA-based systems due to its inherent ability to exploit the frequency selectiveness of wideband channels both in time and frequency domain. However, one of the main issues associated to dynamic scheduling is the high amount of signaling overhead required to provide users with resource allocation information. While the impact of control channel limitations on LTE VoIP capacity has been widely studied yet, tradeoffs associated to control channel usage and the provision of QoS for Non-Real Time (NRT) services has been basically omitted in current literature. In this paper, such tradeoffs have been addressed from several perspectives. Results show that the relationship between scheduling policies, offered levels of QoS (expressed in terms of guaranteed bit rates) and control channels capacity is not trivial and requires careful planning.**

I. Introduction

The 3rd Generation Partnership Project (3GPP) introduced a set of enhancements to the Universal Mobile Telecommunications System (UMTS) under the name of Long Term Evolution (LTE) in its release 8 [1]. LTE is the brand name for emerging and developed technologies that comprise the existing 3G and 4G networks. According to [2], LTE is the fastest developing mobile system technology ever. Currently, 24 commercial LTE systems are launched and at least 91 networks are anticipated to start operations by the end of 2012. Triggered by such expectations, manufacturers are developing a wide range of LTE devices including notebooks, tablets, smartphones, modules and PC cards to offer new and attractive next generation mobile services and applications. From the operators' point of view, this situation establishes important technical challenges among which the provision of acceptable (but competitive) levels of Quality of Service (QoS) is of utmost relevance.

In order to accomplish such a target, mobile operators are required to optimize and tune their infrastructures according to their needs and/or business cases. LTE provides by itself a packet-optimized Radio Access Technology (RAT) based on Orthogonal Frequency Division Multiple Access (OFDMA) allowing flexible bandwidth allocation, high data rates and low latency [3]. Moreover, a novel network architecture has been designed to support packet-switched traffic with seamless mobility. However, in order to (1) promote competition between manufacturers and (2) offer flexibility to mobile operators, some elements have not been included explicitly within the LTE specifications. Among these, *scheduling* is probably the most important. The MAC scheduler determines how downlink (and uplink) channels in the LTE air interface are used. The scheduler allocates radio resources in such a way as to satisfy QoS requirements [4] and optimize system performance. Different schedulers may result in significantly different levels of users satisfaction and system performance, and hence mobile operators implement *vendor-specific* solutions according to their needs.

Within the MAC sublayer, the scheduler can be viewed as the control unit responsible for resource allocation while the rest of MAC entities are the ones carrying out such decisions. These include performing multiplexing, Hybrid-Automatic Repeat reQuest (HARQ), transport block processing, subframe construction, etc. Therefore, scheduling is a fundamental piece within the overall Radio Resource Management (RRM) framework.

Scheduling as a mean to provide QoS in multiservice environments has been widely studied by the research community and many theoretical and practical contributions (some of them presented as feasible solutions for LTE) have been proposed [5], [6], [7]. Nevertheless, practical limitations of real systems, and their impact on system performance are often missed. In the context of scheduling for LTE networks, one important aspect that needs to be taken into account is the capacity of control channels. The impact of this limitation on system capacity has been studied in [8] for Voice over Internet Protocol (VoIP) service which features reduced packet size and strict delay bounds. In [8], a comparative analysis between *Semi-Persistent* (SP) [9] and *Dynamic* [10] scheduling is presented. Conclusions clearly suggest that SP scheduling is a good alternative to make efficient usage of the Physical Downlink Control Channel (PDCCH) in LTE when VoIP is considered. Power control schemes aiming at improving PDCCH capacity together with practical implementation and related issues have been presented in [11], [12].

On the other hand, given that there is no evident relationship between cell throughput and the number of users scheduled

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per TTI when Non-Real Time (NRT) services are considered, the impact of the LTE PDCCH capacity on such context has gone unnoticed. Only few works ([13] and [14]) addressing such issue have been presented. This paper also deals with the same framework, nevertheless the study presented herein differs from them in that:

1) A pure QoS-oriented scheduler (fed by a CQI-based[1] channel quality reporting scheme) explicitly designed for multi-service environments is considered. Thus the impact of PDCCH resources consumption on performance is evaluated **for different levels of QoS** (measured in terms of offered bit rates).
2) Additional perspectives are also provided such as fairness, overall Block Error Rate (BLER), users satisfaction ratio and energy efficiency.

Therefore, in this paper, additional insights into the appropriate selection of some scheduling parameters affecting the provisioning of QoS for NRT services are presented. While for VoIP the relationship between the amount of resources devoted to the PDCCH and system capacity is evident, in case of NRT flows (demanding different bit rates) such connection is not that clear. To the best of the authors' knowledge, this study is not available in the existing LTE-related literature.

The paper is organized as follows: Section II provides a description of the system model, network setting and research methodology. An overview of the PDCCH resource allocation scheme and additional network elements is presented in Section III. Finally, Sections IV and V close the paper with the analysis of numerical results and conclusions respectively.

II. System Model and Methodology

In this work, the downlink of an LTE-based cellular network that largely follows the LTE specifications [16] was considered. To be precise, the system has N_{SC} = 360 allocable subcarriers spaced 15 kHz and so the useful bandwidth is 5.4 MHz in which 30 Physical Resource Blocks (PRBs) are available, i.e. $N_{\mathrm{RB}}^{\mathrm{DL}} = 30$. The conclusions obtained in this study can be considered independent of the value of $N_{\mathrm{RB}}^{\mathrm{DL}}$, and hence more or less available PRBs would just shift the absolute values of results. The transmission Time Interval (TTI) is 1 ms and it contains 14 OFDM symbols where 11 are used for data transmission. Asynchronous Hybrid-Automatic Repeat reQuest (HARQ) with a maximum number of 3 re-transmissions is implemented. The minimum delay between retransmissions is 8 TTIs [15] and a maximum number of 8 parallel HARQ processes per user is assumed. Link level abstraction and so BLER prediction is based on look-up-tables following [17] and [15]. Channel State Information (CSI) reporting scheme is based on CQIs and Reference Signals (RS) as defined in [15]. It is worth mentioning that, once CQI values are reported, a *lifetime* equal to 15 ms ($\approx 0.25 \cdot T_C^{50\%}$) is assumed to avoid erroneous MCS prediction. The 0.5 coherence time is defined as $T_C^{50\%} = 0.42 \cdot f_d^{-1}$ where f_d is the maximum Doppler frequency [18]. Outdated CQI values are then replaced by the last *wideband CQI* value. Additional simulation details and the rest of the LTE setting is shown in Table I.

[1]A CQI is a number ranging from 0 to 15 that refers to specific modulation and code rate combinations; see Section 7.2.3 in [15] for details.

Table I
Simulation and LTE parameters.

Parameter	**Value**	
Cells power	43 dBm	
Frequency reuse factor	1 (Full reuse)	
Inter-site distance	1.5 km	
UE noise figure	7 dB	
Propagation model	3GPP's Urban macrocellular [19]	
Carrier frequency (f_c)	2.14 GHz	
Shadowing	Based on multiple correlated layers [20]	
	Mean:	0 dB
	Standard deviation:	8 dB
	Sites correlation:	0.5
	Decorrelation distance:	20 m
Channel model	Extended ITU Pedestrian B [21]	
	Temporal resolution:	1 ms
	Frequency resolution:	15 KHz
	Doppler frequency (f_d):	5.94 Hz
	(f_c = 2.14 GHz and v = 3km/h)	
CSI reporting	Periodic full band (One CQI per PRB)	
	Reporting delay:	3 TTIs
	Reporting period:	5 TTIs
Mobility model	Urban vehicular [22]	
	Users speed:	3 km/h
	Correlation distance:	20 m
	Main angle:	90º
	Change dir. probability:	20%
Antennas	Kathrein 800 10271 Xpol TriSec	
	Gain:	19.33 dBi
	3 dB bean:	65º
	Front-to-back ratio:	> 25 dB
Link abstraction	Mutual Information Equivalent SINR Mapping (MIESM), [23]	
Max. users' power boost	Δ_{PB} = 1.0 dB	
LTE: Transmission mode	Single-antenna port	

The cellular layout corresponds to an urban and macrocellular scenario composed by 19 sites (57 tri-sectorial cells) having hexagonal/regular geometry. Statistics are collected from the 3 central cells (having two interference tiers) to avoid border effect. The whole system has been embedded in a system level simulator which is fed by a link level one, both programmed in C++. The evaluation study has been done by means of Monte Carlo simulations. Results were obtained from 500 independent experiments, each one being run for 60 seconds to account with traffic dynamics. An average number of 20 users per cell were always uniform randomly spread.

In this work, full buffers traffic model has been considered. The choice of this traffic model attends to the fact that this model is suitable to study the system performance when different target rates R_{T} are offered to users. Therefore there is not loss of generality emulating the provisioning of QoS for different NRT services.

III. Interworking description

In this section, two additional network functionalities that play an important role on the conclusions of this study are described.

Table II
PDCCH FORMATS DESCRIPTION.

Format	CCEs	REGs	PDCCH bits	Code Rate	γ^{T} [dB]
0	1	9	72	2/3	3.5
1	2	18	144	1/3	-1.0
2	4	36	288	1/6	-4.00
3	8	72	576	1/12	$<$ -4.00

A. Scheduling

In this work, the scheduling implementation corresponds to the Capacity-driven Resource Allocation (CRA) scheduler proposed in [7]. The CRA scheduler, dynamically controls the resource sharing among flows. Thus, the CRA scheduler fits perfectly to the research objectives in this work since allows allocation of different target rates in a flexible manner. In addition, the *joint system capacity* definition has been taken into account. The joint system capacity is defined as the maximum total offered load in which all provided services fulfill a user satisfaction ratio threshold; additional details can be found in [7]. Modulation and Coding Scheme (MCS) selection is done in such a way as to maximize the spectral efficiency (according to reported CQI figures) and this strategy is kept constant for all cases. In order to make this study feasible, two different functional parameters of the CRA scheduler are considered:

1) The target bit rate (R_{T}): the target throughput the scheduler tries to deliver to each user in the system.
2) The scheduling set size (N_{G}): the maximum number of downlink grants the scheduler is allowed to make at each TTI per cell.

B. PDCCH Resource allocation

In LTE, downlink control channels[2] include Downlink Control Information (DCI), Control Format Indicator (CFI) and HARQ Indicator (HI). In this work, the focus is on DCI which is carried over the PDCCH. The PDCCH is located in the first m OFDM symbols of each subframe, where $m \in \{1, 2, 3, 4\}$. Since 11 OFDM symbols are devoted to data transmission, in this study $m = 3$. Each PDCCH is transmitted using one or more Control Channel Elements (CCEs), where each CCE contains N_{REG} = 9 sets of 4 Resource Elements (REs) known as Resource Elements Group (REGs). The DCI carries downlink (and uplink) scheduling assignments, power control commands and additional information required to decode and demodulate data symbols in the downlink (encode and modulate data symbols in the uplink). Since the information carried by the PDCCH is very important, a target BLER of 1% is pursued. In order to satisfy such a high performance level, both Link Adaptation and Power Control have been defined for the PDCCH [12]. In particular 4 different PDCCH formats have been specified, all of them use QPSK as modulation scheme while 4 different coding rates can be selected based on the wideband channel quality of users. Therefore, once the DCI size is set, the PDCCH resources consumption depends basically on the wideband channel quality of users. Lets assume that γ_x^{T} is the required wideband Signal to Interference plus Noise Ratio (SINR) to achieve a BLER of 1% when the PDCCH format x is employed, then, the following equation must be satisfied:

[2]Additional details about transmission configuration and modulation for control channels can be found in [24].

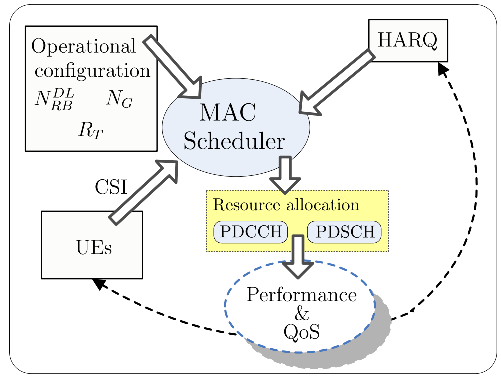


Figure 1. Overall system interworking.

$$\bar{\gamma} + \Delta_{\mathrm{PB}} \geq \gamma_x^{\mathrm{T}} \quad (1)$$

where $\bar{\gamma}$ and Δ_{PB} are the wideband SINR reported by users and the maximum allowed power-boost users can get respectively. PDCCH formats defined for LTE together with the target SINR values used in this work are shown in Table II. Target SINR values were obtained by means of link level simulations. Finally, a simplified view of the whole system interworking is depicted in Figure 1. Basically, scheduler operation depends on the following inputs: operational configuration of the scheduler properly said (N_{G}, R_{T} and $N_{\mathrm{RB}}^{\mathrm{DL}}$), users' channel status given by CSI reports and HARQ acknowledgments. The output (and hence the overall system performance) includes the actual resource allocation which comprises how both PDCCH and PDSCH resources are going to be shared among users.

C. DCI capacity

As it was mentioned before, the amount of resources devoted to carry the PDCCH and hence the whole downlink control signaling is limited. Recall that in addition to the DCI, also the CFI and HI are transmitted over the same set of resources allocated to the PDCCH although through different physical channels: the Physical Control Format Indicator Channel (PCFICH) and Physical HARQ Indicator Channel (PHICH) respectively. Moreover, RSs are embedded into the first OFDM symbol of each subframe. Since resource consumption of both CFI and HI is variable [24], [15], a practical rule of thumb is assume that the amount of resources devoted to the DCI is approximately equal to f = 4/5 of the total PDCCH capacity [11].

In this study, only downlink is considered, so we assume that only 50% of the resources devoted to the PDCCH would be available. The rest of resources are reserved to uplink grants. It is worth mentioning that the minimum resource unit allocated to one single user for control signaling is a CCE.

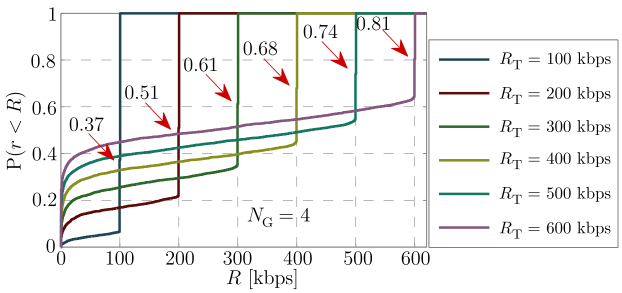


Figure 2. CRA scheduler operation: CDF of users' rate.

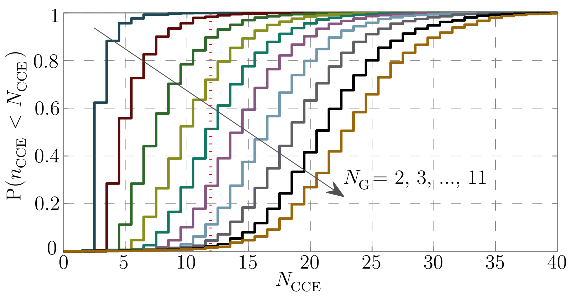


Figure 3. CCE consumption: $R_T = 100$ kbps.

Therefore, an upper bound for the number of avaiable CCEs is computed according to:

$$N_{\rm CCE}^{\rm Max} = \frac{1}{2} \cdot \frac{f \cdot m \cdot N_{\rm SC}}{4 \cdot N_{\rm REG}} = 12 \tag{2}$$

IV. Numerical Results

In this section, numerical results are presented and analyzed. In order to determine the impact of the PDCCH resources consumption on the global QoS experienced by users, different independent experiments were performed. Basically, the study has two degrees of freedom: the maximum number of users that can be scheduled per TTI/cell and the offered bit rate.

A. Scheduler operation

In order to better understand the results, the general operation of the CRA scheduler is illustrated first by means of the Cumulative Distribution Function (CDF) of the users' average rate $\bar{R}$ for different values of $R_{\rm T}$ and $N_{\rm G} = 4$. Figure 2 shows the basic principle of the CRA scheduler (clearly QoS-oriented) where only the minimum amount of resources required to achieve the target bit rate is allocated to users. As expected, from Figure 2 it can be seen that the lower the value of $R_{\rm T}$, the higher the percentage of users achieving such rate. Given this, the effect of $N_{\rm G}$ will be studied in the following subsections.

B. CCE consumption

In order to illustrate the pace at which PDCCH resources are used, the CDF of the number of CCE per TTI/cell $N_{\rm CCE}$ as a function of $N_{\rm G}$ (assuming that resources for PDCCHs are never fully consumed) is shown Figure 3. The dashed red line indicates the value of $N_{\rm CCE}^{\rm Max}$. This is important because

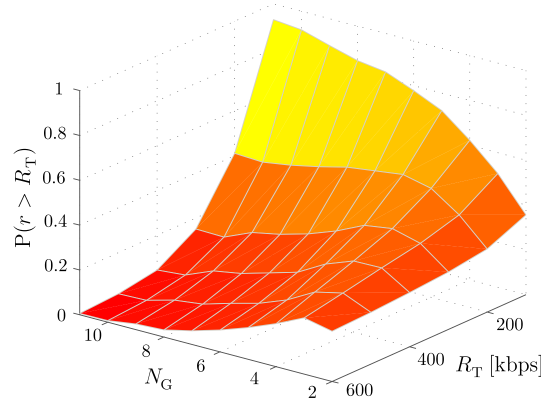
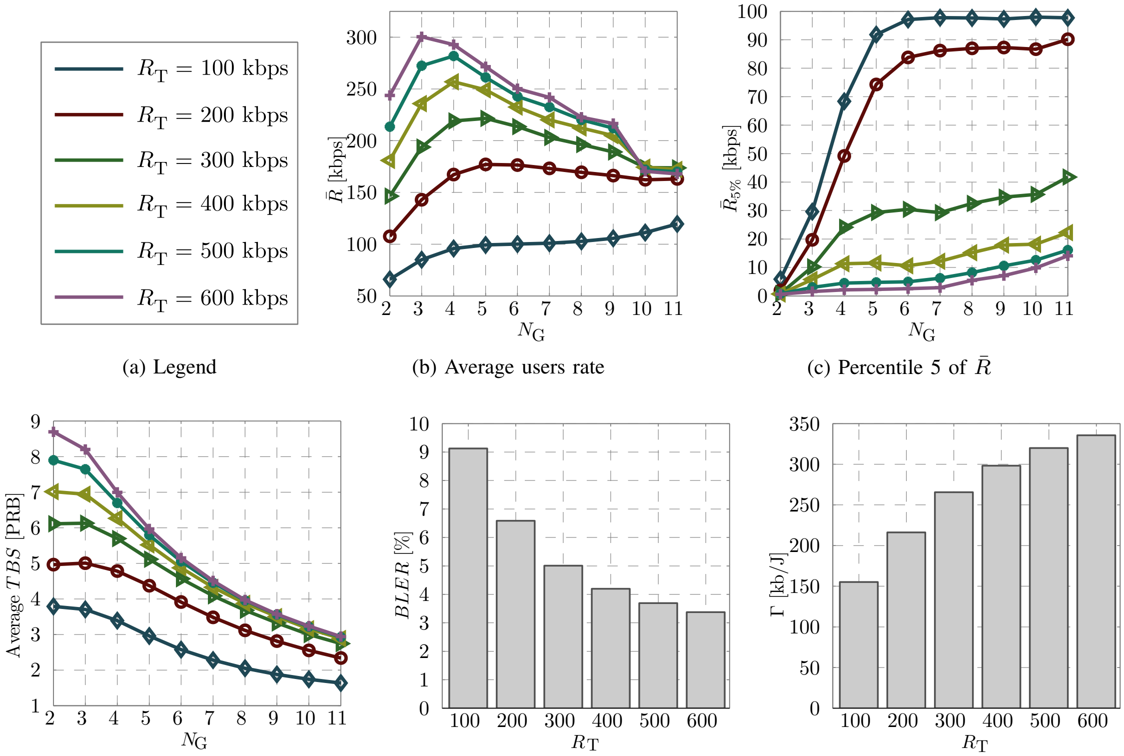


Figure 4. Users satisfaction probability.

in practice, schedulers are forced to verify the availability of PDCCH resources before schedule each user. From the figure it can be seen that if only a blocking probability of around 5-10% due to PDCCH capacity were allowed, then the choice of $N_{\rm G}$ = 3-4 would be required. However, as it will be shown in the following subsections, this limitation plays an important role in the provisioning of QoS for NRT services.

C. Users satisfaction ratio

Figure 4 shows the joint system capacity surface obtained for the test space, i.e. $N_{\rm G} \in \{2, 3, ..., 11\}$ and $R_{\rm T} \in \{100, 200, ..., 600\}$. Any point in the surface can be understood as the probability of a user to obtain a throughput at least equal to $R_{\rm T}$. As it can be seen, for low values of $R_{\rm T}$ the joint system capacity is clearly limited by the amount of available PDCCH resources, thus overall satisfaction level is directly proportional to the number of users the scheduler can attend. Recall that it is assumed that resources for PDCCHs are never fully consumed in order to determine when this constrain is a limiting factor (bearing in mind the value of $N_{\rm CCE}^{\rm Max}$ previously computed). This behaviour goes in the line with results reported for VoIP in [8], specifically for the case of dynamic scheduling where being VoIP a service demanding very low bit rates, the capacity is effectively limited by the control channel capacity. On the other hand, as $R_{\rm T}$ grows, the optimum value of $N_{\rm G}$ becomes smaller. This is due to the fact that the CRA scheduler operates in such a way as to maximize the number of satisfied flows. Therefore, for high values of $R_{\rm T}$, overall satisfaction becomes inversely proportional to $N_{\rm G}$, i.e an opposite behaviour compared to cases where $R_{\rm T}$ is small. At this point it is important to recall that the joint system capacity is in general a function of the load and traffic mix [7]. Results shown by Figure 4 clearly suggest that in order to let the system operate efficiently from the radio resource allocation perspective, it is important to carefully characterize the system performance not only taking into account traffic features (offered QoS and expected load) but also scheduling policy and availability of resources available for PDCCH.



(a) Legend (b) Average users rate (c) Percentile 5 of $\bar{R}$

(d) Average Transpor Block Size (e) BLER (f) Energy efficiency

Figure 5. Additional results.

Clearly, given the constraint seen in the previous subsection (N_G = 3-4), the impact of the PDCCH capacity would not be harmful if high values of R_T were pursued, while for low values of R_T the system capacity would be seriously penalized.

D. Additional results

To close this section, Figure 5 shows a set of additional results providing more insight into the tradeoffs associated both to the control channel resources consumption and targeted QoS levels. Figures 5b and 5c correspond to the average users rate $\bar{R}$, and its percentile 5 $\bar{R}_{5\%}$ (users likely to be in the cell edge) respectively. Glancing at Figure 5b, it can be seen that the optimum value of N_G grows as R_T decreases. This is due to the fact that $\bar{R}$ is proportional to the overall satisfaction level represented in Figure 4, therefore it is expected that higher values of $\bar{R}$ coincide with optimal values of N_G (for each R_T) from the users satisfaction probability perspective. On the other hand, recall that the CRA scheduler operates in such a ways as to maximize the number of satisfied flows (and hence the overall satisfaction); however, such maximization is at expense of a cell edge performance degradation since *unlucky* users are then more likely to be *forgotten* by the scheduler in order to satisfy users in better conditions and hence maximize the overall satisfaction ratio. Results also indicate that this effect is more pronounced as R_T grows. In fact, focusing on Figure 5c, it is clear that for higher values of R_T, $\bar{R}_{5\%}$ goes further from them. For instance, while for R_T = 100 kbps, $\bar{R}_{5\%}$ is within 95% of this value (provided that $N_G \geq 6$), for R_T = 600 kbps, $\bar{R}_{5\%}$ is below of 5% of the targeted rate no matter the value of N_G. Thus, for high values of R_T, a tradeoff appears between the overall users satisfaction ratio and cell edge performance. It is possible, by increasing N_G, to improve $\bar{R}_{5\%}$ (and hence the overall fairness) since more users are attended per TTI, nevertheless this small enhancement comes at expense of significant spectral efficiency losses.

The average TBS obtained for each experiment is shown by Figure 5d. As expected, the average TBS is directly correlated to N_G. As more users are selected by the scheduler per TTI, the average size of transport blocks will decrease independently of R_T. This behaviour has an important implication: since the error correction capability of the LTE turbo code is favored by greater transport blocks (and so longer codewords), scenarios resulting in greater average TBS are expected to have better BLER as it will be shown shortly.

Figures 5e and 5f show average BLER and energy efficiency levels respectively. In order to provide a better understanding of results, averages are taken for each set of experiments corresponding to each value of R_T. As it can be seen, both BLER and energy efficiency are proportionally improved with R_T. In the first case, this is a direct consecuence of the usage of higher TBSs (due to the improved error correction capability explained previously) while in the last case, gains in energy efficiency are correlated to the fact that for high values of R_T, the CRA scheduler tends to select users that can be satisfied easily, thus favoring the spectral efficiency. Recall that energy efficiency is computed as the ratio of total transmitted payload and energy consumption. Therefore, it can be concluded that settings improving both BLER and spectral efficiency tend to be more efficient from the energy perspective.

V. Conclusions

A study of the impact of the PDCCH capacity on the provisioning of QoS for NRT services has been conducted. After (1) describing the way in which PDCCH resources are allocated in LTE and (2) provide means to estimate practical DCI capacity limit; a set of experiments were performed in order to investigate **if important tradeoffs from several RRM perspectives** exist when provisioning QoS to NRT flows. The answer is yes. The main results can be summarized as follows:

- The appropriate selection of scheduling and QoS parameters is clearly affected by the limited amount of control channel resources in LTE. In this study, it has been shown that PDCCH capacity constrain can also be a limiting factor for NRT traffic where low target bit rates are targeted.
- Although PDCCH capacity is not a limitation when ambitious target bit rates are pursuit, attention must be paid then to associated tradeoffs between spectral efficieny and fairness which start playing an important role under such circunstances.
- The important relationship betwen targeted bit rates and TBS + BLER + energy efficiency has also been identified and analyzed. Results clearly suggest that while by targeting lower bit rates the overall satisfaction can be maximize, higher targeted bit rates favor the performance from the efficiency perspective.
- To the light of the results, several research alternatives arise:
  - Investigate mechanisms to either reduce the effective payload of the DCI or increase the available capacity for the PDCCH.
  - Further investigate the case where different values of R_{T} are assigned to different groups of users.
  - Finally, development of a more analytical/generic framework considering elements such as multiservice scenarios (with different traffic mix) has not been effectively addressed yet.

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