Evaluating Uplink Schedulers in LTE in Mixed Traffic Environments

Mohamed Salah
ECE Department
Queen's University
Kingston, ON
mohamed.salah@queensu.ca

Najah Abu Ali
College of IT
UAE University
Al-Ain, UAE
najah@uaue.ac.ae

Abd-Elhamid Taha
School of Computing
Queen's University
Kingston, ON
taha@cs.queensu.ca

Hosam Hassanein
School of Computing
Queen's University
Kingston, ON
hossam@cs.queensu.ca

***Abstract*—3GPP's Long Term Evolution is defined by the standardization body's Release 8 and 9, and provides more than a substrate for 3GPP's IMT-Advanced Candidate, namely LTE-Advanced, which is due to be defined in Release 10. Both LTE and LTE-Advanced have SC-FDMA in their uplink, a multi-carrier access technique requiring contiguous subcarrier allocations for each UE. No scheduling algorithm, however, is dictated by the standard and several proposals have hence been presented to be implemented by vendors. A definite scheduling requirement is the support of QoS attributes of different types of uplink traffic. Our intent in this study is to evaluate the connection-level performance of representative scheduling proposals, with focus on QoS aspects. Specifically, we utilize a mixed type of traffic flows and evaluate the schedulers in terms of per-user throughput, packet loss and fairness.**

I. INTRODUCTION

The multiple access technique utilized in 3GPP's Long Term Evolution (LTE) is Single Carrier FDMA (SC-FDMA) [1]. This technique enables LTE, first defined in 3GPP Release 8 with enhancements described in Release 9, to offer a substantial improvement in terms of spectral efficiency and throughput. SC-FDMA also allows for preserving battery power as it has been demonstrated to have a Peak-to-Average-Power-Ratio (PAPR) lower than that of OFDMA.

SC-FDMA is a multi-carrier access technique, and therefore allows for multi-user diversity and adaptive modulation and coding, and is capable of exploiting channel conditions in both time and frequency. A Packet Scheduler (PS) operating above SC-FDMA can be designed to allocate each User Equipment (UE) a portion of the bandwidth over which the UE experiences relatively better channel conditions. Such scheduling mode is called Channel-Dependent Scheduling (CDS). For SC-FDMA to offer a lower PAPR, it requires allocating contiguous subcarriers to individual UEs — a challenging constraint in scheduler design as it may restrict frame utilization. LTE, and its IMT-Advanced evolution LTE-Advanced, are also both designed as an all-IP architecture, and consequently must deliver the various IP services and applications while offering their respective Quality of Service (QoS) guarantees. An LTE uplink scheduler hence needs to handle a range of requirements in terms of delay, Guaranteed Bit Rate (GBR) or target Bit Error Rate (BER). VoIP, online gaming, and video conferencing are all examples of applications to be widely used in LTE.

The standard details both the architectural aspects and the signalling mechanisms associated with uplink scheduling of connection/bearer requests and grants between the UE and the eNodeB [2]. The standard, however, does not specify a certain scheduling algorithm for either the uplink or the downlink direction. Accordingly, several proposals operating under different objectives have been presented in the literature for SC-FDMA-based scheduling in LTE uplink. In previous work [3], we offered a preliminary evaluation environment for observing the aggregate (per-eNodeB) performance of the different schedulers. The evaluation offered did not address the QoS characteristics of the schedulers, nor did it observe their connection-level performance. To our knowledge, such an investigation is yet to be made for uplink schedulers in LTE. Given the rising number of commitments (to both LTE and LTE-Advanced) [4], it becomes unavoidable to provide this investigation.

Our contribution in this paper is offering an extendible environment in which uplink schedulers in LTE, in addition to other networks utilizing OFDM-based access techniques, can be evaluated in a repeatable and practical manner. For the purpose of this study, we focus on representative proposals that are compliant to 3GPP's most recent releases. The simulation environment is also representative of the most common LTE operation environments, namely sparse urban. We utilize traffic mixes using traffic models prescribed by 3GPP for evaluating LTE and LTE-Advanced networks [5] [6].

The remainder of the paper is organized as follows. In Section II, we provide an overview of the uplink LTE scheduler operation. We next offer a brief survey of schedulers proposed for uplink LTE, including schedulers to be evaluated in our study. In Section IV, we describe in detail our simulation environment together with the utilized traffic models and the metrics chosen as basis for evaluation. The following section reviews the results obtained. Finally, we conclude in Section VI.

978-1-61284-231-8/11/$26.00

II. LTE UL SCHEDULER'S OVERALL DESIGN

The main goal of the scheduler in LTE uplink is to allocate SC-FDMA subcarriers to a subset of UEs to maximize a system-defined objective. The system's objective can be defined as maximization of throughput, fairness, delay requirements, power usage, GBR satisfaction, etc. The scheduler in LTE uplink assigns resources to UEs in chunks of resource blocks (RB), with each RB spanning 12 SC-FDM subcarriers.

When looking at the LTE uplink schedulers' design, one can deduce that almost all proposed schedulers can be divided into two scheduling units: Time Domain Packet Scheduler (TDPS) unit, and Frequency Domain Packet Scheduler (FDPS).

TDPS performs UE filtering, where it selects a subset of UEs that are to be scheduled in the upcoming scheduling interval. The UE subset is passed afterwards to the FDPS where RB allocation for the UE subset takes place.

III. RELATED WORK

Scheduling algorithms for LTE uplink have been discussed by many authors [7]–[14]. Some proposals have been made based on maximizing 'classical' objectives, such as throughput and fairness. One of the earliest proposals were made in [7]. The authors proposed two Proportionally Fair (PF) schedulers that allocate RBs using localized (contiguous) scheme and interleaved (non-contiguous) allocation. The authors showed significant increase in the cell's aggregate throughput with the localized scheme compared to interleaved one, showing the advantage of contiguous allocation of the uplink performance.

In [8], the authors proposed a heuristic localized gradient algorithm (HLGA) to allocate contiguous RBs to each UE. The algorithm was proposed with H-ARQ awareness, where a subset of RBs are reserved for H-ARQ process for previous, unsuccessful transmissions. The RBs reserved for H-ARQ process are removed from the RB set, where the remaining RBs become the ones available for new transmissions. The work has been extended in [9] to include allocation 'pruning', where the number of RBs is adjusted according to the buffer size at the UE's end. The study showed an improvement in performance as adding the buffer awareness of the scheduler leads to better utilization of the available resources. The study also showed that the limited buffer status feedback to the eNodeB can still result in wasting some of the available radio resources.

The work in [10] is another contribution to CDS scheduling design. The authors in [10] proposed three CDS schedulers with PF-based utility function: First Maximum Expansion (FME), Recursive Maximum Expansion (RME), and Minimum Area Difference (MAD). The performance of the proposed schedulers were evaluated and compared to a reference round robin scheduler, where they showed performance improvement in terms of spectral efficiency and fairness. The results showed comparable performance levels of both RME and MAD algorithms, while both outperformed FME.

The authors in [11] have extended the work of [10] by introducing two variants of RME scheduler. The study showed improvement of one RME variant by 15% compared to RME in terms of spectral efficiency with a linear increase in computational complexity. The UL scheduler's performance showed further improvement with the other RME search tree variant where higher complexity level is allowed.

In [12], where a binary search tree-based PF scheduler was proposed for LTE uplink, the scheduler divides the available RBs into fixed-sized Resource Chunks (RCs) and distributes them among the available UEs. The performance of the scheduler was evaluated in terms of throughput and noise rise, where the scheduler showed a significant improvement compared to Round-Robin (RR) variant base scheduler.

The authors in [12] have also introduced an adaptive transmission bandwidth based scheduler in [13], where the resources assigned per UE dynamically changes in every scheduling interval in contrary to the scheduler proposed in [12]. The study showed an improvement of 20% in average cell throughput compared to the one in [12].

The work in [13] was further enhanced in [14], where they have proposed throughput-based PF metric in TD, combined with an SINR-based PF metric in FD. Results have shown that such a combination have improved the average cell throughput by 21%, and 37.5% in outage user throughput.

IV. SIMULATION ENVIRONMENT

The performance evaluation was executed within a single-cell environment that assumes no inter-cell interference present. The cell is assumed to have a hexagonal layout with 1 km radius. The eNodeB is equipped with an omnidirectional antenna that communicates on the uplink using SC-FDMA. The eNodeB is situated at the center of the cellular grid, with the UEs being uniformly distributed within the cell coverage. The environment is assumed to be an urban one, where signal communication path of the signal is assumed to be of NLOS nature. Table I lists the simulation parameters used in our LTE uplink simulator.

The operating bandwidth on the uplink is 10 MHz, subdivided into 50 RBs with each RB spanning a bandwidth of 180 kHz. Two RBs are reserved for uplink control channels, while the remaining 48 RBs constitute the physical uplink shared channels (PUSCH). The simulator assumes that each UE sends a sounding reference signal spanning the entire bandwidth periodically, hence the eNodeB is assumed to have a full knowledge of the uplink channel condition per UE for every TTI.

The channel model employed here is for Typical Urban (TU) environment, where the microscopic effects are modeled using ETU multipath fading described in [15]. The typical urban path loss and shadowing of the simulation environment are listed in Table I, being adopted from [16].

Using the channel model described above, the channel impulse response is generated based on Tapped Delay Line (TDL) model, from which the frequency response of the channel is generated to obtain per-subcarrier channel gain.

The resulting per-subcarrier gain is used to compute the

TABLE I
SYSTEM SIMULATION PARAMETERS

Cellular Layout	Single-Cell with Omnidirectional Antenna
System Bandwidth	10 MHz
Carrier Frequency	2 GHz
Number of Resource Blocks	50
TTI Duration	1 ms
Max. UE Tx Power	25 dBm
Path Loss Model	$128.1 + 37.6\log_{10}(d[km])$
Shadowing	Log-normal with 8 dB st. dev.
UE-eNodeB Min Distance	90 m
Power Delay Profile	TU6 Profile, 6 taps
Channel Estimation	Ideal
MCS Settings	QPSK [1/10 1/6 1/4 1/3 1/2 2/3 3/4] 16QAM [1/2 2/3 3/4]
eNodeB Antenna Gain	15 dBi
eNodeB Noise Figure	5 dB
UE Antenna Gain	0 dBi
UE Noise Figure	9 dB
UE Speed	0..3 km/h
Frequency Reuse Factor	1

SINR per subcarrier according to (1),

$$\gamma_{i,k} = \frac{P_{i,k} \cdot |H_{i,k}|^2}{L_i \cdot \sigma_n^2 \Delta f} \tag{1}$$

where $\gamma_{i,k}$ is the SINR for UE i at subcarrier k, $P_{i,k}$ is the power allocated by UE i to subcarrier k, $L_{i,k}$ is the power loss experienced by UE i, σ_n^2 is the noise density per Hz, and Δf is the subcarrier spacing.

1) Link Adaptation Model: The link adaptation model is used in our simulator to predict the appropriate Modulation and Coding Scheme (MCS) to use when transmitting the data on assigned RBs. Once the packet scheduler assigns UEs their corresponding RBs, the scheduler unit is to determine the effective SINR for each UE i, denoted by γ_i, for the assigned RBs. γ_i is calculated using $\gamma_{i,k}$ according to (2),

$$\gamma_i = \left(\frac{1}{\frac{1}{N_i}\sum_{k=1}^{N_i} \frac{\gamma_{i,k}}{\gamma_{i,k}+1}} - 1 \right)^{-1} \tag{2}$$

With N_i being the number of contiguous subcarriers assigned to UE i. γ_i is mapped to a pre-determined MCS based on the MCS-to-SINR mapping from the BLER curves demonstrated in Figure 4 in [17].

2) Traffic Model: The Traffic Models used in the simulator are based on [6]. For the purpose of our simulator, 3 traffic models have been adopted for use, which are shown in Table II.

A. Performance Metrics

Now, in order to evaluate the performance of the system under the use of different uplink schedulers, the following metrics are measured to quantify the performance of our system

TABLE II
TRAFFIC PROFILES. [5] [6]

Traffic Type	QCI [6]	GBR [18]	MBR
VoIP	1	12.2 kbps	64 kbps
Video Streaming	4	64 kbps	1024 kbps
FTP	6	0	2048 kbps

1) Total Throughput: which is measured as

$$\bar{T}_{cell} = \frac{B}{t_{sim}} \tag{3}$$

Where B is the total number of received bits, t_{sim} is the total simulation time.

2) Intra-Class Fairness: which represents the fairness among UEs of the same class. The Intra-class fairness is calculated using the min-max fairness index. The intra-class fairness index can be calculated as:

$$F_{min-max} = \frac{\bar{T}_i}{\bar{T}_j} \tag{4}$$

where $\bar{T}_i$ is the throughput of UE i with minimum average throughput, and $\bar{T}_j$ is the throughput of UE j with maximum average throughput.

3) Packet Loss: which is a measure of the percentage of packets being dropped per QoS class over the entire simulation time.

4) Packet Delay: which is the measure of the delay incurred by a successfully transmitted and received packet.

V. RESULTS

In this section, we showcase some of the results obtained from the evaluation environment discussed above. Each result point is obtained by averaging the results of 15 runs to provide a more representative picture of the performance of the different schedulers.

Figure 1 below shows the Cell's total throughput as a function of the number of UEs present in the cell. Beyond twenty UEs in the cell, the schedulers' throughputs aggregate in two distinct groups. The first group have an RR-like performance, where the HLGA and FME show no significant improvements as a CDS schedulers compared to a channel-blind scheduler such as RR. The second group are similar in performance to the Max-SNR scheduler, and includes the RME, the PF-BST and the Greedy schedulers.

Figure 2 shows how the different schedulers compare in terms of fairness, based on the the Min-Max fairness described above. Together with Figure 1, this figure illustrates that certain objectives (throughput or fairness) can be achieved using schedulers with varying degrees of computations. In the figure, the schedulers HLGA and FME exhibit better fairness compared to other algorithms. Note that these same two algorithms exhibited the worst throughput performance in Figure 1. Figure 2 also shows a non-intuitive result, with the RR algorithm demonstrating a fairness level worst than all other simulated CDS schedulers other than the Max-SNR scheduler. However, the fact that RR aims at maximizing

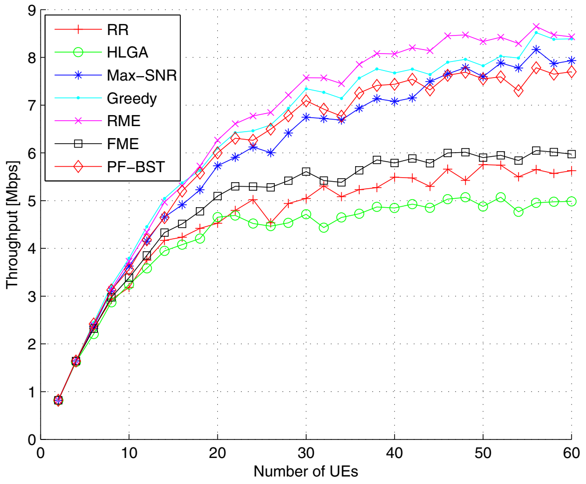

Fig. 1. Cell's Aggregated throughput as a function of UL traffic load (number of UEs)

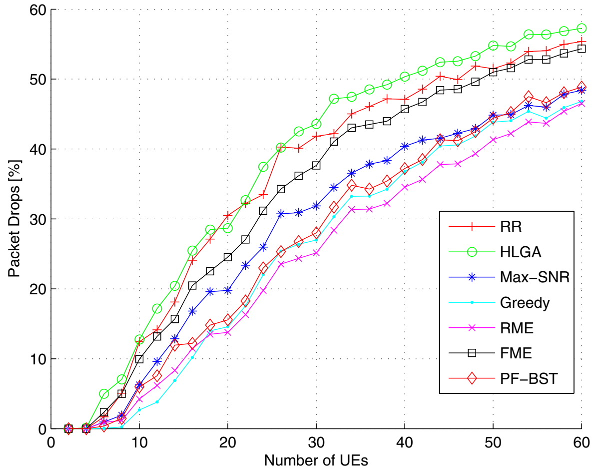

Fig. 3. The percentage of packet loss within the system.

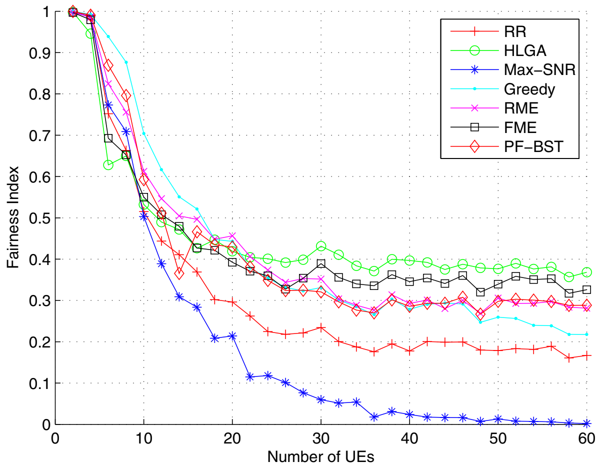

Fig. 2. Cell's Aggregated Min-Max Fairness

fairness in terms of resource allocation among UEs does not necessarily guarantee that the UEs utilize these equally allocated resources with equal efficiency.

Figure 3 shows the percentage of packet loss within the cell. The order of performance levels of the schedulers here are similar to the performance levels shown in Figure 1. The ability for the schedulers to achieve better throughput leads to a lower average packet loss over the entire cell. The general expectation for such evaluation is for the schedulers to saturate in performance at a certain level (i.e. beyond a certain number of UEs). This saturation level is partially discernible in the figure, but requires expanding on the number of simulated users to be fully visible.

A closer examination of how the different simulated schedulers are designed sheds further light on their demonstrated performance. For example, a disadvantage in HLGA is that it allocates resources to the same UE in two consecutive allocations, where the two allocated RBs are separated by a group of non-assigned RBs. In this case, the scheduler assigns all the "in-between" RBs to the same UE, regardless of the value of the UE's scheduling metric or channel quality. This disregard causes degradation in the system performance due to resource mismanagement, as a UE can get assigned RBs with significant variation in their channel quality.

On the other hand, FME is disadvantaged in its second part of operation where it exercises no prioritization to decide which side to choose after assigning the RBs to the first user. Exercising a prioritization that would maximize the global gain would overcome the instance where some UEs might be allocated RBs on one side of the spectrum despite having potentially a better performance if the resources allocated were on the other side.

The above design issues found in HLGA and FME are absent from the other simulated schedulers. RME differs from FME in how resources are allocated to the first UE, and how this step is repeated recursively for all other UEs. This modification increases RME's awareness of channel conditions per UE i at each RB k. Meanwhile, the Greedy and PF-BST algorithm are based on grouping consecutive RBs into RCs such that the number of RCs are either less than or equal to the number of UEs active within the cell.

A. Complexity Analysis

With the exception of PF-BST algorithm, all the other algorithms examined in this study perform a linear search on the metrics of all schedulable UEs per each RB block. Each iteration performs search operations of the order $N_{UE} \cdot N_{RB}$, commonly to find the maximum UE-RB metric. Such concept even applies on RR and Greedy schedulers, where a RC can be as small as a single RB. Therefore, the complexity of the scheduling algorithms in this case can be of the order $O\left(N_{UE} \cdot N_{RB}\right)$.

The authors in [12] proposed PF-BST as a search-tree-based derivation from Greedy algorithm to maximize the global utility metric, though at the expense of increasing the computational complexity. The algorithm, in its way to find the allocation pattern that maximizes the scheduler's utility function, constructs a binary search tree of the possible UE-RB mapping patterns. Afterwards, it searches the tree to find the suboptimal UE-to-RB mapping. In doing so, the constructed search tree can have up to N_{UE} levels, with each level l containing 2^l search nodes, assuming the root node to be level 0. As a result, the binary tree construction and search operation take at the order of $2^{N_{UE}}$ iterations to complete the scheduling operation. Hence, complexity level of the PF-BST operation is in the order of $O\left(2^{N_{UE}}\right)$.

Despite the algorithm's high complexity level, the results in Figures 1 and 2 show little improvement of PF-BST performance relative to the simpler Greedy algorithm. The results suggest that the performance improvement is not significant enough to justify the increase in the computational complexity of the scheduler. In addition, simulation-wise, PF-BST was noted to take significantly longer real-time to complete than the other schedulers. Therefore, it would lead to think how unfeasible to implement an algorithm with such complexity at the eNodeB, where a scheduler has to perform scheduling decisions within a TTI interval as short as 1 ms.

VI. CONCLUSION

A definite void exists when it comes providing an evaluation environment for comparing schedulers proposed for the uplink in LTE. Our intent in this paper is to offer such an evaluation environment that is extendible and that allows for utilizing recommended (per-standard) traffic models. Our observation is that the standards proposed in the literature so far perform almost similarly. With SC-FDMA as the technology of choice, a constraint of contiguous subcarrier allocation generally limits the scheduler's performance. In addition to exploiting the basic tradeoff between scheduling throughput and fairness, consider per-connection performance — the focus of this study— has been observed to be achievable at reasonable complexity.

We believe that further work is necessary in establishing a benchmark environment for evaluation. Our intent is extending this work to accommodate advanced antenna configurations, and to allow the possibility of evaluating the performance of the HARQ/ARQ using different scheduling approaches.

ACKNOWLEDGMENT

This work is supported by a grant from the Natural Science and Engineering Research Council of Canada (NSERC) and by a grant from Qatar Foundation (QF) under the National Priorities Research Program (NPRP).

REFERENCES

[1] "Overview of 3gpp release 8," 2008. Available from http://www.3gpp.org/Release-8; accessed 1 April 2010.

[2] 3GPP, "Evolved Universal Terrestrial Radio Access (E-UTRA); Physical Layer Procedures," TR 36.213, 3rd Generation Partnership Project (3GPP), Mar. 2010.

[3] K. Elgazzar, M. Salah, A.-E. M. Taha, and H. Hassanein, "Comparing uplink schedulers for lte," in *IWCMC '10: Proceedings of the 6th International Wireless Communications and Mobile Computing Conference*, (New York, NY, USA), pp. 189–193, ACM, 2010.

[4] http://www.gsacom.com/news/gsa_309.php4.

[5] 3GPP, "Physical Layer Aspect for Evolved Universal Terrestrial Radio Access (UTRA)," TR 25.814, 3rd Generation Partnership Project (3GPP), Oct. 2006.

[6] 3GPP, "LTE Physical Layer Framework for Performance Verification," TS R1-070674, 3rd Generatin Partnership Project (3GPP), Feb. 2007.

[7] J. Lim, H. Myung, K. Oh, and D. Goodman, "Proportional Fair Scheduling of Uplink Single-Carrier FDMA Systems," pp. 1 –6, sep. 2006.

[8] M. Al-Rawi, R. Jantti, J. Torsner, and M. Sagfors, "Opportunistic Uplilnk Scheduling for 3G LTE Systems," in *Innovations in Information Technology, 2007. IIT '07. 4th International Conference on*, pp. 705 –709, 18-20 2007.

[9] M. Al-Rawi, R. Jantti, J. Torsner, and M. Sagfors, "On the Performance of Heuristic Opportunistic Scheduling in the Uplink of 3G LTE Networks," in *Personal, Indoor and Mobile Radio Communications, 2008. PIMRC 2008. IEEE 19th International Symposium on*, pp. 1 –6, 15-18 2008.

[10] L. Ruiz de Temino, G. Berardinelli, S. Frattasi, and P. Mogensen, "Channel-Aware Scheduling Algorithms for SC-FDMA in LTE Uplink," in *Personal, Indoor and Mobile Radio Communications, 2008. PIMRC 2008. IEEE 19th International Symposium on*, pp. 1 –6, 15-18 2008.

[11] F. Liu, X. She, L. Chen, and H. Otsuka, "Improved Recursive Maximum Expansion Scheduling Algorithms for Uplink Single Carrier FDMA System," pp. 1 –5, may. 2010.

[12] F. Calabrese, P. Michaelsen, C. Rosa, M. Anas, C. Castellanos, D. Villa, K. Pedersen, and P. Mogensen, "Search-Tree Based Uplink Channel Aware Packet Scheduling for UTRAN LTE," in *Vehicular Technology Conference, 2008. VTC Spring 2008. IEEE*, pp. 1949 –1953, 11-14 2008.

[13] F. Calabrese, C. Rosa, M. Anas, P. Michaelsen, K. Pedersen, and P. Mogensen, "Adaptive Transmission Bandwidth Based Packet Scheduling for LTE Uplink," in *Vehicular Technology Conference, 2008. VTC 2008-Fall. IEEE 68th*, pp. 1 –5, 21-24 2008.

[14] F. Calabrese, C. Rosa, K. Pedersen, and P. Mogensen, "Performance of Proportional Fair Frequency and Time Domain Scheduling in LTE Uplink," pp. 271 –275, may. 2009.

[15] 3GPP, "Evolved Universal Terrestrial Radio Access (E-UTRA); Radio Resource Control (RRC); Protocol specification," TS 36.101, 3rd Generation Partnership Project (3GPP), June 2010.

[16] 3GPP, "Evolved Universal Terrestrial Radio Access (E-UTRA); Radio Frequency (RF) System Scenarios," TR 36.942, 3rd Generation Partnership Project (3GPP), Apr. 2010.

[17] 3GPP, "DL E-UTRA Performance Checkpoint," TS R1-071967, 3rd Generatin Partnership Project (3GPP), Feb. 2007.

[18] 3GPP, "Typical Examples of Radio Access Bearers (RABs) and Radio Bearers (RBs) Supported by Universal Terrestrial Radio Access (UTRA)," TR 25.993, 3rd Generation Partnership Project (3GPP), Apr. 2010.