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LTE Time-Domain Uplink Scheduler for QoS Provisioning

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***Abstract*—This paper introduces a novel time-domain (TD) LTE uplink scheduler called *Z-Based QoS Scheduler* (ZBQoS) which is fully standard-compliant. The ZBQoS scheduler provides Quality of Service (QoS) requirements, supporting delay bound and guaranteed rate even when the network is *heavily loaded*. We evaluate the proposed scheduler under heterogeneous traffic and compare its performance to that of another TD scheduler, called *Bandwidth and QoS Aware* (BQA), recently proposed. Simulation results show that ZBQoS scheduler reduces significantly delay of real-time traffic, while it is able to maintain lower packet loss ratio (PLR), when compared with the performace of the BQA scheduler which greatly surpasses the recommended PLR value under *heavily loaded* scenarios.**

***Keywords*—LTE, Quality of service, Radio access networks, Resource management, Scheduling algorithm.**

I. INTRODUCTION

Long Term Evolution (LTE) was developed with the aim to support the Quality of Service (QoS) requirements of various multimedia applications available on the Internet [1]. In line with that, the LTE Radio Resource Management (RRM) block located at the base station, called the evolved NodeB (eNB), performs two major tasks: Radio Admission Control (RAC), to decide about the admission of new connections, and Packet Scheduling (PS), to distribute radio resources among user equipments (UEs). The LTE standard does not define any specific admission control policy and scheduling algorithm, which are left to the vendors to implement [1]. As a consequence, the LTE Radio Admission Control and Packet Scheduling have attracted the attention of researchers from both industry and academy.

LTE PS comprises time-domain (TD) and frequency-domain (FD) scheduling algorithms. The TD scheduler selects a group of UEs requests to be scheduled in the following transmission time interval (TTI) based on their QoS requirements. The selected group is passed to the FD scheduler which determines the Physical Resource Blocks (PRBs) that should be assigned to them based on the channel quality. Besides supporting QoS requirements, the time-domain scheduler can reduce the complexity of the frequency-domain scheduler by limiting the number of requests passed to it, since the complexity of the FD scheduling algorithm depends on the number of requests to be scheduled. Figure 1 shows the PS concept in LTE uplink.

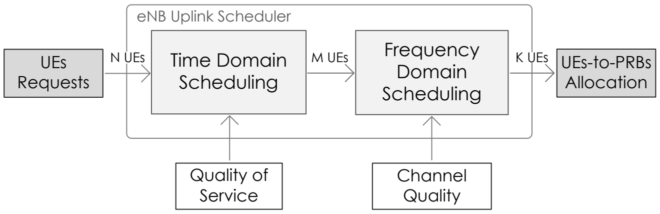

Figure 1. Packet Scheduling Overview in LTE uplink

This paper introduces a new time-domain uplink scheduler for LTE networks, called *Z-Based QoS Scheduler* (ZBQoS) which employs delay-related and rate-related metrics to prioritize the UEs requests. The ZBQoS scheduler employs a relaxed z-shaped function to assign priority to requests based on a delay-related metric, so that requests with expiring deadlines can be served first and real-time traffic is prioritized over non real-time traffic. The proposed solution provides delay bound and guaranteed rate according to the LTE specification. To the best of our knowledge this is the first standard-compliant TD uplink scheduler that is able to support both delay bound and guaranted rate requirements even in heavy load network conditions.

The performance of the ZBQoS scheduler was compared to that of the *Bandwidth and QoS Aware* (BQA) scheduler [2], a recently proposed scheduler which also provides delay and rate guarantees. Results derived via simulation show that the ZBQoS scheduler reduces delay of real-time traffic up to 50% as well up to 20% for non real-time traffic, when compared with the delays produced by the BQA scheduler. Furthermore, the ZBQoS scheduler is able to maintain the packet loss ratio (PLR) below 1% for real-time traffic while the BQA scheduler produces PLR up to 15%, which greatly surpasses the recommended 1% value for this traffic.

This paper is organized as follows. Section II describes the LTE provisioning of QoS requirements for uplink traffic. Section III discusses related work. Section IV introduces the proposed standard-compliant time-domain LTE uplink scheduler. Section V presents the frequency-domain scheduler jointly used with the time-domain scheduler. Section VI details the simulation model, the scenarios used and describes the results derived via simulations. Finally, Section VII concludes the paper.

II. QOS FRAMEWORK OF LTE NETWORKS

In order to support the QoS requirements of multimedia applications, flows are mapped onto dedicated bearers and a QoS Class Identifier (QCI) assigned to each bearer. In LTE, there are two types of bearers: Guaranteed Bit Rate (GBR) and non-GBR (nGBR). GBR receives guaranteed data rate, while non-GBR does not. The assigned QCI value determines how the bearer should be served considering the following parameters: resource type, priority, Packet Delay Budget (PDB), and Packet Error Loss Rate (PELR). The PDB provides a delay bound with confidence level of 98 percent, i.e., it it as a "soft upper bound". The PELR defines an upper bound to the packet loss rate non-related to congestion. The priority level indicates the bearer priority.

In addition to the QCI, each bearer is characterized by the following QoS attributes:

- **Guaranteed Bit Rate** (GBR) which refers to the minimum bit rate that should be sustained for GBR bearers.
- **Maximum Bit Rate** (MBR) which sets an upper bound to the data rate of GBR bearers.
- **Allocation and Retention Priority** (ARP) which indicates the priority of allocation and retention of bearers. It is used during bearer establishment by the RAC mechanism.

UEs use two signaling messages, called Scheduling Request (SR) and Buffer Status Report (BSR), to request resources to the eNB for uplink transmissions. The SR informs the eNB that the UE has an unspecified amount of data to send and the BSR allows UE to inform the eNB about the amount of buffered data to be sent and their priority.

Based on the QoS requirements of each bearer and on the BSRs received by the eNB, the TD uplink scheduler performs a prioritization of the currently active UEs to be scheduled for the upcoming TTI.

III. RELATED WORK

Although several LTE uplink schedulers have been proposed for the frequency domain [3]–[6], there are only a few proposals for the time domain which deal with QoS provisioning.

Delgado and Jaumard [7] proposed two schedulers for LTE uplink, called Single Channel Scheduling Algorithm (SC-SA) and Multiple Channel Scheduling Algorithm (MC-SA). These algorithms use the same metric to select the request to be multiplexed in the time and in the frequency domains. They assume that the minimum rate should be guaranteed to all traffic flows, such assumption violates the LTE specification since nGBR bearers do not have any guaranteed rate requirement. Moreover, this proposal does not consider the limitations of the control channel, since it allocates as many UEs as there are PRBs available. The maximum number of UEs that can be scheduled per TTI in each direction is 10 for 10 MHz of bandwidth (BW) when considering the limitations of the control channel [8].

Anas *et al.* [9] introduced an uplink TD scheduler that takes into account the minimum rate parameter of GBR traffic flows but, as in Delgado and Jaumard proposals [7], it uses this GBR parameter to provide service to nGBR bearers. This scheduler assumes a maximum number of eight scheduled UEs requests per TTI for 10 MHz. However, it does not take into account any delay-related parameter.

Recently, a new LTE uplink scheduler called *Bandwidth and QoS Aware* (BQA) was introduced [2]. It supports both guaranteed rate and delay bound and it takes into account the limitations of the control channel. However, it also uses GBR parameters to provide service to nGBR bearers, and, therefore it is not standard-compliant.

Two important metrics to analyze the performance of a QoS-aware scheduler are packet loss rate and throughput per user, however, in the evaluation of the aforementioned schedulers these metrics were ignored.

IV. STANDARD-COMPLIANT TIME-DOMAIN PACKET SCHEDULER

This section introduces a novel standard-compliant scheduler called *Z-Based QoS Scheduler* (ZBQoS). The ZBQoS scheduler follows the LTE specification and employs QoS-related metrics to prioritize users for scheduling.

ZBQoS selects a subset of UEs requests based on QoS metrics to be scheduled by the frequency-domain algorithm in the following TTI. The value of the QoS metric used for the selection is the minimum between the value of a delay-related metric and the value of a rate-related metric. The non-GBR bearers use only a delay-related metric specific to the type of traffic served by this class.

First, the scheduler calculates the metric value for each UE with pending transmissions to define the UE request priority. Then UEs requests are sorted in a decreasing priority order and the algorithm selects a group to be sent to the frequency-domain scheduler. By limiting the number of UEs sent to the FD scheduler, the probability of serving low priority users with better channel quality decreases, additionally, the complexity of the FD scheduler also decreases. The maximum number of UEs sent to the FD scheduler is configurable and it should be at least equal to the maximum number of requests that can be scheduled per TTI in the frequency domain.

The priority value associated to the request of the UE u at time interval n for the bearer i is denoted by $M_{u_i}^{QoS}(n)$ and defined as:

$$M_{u_i}^{QoS}(n) = \begin{cases} \min(D_{u_i}^{GBR}(n), R_{u_i}(n)), & \text{for GBR} \\ D_{u_i}^{nGBR}(n), & \text{for nGBR} \end{cases} \quad (1)$$

$D_{u_i}^{GBR}(n)$ and $D_{u_i}^{nGBR}(n)$ are the delay-related metrics for user u at the time interval n for bearer i, of the type GBR and non-GBR, respectively. $R_{u_i}(n)$ is the rate-related metric for UE u at time interval n for bearer i.

Priority is given to requests with delay close to the user's Packet Delay Budget. In addition, it is necessary to differentiate GBR from nGBR bearers. However, prioritizing GBR over nGBR bearers may lead to unnecessary loss of nGBR requests. To deal with the dynamic setting of priority values, a z-shaped function is applied to the delay-related metric for nGBR bearers.

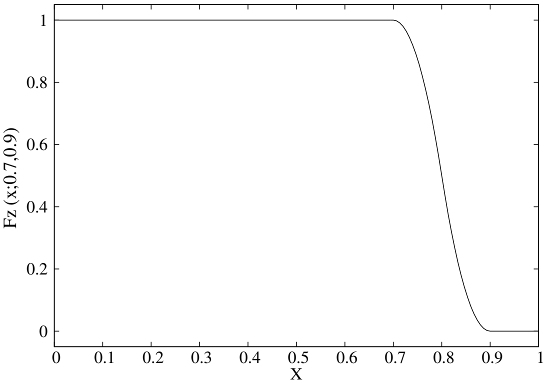

Figure 2. Relaxed z-shaped function with parameters $a = 0.7$ and $b = 0.9$

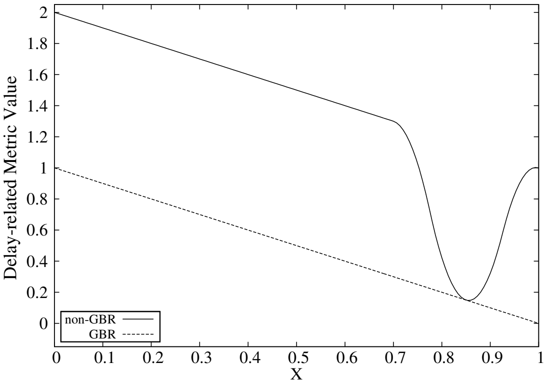

Figure 3. Delay-related metric value for GBR and nGBR bearers as a function of the ratio x

A relaxed z-shaped function is defined as:

$$f_z(x;a,b) = \begin{cases} 1, & \text{if } x \leq a \\ 1 - 2\left(\frac{x-a}{b-a}\right)^2, & \text{if } a < x \leq \frac{a+b}{2} \\ 2\left(\frac{x-b}{b-a}\right)^2, & \text{if } \frac{a+b}{2} < x \leq b \\ 0, & \text{if } x > b \end{cases} \tag{2}$$

where x is the function input and the parameters a and b delimitate the range of x values corresponding to the slope in Figure 2.

In order to employ the relaxed z-shaped function to the delay-related metric, the ratio x gives a measure of how close a delay is to the Packet Delay Budget.

$$x = \frac{HoL_u^i(n)}{PDB^i} \tag{3}$$

where $HoL_u^i(n)$ is the head of the line packet delay for bearer i of UE u at time interval n. PDB^i is the Packet Delay Budget of bearer i and its value depends on the QCI assigned to bearer i. When x is close to 1, the bearer has high priority since its HoL packet delay is close to the Packet Delay Budget.

Different expressions based on the relaxed z-shaped function were tested in the scheduling algorithm and the equations 4 and 5 isolate the GBR bearers from the nGBR bearers. These two metrics give absolute priority to GBR bearers with x values greater than 0.85, giving to the GBR bearers higher priority over any nGBR bearers.

The delay-related metric for non-GBR bearers is defined as:

$$D_{u_i}^{nGBR}(n) = 2 - x + f_z(x;0.7,0.85) - f_z(x;0.85,1) \tag{4}$$

High priority to non-GBR bearers is given only when x is greater than 0.7.

The delay-related metric for GBR bearers is defined as:

$$D_{u_i}^{GBR}(n) = 1 - x \tag{5}$$

Figure 3 shows the delay-related metric value for GBR and nGBR bearers as a function of the parameter x. It is interesting to note that $D_{u_i}^{GBR}(n)$ value is always higher than $D_{u_i}^{nGBR}(n)$ (the higher the metric value, the lower is the priority). For x greater than 0.75, when the metric value for nGBR bearers is below 1, a nGBR bearer can receive higher priority than a GBR bearer with low x value associated to it.

The rate-related metric for GBR bearers is defined as:

$$R_{u_i}(n) = \frac{R_{sch_{u_i}}(n)}{GBR_u^i} \tag{6}$$

where GBR_u^i is the minimum guaranteed bit rate for bearer i of UE u and $R_{sch_{u_i}}(n)$ is the weighted average rate given to bearer i of UE u at time interval n defined as:

$$R_{sch_{u_i}}(n) = \left(1 - \frac{1}{T_{PF}}\right) R_{sch_{u_i}}(n-1) + \frac{1}{T_{PF}} \hat{r}_{sch_u}(n) \tag{7}$$

where T_{PF} is the duration of a window used for measuring the obtained rate. $\hat{r}_{sch_u}(n)$ is the instantaneous achievable rate in case UE u is scheduled at the time interval n. This metric is close to 0 when no transmission opportunity has been given to the bearer and close to 1 when the minimum bit rate for that bearer is provided.

The QoS scheduling metric in (1) is defined for a UE with a single bearer i. For a multi-bearer UE, the metric is calculated as:

$$\min M_{u_i}^{QoS}(n), i \in \{B_i\}, \tag{8}$$

where $\{B_i\}$ is the set of bearers belonging to a given UE u at the time interval n.

In LTE uplink, when a UE has more than 4 bearers, all of them are grouped into 4 radio bearer groups (RBGs) to reduce signaling overhead. Each RBG contains bearers with similar QoS requirements. In this case, the QoS requirements that should be used in (1) are related to the most restrictive bearer in the RBG.

V. FREQUENCY-DOMAIN SCHEDULING

We employed a modified version of the First Maximum Expansion (FME) algorithm [3] in the frequency-domain with an FD Proportional Fair (PF) metric instead of the Maximum Throughput (MT) one. We used FME with PF metric since it yields a better performance than the use of MT. Moreover, it provides a good trade-off between spectral efficiency and fairness [10]. The main difference between the version used and the one presented in [3] is that, in this paper, the PRB allocation takes into account the current buffer size of the

Table I. TRAFFIC MODEL AND QOS REQUIREMENTS

Service	VoIP	Video	CBR
Description	G.729 ON/OFF Model	H.264 Trace-based[a]	1000 Bytes every 8 ms
Bit Rate	12.2 Kbps	128 Kbps	1 Mbps
QCI	1	2	8
PDB	100 ms	150 ms	300 ms
GBR	12.2 Kbps	128 Kbps	N/A[b] 128 Kbps[c]
Proportion	2 (40%)	2 (40%)	1 (20%)

[a] We use the trace of the video Foreman available in LTE-Sim [12].
[b] for the ZBQoS scheduler.
[c] for the BQA scheduler.

Table II. SIMULATION PARAMETERS

Parameter	Value
System Type	Single Cell
Cell Radius	0.5 Km
Channel Model	Macro-Cell Urban Model
Numbers of UEs in the Cell	5-150
UE Speed	3 km/h
System Bandwidth	5 MHz
Number of Resource Blocks	25 (BW per RB: 180 KHz)
Carrier Frequency	2 GHz
Frame Structure	FDD
TTI Duration	1 ms
Simulation Duration	100.000 TTIs (100 seconds)
UL Schedulers	TD: BQA FD: PF-FME TD: ZBQoS FD: PF-FME
Max. UEs passed to the FDPS	5
Max. Schedulable UEs per TTI	5 [2]
T_{PF}	50 ms
Number of Replications	5

UEs in addition to the channel condition at the moment of the allocation of Physical Resource Blocks. The inclusion of this condition avoids wastage of resources. The FD scheduler allocates PRBs to the UEs requests and then the eNB sends the grants to the UEs through the available control channels.

VI. PERFORMANCE EVALUATION

In this section, we evaluate the performance of the proposed scheduler, using the LTE-Sim simulator version 3.1 [11]. LTE-Sim is an event-driven packet level simulator developed in C++ widely used for simulating MAC functions of E-UTRAN. We implemented the proposed uplink packet scheduler and improved the implementation of the uplink part of the simulator. We introduced the support to QoS for uplink transmissions and divided the uplink scheduling in time and frequency domains.

The performance of the proposed time-domain LTE uplink scheduler was compared to the performance of another TD scheduler, called BQA, recently proposed [2]. Despite having the same objective of our scheduler (to provide delay bound and guaranteed rate), BQA is not standard-compliant since it uses GBR parameters for non-GBR bearers. In order to do a fair comparison, the FD scheduler described in Section V is used for both schedulers.

A. Simulation Model

The simulation scenario is composed of a single cell, one eNB and several UEs (varying from 5 to 150, with increments of 5). Users are uniformly distributed and for every two users transmitting VoIP traffic and two users transmitting video traffic there is one user transmitting CBR traffic. VoIP and video traffic are transmitted using GBR bearers and CBR (best effort traffic) uses non-GBR bearers. Table I summarizes the traffic model employed in the simulation and their QoS requirements.

When the delay of a packet is higher than the PDB, the packet is dropped. This process is performed every TTI by the UE in the beginning of the scheduling round. Information about the delay of the HoL packet of each radio bearer is considered to be available at every TTI at the eNB.

The effect of the Hybrid Automatic Repeat Request (HARQ) process is not considered. Moreover, as the performance evaluation focuses on the uplink scheduling, no radio admission control is implemented at the eNB. The UEs are distributed in the beginning of the simulation and they remain active for the entire simulation duration. In addition, to avoid intra-user scheduling interferences, each UE is assumed to have only one bearer with a single traffic class.

Table II summarizes the main configuration parameters used in this paper.

B. Simulation Results

The figures presented in this section show mean values with confidence intervals with 95% confidence level derived using the independent replication method. Average delay, packet loss ratio (PLR), average throughput per UE, and intra-class fairness index are used for comparison. All of these metrics are presented as a function of the number of UEs in the cell (i.e. traffic load).

The scheduler behavior was analyzed under three distinct loads. *Underloaded* scenarios comprise 5 to 50 UEs and under this load QoS requirements are supported. *Overloaded* scenarios comprise 55 to 120 UEs and under this load QoS can be provisioned to real-time traffic. Under *heavily loaded* traffic (125 to 150 UEs), only the proposed scheduler can provide QoS guarantees to real-time traffic.

Figure 4 shows the PLR for CBR users. As the network load increases the packet loss ratio also increases. The ZBQoS produces lower PLR values when the network is *overloaded* but slightly higher PLR values when the network is *heavily loaded*. However, the lower PLR given by the BQA scheduler is achieved at the expense of the QoS provisioning for video traffic.

ZBQoS is able to provide a no loss service to video traffic (Figure 5), which does not happen with the service provided by the BQA scheduler. As mentioned in [13], 1% is the maximum acceptable PLR for video traffic without affecting the users' quality of experience. Moreover, the packet loss ratio produced by BQA increases with the traffic load, reaching 15% under heavy load.

Moreover, both schedulers produce a no loss service to VoIP traffic as a consequence of its low bandwidth demand and high priority.

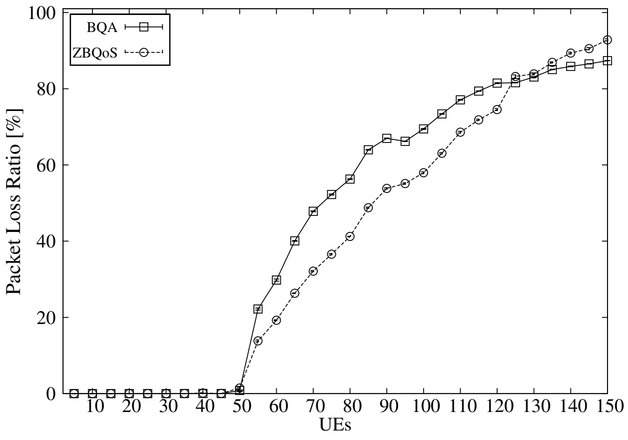

Figure 4. Packet Loss Ratio for CBR Traffic

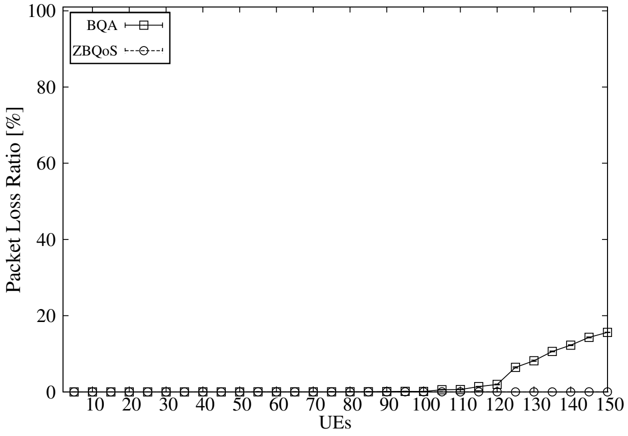

Figure 5. Packet Loss Ratio for Video Traffic

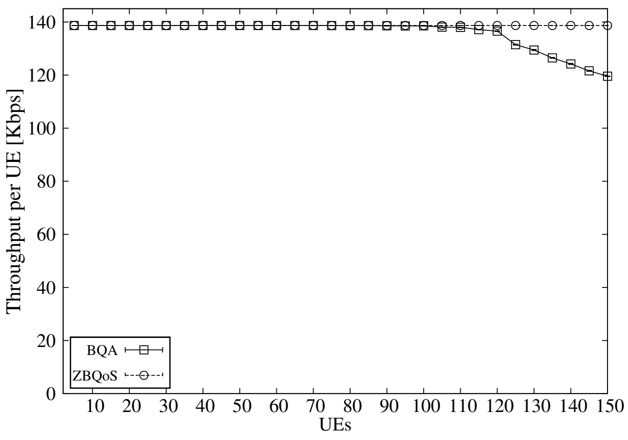

Figure 6. Average Throughput per User for Video Traffic

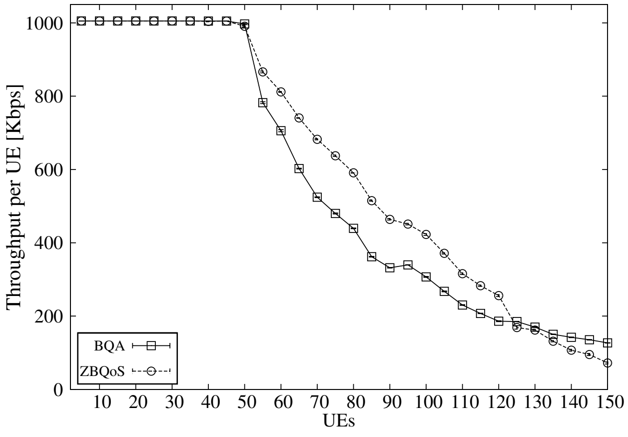

Figure 7. Average Throughput per User for CBR Traffic

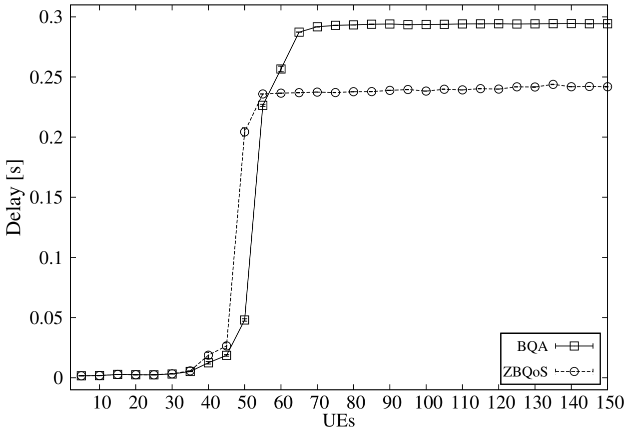

Figure 8. Average Packet Delay for CBR Traffic

Figures 6 and 7 show the throughput per UE for video and CBR users, respectively. These graphics show that the lack of capacity of the BQA scheduler to prioritize video traffic leads to the inability to guarantee minimum rate to this traffic (Figure 6) when the network is *heavily loaded*. The proposed scheduler decreases the rate of CBR traffic (best effort, Figure 7) to support the minimum rate QoS requirement of video traffic under heavy load.

Figures 8, 9 and 10 show the average delay for CBR, video, and VoIP traffic, respectively. For all types of traffic, the performance of both schedulers is similar when the network is *underloaded*. The delay produced by ZBQoS is 20% lower than the delay given by BQA for CBR traffic. Moreover, ZBQoS produces lower delays than the BQA scheduler for video traffic under heavy load. Delay values can be up to 50% of those given by the BQA scheduler. The delays produced by ZBQoS for VoIP traffic are higher than those produced by BQA when the network is overloaded but it is still below the QoS requirement bound.

Figure 11 shows the Jain's Index [14] of the throughput per bearer. One disadvantage of the ZBQoS scheduler is that it does not provide balanced service to non-GBR bearers. Under overloaded scenarios, some bearers are able to obtain higher throughput than others. Such unbalance does not happen when the BQA scheduler is employed. For video and voice traffic, both schedulers provide fair treatment, being the Jain's Index very close to 1.

VII. CONCLUSIONS

This paper introduced a novel time-domain scheduler for dynamic packet scheduling in LTE networks called ZBQoS

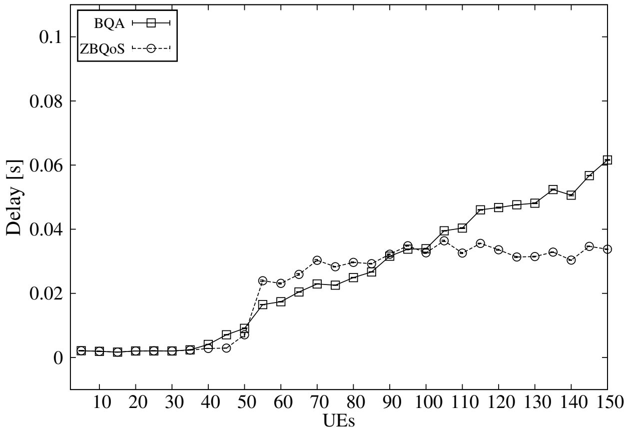

Figure 9. Average Packet Delay for Video Traffic

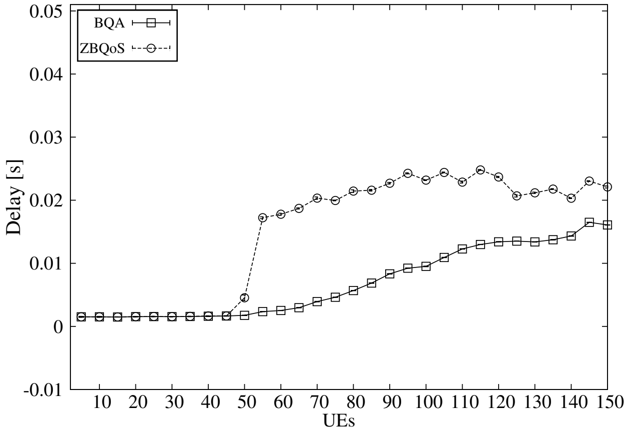

Figure 10. Average Packet Delay for VoIP Traffic

which is standard-compliant and guarantees QoS. The performance of the ZBQoS scheduler proposal was compared to that of the BQA scheduler, which is not compliant to the LTE standard. Simulation results show that the proposed scheduler provides lower packet loss ratio than those given by the BQA scheduler. Moreover, the BQA scheduler produces PLR greater than the maximum acceptable rate under heavy load. The ZBQoS scheduler reduces the delay in 20% for non real-time traffic when compared to the delay values given by BQA and it reduces the delay for real-time traffic up to 50% under heavy load. As future work, we will investigate how the number of users passed to the FD scheduler can affect performance, and how to optimize the duration of the throughput computation window.

ACKNOWLEDGMENT

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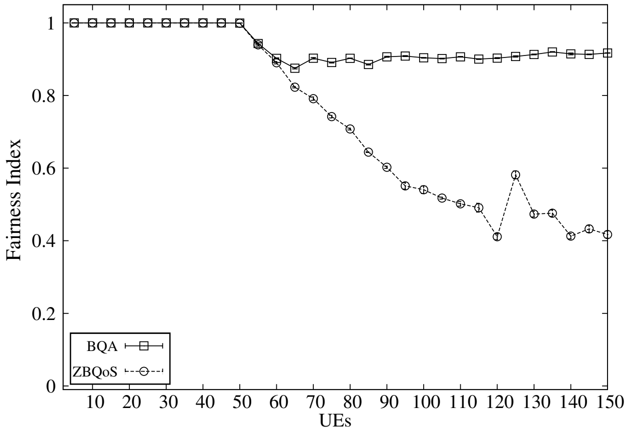

Figure 11. Intra-Class Fairness Index for CBR Traffic

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