DRX and QoS-aware Energy-efficient Uplink Scheduling for Long Term Evolution

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***Abstract*—Discontinuous reception (DRX) is supported in 3GPP Long Term Evolution (LTE) to reduce power consumption of user equipments (UEs). Power conservation achieved via DRX can be further increased with a packet scheduler that takes DRX states into consideration. Thus, in addition to quality of service (QoS) and fairness factors, which have been the main focus so far in scheduler design, energy efficiency must also be considered in scheduling. In this paper, we introduce a DRX and QoS-aware uplink packet scheduling algorithm (DQEPS) for LTE networks. One of the main reasons of poor DRX utilization is the continuous uplink packet traffic generated by applications working in the background. Accordingly, we first lay out the cumulative distribution functions (CDF) of inter-packet arrival durations constructed by inspecting uplink packet transmission for various applications. Then, we form metrics for each bearer using these CDFs along with the DRX states, QoS parameters, channel conditions, and the buffer status of the bearers. Using these metrics, we develop a scheduling algorithm for the uplink, which aims to maximize power conservation of DRX mechanism by scheduling packets in a way that tries to minimize ON duration, while meeting the QoS requirements. Performance evaluations indicate that DQEPS reduces power consumption significantly compared to the previously proposed methods for LTE.**

***Index Terms*—Long Term Evolution; packet scheduling; uplink; quality of service; fairness; limited feedback**

I. INTRODUCTION

The battery lifetime of mobile terminals is limited. To address this issue, LTE supports discontinuous reception (DRX), which enables user equipments (UE) to switch their transceivers off when they do not receive or send packets. A properly designed scheduler can have a big impact on the amount of conserved energy by scheduling packets so that inactive time of the DRX cycle is maximized. However, most of the applications running on mobile devices today, such as video streaming or voice over IP (VoIP) have QoS requirements like minimum transmission rate, maximum delay or packet error rate, which often require frequent packet transmission. Therefore, there is a need for a scheduler which is both DRX and QoS-aware and which aims to strike a balance between the demands of these two mechanisms.

QoS-aware packet schedulers are studied in [1] and [2], however, these solutions do not consider LTE-specific requirements. In LTE, the resources that can be assigned to a UE have both time and frequency dimensions. For optimal solution, packet scheduler should jointly consider time and frequency. However, most of the proposed solutions take the decoupled time/frequency domain packet scheduler approach as proposed in [3]. The time domain packet scheduler (TDPS) prioritizes the UEs to be scheduled, generally according to QoS requirements. Frequency domain packet scheduler (FDPS) assigns radio resources to UEs in accordance with their channel conditions. With such a decoupled approach, TDPS limits the number of multiplexed users, reducing both the signaling overhead and the FDPS complexity.

There are several studies in the literature that focus on power consumption for LTE [4] - [6]. However, they either do not focus on scheduling, or concentrate merely on TDPS. In [7], a DRX-aware scheduling method is presented. However, the method is not QoS-aware. Furthermore, it does not explain how channels are assigned to users.

A scheduler that aims to be both DRX and QoS-aware can achieve better performance with proper packet arrival estimation. Packet arrival estimation enables the scheduler to act proactively, increasing the possibility of reducing energy consumption while meeting QoS requirements. To the best of our knowledge, none of the previously proposed uplink scheduling methods for LTE use estimation of packet arrivals.

In this paper, we present DQEPS, an uplink scheduler for LTE that considers power consumption as well as QoS and packet arrival estimation. The salient features of DQEPS are

- DRX awareness to increase energy efficiency
- Packet inter-arrival time estimation
- A novel approach for using packet loss and error rate requirements to match UEs with channel conditions

The remainder of this paper is organized as follows. In Section II, we provide the background information on uplink packet scheduling and DRX in LTE. In Section III, we present the DRX and QoS-aware scheduler (DQEPS) in detail. We present details about the simulation environment, as well as the results in Section IV. Finally, in Section V, we present our concluding remarks.

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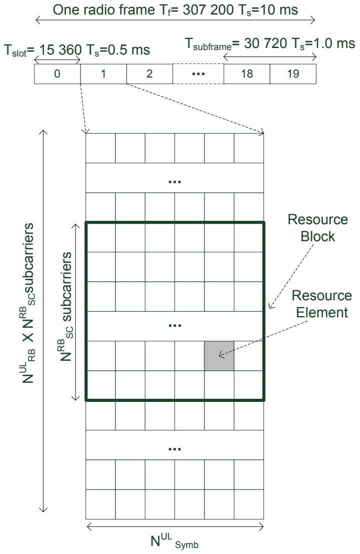

Fig. 1: Radio frame structure in LTE.

TABLE I: QoS attributes [9].

QCI	***Bearer type***	***Priority***	***Delay budget***	***PLER***	***Example application***
1	GBR	2	100 ms	$1e^{-2}$	VoIP
2	GBR	4	150 ms	$1e^{-3}$	Video call
3	GBR	3	50 ms	$1e^{-3}$	Real time gaming
4	GBR	5	300 ms	$1e^{-6}$	Buffered streaming
5	Non-GBR	1	100 ms	$1e^{-6}$	IMS signaling
6	Non-GBR	6	300 ms	$1e^{-6}$	YouTube, p2p
7	Non-GBR	7	100 ms	$1e^{-3}$	Interactive gaming
8	Non-GBR	8	300 ms	$1e^{-6}$	Twitter, Facebook
9	Non-GBR	9	300 ms	$1e^{-6}$	Twitter, Facebook

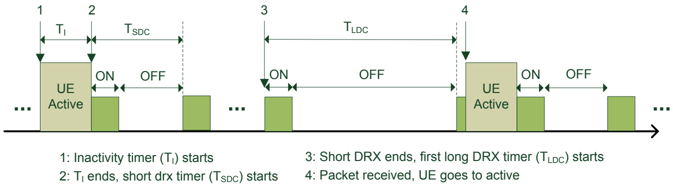

Fig. 2: DRX operation in LTE.

II. OVERVIEW OF UPLINK PACKET SCHEDULING IN LTE

In this section we present information about LTE-specific details that are used by DQEPS such as radio resource structure, representation of QoS parameters and DRX operation.

LTE uses a time-slotted mechanism that consists of 10 ms long radio frames. A radio frame is divided into ten 1ms long subframes called transmission time intervals (TTI). Each TTI is further divided into two 0.5 ms slots. In the frequency domain, one slot is divided into regions of 180 kHz bands. This 0.5 ms × 180 kHz time-frequency block constitutes the basic radio resource unit termed as the Physical Resource Block (PRB), which is the minimum resource unit for scheduling [8]. The radio frame structure is shown in Fig. 1.

In LTE, different transmit/receive data buffers are used for different traffic flows. These flows are organized into logical traffic pipes named bearer services. A set of QoS attributes are associated with each bearer, depending on the type of traffic it carries, as given in Table I. Prominent QoS attributes are [9]:

- *Bearer type:* Reflects if the associated bearer type is guaranteed bit rate (GBR) or non-GBR. The former has to provide a minimum data rate, the latter does not.
- *Packet Delay Budget (PDB):* The maximum packet delay.
- *PLER:* The maximum tolerable number of packets received in error or are lost.

In LTE, two DRX cycles can be set for each UE, named the long (T_{LDC}) and the short (T_{SDC}) DRX cycles. A basic DRX cycle consists of an ON period (T_{ON}), during which UE transceiver is on, followed by an OFF period, during which UE transceiver is turned off. If the short timer is enabled, a number of short periods exist before a long period. An inactivity timer (T_I) is set to trigger DRX cycle after its expiry. This timer is activated before the first DRX cycle and is refreshed when a packet arrives. In Fig. 2, we present the DRX operation.

III. DRX AND QOS-AWARE ENERGY EFFICIENT PACKET SCHEDULING (DQEPS)

The aim of DQEPS is to schedule packets so that energy consumption of UEs are minimized while their QoS requirements are met. Thus, the main optimization problem is,

$$\min_{N_j, T_j} \left(E_{cons} = N_j \cdot E_{tr} + T_j \cdot P_{rcv} \right) \tag{1}$$

s. t.

$$R_{j,b} \geq GBR_{j,b} \tag{2}$$

and

$$D_{j,b} \leq PDB_{j,b}, \forall j \in J, \forall b \in B_j \tag{3}$$

where, N_j is the total number of PRBs assigned to UE j and E_{tr} is the average energy required to transmit one PRB. E_{tr} is calculated considering a worst-case path loss as given in [10]. T_j is the number of TTIs UE j spends in non-sleeping state and P_{rcv} is the power spent in one TTI when transceiver is listening to the channel. Constraints represent QoS requirements. J is the set of UEs, and B_j is the set of all bearers of UE j. $R_{j,b}$ and $GBR_{j,b}$ are the current transmission rate and guaranteed bit rate for bearer b of user j, respectively. $D_{j,b}$ and $PDB_{j,b}$ are the maximum experienced packet delay and packet delay budget for bearer b of UE j, respectively. N_j and T_j depend on $R_{j,b}$ and $D_{j,b}$, however, open form expressions are not available.

As mentioned in Section I, DQEPS utilizes a decoupled time/frequency approach. First, TDPS of DQEPS, i.e., TD-DQEPS, runs and selects a set of UEs that must be scheduled according to DRX operation and QoS requirements, and thus, determines T_j for each UE. Following TD-DQEPS operation, FDPS of DQEPS, i.e., FD-DQEPS is executed. The set of UEs chosen by TD-DQEPS is sent as input to FD-DQEPS. FD-DQEPS allocates PRBs to these UEs according to channel

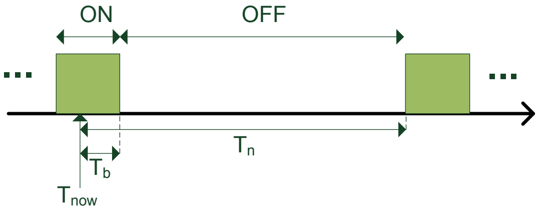

Fig. 3: T_b and T_n.

conditions and QoS requirements, thus, determines N_j for each UE. Since P_{rcv} and E_{tr} are constant and T_j and N_j are decoupled, the optimization problem is transformed into two independent optimizations: $\min T_j$ and $\min N_j$. First minimization is handled by TD-DQEPS and the second is handled by FD-DQEPS, as detailed in the following sections.

A. TD-DQEPS Operation

TDPS design relies on a priority metric indicating each UE's urgency for transmission to meet its QoS requirements. However, significant power conservation can be achieved by introducing also DRX-awareness into the TDPS. We define two time intervals to make TD-DQEPS DRX-aware, i.e., T_b and T_n. T_b is the number of TTIs before UE goes to sleep, and T_n is the number of TTIs until UE's *next* ON period, as shown in Fig. 3.

First, the set, J, of UEs that have packets in their buffer and are not in DRX sleep are determined. Then, the minimum number of packets that must be sent during T_b, i.e., N_j^{min}, is calculated. It is the sum of packets that must be sent to meet throughput and delay constraints, i.e., N_j^t and N_j^d, and the number of estimated packet arrivals, i.e., N_j^e

$$N_j^{min} = N_j^t + N_j^d + N_j^e \tag{4}$$

N_j^t is calculated as

$$N_j^t = \max\left(0,\, GBR \cdot (T_{tot} + T_b) - N_{tot}\right) \tag{5}$$

where GBR is the required minimum packet rate, T_{tot} is the time elapsed since connection started, and N_{tot} is the total number of packets sent so far.

The scheduler does not have the knowledge of actual delays of the packets since the packets are in the buffers of the UEs. To help evolved Node B (eNB) in uplink scheduling, UEs send buffer status reports (BSR) to eNB reporting the number of packets in their buffers. However, packet delay information is not included in these reports. Thus, eNB has to estimate the delay for the packets. Delay estimation methods such as [11] may be used. After delays are estimated, all bearers are checked to see if $T_d^{est} + T_n < T_d^{bdgt}$. Here, T_d^{est} is the estimated delay and T_d^{bgt} is the delay budget for the bearer as given in Table I. If this holds for any of the bearers, then this UE must transmit its packets during T_b to meet its delay constraint. Thus, N_j^d is increased by one for each such packet.

Mobile applications generate packet traffic, even when there is no user interaction. To obtain an estimate about the background packet inter-arrival times for applications that are widely used such as Facebook, Twitter and YouTube, we performed experiments in a physical experimental testbed. We used a network sniffer to obtain background packet arrival times of these applications. Data packages were taken from a mobile phone and 3G connection was used. First, all of the applications running on the mobile phone were closed. Then, only the application for which data is to be gathered was run. After an initial time period to allow for the application to download all of its content and complete its initialization process, the network sniffer was run. Data was acquired for 30 minutes with no user interaction on the mobile phone.

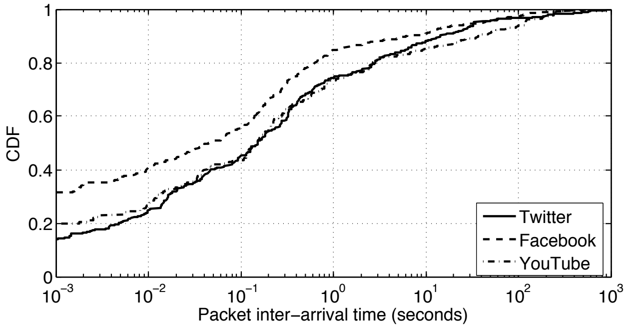

Fig. 4: CDFs for background packet inter-arrival times.

In Fig. 4, we present the CDFs for packet inter-arrival times for these applications. Using this empirical data, we calculate the expected number of packet arrivals (N_j^e) within T_n. Once N_j^t, N_j^d and N_j^e are determined, the minimum transmission rate during T_b can be calculated as $r_j^{min} = N_j^{min}/T_b$. Finally, the following metric is formed,

$$M_T = \frac{(r_j^{min} + r_j^{cur})}{r_j^{avg}} \cdot T_b \tag{6}$$

where r_j^{cur} is the maximum transmission rate achievable under the current channel conditions and r_j^{avg} denotes the average UE throughput until now, calculated as outlined in [12].

Calculation of r_j and the parameters that make up r_j, i.e., N_j^t, N_j^d and N_j^e are all performed with regard to the operation of the DRX mechanism, and thus, introduce DRX-awareness to DQEPS. The denominator term introduces fairness as follows: When a UE is not scheduled, its transmission rate decreases, increasing the metric for that UE and increasing its chance to be scheduled. Conversely, the metric decreases for UEs which had high transmission rate in the past, making room for UEs which had less transmission rate. When a UE is scheduled for transmission, DRX operation is terminated and inactivity timer (T_I) is started. Thus, the later a UE is scheduled during its ON period, the longer its overall active time will be. The reason for multiplication with T_b in (6) is to force scheduling of nodes close to the beginning of their ON periods to minimize the prolonging of the active time of UEs.

TDPS selects N users from J with the highest M_T metric and passes them to the FDPS. The value of N is determined by the signaling constraints and the number of PRBs in the scheduling bandwidth.

B. FD-DQEPS Operation

The general approach in designing a FDPS is to form a metric that increases a certain satisfaction criteria for PRB allocation. This criteria may be fairness, conformance to QoS constraints, throughput maximization, delay minimization or a combination of these. When FDPS allocates PRBs to UEs, more PRBs are assigned to UEs with higher metrics.

The aim of FD-DQEPS is to $\min N_j$, i.e., the number of resource blocks assigned to each UE. Since this cannot be done by reducing the packets that the UE has to send, the only way is to assign the PRBs to the UE such that it can send its data with the highest possible packet transmission rate and with minimal packet losses and retransmissions.

The metric used by FD-DQEPS is formed in two stages. In the first stage, an initial metric that helps in minimizing packet losses and retransmissions is formed. The idea behind this metric can be explained as follows. Under adverse channel conditions, packet errors may be inevitable. In such situations, bearers which have more tolerable bit error rate requirements should be chosen. As channel conditions get better, bearers with more strict bit error rate requirements should be favored.

The initial metric tries to match PLER requirements with the channel states. First, the logarithms of the PLER requirement of each connection as given in Table I is normalized in a way that the maximum PLER value corresponds to 0 and the minimum PLER value corresponds to 1. Then, the value representing channel conditions is also normalized to 1. The distance between these two values indicate the suitability of the channel conditions and the PLER requirements of the connections. If normalized PLER value is larger than normalized channel condition, the required PLER may not be supported by this channel. Another connection with less strict PLER requirements may be more appropriate to this channel. If normalized PLER value is smaller than normalized channel condition, then the channel may be too good for this connection and may be able to support connections with more strict PLER requirements. Therefore, as the distance between these two normalized values get smaller the connection gets more suitable to the channel conditions. The metric is calculated as follows,

$$U_j^c = \left| \frac{PLER_{max} - PLER_{req}^b}{PLER_{max} - PLER_{min}} - C_j^c \right| \tag{7}$$

Here, $PLER_{max}$ and $PLER_{min}$ are logarithms of the maximum and minimum values of packet loss rate given in Table I (i.e. -2 and -6, respectively). $PLER_{req}^b$ is the packet loss rate requirement of bearer b. Note that the division is to normalize PLER values to one. The first term is a constant for each bearer and can be pre-calculated. $C_j^{c,b}$ is a metric indicating the current channel conditions We assume that $C_j^{c,b}$ is normalized to 1.

In the second stage, the final metric that combines U_j^c with additional terms to match QoS requirements and channel conditions with a certain degree of fairness is formed. The term r_j^{min} calculated by TD-DQEPS is also used in the FD-DQEPS final metric. This term helps FD-DQEPS to allocate larger amount of PRBs to those UEs with more urgent packets to send. Without this term, less PRBs are allocated to these UEs, but since they have more packets to send, they get scheduled again in the next TTI, prolonging their active time. The FDPS of DQEPS tries to allow UEs with greater number of packets with QoS needs to transmit in bursts when channel conditions favor them. Thus, UEs meet their QoS requirements and also conserve energy. The final metric is calculated as,

$$M_j^c = \frac{r_j^{cur}}{r_j^{avg}} \cdot \frac{r_j^{min}}{U_j^c} \tag{8}$$

The denominator term, r_j^{avg}, provides a degree of fairness. It decreases the metric for UEs which obtained greater average transmission rates up until this instant and allows for other UEs with lower average transmission rates to obtain more PRBs. The term r_j^{cur} in the numerator increases the metric for UEs with better channel conditions, which results in more PRB allocation for these UEs.

When assigning PRBs to UEs, FD-DQEPS must meet the contiguity constraint. When M_j^c is determined for every node in J and every available channel c, a matrix M, of these values is formed. Channel allocation is performed by the method used in [13]. Allocation begins with selecting the maximum element $M(c, j)$ in the matrix and assigning channel corresponding to PRB c to UE j. Then FDPS extends the allocation, adding neighboring PRBs to UE j's allocation until another UE with a higher metric is met or all of the packets of UE j is scheduled, or UE j has reached its maximum transmission power. Then, the scheduler selects a new UE and the process goes on until all PRBs are scheduled. This method satisfies the contiguity requirement of the SC-FDMA transmission, while maximizing channel utilization.

IV. PERFORMANCE EVALUATION

In this section, we present performance evaluations of DQEPS with comparison to various previously proposed solutions. Simulation parameters are given in Table II. The methods we compare DQEPS with use a combination of the following TDPS and FDPS metrics:

DRX-aware (TD-DRX): This is the DRX-aware TDPS proposed in [7].

Time-Domain Proportional Fair Throughput (TD-PF): This method prioritizes users according to a proportional fair metric

TABLE II: System Simulation Settings.

Parameter	Setting
Carrier frequency	2GHz
Transmission bandwidth	10 MHz
Effective bandwidth	9 MHz
Number of PRBs	50
Sub-frame duration	1 ms
Packet size	2048 bits
Buffer size	2 Mbits
Max. UE transmit power	23 dBm
Simulation duration	800 TTIs

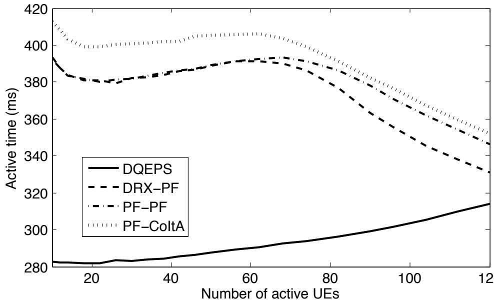

Fig. 5: Average active time of UEs.

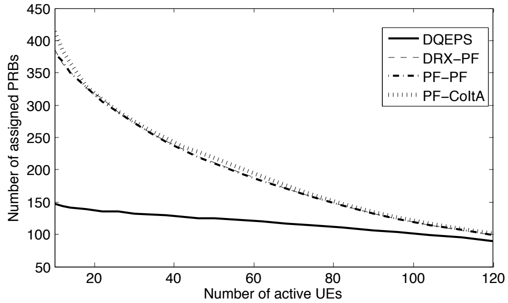

Fig. 6: Number of average PRBs assigned to each UE.

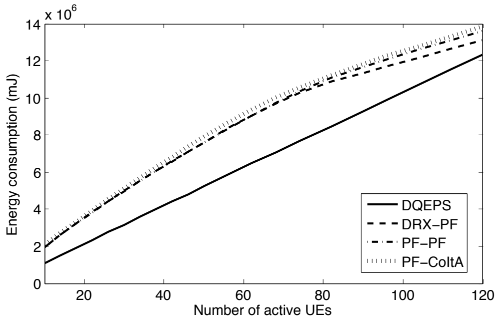

Fig. 7: Overall energy consumption.

given as $M_{PF} = \hat{T}_{WB}/R_{avg}$ where, $\hat{T}_{WB}$ is the estimated wideband throughput for the user and R_{avg} is the average transmission rate. The denominator introduces *memory* so that if a node was not scheduled for some time, its priority increases, providing fairness.

Frequency-Domain Proportional Fair Throughput (FD-PF): This method allocates PRBs to the users according to a proportional fairness metric given as $M_{PF}(p) = \hat{T}(p)/R_{avg}$, where, $\hat{T}(p)$ is the estimated maximum throughput of the user on PRB p. The denominator term provides fairness in a similar way to TD-PF.

Carrier over Interference to Average (FD-CoItA): Aims to assign more PRBs to users with better channel conditions [14]. Its metric is $M_{CoItA} = \hat{CoI}(p)/\sum_{p=1}^{N_{PRB}} \hat{CoI}(p)$ where $\hat{CoI}(p)$ is an estimation of the Signal to Interference and Noise Ratio (SINR) on PRB p. The denominator is an estimation of the average channel quality of the user.

In the simulations, we choose three combinations of these TDPS and FDPS methods to compare with DQEPS: DRX-PF, PF-PF and PF-CoItA. DRX-PF uses TD-DRX as TDPS and FD-PF as FDPS. We chose this one to see how DQEPS performs compared to another DRX-aware scheme. PF-PF is a full PF method and is chosen to investigate how a scheme with only fairness consideration performs. PF-CoItA uses PF-TDPS and CoItA-FD. It is chosen to compare FP-DQEPS with another scheme which allocate channels according to UEs' channel conditions. In our energy calculations, we use the power consumption model given in [15]. We calculate the transmission power for one PRB considering a worst-case path loss as given in [10]. We use packet arrivals as obtained from the network sniffer as detailed in III-A. In the following sections, we present our performance evaluation results and related discussion on various aspects of the compared methods.

A. PRB Assignment Efficiency

In Fig. 5, we depict the average active time of a UE, which is considerably lower for DQEPS, especially at lower network load, where DQEPS provides up to 29.29 % less active time compared to the closest method. Low active time of DQEPS is obtained by the T_b factor in TD-DQEPS metric, given in Section III-A. This term forces DQEPS to schedule packets near the beginning of UEs ON times, lowering the prolonging of active time. As explained in III-B, FDPS of DQEPS is designed to assign bursts of PRBs to UEs when their channel conditions are good, resulting in higher transmission and lower error rates. Thus, more packets can be sent per PRB and less retransmissions due to packet errors are needed. Therefore, DQEPS uses significantly less number of PRBs in transmitting the same amount of data. This is seen in Fig. 6, where we present the average number of PRBs assigned to an UE. DQEPS uses less number of PRBs for all cases.

B. Energy Consumption

In Fig. 7, we show the sum of energy consumption in listening mode and in active transmission mode. Because of its lower active time and ability to transmit its data in less number of PRBs, DQEPS uses the least amount of energy providing up to 49.45% energy conservation at low network loads compared to other methods.

C. Packet Transmission Rate

The overall throughput is given in Fig. 8. DQEPS has lower throughput at low traffic, but it is the most resilient to congestion. The greatest difference is for 90 active UEs, with DQEPS having 15.28% less throughput than PF-CoItA. This is because DQEPS is primarily concerned about energy consumption. As long as the connection meets the GBR requirement and the queued packets do not exceed the delay budget, DQEPS lets the packets remain buffered which is not the case for other methods. Thus, continuous existence of buffered packets causes the overall throughput to be lower than the others.

In Fig. 9, we present the percentage of GBR bearers that meet their QoS requirements. We see that DQEPS performance

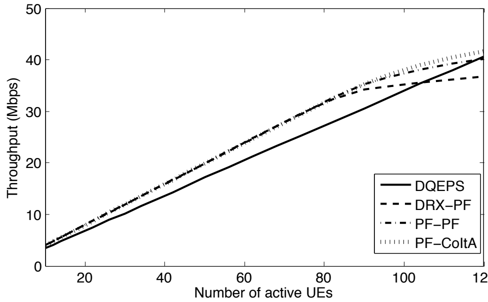

Fig. 8: Total throughput.

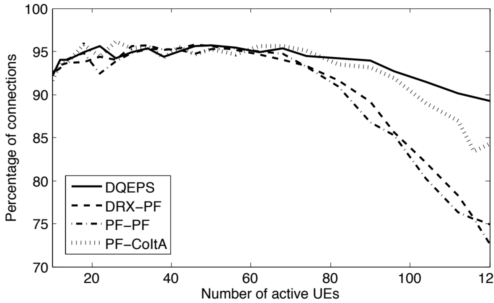

Fig. 9: Percentage of connections that meet GBR requirement.

is similar to other methods up to 80 active UEs. As congestion starts, the performance of methods that use FD-PF deteriorate rapidly since they allocate PRBs to non-GBR resources to achieve fairness and this causes GBR connections to fail at meeting their rate requirements. DQEPS proves to be the most resilient to congesiton. Since PF-CoItA tries to use channel conditions it performs better than FD-PF based methods.

D. Packet Delay

In Fig. 10, we present the percentage of packets that fail to meet their delay budgets. We see that all methods have very low percentages until network becomes congested. DQEPS is the most resilient to congestion, providing up to 2.85% better performance than its closest competitor for 120 active UEs.

Overall, DQEPS provides a significant amount of energy conservation with similar performance in terms of conformance to GBR and delay QoS requirements. The trade-off is a slight drop in the overall cell throughput.

V. CONCLUSIONS

In this paper we introduced a new uplink scheduling method for 3GPP LTE. We layout the results of our investigations on traffic behavior of various popular wireless applications and use the gathered data to estimate packet arrivals. Our method make use of these estimations as well as channel estimations and QoS requirements and also provides a mechanism for DRX awareness. Simulation results show that our method can provide very similar results in terms of meeting the QoS requirements compared to other methods with significant energy conservation.

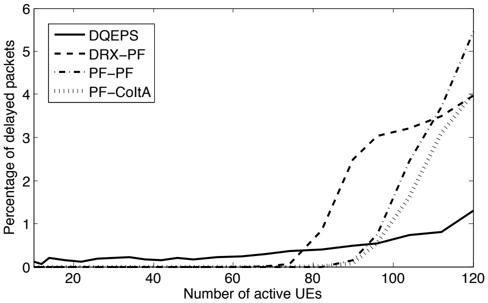

Fig. 10: Percentage of packets that fail to meet delay budget.

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REFERENCES

[1] T.-D. Nguyen, Y. Han, “A Proportional Fairness Algorithm with QoS Provision in Downlink OFDMA Systems,” *IEEE Communication Letters,* vol. 10, no. 11, November 2006

[2] F. R. Farrokhi, M. Olfat, M. Alasti, K.J. Ray Liu, “Scheduling Algorithms for Quality of Service Aware OFDMA Wireless Systems,” *in Proc. IEEE Globecom 2004,* vol. 4, pp. 2689-2693, November 2004

[3] A. Pokhariyal, K.I. Pedersen, G. Monghal, I.Z. Kovacs, C. Rosa, T.E. Kolding, P.E. Mogensen, “HARQ Aware Frequency Domain Packet Scheduling with Different Degree of Fairness for the UTRAN Long Term Evolution,” *IEEE 65th Vehicular Technology Conference, 2007,* pp. 2761-2765, April 2007

[4] M. Lauridsen, A. R. Jensen, P. Mogensen, “Fast Control Channel Decoding for LTE UE Power Saving,” *in Proc. IEEE 75th Vehicular Technology Conference (VTC Spring),* pp1-5, 2012

[5] F-W Li, Y-Q Zhang, L-W Li, “Enhanced discontinuous reception mechanism for power saving in TD-LTE,” *in Proc. 3rd IEEE International Conference on Computer Science and Information Technology (ICCSIT),* pp. 682-686, vol. 9, 2010

[6] K. Aho,T. Henttonen, J. Puttonen, T. Ristaniemi, “Trade-Off between Increased Talk-Time and LTE Performance,” *in Proc. Ninth International Conference on Networks (ICN),* pp. 371-375, 2010

[7] H. Bo, T. Hui, C. Lan, Z. Jianchi, “DRX-Aware Scheduling Method for Delay-Sensitive Traffic,” *IEEE Communications Letters,* vol.14, no.12, pp.1113-1115, December 2010

[8] 3GPP, “Evolved Universal Terrestrial Radio Access (E-UTRA); Physical Channels and Modulation, *TR 36.211, 3rd Generation Partnership Project (3GPP),* Mar. 2010

[9] 3GPP, “Policy and charging control architecture, *TS 23.203, 3rd Generation Partnership Project (3GPP),* Mar. 2013

[10] M. Lauridsen, A. R. Jensen, P. Mogensen, “Reducing LTE Uplink Transmission Energy by Allocating Resources,” *in Proc. IEEE Vehicular Technology Conference,* pp.1,5, 2011

[11] S. Kwon, N-H Lee “Uplink QoS Scheduling for LTE System,” *in Proc. IEEE Vehicular Technology Conference,* pp. 1-5, 2011

[12] A. Jalali, R. Padovani, and R. Pankaj, “Data Throughput of CDMA-HDR High Efciency-High Data Rate Personal Communication Wireless System, *in Proc. IEEE Vehicular Technology Conference,* pp. 18541858, 2000.

[13] F. D. Calabrese, C. Rosa, M. Anas, P. H. Michaelsen, K. I. Pedersen, P. E. Mogensen “Adaptive Transmission Bandwidth Based Packet Scheduling for LTE Uplink,” *in Proc. IEEE Vehicular Technology Conference,* pp. 1-5 , 2008

[14] G. Monghal, K. I. Pedersen, I. Z. Kovacs, P. E. Mogensen, “QoS Oriented Time and Frequency Domain Packet Schedulers for The UTRAN Long Term Evolution,” *in Proc. IEEE Vehicular Technology Conference,* pp.2532,2536, 2008

[15] Nokia, R2-071285, “DRX parameters in LTE, March 2007