Long Term Evolution Downlink Packet Scheduling using A Novel Proportional-Fair-Energy Policy

C. Turyagyenda, T. O'Farrell and W. Guo
Department of Electronic and Electrical Engineering
The University of Sheffield
Sheffield, United Kingdom
(c.turyagyenda, t.ofarrell and w.guo)@sheffield.ac.uk

Abstract*—Inter-cell interference (ICI) is a key limiting factor to the general performance of a multi-cell multi-user radio access network. The channel quality of cell edge users is greatly impaired by ICI owing to the fact that cell edge users are furthest away from the their serving base station and closest to the interfering base stations. As a result the Quality of Service (QoS) and energy efficiency of the E-UTRAN is primarily dependant on the cell edge users. Firstly, we propose a new Time Domain Packet Scheduling criterion that endeavours to reduce the variation in the energy performance, of the users, in a temporal sense. The proposed criteria aims to strike a balance between two user prioritisation criteria that result in energy performance at the two extremes of the energy consumption range. The paper shows that this improves the mean energy efficiency of the E-UTRAN. Secondly, we introduce an energy optimisation algorithm to complement the Time Domain Packet Scheduler. The new energy aware packet scheduling criteria is compared against the established throughput based proportional fair scheduler with uniform power allocation and is shown to produce 20% Energy Reduction Gains (ERG) without compromising the spectral efficiency and QoS performance.

Keywords-Packet Scheduling; LTE; Energy Consumption Ratio;

I. INTRODUCTION

Due to the rapid growth of wireless technologies and usage, a new issue in the design of future mobile cellular systems has been apparent for close to four years, namely, the energy consumption of the radio access network. The volume of transmitted data increases approximately by a factor of 10 every five years, which corresponds to an increase of the associated energy consumption by approximately 16 to 20%. Currently, 3% of the world's energy is consumed by telecommunications infrastructure which accounts for 2% of the world's CO_2 emissions [1]. In a suburban area of 100 Km^2, long-term evolution (LTE) requires a total of 124 base stations (BSs) and transmits a total power of 607.2KW [2]. Thus each base station can require up to 4.9KW of electrical power which can lead to an energy consumption of tens of mega watt hours (MWh) per annum. If this energy consumption is doubled every 5 years, serious energy supply and environmental problems will arise. Inter-cell Interference (ICI) is a key limiting factor to the Radio Frequency (RF) energy performance of a multi-cell multi-user radio access network. In order to improve the RF energy performance of the E-UTRAN, there is an essential need to create innovative methods that mitigate the effects of ICI.

A. Review

The spectral efficiency and throughput performance of packet scheduling protocols for the Universal Mobile Telecommunications Systems (UMTS) terrestrial radio access network (UTRAN) LTE system or the Evolved UTRAN (E-UTRAN) have been extensively studied e.g. in [3] and [4]. However, the energy consumption performance has received considerably less consideration despite the significant carbon foot print of BSs.

To the authors' knowledge the energy efficiency of packet schedulers for the LTE downlink has not been investigated comprehensively with only a few works on the subject found in the public domain literature. The authors in [5] proposed the introduction of small delays in LTE uplink transmissions and showed that the power savings achieved could enhance the battery life of mobile devices. The authors in [6] and [7] presented an energy performance evaluation of the state-of-the-art packet scheduling protocols for the LTE downlink while in [8] it was shown that multiple antenna techniques, particularly Space Frequency Block Coding (SFBC), mitigated the effects of ICI thus improving the LTE downlink energy performance of the packet schedulers, however they fail to address the issue of how packet scheduling could be exploited to improve energy efficiency. In [9] a Bandwidth Expansion Mode (BEM) technique was proposed that allocates more low power physical resource blocks (PRBs) to users under low load conditions hence reducing the energy consumption of the E-UTRAN. It should be noted that the BEM technique fails to produce energy savings under high load conditions.

It is worth noting that for a fixed cell deployment, packet scheduling techniques can only affect the RF transmit power, consequently these techniques have substantially greater impact on the energy performance in a Cloud infrastructure Radio Access Network (C-RAN) deployment (i.e. where the radio head power is greater than the overhead power) compared to the traditional BS deployment (where the overhead power is greater than the radio head power). In order to adequately compute the energy efficiency of the packet schedulers, energy metrics need to be specified. A framework for measuring the energy efficiency of a telecommunications network and equipment can be found in [10] where the average power consumption to effective throughput ratio has been proposed as an energy consumption ratio (ECR) metric.

B. *Research Contribution*

This study presents a new energy consumption aware Time Domain Packet Scheduling policy that incorporates the temporal dynamic user energy performance in its prioritization metric. The proposed Proportional Fair Energy Consumption Ratio (PF-ECR) scheduler utilizes the users' cumulative past average ECR and/or the users' instantaneous ECR to assign different scheduling priorities to the users. The proposed PF-ECR metric strives to maintain a balance between two competing interests, namely; prioritizing inner cell users results in less PRBs being allocated and hence less RF power and energy expended however, this comes at the expense of cell edge user service experience. On the other hand prioritizing cell edge users improves their service experience at the expense of energy efficiency in that more PRBs are utilized thus more RF power and energy is expended. The proposed PF-ECR scheduler is equally applicable at both low and high offered loads.

Furthermore, this study introduces an RF energy optimization algorithm that exploits the sub-carrier domain to enhance the PF-ECR Scheduler energy performance. The energy optimization algorithm is based on the concept of a variable power allocation for each assigned sub-carrier and constitutes two stages, namely; a Lower Order Modulation Assignment stage and a Power Reduction stage. To obtain a comprehensive performance evaluation of the packet schedulers the following measurands were used; Energy Efficiency Performance (ECR), Spectral Efficiency Performance and User Quality of Service (QoS) Performance.

C. *Paper Outline*

Section II describes the packet scheduling model considered. Section III presents the system model and list of simulation assumptions. The simulation results comparing the performance of the Packet schedulers are presented in Section IV. Finally, Section V concludes the paper.

II. PACKET SCHEDULING MODEL

The packet scheduler is decoupled into three independent stages with the Time Domain Packet Scheduler (TD-PS) as the first stage, the Frequency Domain Packet Scheduler (FD-PS) as the second stage and the new sub-carrier energy optimisation algorithm as the third stage as depicted in Fig. 1.

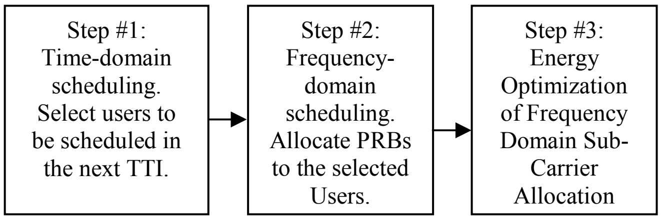

Figure 1. Decoupled TD-PS, FD-PS and Energy Optimisation

A. *Time Domain packet Scheduling*

The TD-PS selects users to be scheduled in the next Transmission Time Interval (TTI) and passes the candidate selection list (CSL) to the FD-PS. The CSL is obtained by ranking all the users according to the TD-PS policy. The following TD-PS metrics have been considered in this paper.

- Time Domain Proportional Fair Throughput (TD-PF-Throughput) Scheduler

$$M[n] = \frac{D[n]}{R[n]}, \tag{1}$$

where $M[n]$ is the time domain scheduling priority metric for user $n, D[n]$ is the wideband throughput estimated by link adaptation and $R[n]$ is the past average throughput of user n calculated with exponential average filtering as defined in [11]. In this study the TD-PF Throughput scheduler was used as the benchmark for packet scheduler comparison.

- Time Domain Proportional Fair Energy Consumption Ratio (TD-PF-ECR) Scheduler

$$M[n] = \frac{ECR[n]}{\overline{ECR[n]}}, \tag{2}$$

where $M[n]$ is the time domain scheduling priority metric for user n. $ECR[n]$ is the wideband RF ECR estimated by link adaptation under the assumption that a user is allocated all the resource blocks. $\overline{ECR[n]}$ is the cumulative past average wideband RF ECR of user n.

- Time Domain Blind Proportional Fair Energy Consumption Ratio (TD-BPF-ECR) Scheduler

$$M[n] = \frac{1}{\overline{ECR[n]}}, \tag{3}$$

where $M[n]$ is the time domain scheduling priority metric for user n. $\overline{ECR[n]}$ is the cumulative past average wideband RF ECR of user n. It is worth noting that the TD-BPF-ECR scheduler doesn't require instantaneous user energy consumption information and is thus simpler to implement compared to the TD-PF-ECR scheduler.

It was assumed that each of the users constituting the CSL had full buffer data traffic.

B. *Frequency Domain Packet Scheduling*

The FD-PS allocates PRBs to users in the CSL provided by the TD-PS. The PRB allocation is carried out based on the concept of localized resource allocation whereby an entire PRB is assigned to a single user. In order to fully exploit the good channels, this study has only considered the maximum Signal to Interference Noise Ratio (SINR) scheduler for the frequency domain defined by equation 4.

$$i' = \max_{i \in N} SINR[i, n] \quad (4)$$

where i' is the PRB allocation to user n, i is the PRB index and N is the total number of PRBs. $SINR[i,n]$ denotes the average SINR of user n on PRB i. This scheduler has the property of maximizing the system throughput.

C. Energy Optimisation of the Sub-Carrier Allocation

The RF energy optimisation of the sub-carrier allocation can be broken down into two stages, namely; a Lower Order Modulation Assignment stage and a Power Reduction stage.

- Lower Order Modulation Assignment

  It is well known that lower order modulation and coding schemes (MCSs) require less transmit power compared to higher order MCSs. The lower order modulation assignment stage takes the PRB allocation performed by the FD-PS and re-distributes the MCS assignment per sub-carrier with a bias towards lower order MCSs without compromising the amount of data that should be carried by the PRB. Equation 5 provides the necessary condition for the lower order modulation assignment stage to be energy efficient.

  $$\beta = \frac{D_i}{C_i} < 1, \quad (5)$$

  where D_i is the amount of data to be transmitted on PRB i at a particular TTI instant and C_i is the data capacity of PRB i at a particular TTI instant. If this condition is not fulfilled the lower order modulation assignment stage will allocate the same MCS levels to the sub-carriers as the FD-PS.

- Fig. 2. presents the Lower Order Modulation Assignment algorithm. Where PRB_i is PRB i, D_i is the amount of data to be transmitted on PRB i, $I_{i,n}$ is the information bits of user n that is assigned PRB i by the FD-PS, N_i is the new data computation based on the new PRB sub-subcarrier MCS level assignment, Φ is the MCS level as defined in Table I with $\Phi = 0$ representing QPSK 1/3 and $\Phi = 26$ representing 64 QAM 6/7. $\Phi_{i,j}$ is the MCS level assignment for sub-carrier j of PRB i and $\Phi_{i,j}^{MAX}$ is the highest MCS level that sub-carrier j on PRB i can support at a particular TTI instant. The Lower Order Modulation Assignment algorithm is broken down into the following steps;

  Step1: Initialise the new PRB sub-subcarrier MCS level assignment to the lowest MCS level $\Phi = 0$.

  Step2: For each sub-carrier check if the new PRB sub-subcarrier MCS level can be supported by the sub-carrier. If the sub-carrier can't support the new PRB sub-subcarrier MCS level then the sub-carrier is assigned the highest MCS level it can support. If the sub-carrier can support the new PRB sub-subcarrier MCS level then the sub-carrier is assigned the new PRB sub-subcarrier MCS level.

  Step3: Using all the sub-carriers within a PRB compute the new data that can be transmitted on the PRB given the new PRB sub-subcarrier MCS level assignment. If the new data is less than the user data that should be transmitted on that PRB, then the new PRB sub-subcarrier MCS level is increased by 1 and steps 2 and 3 are repeated. If the new data is greater than or equal to the user data that should be transmitted on that PRB, then the current PRB sub-subcarrier MCS level assignment is maintained.

  Step4: Repeat steps 1, 2, and 3 for all PRB allocated by the FD-PS.

- Power Reduction Stage

  Once the MCS level assignment for every allocated sub-carrier is finalised, the power reduction stage reduces the transmit power to the lowest permissible transmit power that can support the assigned MCS. For each allocated sub-carrier the transmit power per sub-carrier is reduced by a factor α.

```
for i = 1 to Number of RBs (N)
    if PRB_i is not assigned by the FD-PS
    continue;
    else
    Initialise: D_i = I_{i,n}
    Initialise: N_i = 0
    Initialise: Φ = 0
      while N_i < D_i
            for j = 1 to Number of Sub-Carriers (12)
              Φ_{i,j} = 0
              if Φ_{i,j}^{MAX} ≥ Φ
               Φ_{i,j} = Φ
               else
               Φ_{i,j} = Φ_{i,j}^{MAX}
               end if
            N_i = N_i + f(Φ_{i,j})
            end for
         if N_i ≥ D_i
         break
         else
         Φ = Φ + 1
         N_i = 0
         end if
      end while
    end if
end for
```

Figure 2. Algorithm for the Lower Order Modulation Assignment

$$\alpha = \frac{\gamma_2}{\gamma_1}, \quad (6)$$

where γ_1 is the realised SINR in the prevailing channel conditions and γ_2 the minimum SINR required to support the particular MCS. The power reduction and hence the energy reduction can be represented as:

$$Enery\ Reduction = P \times T \times \left(\sum_{i=1}^{Q} \sum_{j=1}^{M} \propto_{i,j} \right), \quad (7)$$

where *j* is the sub-carrier index and *M* is the number of sub-carriers per PRB. *i* is the PRB index and *Q* is the number of allocated PRBs which is a subset of the total number of system PRBs. *P* is the transmit power per sub-carrier and *T*=1ms is the duration of one TTI. We now consider the system model.

TABLE I. LINK ADAPTATION TABLE WINNER II URBAN MACRO

MCS	SNR Range (dB)	Rate (MBit/s)	MCS Level(Φ)
QPSK, 1/3	-4.06 to -2.60	0.35	0
	-2.60 to 0.06	1.98	1
	0.06 to 1.94	5.60	2
	1.94 to 3.70	9.21	3
	3.70 to 4.70	10.81	4
QPSK, 1/2	4.70 to 5.70	13.00	5
	5.70 to 6.95	15.10	6
16QAM, 1/3	6.95 to 8.95	18.70	7
	8.95 to 10.71	21.63	8
16QAM, 1/2	10.71 to 12.71	29.06	9
	12.71 to 13.65	32.71	10
	13.65 to 14.47	33.10	11
16QAM, 3/4	14.47 to 15.07	33.88	12
	15.07 to 15.26	41.20	13
64QAM, 3/5	15.26 to 17.26	43.09	14
	17.26 to 19.26	55.70	15
	19.26 to 20.10	59.84	16
	20.10 to 22.23	60.40	17
64QAM, 3/4	22.23 to 24.23	71.82	18
	24.23 to 26.23	74.66	19
	26.23 to 27.60	75.60	20
	27.60 to 28.81	75.60	21
64QAM, 6/7	28.81 to 30.81	79.49	22
	30.81 to 32.81	83.33	23
	32.81 to 34.81	85.23	24
	34.81 to 36.81	85.67	25
	> 36.81	86.40	26

III. SYSTEM MODEL

An LTE simulator has been developed in MATLAB to evaluate the E-UTRAN downlink Radio Head (RH) ECR, spectral efficiency and user QoS for various packet schedulers in a multi-cell multi-user system model. Communication between the evolved Node B (eNB) and the user equipments (UEs) is based on the single input single output (SISO) criteria. The location coordinates of the UEs are randomly assigned following a uniform distribution while the location coordinates of the eNBs are fixed. In addition each UE experiences ICI from the first tier of six neighbouring cells. The path loss and the multipath fading are computed from the WINNER II Urban Macro channel models [12]. The packet scheduler interacts with the Admission Control (AC), Channel Quality Indication Manager (CQI), and Link Adaptation (LA). CQI calculates the average SINR of each user on every sub-carrier. LA selects the MCS based on the SINR (see Table I). AC selects the users to be passed to the packet scheduler. The main simulation parameters are detailed in Table II.

A. Base Station Energy Models

The BS power consumption is the sum of the Radio Head (RH) power and the Overhead (OH) power. Since packet scheduling techniques only affect the RH energy, this study addressed the packet scheduler RH energy efficiency. Although OH power is significant in traditional BS deployments, future BS deployments are envisaged to have low OH power, e.g. the Cloud infrastructure Radio Access Network (C-RAN) [13], hence packet scheduling will have a significant impact on the energy efficiency of such networks. The RH power $P_{RH} = P_{RF}/\mu_\Psi$ where μ_Ψ is the aggregate efficiency of the radio head components and P_{RF} is the RF transmit power.

B. Energy Metrics

This study employed the energy consumption ratio (ECR) metric to quantify the energy performance of the packet schedulers. The ECR metric is defined as the energy per delivered application bit and provides the energy consumption in Joules consumed for transportation of one application bit. Equation (8), computes the RH ECR for one eNB, where E^{RH} is the RH energy required to deliver *M* application bits, P_j^{RF} is the RF transmit power on sub-carrier *j* and *Z* is the total number of utilised sub-carriers, *T* is the TTI and *f*(*SINR*[*n*,*j*]) is the LA function (of Table I) which determines the MCS and hence the number of bits that can be transmitted on sub-carrier *j* by scheduled user *n*.

$$ECR^{RH} = \frac{E^{RH}}{M} = \frac{\frac{T}{\mu_\Psi}\sum_{j=1}^{Z} P_j^{RF}}{\sum_{j=1}^{Z} f(SINR[n,j])}, \quad (8)$$

For each TTI, the E-UTRAN RH ECR for the packet schedulers is computed as the average RH ECR over all eNBs in the E-UTRAN. The energy comparison is performed using RH ECR Cumulative Distribution Function (CDF) plots drawn from 1000 TTIs with the TD-PF-Throughput scheduler as the baseline.

The percentage energy reduction gain (ERG) is defined as;

$$ERG = \frac{ECR_1^{RH} - ECR_2^{RH}}{ECR_1^{RH}} \times 100\%, \quad (9)$$

where ECR_1^{RH} and ECR_2^{RH} are the RH ECRs for the reference system and the system under test, respectively.

IV. SIMULATION RESULTS AND ANALYSIS

The eNB energy efficiency (ECR) is made up of the energy efficiency (ECR) of individual user transmissions at any TTI instant. The PF-Throughput criteria aims to schedule users

Mobile Virtual Centre For Excellence (MVCE)

TABLE II. SIMULATION PARAMETERS AND MODEL ASSUMPTIONS

Parameter	Setting
System bandwidth	20 MHz
Sub carriers per PRB	12
Cellular Layout	Hexagonal grid, 19 cell sites, Omni-directional
Cell-site radius	1000m Macro cell
Total transmit power	20 Watts
Number of users (UEs)	25 users per cell
Downlink Transmission Band	2.11-2.17 GHz
Number of Resource Blocks	100
Path Loss Model	WINNER II Channel model (Urban Macro)
Multipath Fading Model	WINNER II Channel model (Urban Macro)
eNB Height	25m (Urban Macro)
UE Height	1.5 m
UE antenna gain	0 dB
Number of interfering cells	6
Channel Estimation	Ideal
CQI delay	1 ms
Modulation and coding schemes	QPSK 1/3, 1/2, 3/4 & 16QAM 1/3, 1/2, 3/4 & 64QAM 3/5, 3/4, 6/7
EPS Bearer data per TTI	1000 bits
μ_Ψ	0.25

such that on average each UE achieves the same throughput performance, however this implies that UEs that have poor channel conditions (cell edge UEs) may be prioritized in order to improve their throughput thus resulting in the eNB utilizing more PRBs hence higher RF transmit power and RH ECR. The eNB RH ECR will constitute both low and high RH ECR values resulting in a high average eNB RH ECR due to the skew resulting from high RH ECR values. The PF-ECR criteria aims to schedule UEs such that on average each UE exhibits the same ECR performance therefore the eNB RH ECR will constitute RH ECR values that are almost equal. This results in a low average eNB RH ECR as there is no skew from high RH ECR values. In order to capture this effect this study divided the E-UTRAN into five regions as show by table III.

TABLE III. MACRO CELL REGIONS

Region Index	Radius Range From Base Station
Region 1	0 metres and 200 metres
Region 2	200 metres and 400 metres
Region 3	400 metres and 600 metres
Region 4	600 metres and 800 metres
Region 5	800 metres and 1000 metres

Fig. 3 presents the eNB RH ECR variance/spread at different regions within the cell. From Fig. 3 it is observed that the PF-Throughput scheduler has a higher RH ECR variance compared to the PF-ECR scheduler particularly at the cell

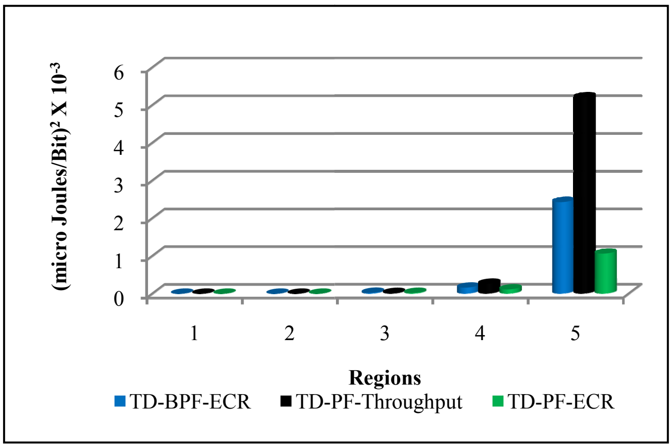

Figure 3. ECR Variance for different cell regions

edge. This is due to the skew resulting from high RH ECR values. The PF-ECR scheduler 'smoothens' out these high RH ECR values by incorporating the temporal dynamic user ECR in its prioritization metric.

The performance of the packet scheduling schemes is evaluated in terms of RH ECR, energy reduction gains (ERG), spectral efficiency and user QoS.

A. Energy Performance Results

Fig. 4 presents the E-UTRAN RH ECR comparison of the baseline TD-PF Throughput scheduler with uniform power allocation against the new TD-PF ECR and TD-BPF ECR scheduler with sub-carrier energy optimisation. The new TD-PF ECR and TD-BPF ECR schedulers with sub-carrier energy optimisation produce median energy reduction gains of 20% and 18% respectively over the TD-PF Throughput scheduler with uniform power allocation. It is worth noting that the RH energy efficiency of the TD-BPF ECR scheduler is very close to that of the TD-PF ECR scheduler and yet it has lower implementation complexity as the instantaneous user ECR is not required.

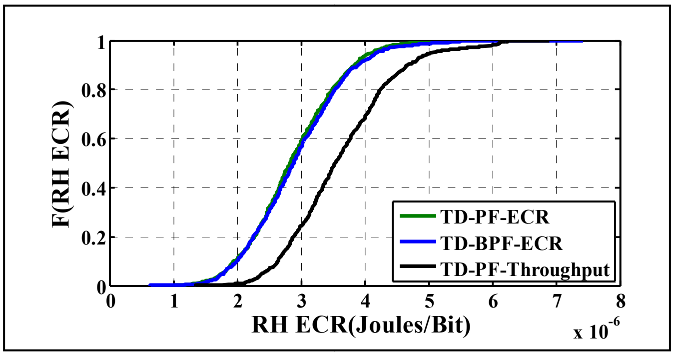

Figure 4. RH ECR CDF Comparing TD-PF Throughput against TD-PF ECR and TD-BPF ECR Schedulers

B. Spectral Efficiency Results

Both the TD-BPF ECR and the TD-PF ECR schedulers with sub-carrier energy optimization achieved a 95% percentile spectral efficiency, of 1.25 Bit/s/Hz, similar to the baseline TD-PF Throughput scheduler with uniform power allocation of $\frac{20}{100}\, Watts$ per PRB.

C. User QoS Results

The user QoS is defined as the percentage of scheduled users and the achieved user data rate. Fig. 5 presents the user QoS performance of the packet schedulers. It was observed that both the TD-BPF ECR and the TD-PF ECR schedulers with sub-carrier energy optimization achieved a user QoS performance similar to the baseline TD-PF Throughput scheduler with uniform power allocation of $\frac{20}{100} Watts$ per PRB. i.e. all the users were scheduled and every user achieved the target data rate of 1MBit/s.

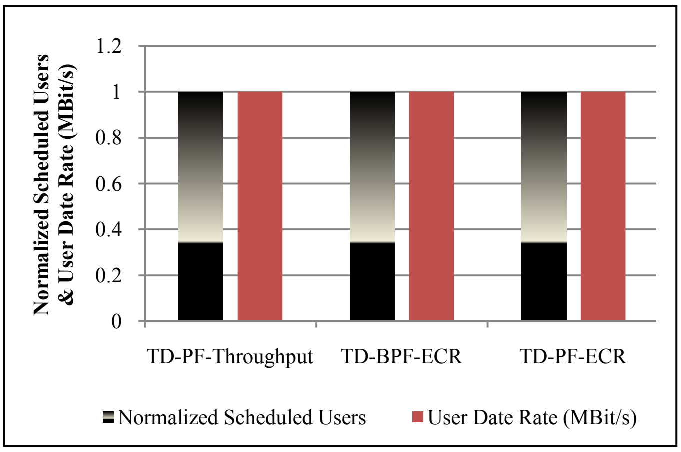

Figure 5. User QoS Results

V. CONCLUSION

This study has evaluated a novel energy consumption aware Time Domain Packet Scheduler that incorporates the temporal dynamic user energy performance in its prioritization metric. The proposed Proportional Fair Energy Consumption Ratio (PF-ECR) scheduler utilizes the users' cumulative past average ECR and/or the users' instantaneous ECR to assign different scheduling priorities to the users. The PF-ECR criteria schedules users such that on average each user exhibits the same ECR performance therefore the eNB RH ECR will constitute RH ECR values that are almost equal. This results in a low average eNB RH ECR as there is no skew from high RH ECR values.

Furthermore, a two stage energy optimisation algorithm implemented on a sub-carrier level was presented to supplement the Time Domain Packet Scheduler. The energy optimisation algorithm is made up of a Lower Order Modulation Assignment stage and a Power Reduction stage. The Lower Order Modulation Assignment stage re-distributes the MCS assignment per sub-carrier with a bias towards lower order MCSs while ensuring that the users' QoS is not compromised. The Power Reduction stage reduces the transmit power to the lowest permissible transmit power that can support the assigned MCS.

Finally, the study has shown that the new composite energy aware packet scheduling criteria produces Radio Head Energy Reduction Gains of 20% compared to the established throughput based proportional fair scheduler with uniform power allocation, without compromising the spectral efficiency performance and user QoS performance. In a suburban area of 100 Km^2, LTE requires a total of 124 BSs and transmits a total power of 607.2KW [2], a 20% ERG translates to power savings of 121.4KW and energy savings of 1063.5 Mega Watt hours (MWh) per annum.

ACKNOWLEDGMENT

The work reported in this paper has formed part of the Green Radio Core 5 Research Programme of the Virtual Centre of Excellence in Mobile & Personal Communications, Mobile VCE. Fully detailed technical reports on this research are available to Industrial Members of Mobile VCE. www.mobilevce.com. We would like to acknowledge David Lister (Vodafone) and Simon Fletcher (NEC) for their valuable feedback and useful comments.

REFERENCES

[1] Report on the FP 7 Consultation Meeting, "Future Mobile and Wireless Radio Systems: Challenges in European Reserch," February, 2008.

[2] M. Deruyck, W. Vereecken, E. Tanghe, W. Joseph, M. Pickavet, L. Martens, and P. Demeester, "Comparison of Power Consumption of Mobile WIMAX, HSPA, and LTE Access Networks," in *proceedings of IEEE Telecommunications Internet and Media Techno Economics,*pp. 1-7, August 2010.

[3] P. Kela, J. Puttonen, N. Kolehmainen, T. Ristaniemi, T. Honttonen, and M. Moisio, "Dynamic Packet Scheduling Performance in UTRA Long Term Evolution Downlink," in *Proceedings of the International Symposium on Wireless Pervasive Computing*, pp. 308-313, May 2008.

[4] A. Pokhariyal, T.E. Kolding and P.E. Mogensen, "Downlink Frequency Domain Packet Scheduling for the UTRAN Long Term Evolution," in *Proceedings of IEEE Personal Indoor and Mobile Radio Communications Conference*, pp. 1-5, September 2006.

[5] Z. Li, C. Yin, G. Yue, "Delay-Bounded Power Efficient Packet Scheduling for Uplink Systems of LTE," in *proceedings of Wireless Communications Networking and Mobile Computing International Conference*, pp. 1-4, October 2009.

[6] D. Sabella, M. Caretti, R. Fantini, "Energy Efficiency Evaluation of State of the Art Packet Scheduling algorithms for LTE," in *proceedings of European Wireless Conference,* pp. 1-4, April 2011.

[7] C. Han, K. C. Beh, M. Nicolaou, S. Armour, A. Doufexi, "Power Efficient Dynamic Resource Scheduling Algorithms for LTE," in *Proceedings of the IEEE Vehicular Technology Conference)*, pp. 1-5, September 2010.

[8] C.Turyagyenda, T.O'Farrell, J.He, P.Loskot, "SFBC MIMO Energy Efficiency Improvements of Common Packet Schedulers for the Long Term Evolution Downlink," in *Proceedings of the IEEE Vehicular Technology Conference*, pp. 1-5, May 2011.

[9] S. Videv, H. Haas, "Energy-Efficient Scheduling and Bandwidth–Energy Efficiency Trade-Off with Low Load," in *Proceedings of the IEEE International Conference on Communication Systems*, pp. 1-5, June 2011.

[10] ECR Initiative: "Network and Telecom Equipment – Energy and Performance Assessment, Test Procedure and Measurement Methodology," Draft 2.1.1, October 2009.

[11] A. Jalali, R. Padovani, R. Pankaj, "Data Throughput of CDMAHDR High Efficiency-High Data Rate Personal Communication Wireless System," in *proceedings of IEEE Vehicular Technology Conference*, Vol. 3, pp. 1854-1858, May 2000.

[12] P. Kyösti, et al., "WINNER II Channel Models," Version 1.1, September, 2007.

[13] H. Jinling, "TD-SCDMA/TD-LTE Evolution-Go Green," in *proceedings of IEEE International Conference on Communication Systems*, pp. 301-305, November 2010.