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Energy Efficiency Comparison of Common Packet Schedulers

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***Abstract*— This paper presents a characterisation of the energy performance of common and well-known packet schedulers in a multi-cell multi-user UTRAN long-term evolution (LTE) system. First, it was shown that the maximum SINR metric is more energy efficient than the round robin metric for both time and frequency domain packet scheduling. Second, it was shown that frequency domain packet scheduling had a greater impact on the energy efficiency of the system than time domain packet scheduling; i.e. RF Energy Reduction Gains (RF-ERG) ranging from 16% to 49% and 2% to 18% respectively.**

Keywords-LTE; Packet Scheduling; Energy Reduction Gains

I. INTRODUCTION

Since their inception, radio access networks have been continuously optimized to achieve enhanced throughput and coverage performance. However, the energy performance has received less consideration despite the inefficiency of the base stations associated to the radio access networks. For example, in cellular networks each base station can require up to 2.7KW of electrical power, which can lead to an energy consumption of tens of mega watt hours (MWh) per annum for wide area networks [1]. This paper presents a characterisation of the energy performance of common and well-known packet schedulers in a multi-cell multi-user radio access network environment.

A. Review

The spectral efficiency, fairness and throughput performance of dynamic packet scheduling protocols in the UTRAN Long Term Evolution (LTE) has been studied extensively e.g. in [2-7], however, the energy consumption performance has received less consideration. Authors in [2] present a decoupled time and frequency domain scheduling framework and evaluates the throughput and fairness performance of different packet scheduling algorithms for the LTE downlink. In [3], it was shown that the frequency domain packet scheduler utilising frequency domain channel reports achieved average system capacity and cell-edge data rate gains of over 40% compared to the frequency-blind but time opportunistic scheduling. Authors in [4] Presented the spectral efficiency of four basic antenna configurations for the LTE downlink, namely: Single Input Single Output (SISO), 1×2 Single Input Multiple Output (SIMO), 2×2 space frequency block coding (SFC) and 2×2 BLAST. In [5], the LTE spectrum efficiency, user throughput and peak data rate performance was compared against that of High-Speed Downlink Packet Access (HSDPA). In [6], it was shown that a decoupled time and frequency domain packet scheduler could be effectively used to control fairness among the users and achieve a throughput and coverage gain of 35% over the time-domain only scheduler. In [7] it was shown that fairness among the users could be controlled by frequency domain metric weighting or time domain priority setting depending on the number of users. It was also shown that metric decoupling between the time and frequency domain schedulers is fundamental for maximising throughput control.

B. Paper Outline

Section II discusses the packet-scheduling model. Section III describes the system model. Section IV presents the performance results and analysis. Section V concludes the paper with a summary of the key results

II. PACKET SCHEDULING MODEL

The Universal Mobile Telecommunications Systems (UMTS) terrestrial radio access network (UTRAN) long-term evolution (LTE) system or the Evolved UTRAN (E-UTRAN) employs Orthogonal Frequency Division Multiple Access (OFDMA) as the multiple access scheme for downlink transmissions. This translates to a time-frequency grid of available physical resource blocks (PRBs) depicted in Fig. 1. The minimum resolution for packet scheduling is the 180 KHz PRB bandwidth in the frequency domain and 1ms Transmission Time Interval (TTI) in the time domain.

The packet scheduler was decoupled into two stages with the Time Domain Packet Scheduler (TD-PS) as the first stage and the Frequency Domain Packet Scheduler (FD-PS) as the second stage. Fig. 2 illustrates the two-step packet scheduling implementation proposed in [2, 3, 6]. The Time Domain Packet Scheduler (TD-PS) selects users to be scheduled in the next Transmission Time Interval (TTI) and passes the candidate selection list (CSL) to the Frequency Domain Packet Scheduler (FD-PS). The Frequency Domain Packet Scheduler (FD-PS) allocates PRBs to users in the candidate selection list (CSL) provided by the TD-PS.

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The separation of packet scheduling into time domain and frequency domain scheduling is advantageous for the following reasons: one improved scheduling flexibility since both time and frequency domains can be configured independently, and two decreased complexity of the Frequency Domain Packet Scheduling (FD-PS) structure since only a sub-set of users are considered for multiplexing on the PRBs.

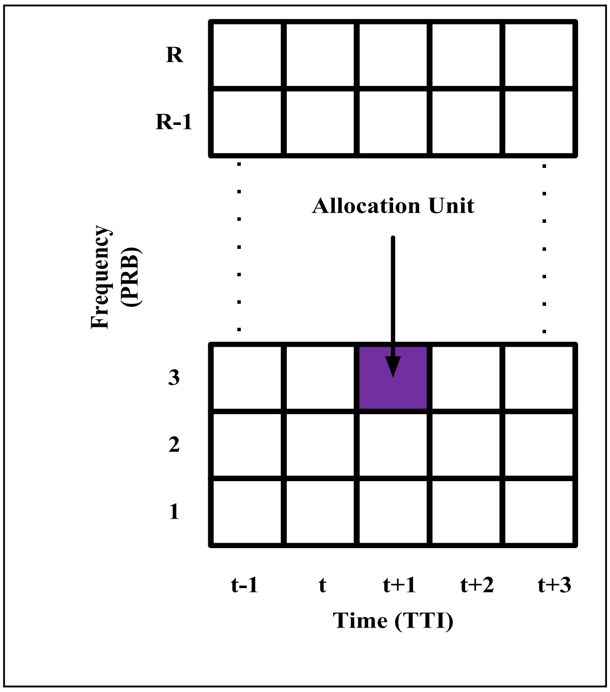

Fig. 1. Physical Resources in a Time-Frequency Grid for OFDMA

Packet scheduling in both the time and frequency domains was carried out using specific scheduling priority metrics. A packet scheduling priority metric serves the purpose of enforcing a particular characteristic(s) of the scheduling algorithm. These characteristics are often a trade-off between the two major performance requirements i.e. maximising the system throughput and promoting fairness among users. Most packet scheduling metrics can be used for both time and frequency domain packet scheduling.

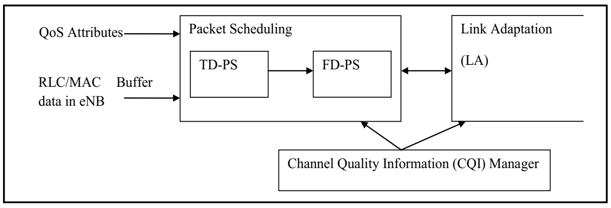

Fig. 2. Packet Scheduling Framework

The packet scheduler interacts closely with the Channel Quality Information (CQI) manager, Link Adaptation (LA) and the RLC/MAC buffer manager. CQI measurements provide a feedback report to the Evolved Node B (eNB) characterising the channel quality. The channel quality is estimated by the UE based on downlink transmission of reference signals and reported to the eNB using the Physical Uplink Control Channel (PUCCH) or Physical Uplink Shared Channel (PUSCH) [8]. Uncompressed CQI feedback or different CQI compression techniques such as, Best-M average CQI and wideband CQI can be utilised. In this study, uncompressed CQI feedback was utilised. Link Adaptation (LA) provides information to the packet scheduler of the supported Modulation and Coding Scheme (MCS) based on the channel quality measurements feedback from the users. The buffer stores the data to be transmitted to the users. In this study, a full buffer was assumed.

A. Time Domain Packet Scheduler (TD-PS)

The TD-PS selects a subset of users form all the users requesting transmission resources. The TD-PS only selects users who:

- Have pending data for transmission
- Configured for scheduling in the next Transmission Time Interval (TTI)

The TD-PS assigns a precedence measure to each of the selected users based on the time domain priority metric.

Additionally, the TD-PS amends the number of selected users based on a control channel check [8]. The control channel check is performed to determine whether there are sufficient resources within the Physical Downlink Control Channel (PDCCH) for each of the selected users. The selected users are appended to the candidate selection list (CSL) which is passed to the Frequency Domain Packet Scheduler (FD-PS).

B. Frequency Domain Packet Scheduler (FD-PS)

The purpose of the Frequency Domain Packet Scheduler (FD-PS) is to allocate PRBs to users in the candidate selection list (CSL) provided by the Time Domain Packet Scheduler (TD-PS). Frequency domain packet scheduling aims to improve the system throughput by exploiting the varied frequency selective fading experienced by different users on different PRBs. Multiple PRBs can be allocated to a user, and the PRBs need not be consecutive. LTE supports both localised and distributed transmission modes. Under the localised transmission mode, all the sub-carriers with a PRB are allocated to the same user while under the distributed transmission mode one PRB can be shared among multiple users [9]. In this study, the localised transmission mode was preferred. The frequency domain packet scheduler can be operated in two modes, namely [2]:

- ByUser- PRBs are allocated to each user in turn until the user is satisfied
- ByPRB- For each PRB, the user with the best PRB specific priority metric is selected

In this study, the “ByUser” mode of operation was chosen. The PRB allocation together with the modulation and coding assignment is finally forwarded to layer one of the eNB.

C. Packet Scheduling Metrics

- Maximum Signal to Interference Noise Ratio (SINR)

  The maximum Signal to Interference Noise Ratio (SINR) metric has the property of maximising the system throughput. This metric prioritises users with high SINR channel quality measurements over users with low SINR channel quality measurements. From link adaptation, higher channel quality values lead to more spectrally efficient modulation and coding schemes. Therefore, the maximum Signal to Noise Ratio (SINR) metric assigns a greater rank measure to the users that can support high instantaneous data rates. The obvious benefit of this metric is the maximisation of both system throughput and spectral efficiency; however, this comes at the cost of fairness since users with low SINR channel quality measurements will receive less of the available radio resources. The maximum SINR metric $M[n]$ for user n is given by equation (1).

$$M[n] = SINR[n], \tag{1}$$

- Proportional Fair (PF)

  The proportional fair metric introduces some degree of fairness to the maximum SINR metric by considering both the instantaneous supportable data rate and the history data rates supported by the user. The proportional fair metric $M[n]$ for user n is given by equation (2).

$$M[n] = \frac{D[n]}{R[n]}, \tag{2}$$

  $D[n]$ is the wideband instantaneous throughput estimated by link adaptation and $R[n]$ is the past average throughput of user n calculated with exponential average filtering as defined in [10].

- Round Robin (RR)

  The Round Robin (RR) metric has the property of allocating resources fairly to all the users. This metric assigns resources to users in closed loop circular manner according to the last scheduled time without regard to the users' channel state information. Therefore, the round robin metric assigns a greater rank measure to the users that have been in the queue the longest. The round robin metric $M[n]$ for user n is given by equation (3).

$$M[n] = \mathrm{T}[n], \tag{3}$$

  $\mathrm{T}[n]$ is the last scheduled time.

III. System Model

An LTE system level simulator was developed in MATLAB to evaluate the E-UTRAN downlink Radio Frequency Energy Consumption Ratio (RF-ECR) for various packet schedulers in a multi-cell, multi-user system environment.

Downlink transmission between the eNB and the user equipments (UEs) was based on the Single Input Single Output (SISO) principle. The location coordinates of the UEs were randomly assigned following a uniform distribution while the location coordinates of the eNBs were pre-assigned and fixed. In addition, each UE experienced Inter-Cell Interference (ICI) from all the neighbouring cells in the radio access network. The main simulation parameters are detailed in Table I.

TABLE I. Simulation Parameters and Model Assumptions

Parameter	Setting
System Bandwidth	20 MHz
Cellular Layout	Hexagonal grid, 19 Cells
Cell Radius	0.5 Km
Maximum Transmit Power	40 W
Number of Users (UEs)	10,20,30,40,50,60,70,80,90 100 UEs per Cell
Downlink Transmission Band	2.11-2.17 GHz
Number of Resource Blocks	100
Path Loss Model	COST 231 HATA Model
Multipath Fading Model	ITU Pedestrian A
eNB Height	20m
UE Height	1.5 m
UE Antenna Gain	0 dB
Channel Estimation	Perfect
CQI delay	1 ms
Modulation and coding schemes	QPSK ½, 16QAM ½ , ¾ & 64QAM ¾
EPS Bearer data amounts per TTI	1 Kbit
System Bandwidth	20 MHz
Cellular Layout	Hexagonal grid, 19 Cells
Cell Radius	0.5 Km
Maximum Transmit Power	40 W
Number of Users (UEs)	10,20,30,40,50,60,70,80,90 100 UEs per Cell
Downlink Transmission Band	2.11-2.17 GHz

A. Path Loss Model

The path loss was computed from the standard COST 231 HATA model [43] defined by equations (4) and (5).

$$L_{dB} = 46.3 + 33.9\log_{10} f_c - 13.82\log_{10} h_b - a(h_m) + (44.9 - 6.55\log_{10} \mathrm{h_b})\log_{10} \mathrm{d} + \mathrm{C}, \tag{4}$$

$$a(h_m) = (1.1\log_{10} 0.7f_c)h_m - (1.56\log_{10} f_c - 0.8), \tag{5}$$

L_{dB} Path loss in decibels.

f_c Operating frequency in MHz

h_b Height of eNB in metres.

h_m Height of UE metres.

d Distance between eNB and UE in kilometres.

C Correction factor of 3dBs for metropolitan centres and 0dB for medium cities and suburban centres.

$a(h_m)$ UE correction factor.

B. Multipath Model

The multipath fading was computed based on the ITU Pedestrian A model [11] [12] with a Root Mean Square (RMS) delay spread of 0.045 µs. From equation (6), a 0.045 µs RMS delay spread results in a 90% coherence bandwidth of approximately 444 KHz. This implies that any two successive PRBs will experience uncorrelated multipath channel gains.

$$Bandwidth_{90\%\ correlation} \approx \frac{1}{50 \times RMS_{delay\ spread}}, \quad (6)$$

C. Signal to Interference Noise Ratio (SINR)

The SINR for SISO was computed for each UE on every PRB from equation (7).

$$SINR = \frac{|h_p|^2 P_{r_{AVG}}}{\sum_{j=1, j\neq p}^{Z} |h_j|^2 P_{j_{AVG}} + w}, \quad (7)$$

p and j are the serving and interfering cell indices respectively. h is the multipath channel gain modelled as a circular symmetric Gaussian random variable of zero mean and variance of 1. $P_{r_{AVG}}$ is the average received signal power, $P_{j_{AVG}}$ is the average received power from the j^{th} interfering cell and the noise power $w = KTB$, where K is the Boltzmann constant, T is the thermal temperature of 290K and B is the resource block bandwidth of 180 KHz.

D. Energy Metrics

A framework for measuring the energy efficiency of a telecommunications network and equipment found in [13] where the power consumption to throughput ratio was proposed as an energy consumption ratio (ECR) metric, equation (8).

$$ECR = \frac{E}{M} = \frac{PT}{M} = \frac{P}{D}, \quad (8)$$

The ECR is defined as the energy per delivered application bit (Joules/Bit), where E is the energy required to deliver M application bits over time T, $D = {}^{M}/_{T}$ is the data rate in bits per second and P is the power.

This study also utilised a variant of the ECR metrics namely, the percentage Energy Reduction Gain (ERG) defined by equation (9).

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

E. Link Adaptation

Link Adaptation (LA) provides information to the packet scheduler of the supported Modulation and Coding Scheme (MCS) based on the channel quality measurements feedback from the users. Table II presents the LA look up table utilised for this study [8].

TABLE II. MODULATION AND CODING LOOKUP TABLE

MCS Level	SINR Range (dB)	Rate (Mbit/s)
QPSK, ½	-8 to 6	16.8
16QAM, ½	6 to 8	33.6
16QAM, ¾	8 to10	50.4
16QAM	10 to 12	67.2
64QAM, ¾	12 to 15	75.6
64QAM	>15	100.8

IV. RESULTS AND ANALYSIS

The Radio Frequency (RF) energy performance of the packet schedulers was evaluated using the RF Energy Consumption Ratio (RF-ECR) metric. In order to characterise the impact of the various packet scheduler components, the following experiments were setup. First the energy performance of the FD-PS was explored by varying the frequency domain priority metric while keeping the time domain metric constant. Second, the energy performance of the TD-PS was explored by varying the time domain priority metric while keeping the frequency domain metric constant.

A. FD-PS Energy Performance

Fig. 3 presents the RF Energy Consumption Ratio (RF-ECR) of the frequency domain packet schedulers with a constant maximum SINR metric as the time domain metric.
Fig. 4 presents the RF Energy Consumption Ratio (RF-ECR) of the frequency domain packet schedulers with a constant round robin metric as the time domain metric.

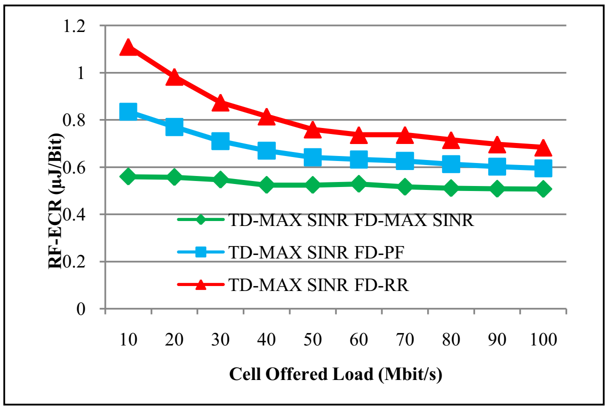

Fig. 3. RF-ECR Vs Offered Load (Fixed TD-MAX SINR Scheduler)

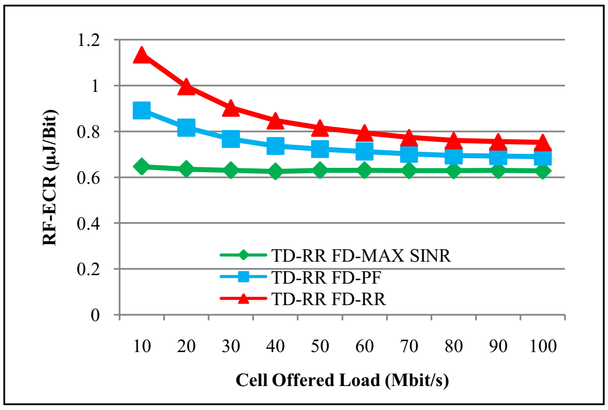

Fig. 4. RF-ECR Vs Offered Load (Fixed TD-RR Scheduler)

From Fig. 3, the frequency domain maximum SINR packet scheduler produced RF Energy Reduction Gains (RF-ERG) ranging from 25% to 49% over the frequency domain round robin packet scheduler.

From Fig. 4, the frequency domain maximum SINR packet scheduler produced RF Energy Reduction Gains (RF-ERG) ranging from 16% to 43% over the frequency domain round robin packet scheduler.
The results in both Fig. 3 and Fig. 4, exhibited the following key features of interest:

- The energy performance of the frequency domain maximum SINR packet scheduler was largely independent of the offered load. This is because the maximum SINR metric better exploits the frequency diversity, experienced by the users, and allocates the PRBs with good channel conditions.
- The energy performance of the frequency domain round robin packet scheduler improved with increasing offered load. The round robin PRB allocation does not consider the user channel state information. However, as the number of users in the system increases, the likelihood of users with good channel conditions also increases; hence the energy performance improvement at higher loads.
- The frequency domain maximum SINR packet scheduler is more energy efficient than the frequency domain round robin packet scheduler. Assigning good channel quality PRBs translates to more transmitted data and hence lower energy consumption ratio values.

B. *TD-PS Energy performance*

Fig. 5 presents the RF Energy Consumption Ratio (RF-ECR) of the time domain packet schedulers with a constant round robin metric as the frequency domain metric.
Fig. 6 presents the RF Energy Consumption Ratio (RF-ECR) of the time domain packet schedulers with a constant maximum SINR metric as the frequency domain metric.

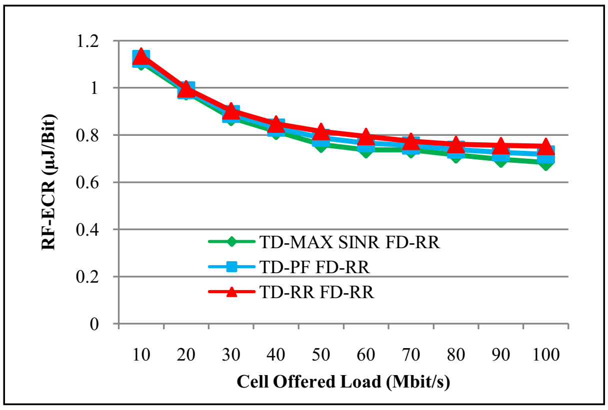

Fig. 5. RF-ECR Vs Offered Load (Fixed FD-RR Scheduler)

From Fig. 5, the time domain maximum SINR packet scheduler produced RF Energy Reduction Gains (RF-ERG) ranging from 2% to 9% over the time domain round robin packet scheduler.
From Fig. 6, the time domain maximum SINR packet scheduler produced RF Energy Reduction Gains (RF-ERG)

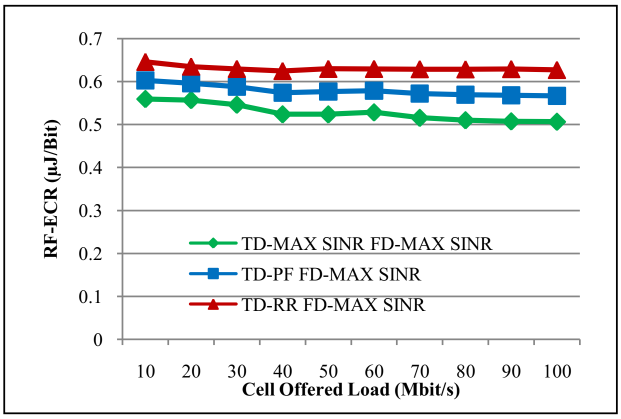

Fig. 6. RF-ECR Vs Offered Load (Fixed FD-MAX SINR Scheduler)

ranging from 13% to 18% over the time domain round robin packet scheduler.
The time domain maximum SINR packet scheduler is more energy efficient than the time domain round robin packet scheduler. This is because the time domain maximum SINR metric produces a candidate selection list of users sorted in descending order from highest to lowest channel quality. Consequently, users with good channel quality will get the first pick of the available PRBs. Since the frequency domain packet scheduler is operated in the "ByUser" mode, more data is transmitted and hence improved energy efficiency.

V. Conclusion

This paper presented a characterisation of the energy performance of common and well-known packet schedulers in a multi-cell multi-user UTRAN long-term evolution (LTE) system.

First, it was shown that the maximum SINR metric is more energy efficient than the round robin metric for both time and frequency domain packet scheduling. However, the energy efficiency of the maximum SINR metric is achieved at the following costs:

- Accurate channel quality measurements;
- Fairness to users with low SINR channel quality measurements

Second, it was shown that frequency domain packet scheduling has a greater impact on the energy efficiency of the system than time domain packet scheduling; i.e. RF Energy Reduction Gains (RF-ERG) ranging from 16% to 49% and 2% to 18% respectively.

In this paper, channel quality aware packet scheduling was shown to improve the energy efficiency of the UTRAN long-term evolution (LTE) system.

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