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Versions

An Adaptive Hybrid Scheduling Algorithm for LTE-Advanced

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Abstract— **The 3rd Generation Partnership Project (3GPP) introduced Long Term Evolution (LTE) in release 8, and afterwards it was updated significantly in later releases (referred to as LTE-Advanced). LTE and LTE-Advanced (LTE-A) aim to achieve higher spectral efficiency, higher data rates, robustness and flexibility. Intelligent channel-aware radio resource scheduling is one of the key features of LTE-A. A number of schedulers proposed in the literature rely on the feedback sent from the Users Equipment (UE) without considering the presence of feedback delay. In this paper, we analyse the effect of the uplink delay on the cell performance of existing schedulers, in terms of throughput and the users' fairness. We then propose an adaptive hybrid scheduler to overcome the effect of the uplink delay on the scheduler performance. The simulation results show that our proposed scheduling algorithm outperforms the existing schedulers in the presence of uplink feedback delay.**

Keywords—LTE; LTE-A; Radio Resources Management; Scheduling Algorithim; Round Robin; Best CQI; Proportional Fair; Kwan scheduler; Fairness; Uplink Delay.

I. INTRODUCTION

Long Term Evolution (LTE) was introduced and standardised by 3GPP in December 2008 and it soon became a commercial reality in several countries of the world. The initial release of LTE (i.e. release 8) supported a peak data rate of 300 Mbps with considerably higher spectral efficiency when compared with existing networks. Higher data rates and spectral efficiency in LTE is achieved by using flexible bandwidth, Orthogonal Frequency Division Multiple Access (OFDMA) in the downlink, Adaptive Modulation and Coding (AMC) and Multiple Input Multiple Output (MIMO) [1]. Additionally, the LTE architecture is fully IP based, in both the radio access and the core network. The tremendous increase in the data traffic handled by the wireless networks necessitated further improvements in the LTE performance, eventually leading to the introduction of LTE-Advanced (LTE-A) as an enhancement of the LTE network.

LTE-A significantly enhances the performance of the LTE network in terms of overall throughput, cell edge user throughput and latency. LTE-A introduced various functionalities (in LTE releases 10-13) such as Carrier Aggregation (CA), Coordinated Multipoint (CoMP), enhanced MIMO and enhanced packet scheduler. Carrier aggregation increases the transmission bandwidth that eventually increases users' throughput [2]. The packet scheduler is the part of the enhanced Node-B (eNB) that assigns resources (resource block) to the users. Moreover, it plays a fundamental role in the enhancement of network throughput and fairness among users.

LTE schedulers are categorised in [3] as follows: Channel-unaware, Channel-aware/QoS-unaware, Channel-aware/QoS-aware, Semi-persistent for Voice over IP (VoIP) support and Energy-aware. The schedulers under the channel unaware category are the only schedulers that operate blindly; they make their scheduling decision without considering the channel conditions (e.g. Round Robin (RR) scheduler). Schedulers in the other categories depend on the feedback sent from the Users Equipment (UE) indicating the channel conditions (i.e. Best Channel Quality Indicator (BCQI), Proportional Fair (PF) and Kwan scheduler [4]).

In general, the schedulers that make scheduling decisions based on the Channel Quality Indicator (CQI) feedback, outperforms the schedulers that blindly schedule the users. However, the throughput performance of such schedulers is reduced significantly in the presence of CQI feedback delay. Likewise the fairness performance of the schedulers is affected by the feedback delay, which is a critical parameter in designing any scheduling algorithm. Although several scheduling algorithms have been proposed for LTE-A, to the best of the author's knowledge, little effort has been devoted to study the impact of uplink delay on the downlink throughput of the cell and the users' fairness.

In this paper, we propose a new metric to evaluate the overall fairness among users that combines both throughput fairness and the distribution fairness. We study the effect of uplink CQI delay on the schedulers' performance in terms of aggregate cell throughput and the overall fairness. We propose a scheduling algorithm that overcomes the performance loss due to uplink CQI delay. Finally, we compare the performance of the proposed scheduling algorithm with state-of-the-art schedulers proposed in the literature.

The rest of this paper is organised as follow: section II gives an overview of the LTE physical layer (PHY). LTE schedulers are briefly explained in section III. In section IV, our proposed algorithm is presented and the system model is explained in section V. Section VI presents and discusses the simulation results. Finally section VII concludes this paper.

II. OVERVIEW OF LTE PHY

LTE access network is based on OFDM schema that uses Single Carrier Frequency Division Multiple Acces (SC-

FDMA) for its uplink and OFDMA is used in the downlink. OFDMA is able to assign multiple sub-carriers to the UE. LTE resources are divided into a time frequency grid; in the frequency domain the sub-channel bandwidth is equal to 180 KHz and in the time domain the channel is divided into 1ms time intervals referred to as Transmission Time Interval (TTI). Each TTI consists of two time slots, each is made up of seven OFDM symbols with a short cyclic prefix. The smallest radio resource a UE can be assigned is called Resource Block (RB), which consists of two time slots and one frequency sub-channel. Despite the constant size of the LTE sub-channel, the LTE system can be configured to a flexible channel bandwidths. Channel bandwidth in LTE is between 1.4 MHz to 20 MHz, accordingly the number of RB per channel various from 6 up to 100 RB [5]. In LTE release 8, the channel feedback matrices consist of three parameters: Rank Indicator (RI), Pre-coding Matrix Indicator (PMI) and CQI. The CQI value is selected according to the Signal to Interference Noise Ratio (SINR) measurements made by the UE. The CQI value is selected to maintain a Block Error Ratio (BLER) of less than 0.1 [5]. The CQI values are quantified into 15 levels, each value represents an effective code rate and a modulation scheme [3].

III. OVERVIEW OF LTE SCHEDULERS

UE resources assignment is done by comparing a scheduling metric (γ) for each RB; the n-th user is assigned the m-th RB only if the scheduling metric value is maximum

$$\gamma_{n,m} = \max_{j} \{\gamma_{j,m}\} \tag{1}$$

A. Round Robin (RR) scheduler

The RR scheduler is a simple, relatively fair and channel unaware scheduler, based on time sharing; it ignores any channel state information. The operating principle of the RR scheduler is to periodically assign resources to the users, so that the resources are equally distributed among the users [3]. The scheduling matric for the n-th user on the m-th RB can be expressed as:

$$\gamma_{n,m}^{RR} = \tau - \Delta_n \tag{2}$$

where τ is the instantaneous time and Δ is the previous time the user n was scheduled. Although the RR scheduler is simple to implement, it is not an efficient scheduler as it provides lower throughput and throughput fairness when compared with other schedulers.

B. Best Channel Qulity Indicator (BCQI) scheduler

The BCQI scheduler normally achieves higher cell throughput and is regarded as a spectral efficient scheduler. The BCQI scheduler assigns resources to a user according to the uplink CQI feedback sent from all the users. In particular, it assigns the RB to the UE with the highest CQI value [3]. The scheduling metric for the BCQI scheduler can be expressed as:

$$\gamma_{n,m}^{BCQI} = \varsigma_n(\tau) \tag{3}$$

where ς is the CQI value of n-th user of the m-th RB. Although cell throughput can be maximized by using a BCQI scheduler, it may cause throughput starvation to several other users with poor channel conditions.

C. Proportonal Fair (PF) scheduler

PF scheduler performs a trade-off between fairness and throughput. The scheduling metric is obtained by dividing the user achievable throughput ω_n with the previous TTI average throughput ϖ [3] as follows:

$$\gamma_{n,m}^{PF} = \frac{\omega_n(\tau)}{\varpi_n(\tau - 1)} \tag{4}$$

D. Kwan Scheduler

In [4], fairness is formatted as an optimisation problem to maximise the sum bit rate of users and proposed *Kwan* scheduler as a suboptimal scheduler. The optimal scheduling optimisation problem is a nonlinear problem that can be solved by the Branch-and-Bound method. On the other hand, the suboptimal scheduler divided the scheduling into two stages, thereby converting the multiuser optimisation problem into parallel single user optimisation problems.

IV. PROPOSED SCHEDULING ALGORITHM AND OVERALL FAIRNESS CRITERIA

A. Proposed Overall Fairness carteria

In LTE, fairness is a critical issue in designing a scheduling algorithm. A fair distribution of resources does not normally result in an identical data rate for the users, because the channel characteristics may vary among the users. The fairness criteria can be categorised into the following two categories [6]:

Throughput Fairness, (F_T) considers the throughput achieved by the users; the Jains fairness index is normally used to measure the throughput fairness within a given time $\Delta\tau$. The throughput fairness F_T can be defined as:

$$F_T(\Delta\tau) = \frac{\{\sum_{n=1}^{N} T_n(\Delta\tau)\}^2}{N \times \sum_{n=1}^{N}\{T_n(\Delta\tau)\}^2} \tag{5}$$

where $N$the total number of users is considered and $T_n(\Delta\tau)$ is the throughput achieved by the user n in time interval $\Delta\tau$.

Distribution Fairness, (F_D) is the fairness related with the number of assigned resources to each user in $\Delta\tau$ and can be expressed as:

$$F_D(\Delta\tau) = \frac{\{\sum_{n=1}^{N} RB_n(\Delta\tau)\}^2}{U \times \sum_{n=1}^{N}\{RB_n(\Delta\tau)\}^2} \tag{6}$$

where $RB_n(\Delta\tau)$ denote to the number of RBs assigned to user n in $\Delta\tau$. For both, F_T and F_D, the maximum fairness is one and the minimum fairness is equal to $1/N$.

Jains fairness index (i.e. F_T) is the most common metric in the literature to evaluate fairness among users. However, in LTE the throughput and the number of assigned resources might differ. On the other hand, distribution fairness also does not properly evaluate the fairness, because the users' channel conditions may differ. In this paper, we propose a new metric to characterize overall fairness and name it Overall Fairness (F_O). The Overall Fairness can be expressed as:

$$F_O = \frac{F_T + F_D}{2} \tag{7}$$

where F_T and F_D are defined in equation (5) and (6).

B. Proposed Scheduling algorithm

The scheduler performs a significant role in the overall users' experience, in reality; scheduler performance is constrained by several factors such as processing time and memory usage. The main reason for these limitations is that in a LTE network, the scheduler is required to make a scheduling decision in one TTI. Consequently, the operating principle of the scheduler should be time efficient.

For schedulers, such as BCQI, Kwan, PF, etc., decisions are based on the feedback sent by the UE. As a result, the uplink delay has a significant impact on the scheduler's performance. To overcome the impact of uplink delay on scheduler performance, we propose an Adaptive Hybrid Scheduling Algorithm (AHSA). The AHSA is introduced to reduce the effect of the uplink delay without compromising users' fairness. The operating principle of AHSA is to adapt the scheduler according to the changes in the channel. In particular, AHSA initially schedules the users according to the Kwan scheduler; to achieve a high data rate without compromising the fairness. Afterwards, AHSA performs a check on the channel throughput to estimate the uplink delay. Accordingly, it decides either to continue scheduling using the Kwan scheduler in case of no uplink delay or to switch the users that experience uplink delay to the PF scheduler. Finally the algorithm repeats the same steps in each TTI; a flow chart of AHSA is shown in Fig. 1.

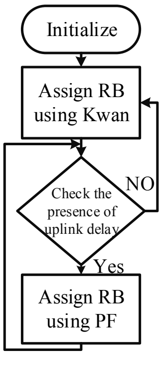


Fig. 1 AHSA flow chart

V. SYSTEM MODEL

In this section, we introduce the simulation parameters and the scenarios, that we used to obtain the simulation results presented in section VI. In order to simulate LTE-A downlink, the approach presented in [7] has been used. Table I shows the main parameters used in the link level simulations.

TABLE I. SIMULATION PARAMETERS

Parameter	Value
Number of eNB	1
Number of UE	20
Channel Model	Typical Urban
Transmission Bandwidth	10 MHz
Carrier Frequency	2.1 GHz
Subcarrier Spacing	15 KHz
UE Channel Estimation	Perfect
Simulation Type	SISO
Cyclic Prefix	Normal
Transmission Time Interval	1000
Uplink Delay	0, 1 (TTI)
Schedulers	BCQI, Kwan, PF and RR

In order to evaluate the performance of the proposed scheduling algorithm and to compare the effect of uplink delay on schedulers' performance, we define the following five scenarios shown in Table II. We categorise scenarios according to the percentage of users experiencing uplink delay.

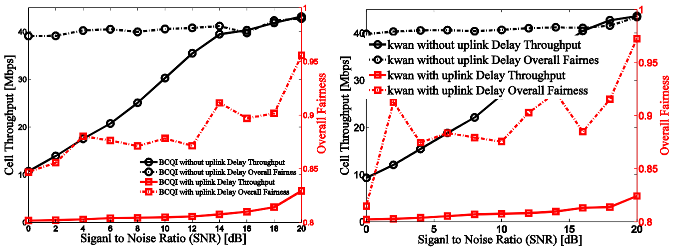
TABLE II. SIMULATION SCENARIOS

Scenario	Percentage of users experience uplink feedback delay
Scenario 1 (S1)	0
Scenario 2 (S2)	25
Scenario 3 (S3)	50
Scenario 4 (S4)	75
Scenario 5 (S5)	100

VI. RESULTS AND DISCUSSION

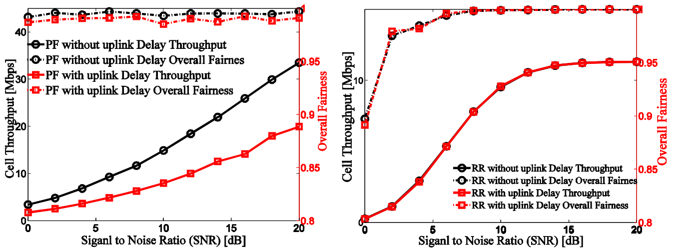
In this section, we study the performance of schedulers presented in Section III with and without the presence of uplink delay in terms of cell throughput and overall fairness. Afterwards, the performance of the proposed scheduling algorithm is evaluated in terms of cell throughput and the overall fairness using link level simulations in the simulation scenarios defined in Section V.

The cell throughput and overall fairness with respect to the SNR for the schedulers with and without the presence of delay are shown in Fig. 2. The cell throughput normally increases with the SNR, however mainly in the presence of delay in the uplink, the throughput decreases significantly as shown in Fig. 2. In particular, RR scheduler is the only scheduler that was not affected by the uplink delay, while the other schedulers' cell throughput is significantly reduced. On the other hand, PF scheduler was not affected as much as BCQI and Kwan scheduler, because its scheduling decision does not rely on the instantaneous feedback sent from the users, but it also considers the average of the previous throughputs. The overall fairness decrease significantly due to uplink delay. As expected, the overall fairness in the schedulers with a high cell throughput is less than the schedulers with a low throughput. Moreover, the fairness decreases in the schedulers that rely on the feedback sent from the UE to schedule, while it does not have the same effect on the schedulers that operate blindly.



a. Effect of uplink delay on BCQI

b. Effect of uplink delay on Kwan

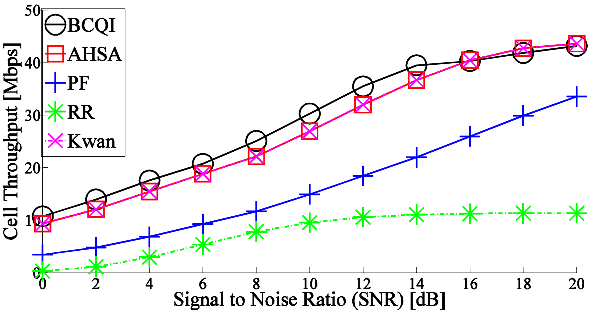


c. Effect of uplink delay on PF

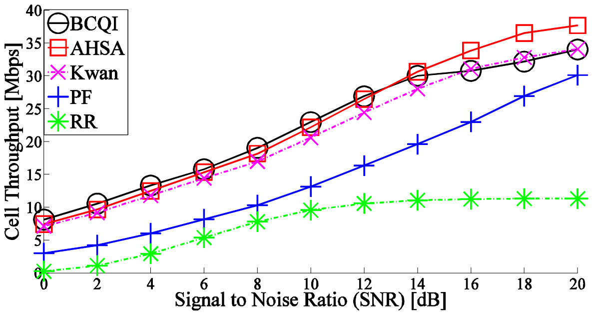
d. Effect of uplink delay on RR

Fig. 2 Effect of uplink delay on different schedulers throughput and F_O

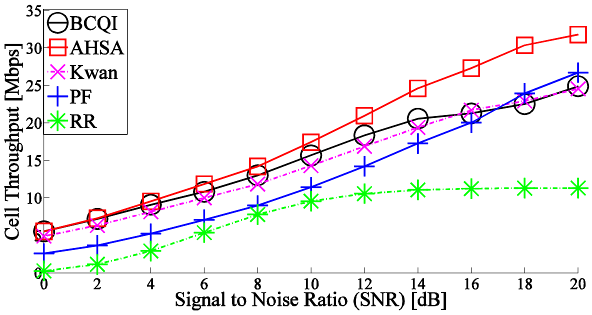
The cell throughput for the schedulers in the considered scenarios is shown in Fig. 3. The cell throughput is maximized in the first and second scenarios by scheduling the UE using BCQI scheduler. Although the throughput of AHSA throughput is less than BCQI, it surpasses the throughput of both the PF and RR schedulers. In the third and fourth scenarios the cell throughput is maximized by using AHSA scheduler. In the fifth scenario mostly the AHSA throughput exceed the rest of the schedulers. The effect of uplink delay on the cell throughput is overcome by AHSA; because it switches the UEs experiencing uplink delay to the scheduler that able to achieve the best performance (i.e. PF scheduler) when they experience uplink delay.



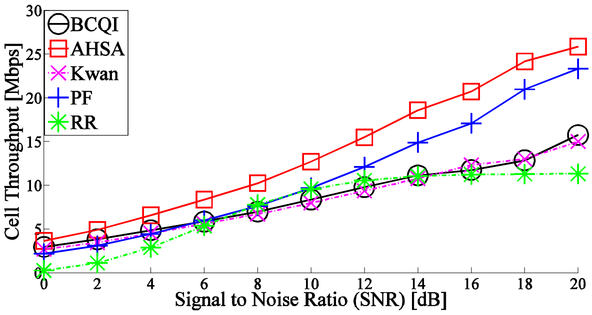
a. Throughput performance in S1



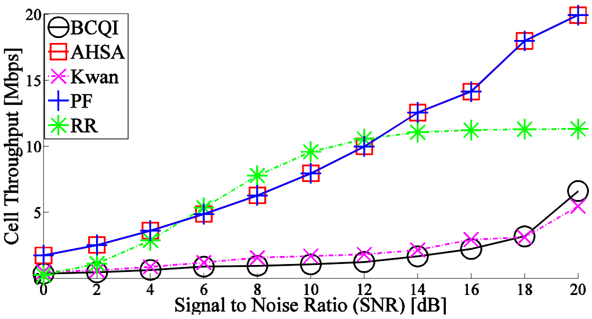
b. Throughput performance in S2



c. Throughput performance in S3



d. Throughput performance in S4

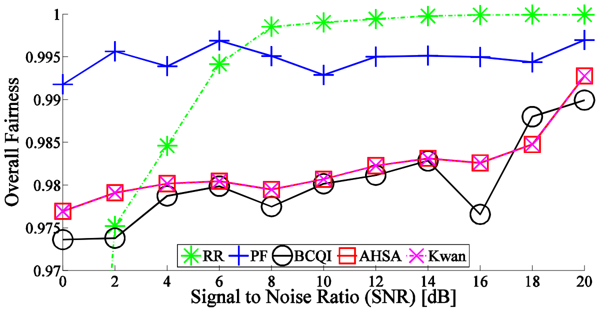


e. Throughput performance in S5

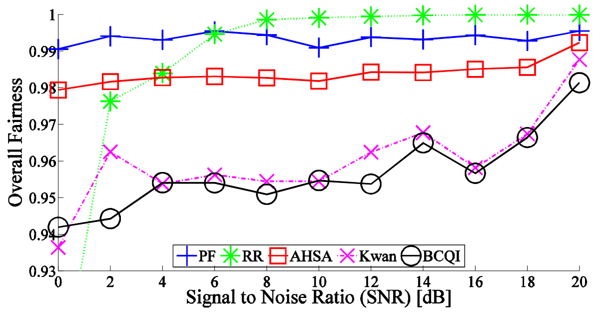
Fig. 3 Cell throughput performance in the proposed scenarios

The overall fairness presented in Fig. 4, shows that the highest overall fairness in S1 is achieved by RR and PF schedulers. On the hand, AHSA fairness performance surpasses the BCQI scheduler. In S2, the AHSA fairness surpasses both Kwan and BCQI, while still less than RR and

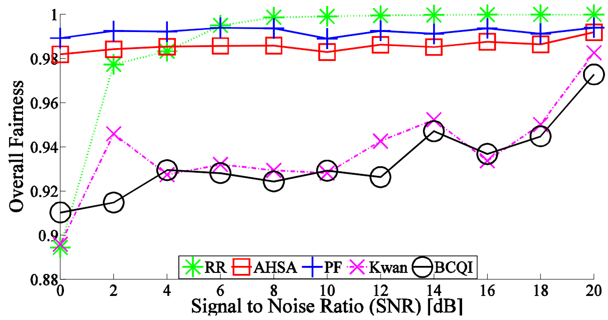
PF schedulers. In S3 and S4 AHSA fairness approaches to the fairness of RR and PF schedulers. In S5, the fairness of AHSA and PF are identical, were they both excided BCQI and Kwan schedulers. AHSA achieves its overall fairness performance because it schedules the delayed UEs by PF scheduler which is a relatively fair scheduler. It makes its scheduling decision depending on the previous users' average throughput (as shown in Section III).



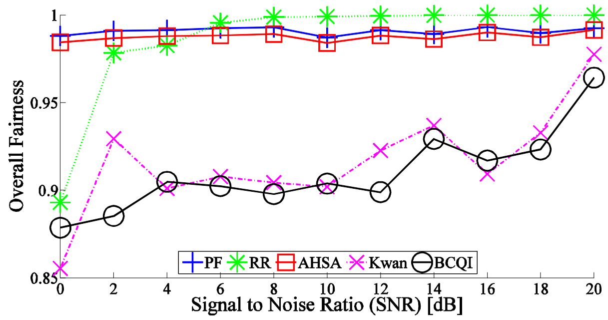
a. F_O performance in S1



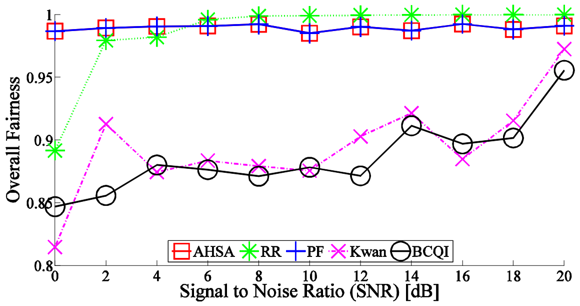
b. F_O performance in S2



c. F_O performance in S3



d. F_O performance in S4



e. F_O performance in S5

Fig. 4 Overall Fairness performance in the proposed scenarios

VII. CONCLUSION

A new fairness metric is proposed in this paper. We studied the effect of uplink delay on the state-of-the-art LTE schedulers with respect to both the cell throughput and the proposed overall fairness metric. An adaptive hybrid scheduling algorithm is proposed in this paper to overcome the impact of uplink delay on both the throughput and the overall fairness. The results show that the schedulers that do not rely on the feedback sent from the UE (i.e. RR scheduler), achieve lower throughput than the rest of the schedulers, but it is the only scheduler that is not effected by feedback delay. The proposed scheduler is able to achieve an enhanced performance in the majority of the simulation scenarios discussed in this paper.

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