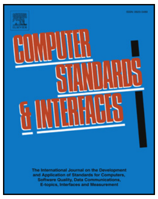
Computer Standards & Interfaces 59 (2018) 96–108

Contents lists available at ScienceDirect

Computer Standards & Interfaces

journal homepage: www.elsevier.com/locate/csi



On the performance of LTE downlink scheduling algorithms: A case study on edge throughput

Coşkun Deniz[a], O. Gokhan Uyan[b], Vehbi Cagri Gungor[b,*]

[a] *Tassomai Ltd., London, UK*
[b] *Department of Computer Engineering, Abdullah Gul University, Kayseri, Turkey*

ARTICLE INFO

Keywords:
LTE
Scheduling
Resource allocation
Radio resource management

ABSTRACT

Radio resource allocation is a crucial task in the LTE networks. To increase the overall user experience, an efficient radio resource allocation algorithm should be utilized. In this work, a new scheduling algorithm has been proposed to increase the edge throughput without sacrificing system throughput. Comparative performance results indicate that the proposed scheduler increases the edge throughput and fairness while limiting degradation in the cell throughput between 0 to 2 percent with respect to the other schedulers.

1. Introduction

Mobile data traffic trends and estimates have shown that demand for mobile data will grow enormously in near future. With new multimedia services, mobile data volume has increased 10 fold since 2011 and it is expected that it will increase 10 fold until 2019 [1]. In order to cope with the growth of data demand, a global standards-developing organization, Third-Generation Partnership Project (3GPP), has started to work on new access technology to meet the mobile traffic demand. 3GPP has standardized new network architecture in December 2008 and they have developed it with the new releases since then.

The new mobile technology is classified as fourth generation mobile technology and it is specifically named as Long Term Evolution (LTE). It has a flat architecture with respect to the previous mobile networks. LTE consists of two sub-networks; Evolved-Universal Terrestrial Radio Access Network (E-UTRAN) and Evolved Packet Core (EPC). Unlike the third generation (3G) mobile technologies which use mostly Code Division Multiple Access (CDMA), Orthogonal Frequency-Division Multiple Access (OFDMA) and Single-Carrier Frequency Division Multiple Access (SC-FDMA) are used for downlink and uplink respectively in E-UTRAN architecture. High data rates and low latency targets can be achieved by using OFDMA and SC-FDMA. These multiple access schemes are based on Orthogonal Frequency-Division Multiplexing (OFDM).

OFDM provides radio resources in both frequency and time domains. OFDM consists of multiple subcarriers, each having same bandwidth, 15 kHz, in the frequency domain. A Resource Block (RB) is the essential transmission unit which consists of 12 subcarriers in half subframe duration (0.5 ms). RBs are allocated to users in each Transmission Time Interval (TTI) which is 1 ms length. Resource allocation is specifically called as scheduling and the scheduler is responsible from assigning resources in both frequency and time domains. The aim of this study is to investigate the throughput and fairness performance of the proposed scheduling algorithm with the fundamental scheduling algorithms, such as Round Robin, Best CQI, MaxMin and Proportional Fair. Importantly, a review of the previous research efforts, which is given in Section 2, shows that most of the previous studies didn't focus on the edge throughput performance of the network.

In this paper, we propose a new scheduling algorithm to increase the overall user experience. Unlike most of the existing studies, this work focuses on the edge users because they have the poorest user experience in a cellular environment. The proposed scheduler takes the edge throughput metric into account at the first place. The main objective of the proposed scheduling algorithm is to increase the edge throughput without sacrificing system throughput. Since the edge users

---

Abbreviations: 3GPP, Third Generation Partnership Project; AMT, Approximate Maximum Throughput; BCQI, Best CQI; BER, Bit Error Rate; CoMP, Coordinated Multi-Point; CF, Cell Frequency; CT, Cell Throughput; CQI, Channel Quality Indicator; CSI, Channel State Indicator; EPC, Evolved Packet Core; ET, Edge Throughput; E-UTRAN, Evolved Universal Terrestrial Access Network; F, Fairness; FFR, Fractional Frequency Reuse; KMT, Kwan Maximum Throughput; LTE, Long Term Evolution; MAC, Media Access Control; MC, Multiple Cell; MCS, Modulation and Coding Scheme; MF, Multiple Frequency; MIMO, Multiple Input Multiple Output; MM, MaxMin; MSCH, MY SCH Not Fair [10]; MT, Mean Throughput; OFDM, Orthogonal Frequency-Division Multiplexing; OFDMA, Orthogonal Frequency-Division Multiple Access; PF, Proportional Fair; PS, Proposed Scheduler; PT, Peak Throughput; RF, Resource Fair; QoS, Quality of Service; RB, Resource Block; RR, Round Robin; SC, Single Cell; SC-FDMA, Single-carrier Frequency Division Multiple Access; SF, Single Frequency; SISO, Single Input Single Output; SNR, Signal-to-Noise Ratio; TB, Transport Block; TTI, Transmission Time Interval; UE, User Equipment; UT, User Throughput

[*] Corresponding author.

E-mail addresses: deniz@tassomai.com (C. Deniz), gokhan.uyan@agu.edu.tr (O.G. Uyan), cagri.gungor@agu.edu.tr, cagri.ggumgor@agu.edu.tr (V.C. Gungor).

https://doi.org/10.1016/j.csi.2018.03.001
Received 14 November 2017; Received in revised form 13 March 2018; Accepted 16 March 2018

mostly have poor channel conditions and low spectral efficiency, system throughput would decrease dramatically by giving additional resources to the edge users. To achieve higher edge throughputs without giving additional resources to the edge users, the proposed scheduler gives the priority to use the RB with high spectral efficiency and while trying to avoid the use of the RB with low spectral efficiency. A more detailed explanation will be given in the Section 3.

In order to evaluate performance of scheduling algorithms, we simulate the LTE environment under several scenarios with different parameters including antenna configuration, antenna type, network topology, mobility, carrier frequency, channel model and the number of UEs. The Vienna LTE System Level Simulator [2,3] has been employed to simulate the LTE environment. We show that proposed scheduler has advantage over the other schedulers in terms of edge throughput without sacrificing system throughput. Moreover, the proposed scheduler shows better system throughput performance for some cases such as 4 × 4 Multiple-Input-Multiple-Output (MIMO) antenna configuration and carrier frequencies greater than 1800 MHz.

The rest of this paper is organized as follows. In Section 2, the related works in the literature are shown. Section 3 explains different scheduling algorithms and introduces the new scheduling algorithm. In Section 4, performance evaluations are explained. Finally, the paper is concluded in Section 5.

2. Related work

There are many studies in literature related to LTE scheduling algorithms. They propose and investigate existing scheduling algorithms in terms of various parameters. The priorities and objectives vary for designing a scheduling algorithm. System throughput, fairness, QoS, energy efficiency and delay constraints are the main objectives of the scheduling algorithms. However, these objectives generally conflict with each other; there is mostly a trade-off among them. Therefore, it is difficult to obtain a better performance in an objective without having performance degradation in others. In the existing studies, it is often focused on improving one performance metric while keeping the other metrics as much as stable. Some of the related scheduling algorithms proposed in the researches are given below. For convenience, the symbols used throughout the paper are listed in Table 1.

Table 1
A list of symbols used in this paper.

Description	Symbol
Number of Resource Block	N_{RB}
Number of user	N_{UE}
Resource Block per user	RB_N
User index	U
User	m
Subcarrier	n
Unscheduled users	UE
CQI feedback	CQI
Instantaneous data rate	R, r
Average data rate	T
Window size	t_c
Spectral efficiency	$C_{n,m}$
Average spectral efficiency	C_{mean}
Pseudo-CQI feedback	$PCQI$
CQI tuning constant	s
Edge throughput	ET
Mean throughput	MT
Peak throughput	PT
User throughput	UT
Cell throughput	CT
Fairness	F
Single-cell/Multi-cell	SC/MC
Directional antenna	D
Omni antenna	O
Single frequency	SF
Multi-frequency	MF

One of the most investigated scheduling algorithms is the Proportional Fair (PF) scheduling algorithm. It was introduced for code-division-multiple-access high-data-rates systems and it was supporting only time-domain scheduling for these systems. Kim and Han [4] extended PF algorithm from time-domain to multicarrier transmission systems. Their modification enabled PF to support scheduling in frequency domain. Based on their work, Sun et al. [5] described an optimal PF algorithm for OFDMA systems and proposed a PF algorithm with reduced-complexity. The results show that the proposed algorithm performed close to the optimal PF scheduling algorithm. Kwan et al. [6] also introduced a PF scheduler and a Max-Rate scheduler that tries to maximize the system throughput. They compared the schedulers in terms of average user throughput and found that PF performance showed uniformity in average throughput with a minor bit rate degradation relative to the Max-Rate scheduler.

Since the LTE imposed the same modulation and coding scheme for the all resources of a user in a single TTI, Schwarz et al. [7] derived a linearization model for multi-user scheduling based on Channel Quality Indicator (CQI) feedback. Their purpose was to calculate the average CQI for all resources of the users with a simple linearized method. Besides that, they proposed a scheduler called Approximate Maximum Throughput (AMT) algorithm and compared it to PF, Best CQI, MaxMin and Kwan Max Rate scheduler. MaxMin scheduler achieves the highest fairness by maximizing the minimum user throughput in a cell. The proposed scheduler showed better performances for small user numbers and it showed similar performance for large user numbers. Schwarz et al. [8] also proposed a scheduler which can be adjusted to obtain specific fairness performance in this study. Adjustable fairness enables the network to achieve a desired fairness goal. They used a method which is based on sum utility maximization of the α-fair utility functions. To achieve the specific fairness target, an appropriate α value should be found which is obtained from the observed CQI probability mass function.

AlQahtani and Alhassany [9] proposed a new scheduling algorithm and compared it with Best CQI and Round Robin (RR). The algorithm is shown below (Algorithm 1).

The scheduler behaves as Round Robin (RR) until the all users obtain the same number of RB. After that, it behaves as Best CQI algorithm, the residue of the RBs is assigned to the user with the highest CQI. Throughput performance of the new scheduler is at between RR – Best CQI. Fairness is declined almost %20 relative to RR. PF algorithm was not in the scope of this work, thus fairness comparison with PF was not available. Gavrilovska and Talevski [10] presented a new Best CQI scheduler to overcome the fairness problem in the existing Best CQI scheduler. The results show that system throughput was improved with the new scheduler and there was no user that experiencing throughput degradation. Their algorithm is shown in Algorithm 2.

Escheikh et al. [11] proposed a new scheduling algorithm to increase system throughput. They aimed to enable a better trade-off between throughput and fairness. New scheduler was compared with existing schedulers i.e. RR, Best CQI and MY_SCH_Not_Fair [10]. They observed significant improvements in system throughput. Fairness performance was not presented in the work. Bechir et al. [12] introduced a new scheduling algorithm and compared it with RR, PF and Best CQI algorithms. The new scheduler was more complex than PF and it performed better than PF in terms of system throughput. While the system throughput was increasing, fairness metric was decreasing up to 20% comparing with RR and PF. The algorithm is given in below (Algorithm 3).

Assaf [13] investigated the prioritization capabilities in LTE networks and proposed an algorithm that leads to have priority access for some users following their QoS Class Identifier (QCI). He modified the Proportional Fair scheduler and implemented prioritization capabilities to it.

Carpin et al. [14] modified Fair Throughput Guarantees Scheduler

Algorithm 1
AlQahtani et al. [9].

```
Input: Number of RB, $N_{RB}$, number of users $N_{UE}$
Compute: RB per UE, $RB_N$
if $CEIL(RB_N) = FLOOR(RB_N)$
  assign the same number of RB, $RB_N$ to each user
else assign the same number of RB, $RB_N$, to each user and distribute extra RB (RBS) to the users randomly
Compute: user index, U = rand($N_{UE}$)
for each $U$
  select RB or RBS with maximum CQI
  assign RB or RBS to the user U
Output: RB allocation matrix, $RBxUE$
```

(FTGS) to be able to operate in frequency domain. They carried out a performance analysis of the new scheduler with the two well-known schedulers, namely Maximum Throughput Scheduler (MTS), Blind Equal Throughput Scheduler (BETS) for the flat and frequency selective fading channels, and for both saturated UDP and TCP traffic source models. FTGS shows a significant performance improvement both in terms of average cell throughput and fairness.

Finally, Qurat-ul-Ain et al. [15] proposed an extension to the generic PF algorithm for the high mobility scenarios and evaluated the new algorithm in the two performance aspects, accuracy and the data rate. Calculation of throughput indicates the data rate, and the accuracy is investigated in terms of Block Error Rate (BLER). They set up single simulation scenario and did not take fairness criteria into the consideration. Results showed that the proposed scheduler enhanced the throughput and BLER performance relative to generic PF algorithm.

3. Scheduling algorithms

3.1. Round Robin (RR)

Round Robin (RR) is a channel-independent scheduling algorithm that used commonly in LTE network. In RR algorithm, shared resources are allocated to the users in turn sequentially. When all users are assigned a resource, it starts from the first user to assign resources recursively. RR algorithm does not take any other parameters into consideration therefore it is one of the simplest scheduling algorithms.

In Fig. 1, radio resources are allocated using RR algorithm. As seen that users can be assigned fading channels therefore throughput can be low and high BER can be observed in the transmission. The lack of channel awareness causes low efficiency in the radio resource management. RR provides high fairness however there is fairness only in terms of the number of RBs that is assigned to each user.

3.2. Best CQI

Best CQI aims to select the user with best channel condition for a particular RB in a time interval. This algorithm performs efficiently in terms of the system throughput. However, there is a lack of fairness from the point of the user throughput. Only the users with high CQIs, (or highest CQI) will be able to send/receive data in this algorithm. Mathematical expression of this algorithm is:

$$\mathrm{k} = \arg \max_{i} R_i \tag{1}$$

where R_i is the instantaneous data rate for user i.

User that has highest channel quality is scheduled until the channel quality of the other users become greater than scheduled user. Only a couple of users can exploit all the resources in Best CQI case. The users that are close to the eNodeB will use almost all of the resources and edge users will be out of connection (Fig. 2).

3.3. MaxMin

MaxMin algorithm tries to maximize the minimum throughput of the users. In this algorithm, it is not possible to increase the throughput of a user without decreasing another. Maximizing the throughput brings fairness to the system. However, the scheduler assigns large amount of resources to the users with low throughput to maximize the minimum user throughput. Since these users mostly have poor channel quality and low spectral efficiency, MaxMin algorithm causes significant decrease in system throughput. To find a balance between fairness and overall system efficiency, Proportional Fair algorithm is present.

3.4. Proportional Fair (PF)

Proportional Fair algorithm provides high fairness by exploiting the channel variations to improve spectral efficiency. Resources are assigned according to a metric which is determined by instantaneous and average throughput of a user.

$$T_m(n) = (t_c - 1)T_m + \sum_{n=1}^{N} \rho_{m,n} R_m(n) \tag{2}$$

$$m^*(n) = \underset{m=1,2,\ldots,M}{argmax} \frac{R_m(n)}{T_m(n)} \tag{3}$$

where $\rho_{m,n} \in \{0, 1\}$ is the vector indicating whether the subcarrier n is allocated to user m or not. $R_m(n)$ *is* the instantaneous throughput for the mth user in the nth subcarrier. $T_m(n)$ denotes the average throughput for the ``mth'' user in a past window. In each subframe, $T_m(n)$ is updated

Algorithm 2
Gavrilovska and Talevski [10].

```
1. Input: Unscheduler users in previous TTI, $UE_m$, CQI feedbacks of the UEs, $CQI_{n,m}$, where n is subcarrier and m is the user id.
2. Compute: argmax($CQI_{n,m}$), find $n$, $m$ index
3. for each $m$
4.   assign $RB_n$ to user $m$ and extract it from $UE_m$
5.     if $UE_m = 0$
6.       break
7. End
8. if there is unassigned $RB_n$
9.   $UE_m$ equals to all users
10.  go to Step 2
11. Output: RB allocation matrix, $RBxUE$
```

Algorithm 3
Bechir et al. [12].

```
Input: CQI in terms of required data rate $R_m(n)$
for each $n$
    Compute: $R_m(n)$ and $T_m(n)$
    find $(m^*, n^*) = \mathrm{argmax}(R_m(n)/T_m(n))$
Schedule user $m$ on $n$ subcarrier. User $m$ will not have permission to be scheduled until $N_{RB}\ x\ N_{UE}$
Output: RB allocation matrix, $RBxUE$
```

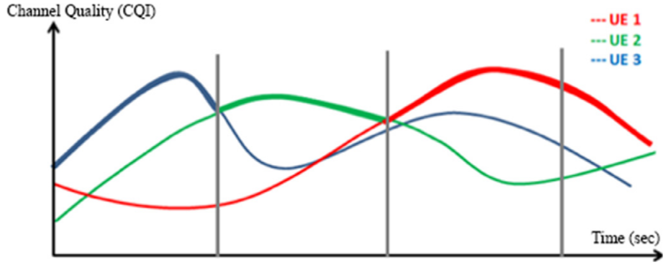


Fig. 1. Round Robin scheduling.

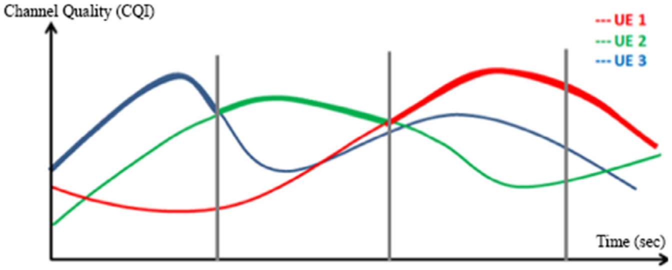


Fig. 2. Best CQI scheduling.

with respect to:

$$T_m(n+1)=\begin{cases}1-\dfrac{1}{t_c}T_m(n)+\dfrac{1}{t_c}R_m(n) & m=m^*(\mathrm{n})\\ 1-\dfrac{1}{t_c}T_m(n) & m\neq m^*(\mathrm{n})\end{cases} \tag{4}$$

where, t_c is the window length that can be adjusted to maintain fairness over a predetermined time horizon. When t_c becomes small, the gain decreases. This is because the scheduler has less time to wait for the peaks. Larger t_c makes the scheduler wait for high peaks and results gain in throughput at the expense of the latency. The proportional fair algorithm from the work [5] is given below (Algorithm 4).

3.5. *Proposed scheduling algorithm (PS)*

In a cellular network, users are distributed in the field around a serving base station. Distance between the user and the base station affects the channel quality of the user. Signal to Noise Ratio (SNR), throughput and delay are affected as well. Users that are close to the cell border have low SNR, low throughput, and high BER in the transmission.

As mentioned in the previous section, PF algorithm assigns resources according to a metric. The metric is calculated by dividing instantaneous throughput by the average throughput. The instantaneous throughput depends on the Transport Block (TB) size which is determined by using the MCS index. And the MCS index is calculated from the SNR value of the channel. The UEs cannot send the SNR values directly but they send an indicator, CQI. Therefore the MCS index is selected based on the CQI values. In wireless broadband communications every user experiences fading channels. For a TTI, a user can report CQI from 1 to 15 for each individual RB. However, only single MCS is used in a TTI for a user. In other words, the same modulation and coding scheme is applied on all of the RBs regardless of CQI.

The purpose of the new algorithm is to increase the edge throughput without obtaining any degradation in system throughput. To achieve this goal, the scheduler gives the priority to the users to be allocated in time-frequency slots whose spectral efficiency is above the average of all users. By applying this methodology, scheduler can keep the MCS as high as possible for all users. In addition, this method gives advantage to the users who have poor channel conditions over the users with high channel quality. To keep the MCS higher,

RBs must not be allocated to the users if their CQIs are lower than the average. Algorithm 5 is applied to the users within each TTI. The PF algorithm [5] is applied after Step 8 in the proposed algorithm.

In Fig. 3, the process of obtaining the Pseudo CQI is shown for a single user. The user has reported CQIs between 6 and 12. (a) In each TTI, CQIs are converted to corresponding spectral efficiency. (b) Then, the average spectral efficiency is calculated and RBs which are greater and less than the average spectral efficiency are detected. RBs that have greater spectral efficiency than the average spectral efficiency are highlighted green. In the next step, CQI values of the highlighted RBs are incremented by s step further and the CQI values of the gray RBs are decremented *s* step below. Here, *s* is the CQI tuning parameter that will change according to application requirements and scenarios. The higher *s* will allow edge users to get more resources and the lower *s* will lead to lower resource allocation for edge users. After obtaining Pseudo-CQI table, PF algorithm is applied and MCS is selected with respect to PCQI values. Resource allocation is completed by using the PF metrics.

4. Performance evaluations

The simulations focus on the throughput and fairness performance of different scheduling algorithms. The main parameters for the simulations are given in Table 3. The parameters change for Mobility, MIMO, Carrier Frequency and FFR subsections. A summary of the simulation parameters of this work and the related work is given in Table 2.

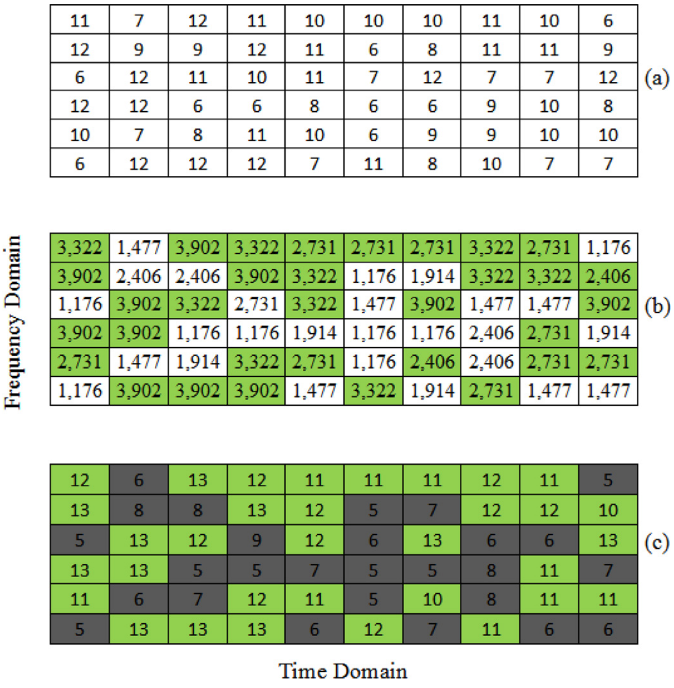
The edge, mean, cell and peak throughput criteria are selected for the performance comparison. The edge throughput is defined as the 5th percentile point of the CDF of user throughput. It can be interpreted as the data rates of the UEs at the cell edge. The mean throughput is

Algorithm 4
Proportional Fair, Sun et al. [4].

```
Input: CQI feedbacks of the UEs, $CQI_{n,m}$
for each n
    Compute: $R_m(n)$ and $T_m(n)$
    find $(m^*, n^*) = \mathrm{argmax}(R_m(n)/T_m(n))$
Output: RB allocation matrix, $RBxUE$
```

Algorithm 5
Proposed scheduler (PS).

```
Input: CQI feedbacks of the UEs, $CQI_{n,m}$
Compute: Coding efficiencies, $C_{n,m}$, and Average Spectral efficiency $C_{mean,m}$ according to the CQI feedback for a TTI of the UEs
for each user $m$
    if $C_{n,m}$ greater than $C_{mean,m}$
        $PCQI_{n,m}$ equals to $CQI_{n,m} + s$
    Else
        $PCQI_{n,m}$ equals to $CQI_{n,m} - s$
for each $n$
    Compute: $R_m(n)$ and $T_m(n)$, using $PCQI_{n,m}$
    find $(m^*, n^*) = \mathrm{argmax}(R_m(n)/T_m(n))$
Output: RB allocation matrix, $RBxUE$
```



(a)

11	7	12	11	10	10	10	11	10	6
12	9	9	12	11	6	8	11	11	9
6	12	11	10	11	7	12	7	7	12
12	12	6	6	8	6	6	9	10	8
10	7	8	11	10	6	9	9	10	10
6	12	12	12	7	11	8	10	7	7

(b)

3,322	1,477	3,902	3,322	2,731	2,731	2,731	3,322	2,731	1,176
3,902	2,406	2,406	3,902	3,322	1,176	1,914	3,322	3,322	2,406
1,176	3,902	3,322	2,731	3,322	1,477	3,902	1,477	1,477	3,902
3,902	3,902	1,176	1,176	1,914	1,176	1,176	2,406	2,731	1,914
2,731	1,477	1,914	3,322	2,731	1,176	2,406	2,406	2,731	2,731
1,176	3,902	3,902	3,902	1,477	3,322	1,914	2,731	1,477	1,477

(c)

12	6	13	12	11	11	11	12	11	5
13	8	8	13	12	5	7	12	12	10
5	13	12	9	12	6	13	6	6	13
13	13	5	5	7	5	5	8	11	7
11	6	7	12	11	5	10	8	11	11
5	13	13	13	6	12	7	11	6	6

Fig. 3. Obtaining pseudo-CQI feedback.

defined as the sum of the average data throughput of each user in the cell divided by the total number of users in the cell. Cell throughput is the sum of the instantaneous data rate of each user in the cell. And the peak throughput is the average data rate of the users at the top 5th percentile of the CDF.

Table 3
Simulation parameters for the single cell multiple user scenarios.

Number of eNodeBs	1
Number of sectors	3
Bandwidth	20 Mhz
Carrier frequency	2100 Mhz
Channel model	Winner + [16]
Antenna configuration	SISO, Directional
Pathloss [dB]	TS 36.942 [17], urban

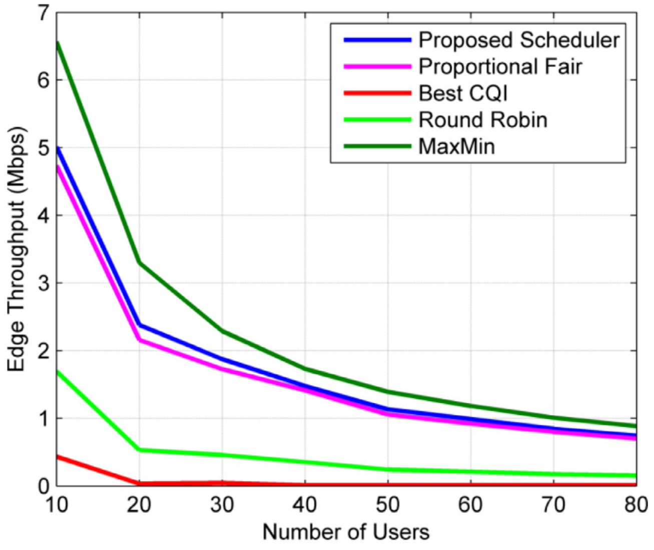


Fig. 4. Edge throughput performances of the schedulers.

4.1. Single-cell & multi-user

Edge throughput results are depicted in Fig. 4. All the algorithms show the same decline trend in throughput when the number of UE increases. The reason for such behavior is that the number of RB per UE is decreasing while number of UE is increasing.

As seen from Fig. 4, MaxMin algorithm serves the highest rate to the

Table 2
Comparison of the related work.

Related work	Scheduling algorithms	Number of users (per cell)	Cell topology	Mobility (km/h)	Antenna type	Antenna config.	CF	Performance metric
Mehlführer [2]	BCQI, RR, PF, RF, MM	20	SC2	3	D3	1 × 1	SF	ET,PT,MT,CT,F
Assaf [13]	PF, PS	10,20	MC4	3	D	2 × 2	SF	MT
Gavrilovska [10]	BCQI, PF	8	SC	3,30	D	1 × 1	SF	UT,CT,BER
Schwarz [7]	BCQI, AMT, KMT, RR, MM	2,25	SC	30	N/S5	1 × 1	SF	CT,F
Schwarz [8]	BCQI, RR, PF, RF, MM, PS	2,15	SC	N/S	N/S	1 × 1	SF	CT,F
AlQahtani [9]	BCQI, RR, PS	10,20,30,40,50	SC	N/S	N/S	1 × 1	SF	CT,F
Escheikh [[11]	BCQI, RR, MSCH	15,35	SC	3	N/S	2 × 2	SF	CT
Bechir [12]	BCQI, PF, RR, PS	5,10,15,20,25	SC	3	N/S	1 × 1	SF	BER,CT,F
Ikuno [20]	FFR, PF, RR	30	MC	5	D	4 × 4	SF	ET,PT,MT,F
Proposed scheduler (PS)	BCQI, RR, PF, MM, PS, FFR	10,20,…,80	SC & MC	5, 30, 100	D & O6	1 × 1,2 × 2,,4 × 4	MF	ET,PT,MT,CT,F

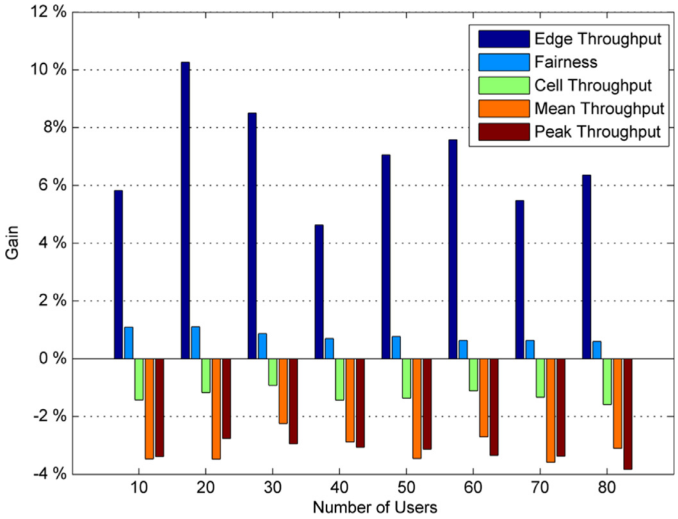


Fig. 5. Gain comparison of PS and PF.

edge users. Proposed Scheduler (PS) shows better performance than the PF algorithm and it serves data rates less than MaxMin algorithm for the edge throughput. Best CQI algorithm provides almost zero data rate at the cell edge. Since Round Robin algorithm is a channel-unaware scheduler, it supports poor data rates to the edge users.

Performance comparison between PS and PF algorithms is given in the Fig. 5. The gain in the edge throughput reaches up to 10 percent depending on the number of users in the cell. Degradation in cell throughput stays under 2 percent. Decrease in the mean and peak throughputs is between 2 and 4 percent.

Fairness performances are shown in Fig. 6. Fairness index is calculated by using Jain's fairness index. Jain's fairness index [18] is formulated below.

$$J(x_1, x_2, \dots, x_n) = \frac{\left(\sum_{i=1}^{n} x_i\right)^2}{n \cdot \sum_{i=1}^{n} x_i^2} \tag{5}$$

where n is the number of users and x_i is the throughput of the ith user.

As seen from Fig. 6, the highest fairness performance is achieved by the MaxMin scheduler. Proposed scheduler shows better performance than the Proportional Fair scheduler in terms of fairness. Round Robin also provides high fairness and Best CQI provides almost no fairness with an index of around 0.6. Cell throughput is an important parameter that shows how efficiently the network works. Cell throughput is theoretically 100 Mbps in downlink under the perfect channel conditions for SISO antenna configuration. The cell throughput is directly related with the channel quality. Poor channel conditions cause degradation in transport block size and cell throughput. Therefore, cell throughput is determined by the channel qualities of the users in the real wireless networks. For that reason, Best CQI algorithm performs close to the theoretical cell throughput since it serves only the users having good channel conditions as shown in Fig. 7.

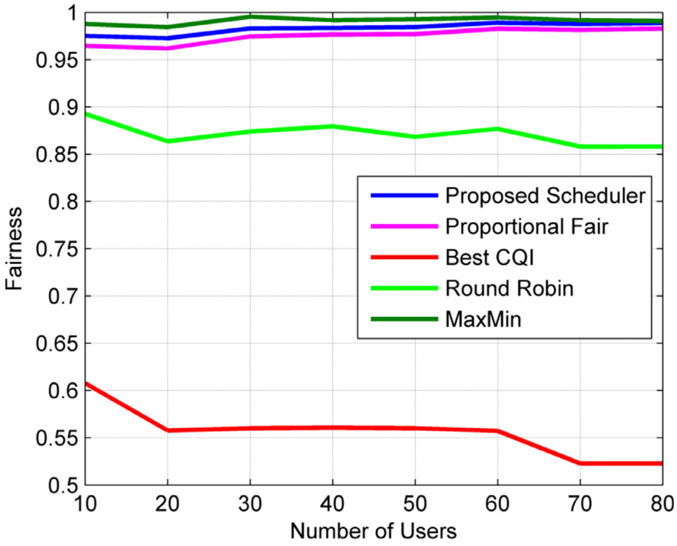


Fig. 6. Fairness performances of the scheduling algorithms.

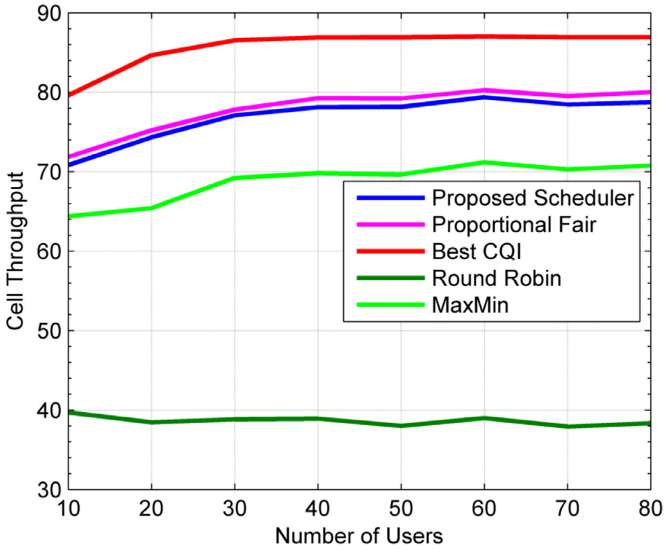


Fig. 7. Cell throughput.

After Best CQI, the highest cell throughput can be reached by using PF and PS algorithms. The proposed scheduler shows slightly less performance in cell throughput. The decrease in the cell throughput is between 0 and 2 percent relative to PF scheduler. MaxMin scheduler can only reach up to 70 Mbps. Consequently it can be said that MaxMin is not efficient from the perspective of the cell throughput. There are almost 26 percent and 10 percent decreases in the cell throughput relative to Best CQI and PF algorithms respectively.

Throughput-SNR results of the three scheduling algorithms are shown Fig. 8 for 30 users. Proportional Fair supports high throughput

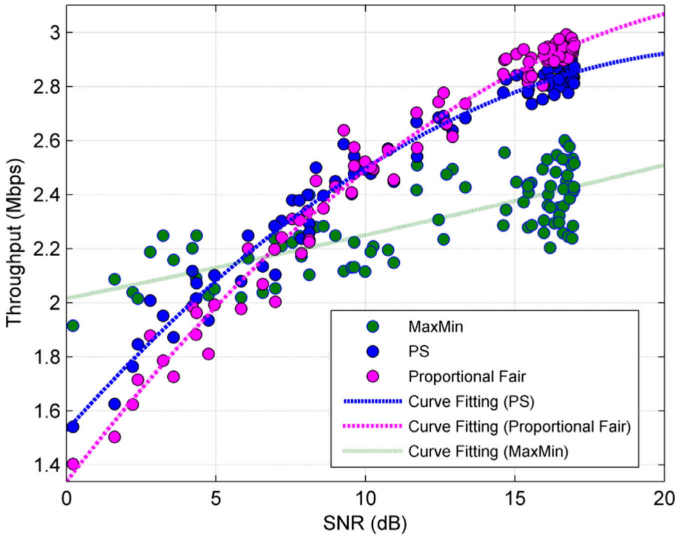


Fig. 8. SNR vs user throughput, 30 users.

for the users with high SNR, MaxMin serves almost same data rates for all users with different SNR. The proposed scheduler increases data rates of the users having SNR lower than 10 dB, which represent edge users, relative to Proportional fair. Proportional Fair scheduler shows better performance than the proposed scheduler after 10 dB.

Priority of the proposed scheduler and MaxMin are to improve the throughput of the users at low SNR. Although MaxMin scheduler provides the highest throughput to the users at below 6 dB, it causes significant decreases in the throughput of the users with higher SNR. However, PS keeps the decreases as much as small in the peak throughputs.

4.2. Mobility

In terms of mobility, E-UTRAN is optimized to support low speeds (< 15 km/h); it shows high performance up to 120 km/h and maintains data link for speeds up to 350 km/h. (up 500 km/h depending on the frequency band.). To compare the throughput performance of the schedulers, three different user velocities has been set in the simulator.

Transmission channel is modeled with channel convolution and additive noise, which gives in Fourier discrete domain [19]:

$$Y(k) = H(k)X(k) + W(k) \tag{6}$$

where k is the discrete frequency $X(k)$ and $Y(k)$ are the transmitted and received signals respectively and $H(k)$ is the channel impulse response and $W(k)$ is the noise. User mobility affects the channel impulse response due to the Doppler shift. The Doppler shift is calculated from the wave length on the carrier frequency λ_0, angle of arrival (downlink) $\phi_{n,m}$, user speed v and direction of travel θ_v [16]:

$$\vartheta = \frac{\|v\| \cos(\varphi_{n,m} - \theta_v)}{\lambda_0} \tag{7}$$

The edge throughput performances for different mobility scenarios are shown in Fig. 9. When the user velocity increases, the performance gap between PS and PF decreases. Proposed scheduler shows almost no improvement in terms of the edge throughput under the high mobility scenario. Fig. 10 helps to find out the effects of mobility on the throughput performance of the users.

Emprical cumulative distribution functions of the throughputs of different mobility scenarios are shown in Fig. 10. Mobility has a negative effect on the throughput for all users regardless of scheduling algorithm. Besides that, the peak throughputs are getting worse in the MaxMin relative to the other algorithms.

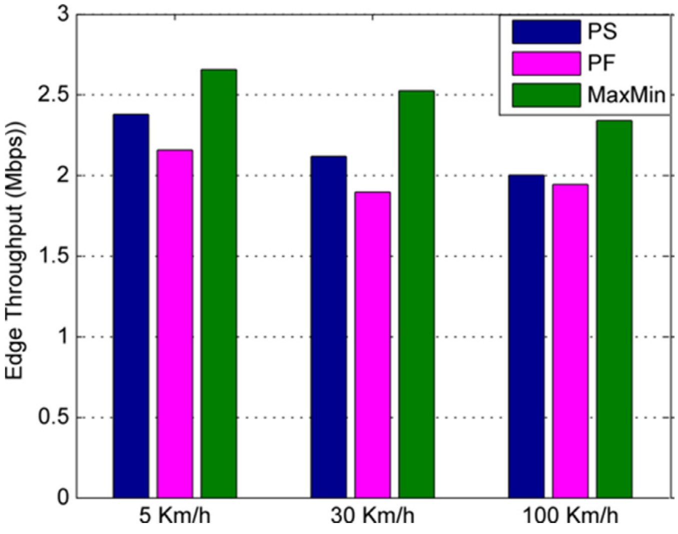


Fig. 9. Mobility vs. edge throughput.

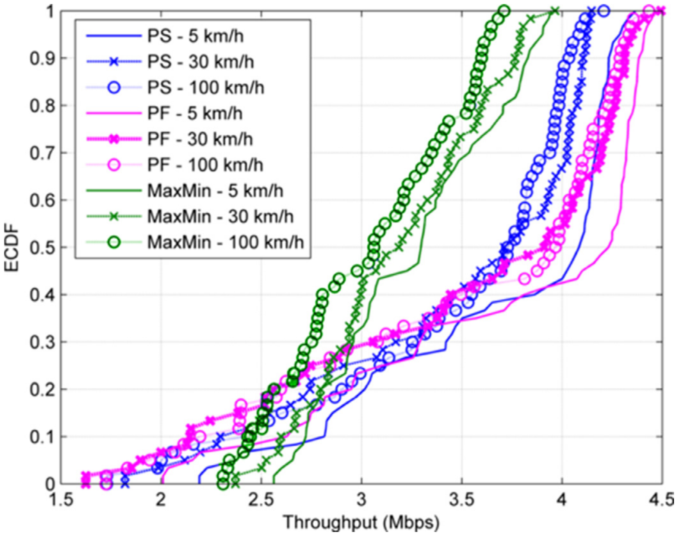


Fig. 10. Mobility vs throughput CDF.

4.3. MIMO

To investigate the behaviour of the schedulers under the different MIMO modes, three different antenna configurations has been set up; 1 × 1, 2 × 2 and 4 × 4. MIMO performances are shown in the figures for the edge throughput, mean throughput and peak throughput. The number of the users is set to 20 for this simulation. The performance results in terms of the edge throughput for three antenna configuration is shown in Fig. 11.

In SISO configuration, as seen before, MaxMin provides highest throughput. With 2 × 2 antenna configuration, all three schedulers perform almost the same in terms of the edge throughput. MaxMin again outperforms PS and PF in 4 × 4 transmission mode and reaches the highest throughput, while PS shows a performance between MaxMin and PF.

In SISO antenna configuration, PS cannot reach performance of PF in terms of mean throughput. All three schedulers behaves similar to SISO in 2 × 2 configuration. However, PS catches PF for 4 × 4 antenna configuration (Fig. 12). It can be seen from Fig. 13, MaxMin performs worst in terms of peak throughput for all antenna configuration. PF

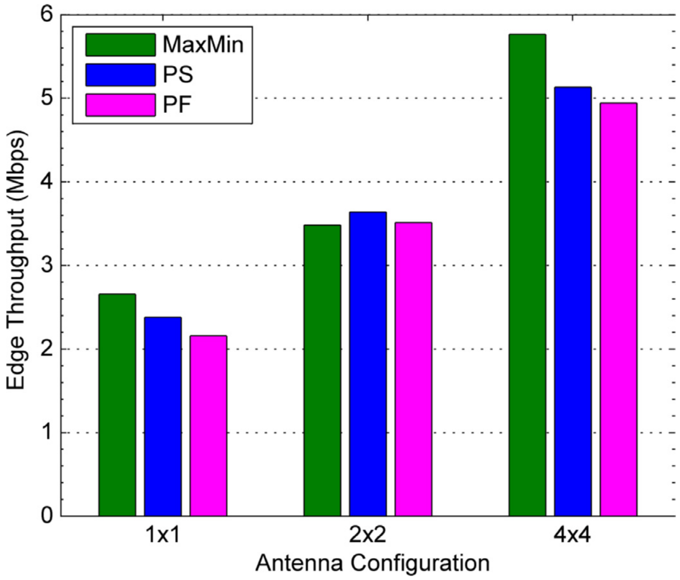


Fig. 11. Edge throughput vs. antenna configuration.

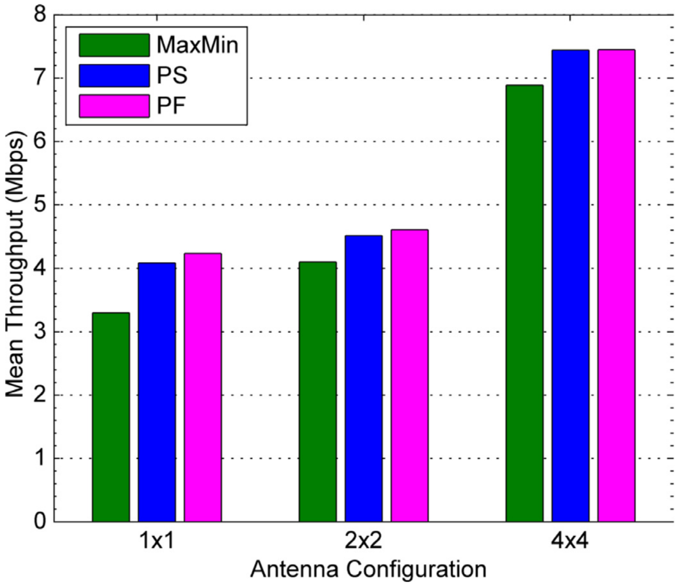


Fig. 12. Mean throughput vs. antenna configuration.

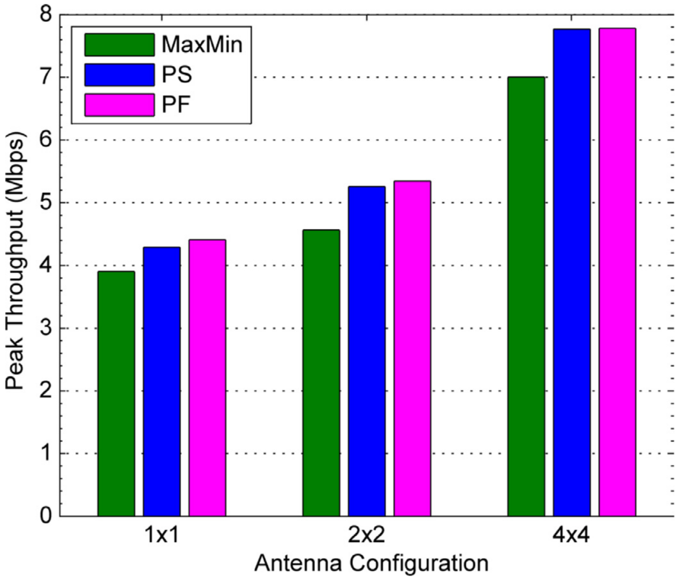


Fig. 13. Peak throughput vs. antenna configuration.

scheduler achieves higher peak throughputs than PS in 1 × 1 and 2 × 2 antenna configuration. However, PS can obtain the same peak throughput for 4 × 4 antenna configuration as well as mean throughput.

Impacts of the antenna configurations on the performance metrics have been investigated in this subsection. Proposed scheduler provides an edge throughput between Proportional Fair and MaxMin algorithms for 1 × 1 and 4 × 4, and passes them for 2 × 2 antenna configuration. It should be underlined that proposed scheduler achieves the same amount of mean and peak throughput by using 4 × 4 antenna configuration with PF scheduler. Additionally it can be seen that there is no decrease in system throughput for both 2 × 2 and 4 × 4.

4.4. Carrier frequency

Carrier frequencies have different effect on the channel quality due to the signal attenuation. Five carrier frequencies are selected to investigate in this work. These frequencies are 800 MHz, 900 MHz,

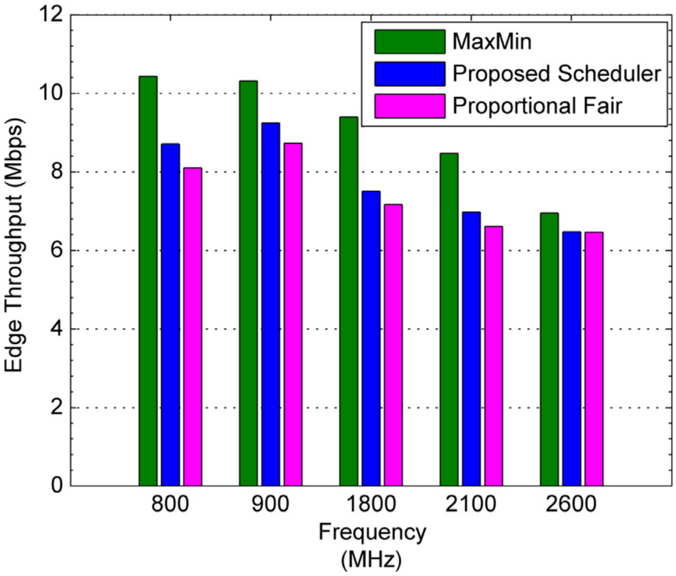


Fig. 14. Edge throughput vs. carrier frequency.

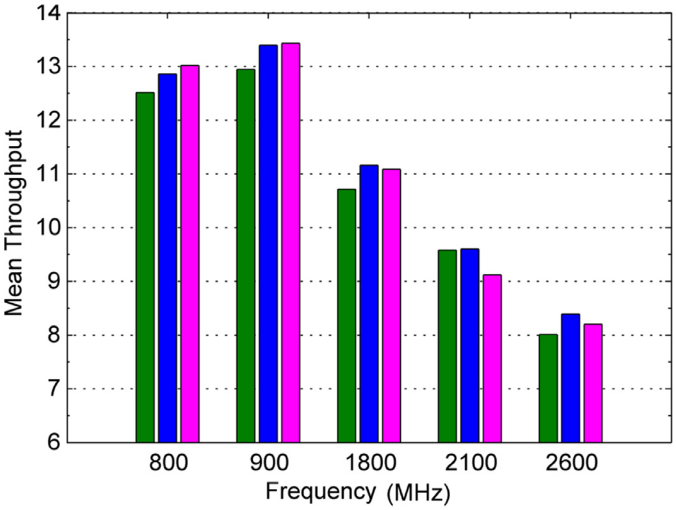


Fig. 15. Mean throughput vs. carrier frequency.

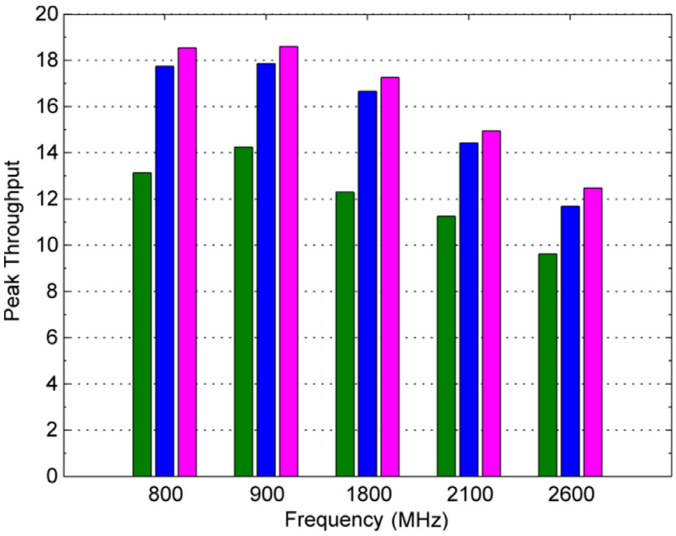


Fig. 16. Peak throughput vs. carrier frequency.

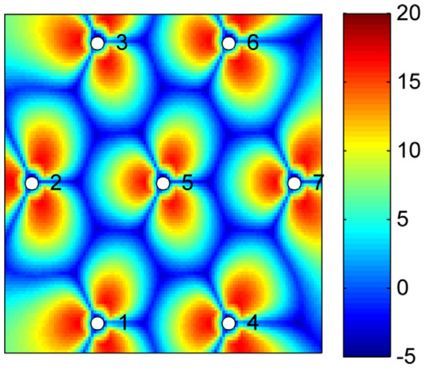


Fig. 17. SNR Map, 7 Site, 21 Cells, 210 Users, 4 × 4.

1800 MHz, 2100 MHz and 2600 MHz. The number of users in this simulation is 10 and cell range is 1 km and pathloss model is selected as suburban.

The edge, mean and peak throughput analysis are shown in Figs. 14–16. In terms of edge throughput, MaxMin serves better at 800 MHz, while PF and PS serves better at 900 MHz among the other frequencies. For mean throughput, 900 MHz is the frequency that the all schedulers reach their highest throughput performances. After 900 MHz, PS outperforms the other schedulers in terms of mean throughput. In terms of peak throughput, all schedulers provides highest throughput at 900 MHz. When the carrier frequency gets higher, the performances are decreasing for all of the schedulers (Fig. 17).

4.5. Multi-cell

In the previous subsections, all simulations has been done by using single site and three-cell network topology. In this subsection, network topology consists of 7 site, 21 cells and 210 users. The antenna configuration is 4 × 4 MIMO. For the single cell topology, the proposed scheduler brings gain at the edge throughput and it causes throughput degradation in average cell throughput relative to PF scheduler. As seen from Fig. 18, gain at the edge throughput still exists with degradation. The gap between edge throughput results of PS and PF schedulers became narrower. Besides that, PS achieves higher mean throughput than PF. In terms of peak throughput, PF performs best among these three schedulers in multi-cell network topology (Fig. 19).

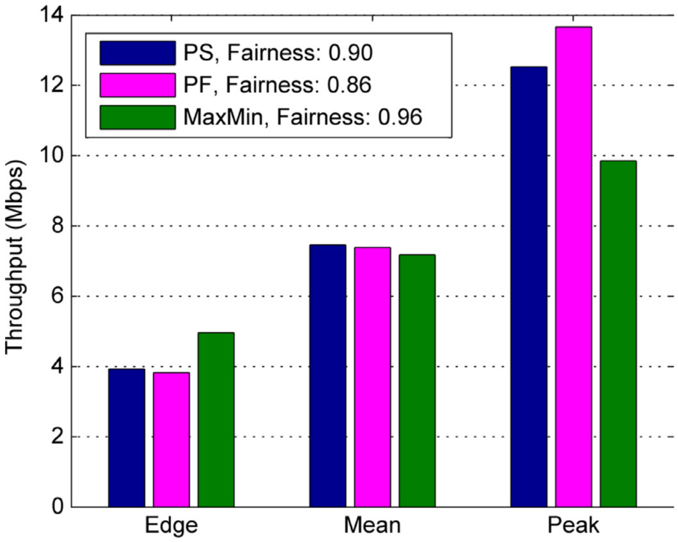


Fig. 18. Edge, mean and peak throughputs.

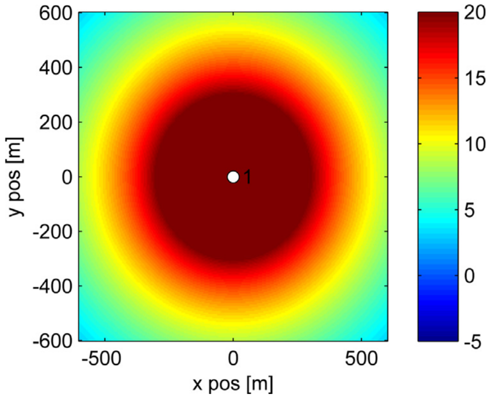


Fig. 19. SNR map, omnidirectional antenna, SISO.

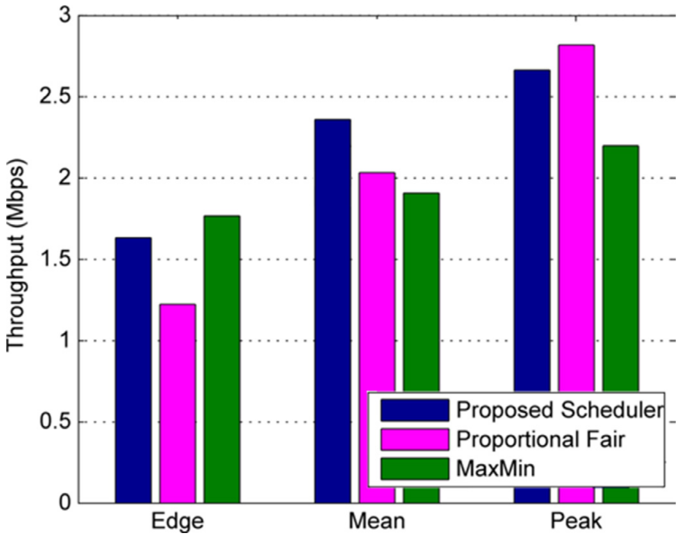


Fig. 20. Edge, mean, peak throughputs for omniantenna.

4.6. Omni-directional antenna

Directional antenna or sector antenna has been used in the previous simulation configuration. This simulation scenario has been setup to observe the effect of the antenna types on the performance of the schedulers. The cell range is 500 m, antenna gain is 5 W and the number of users is 30.

Fig. 20 depicts the edge, mean and peak throughput values of the scheduling algorithms. It indicates that schedulers show different behavior in terms of mean throughput for the omnidirectional antenna and directional antenna cases. In terms of the mean throughput, PS serves highest data rate to the users relative to the other schedulers. The peak and the edge throughput performances of the schedulers are the same for omnidirectional and directional antenna cases.

4.7. FFR

Fractional Frequency Reuse is based on splitting cell area into two and the system bandwidth into a number of distinct sub-bands according to a chosen reuse scheme. Cell area is divided into a center part called Full Reuse (FR) zone and outer part called Partial Reuse (PR) zone. In FR zone, interference is lower and a single reuse factor is used. In PR zone, interference is higher therefore higher reuse scheme is employed in that zone to minimize the interference. Fig. 21 shows the PR reuse factor is set as 3.

A fraction β_{FR} of the total system bandwidth is assigned to the FR zones and remaining part of the bandwidth $(1 - \beta_{FR})$ employs a reuse-n

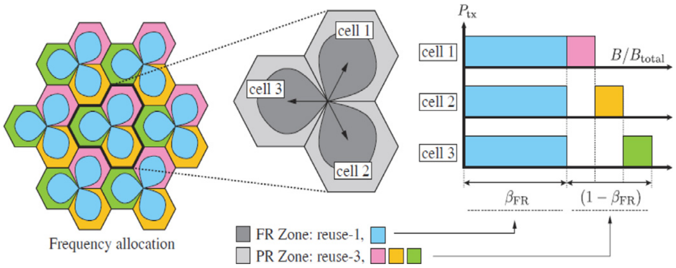


Fig. 21. Frequency partitioning of the cells.

Table 4
Simulation parameters for FFR.

Number of eNodeBs	57
Number of users	570
User speed	5 km/h
β_{FR}	[0.3 0.5 0.75]
Γ (dB)	[−5 0 5 10 15 20]
Bandwidth	20 Mhz
Carrier frequency	2100 Mhz
Inter-cell distance	500 m
Antenna configuration	4 × 4, Directional
Minimum coupling loss	70 dB [13]
Channel model	Winner Phase II [16]
Simulation length	50 TTI

factor. The boundary of FR zone is determined by using Γ, which denotes SINR at a position.

In the previous work [20], round robin and proportional fair algorithms has been used to investigate FFR performance. In another work [21], Gok and Koca evaluated the performance of FFR schemes using round robin, proportional fair and Best CQI schedulers. In this subsection, we evaluate FFR performance by using proposed scheduling and proportional fair algorithm. For each scheduling algorithm, the parameters have been set to the values in the Table 4.

Figs. 22–24 depict the edge, mean and peak throughput results of the scheduling algorithms for different β_{FR} values. Γ is fixed at 10 dB to observe the impact β_{FR} on the performance. The proposed scheduler performs better in terms of the edge throughput with low β_{FR} . On the contrary, peak throughput performances of the proposed scheduler are getting higher when β_{FR} gets higher. In terms of fairness, both of the scheduling algorithms perform almost the same for all β_{FR} values and

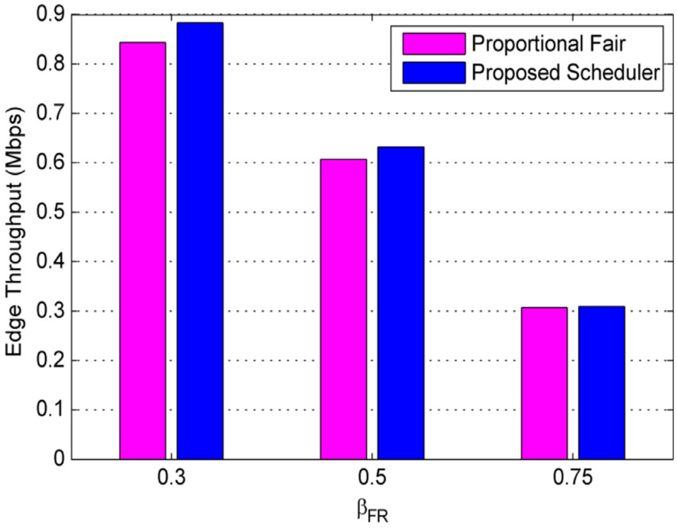


Fig. 22. Edge throughput vs β_{FR}.

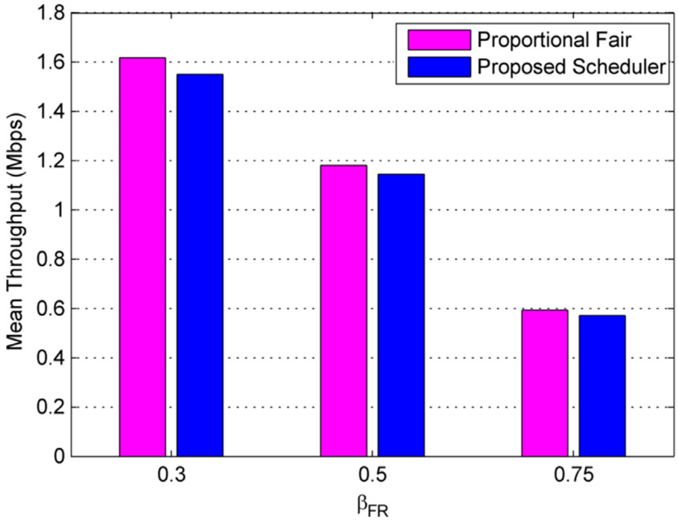


Fig. 23. Mean throughput vs β_{FR}.

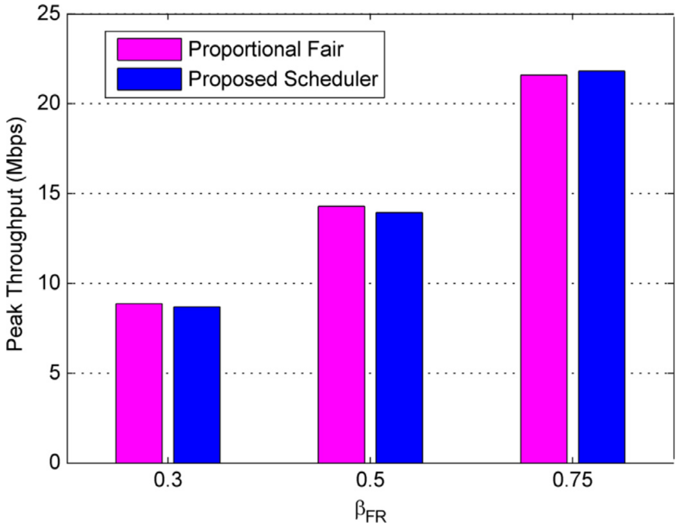


Fig. 24. Peak throughput vs β_{FR}.

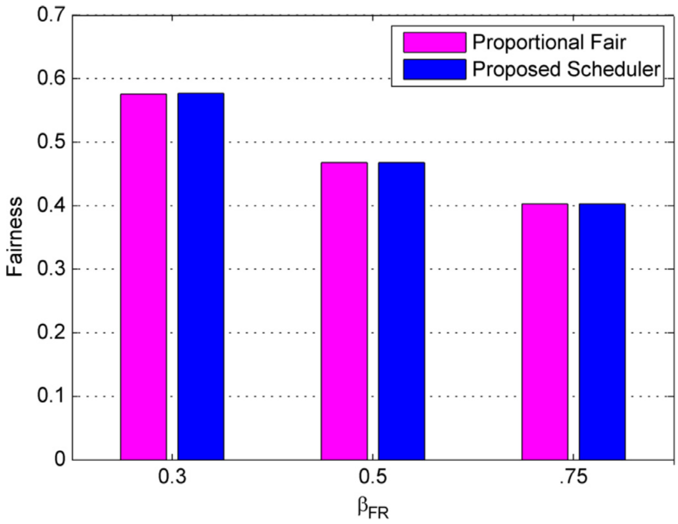


Fig. 25. Fairness vs β_{FR}.

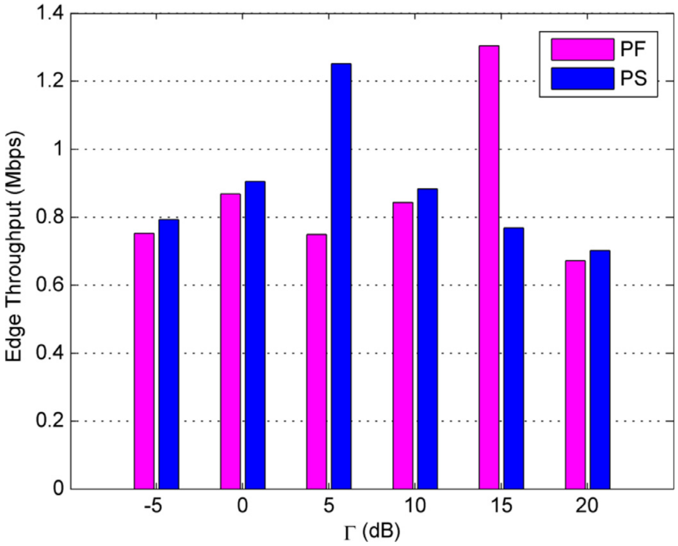


Fig. 26. Edge throughput vs Γ.

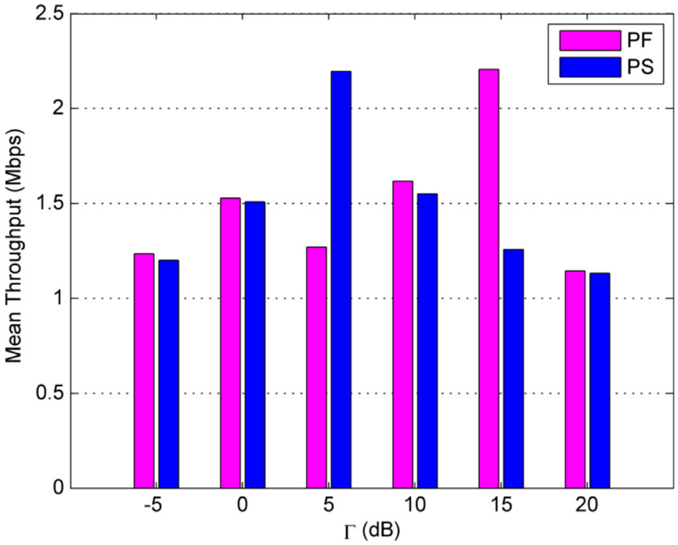


Fig. 27. Mean throughput vs Γ.

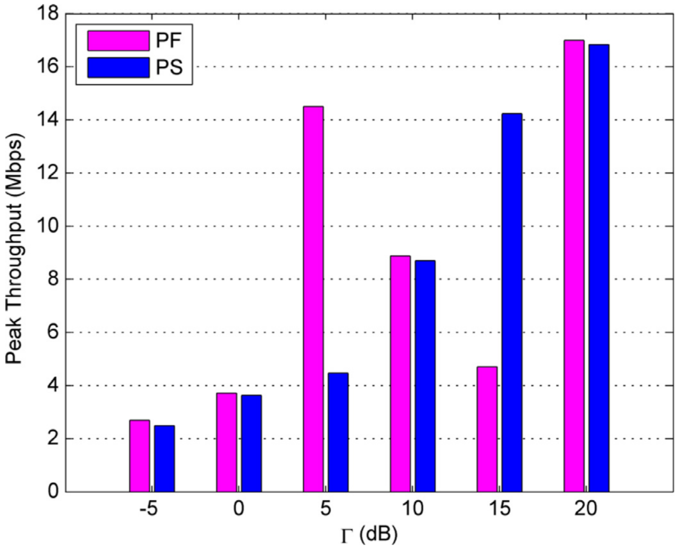


Fig. 28. Peak throughput vs Γ.

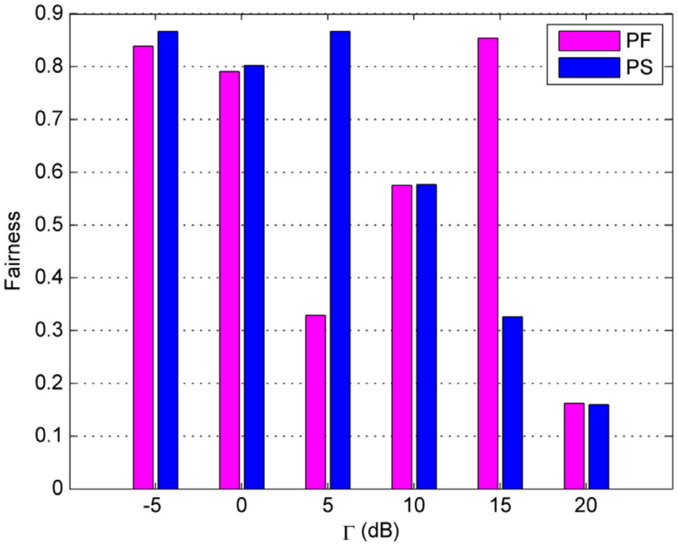


Fig. 29. Fairness vs Γ.

they both decline with β_{FR}. Fig. 25 shows the fairness results of the scheduling algorithms.

Figs. 26–29 depict the edge, mean, peak throughput and fairness results for six different Γ values. β_{FR} is fixed at 0.3 for these scenario. As seen from the figures, the proposed scheduler shows better performance for the edge and mean throughput and fairness when Γ is less than 15 dB. On the contrary, Proportional fair scheduler shows better performance when Γ is greater than 15 dB. It can be said that optimum Γ value is 5 and 15 dB for proposed scheduler and proportional fair algorithm respectively. For maximum peak throughput performance, Γ should be set to 20 dB for both schedulers.

4.8. *Summary of results*

In this section, we have shown the performances of scheduling algorithms under several parameters. In the first subsection, we examined the scheduling algorithms under different user loads. For a single cell with SISO antenna configuration, the proposed scheduler causes degradation up to 2 percent in the cell throughput which can be interpreted as an indicator of system throughput. In terms of edge throughput, the proposed scheduler increases the performance relative to proportional fair regardless of the number of the users exist in the network. Since there is a big performance gap between Round Robin and Best CQI algorithms relative to the other schedulers, these algorithms have been removed from the results after these subsections.

In the mobility subsection, user speeds were set to 5, 30, 100 km/h in three different simulations. Performance of the proposed scheduler has been decreased for all metrics more than other schedulers.

Effects of different carrıer frequencies on the performance metrics were investigated in the fourth subsection. Cell range has been set to 1 km to observe the changes more clearly. It is shown that edge throughput increases when the carrier frequency decreases. It is important that the proposed scheduler achieves highest system throughput and mean throughput for the higher frequencies, i.e. 1800, 2100 and 2600 MHz.

In multi-cell subsection, we set up a network which consists of 7 sites, 21 cells and 210 users. Proposed scheduler performs better than both MaxMin and Proportional Fair algorithms in terms of the mean throughput. There are no differences between single and multi-cell scenarios for the edge and peak throughput results.

In the Omni antenna subsection, bi-directional antenna is replaced with an omnidirectional antenna to see the impact of antenna type on

Table 5
Overview of performance evaluations of scheduling algorithms.

	Round Robin	Best CQI	MaxMin	Proportional Fair	Proposed Scheduler
Edge Throughput	❗	❌	✅	✅	✅
Mean Throughput	❌	✅	❗	✅	✅
Peak Throughput	❗	✅	❌	❗	❗
Fairness	❗	❌	✅	✅	✅

Good: ✅ Bad: ❌ Moderate: ❗

the throughput performances. For omni-directional with SISO antenna configuration, the proposed scheduler causes decrease in the edge throughput. On the contrary, the proposed scheduler increases the mean throughput relative to other scheduling algorithms.

The performance of FFR combined with the Proportional Fair and the proposed scheduler is analyzed in the last subsection. We set up simulations with three different β_{FR} and six different Γ values. The edge and mean throughputs decrease when β_{FR} increases for both schedulers. We show that the proposed scheduler and Proportional Fair algorithm has different behavior for the same Γ value. Optimum Γ is 5 and 15 dB for the proposed scheduler and the Proportional Fair algorithm respectively. To obtain maximum peak throughput performance, Γ should be set to 20 dB for both schedulers.

5. Conclusion

In this study, we proposed a new LTE downlink scheduling algorithm and we investigated throughput and fairness performances of the proposed algorithm with the four different existing scheduling algorithms, i.e., Round Robin, Proportional Fair, MaxMin and Best CQI. Simulations have been performed with multiple scenarios to observe the impact of the parameters on the performance metrics of the scheduling algorithms. In each scenario, we focused on the one of the following parameters: the number of users, the number of cells, the carrier frequency, the antenna type and configuration, FFR and the mobility. The simulation results were evaluated in terms of the edge, mean, peak and cell throughputs and fairness.

As a result, it was found out that in terms of edge throughput, the proposed scheduler showed better performance compared to the Proportional Fair algorithm. Although MaxMin algorithm was developed to maximize the edge throughput without any constraint on system throughput, the proposed scheduler showed significantly close results with MaxMin. Besides that, the proposed scheduler kept the system throughput much higher than MaxMin algorithm. A summary of the results is given in Table 5. The proposed scheduler achieved much higher data rates than other scheduling algorithms in terms of the edge throughput. Even the proposed scheduler caused degradation in the mean and peak throughput, the decrease in the mean and peak throughput stayed between 0 and 2 percent. In addition to that, the proposed scheduler showed better mean throughput than the Proportional Fair scheduler in some scenarios, with 4 × 4 MIMO, carrier frequencies higher than 1800 MHz. We can say that the proposed algorithm balances the tradeoff between overall system throughput and edge throughput when the gain in the edge throughput is taken into account. In terms of the peak throughput, the proposed scheduler stayed behind of the Proportional Fair in all scenarios, since the proposed scheduler is not designed to increase the peak throughputs of the users. Finally, we should note that fairness performance of the proposed scheduler is higher than that of the Proportional Fair and less than MaxMin scheduler.

References

[1] C.V.N. Index, Global Mobile Data Traffic Forecast Update 2014–2019, (2014) *White Pap*.
[2] C. Mehlführer, J.C. Ikuno, M. Simko, S. Schwarz, M. Wrulich, M. Rupp, The Vienna LTE simulators-enabling reproducibility in wireless communications research, EURASIP J. Adv. Sig. Proc. 2011 (2011) 29.
[3] S. Schwarz, J.C. Ikuno, M. Simko, M. Taranetz, Q. Wang, M. Rupp, Pushing the limits of LTE: a survey on research enhancing the standard, Access IEEE 1 (2013) 51–62.
[4] H. Kim, Y. Han, A proportional fair scheduling for multicarrier transmission systems, IEEE Commun. Lett. 9 (3) (2005) 210–212.
[5] Z. Sun, C. Yin, G. Yue, Reduced-complexity proportional fair scheduling for OFDMA systems, 2006 International Conference on Communications, Circuits and Systems, 2006, pp. 1221–1225.
[6] R. Kwan, C. Leung, J. Zhang, Proportional fair multiuser scheduling in LTE, IEEE Signal Process. Lett. 16 (6) (2009) 461–464.
[7] S. Schwarz, C. Mehlführer, M. Rupp, Low complexity approximate maximum throughput scheduling for LTE, Conference Record - Asilomar Conference on Signals, Systems and Computers, 2010, pp. 1563–1569.
[8] S. Schwarz, C. Mehlführer, M. Rupp, Throughput maximizing multiuser scheduling with adjustable fairness, IEEE International Conference on Communications, 2011, pp. 1–5.
[9] S.A. Alqahtani, M. Alhassany, Performance modeling and evaluation of novel scheduling algorithm for LTE networks, 2013 IEEE 12th International Symposium on Network Computing and Applications, 2013, pp. 101–105.
[10] L. Gavrilovska, D. Talevski, Novel scheduling algorithms for LTE downlink transmission, 2011 19thTelecommunications Forum (TELFOR) Proceedings of Papers, 2011, pp. 398–401.
[11] M. Escheikh, H. Jouini, K. Barkaoui, Performance analysis of a novel downlink scheduling algorithm for LTE systems, Advanced Networking Distributed Systems and Applications (INDS), 2014 International Conference on, 2014, pp. 13–18.
[12] N. Bechir, M. Nasreddine, A. Mahmoud, H. Walid, M. Sofien, Novel scheduling algorithm for 3GPP downlink LTE cellular network, Procedia Comput. Sci. 40 (2014) 116–122.
[13] S.S. Assaf, Performance Analysis of Prioritization in LTE Networks with the Vienna LTE System Level Simulator, MS thesis Universitat Politècnica de Catalunya, 2014.
[14] M. Carpin, A. Zanella, J. Rasool, K. Mahmood, O. Grondalen, O.N. Osterbo, A performance comparison of LTE downlink scheduling algorithms in time and frequency domains, IEEE International Conference on Communications, 2015, pp. 3173–3179.
[15] Qurat-ul-Ain, S.R. ul Hassnain, M. Shah, S.A. Mahmud, An evaluation of scheduling algorithms in LTE based 4G networks, Emerging Technologies (ICET), 2015 International Conference on, 2015, pp. 1–6.
[16] P. Kyösti, J. Meinilä, L. Hentilä, X. Zhao, T. Jämsä, C. Schneider, M. Narandzi, M. Milojevi, A. Hong, J. Ylitalo, V.-M. Holappa, M. Alatossava, R. Bultitude, Y. De Jong, T. Rautiainen, IST-4-027756 WINNER II D1. 1.2 V1. 2 WINNER II Channel Models.pdf, IST-4-027756 WINNER II D1. 1.2 V1. 2 WINNER II Channel Models.pdf 1 projectscelticinitiativeorg, 2008, p. 82.
[17] Evolved Universal Terrestrial Radio Access, Radio Frequency (RF) System Scenarios, Radio Frequency (RF) System Scenarios 8 (2009), p. 56. Technical Report, Release.
[18] R. Jain, A. Durresi, G. Babic, Throughput fairness index: an explanation, ATM Forum Contribution, 45 1999, pp. 1–13.
[19] M. Pelcat, S. Aridhi, J. Piat, J.-F. Nezan, Physical Layer Multi-Core Prototyping: A Dataflow-Based Approach for LTE EnodeB 171 Springer Science & Business Media, 2012.
[20] J.C. Ikuno, M. Taranetz, M. Rupp, A fairness-based performance evaluation of fractional frequency reuse in LTE, Smart Antennas (WSA), 2013 17th International ITG Workshop on, 2013, pp. 1–6.
[21] A. Gok, M. Koca, Performance evaluation of frequency planning and scheduling schemes in OFDMA Networks, Communications and Networking (BlackSeaCom), 2014 IEEE International Black Sea Conference on, 2014, pp. 149–153.

Coşkun Deniz received the B.Sc. Electronics Engineering degree in 2010 from the Department of Electronics Engineering at the Gaziantep University, Turkey. In 2015, he received his Master of Science degree from the Department of Computer Engineering at Bahçeşehir University, Turkey under the supervision of Dr. Vehbi Cagri Gungor. His research interests span both computer networking and software development.

O. Gokhan Uyan received his B.S degree in Computer Science from Bilkent University, Ankara, Turkey, in 2005. He received his M.S. degree in Electrical and Computer Engineering from Abdullah Gul University, Kayseri, Turkey in 2016 under the supervision of Dr. Vehbi Cagri Gungor. Currently, he is a Ph.D. student in Electrical and Computer Engineering and Research Assistant at Computer Engineering Department at Abdullah Gul University. His main research interests are in wireless and mobile communications, wireless and ad-hoc sensor networks, fuzzy logic and intelligent optimization algorithms, image processing.

V. Cagri Gungor received his B.S. and M.S. degrees in Electrical and Electronics Engineering from METU, Ankara, Turkey, in 2001 and 2003, respectively. He received his Ph.D. degree in electrical and computer engineering from the Broadband and Wireless Networking Laboratory, Georgia Institute of Technology, Atlanta, GA, USA, in 2007. Currently, he is an Associate Professor and Chair of Computer Engineering Department, Abdullah Gul University (AGU), Kayseri, Turkey. His current research interests are in smart grid communications, machine-to-machine communications, next-generation wireless networks, wireless ad hoc and sensor networks, cognitive radio networks. Dr. Gungor has authored several papers in refereed journals and international conference proceedings, and has been serving as an editor, reviewer and program committee member to numerous journals and conferences in these areas. He is also the recipient of TUBITAK Young Scientist Award in 2017, Science Academy Young Scientist Award (BAGEP) in 2017, Turkish Academy of Sciences Distinguished Young Scientist Award (TUBA-GEBIP) in 2014, the IEEE Trans. on Industrial Informatics Best Paper Award in 2012, the European Union FP7 Marie Curie IRG Award in 2009, Turk Telekom Research Grant Awards in 2010 and 2012, and the San-Tez Project Awards supported by Alcatel-Lucent, and the Turkish Ministry of Science, Industry and Technology in 2010.