Delft University of Technology

MOBILE NETWORKS

EE4396

Assignment - Packet scheduling in LTE/5G networks

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1 BACKGROUND

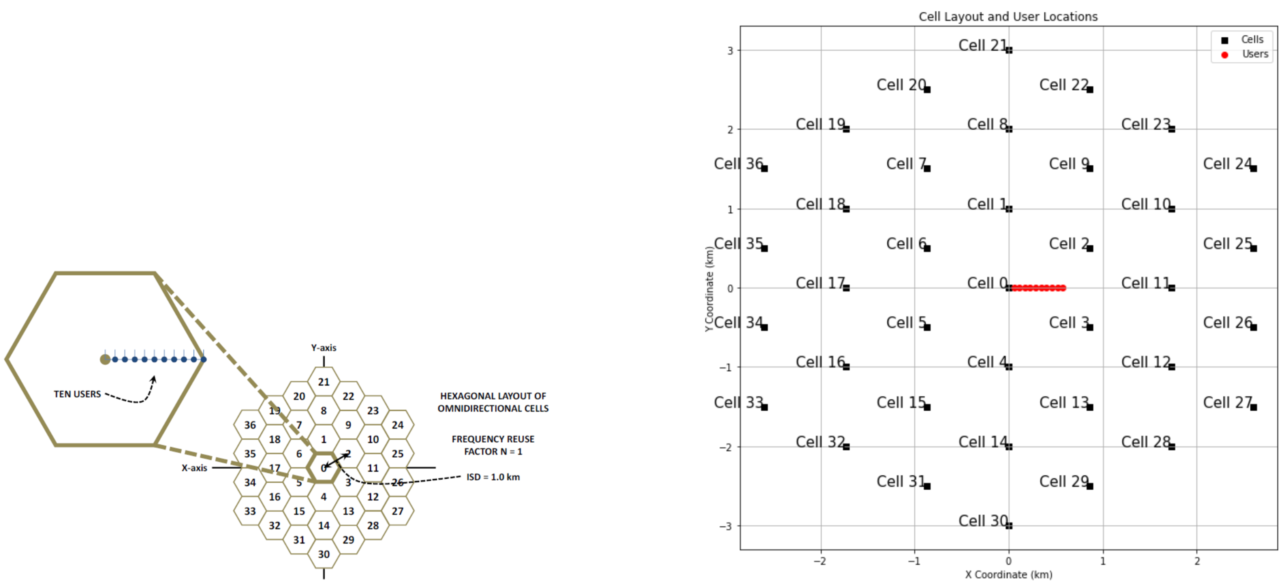
The objective of this assignment is to assess different packet scheduling methods in LTE/5G networks, in order to assess the gains from multi-user and frequency diversity, and quantify the trade-off between efficiency and different measures of fairness. The downlink of an LTE/5G network of 37 omnidirectional cells arranged in a hexagonal layout with an inter-site distance of 1.0 km is being considered as shown in figure 1. In cell 0(the origin), ten distinct users are located on a line from the cell to the cell edge, with equal distances from the cell site to the first user and then to each subsequent user. The radius R of the hexagon is related to the intersite distance by the formula:

$$R = \frac{\text{Intersite distance}}{\sqrt{3}} = \frac{1}{\sqrt{3}}$$

The distance between the center of the hexagon and the midpoint of any edge (the apothem) is:

$$\text{Apothem} = \frac{1}{2} \times \text{Intersite distance} = \frac{1}{2}$$

Using these relations, the coordinates for the first tier of hexagons was derived using pythagoras and scaled to get the outer tiers as shown in figure 1



(a) Considered LTE/5G Network

(b) Cell-Users layout

Figure 1: Cell Layout

Each cell is assigned a frequency carrier comprising 50 180 kHz-wide Scheduling Resource Blocks (SRBs), numbered 1, 2, . . . , 50, and deployed with a frequency reuse factor of $N = 1$ (contiguous reuse). The propagation environment is characterized by a distance-based path gain (in dB) equal to $-(115\ \text{dB} + 35 \times \log_{10}(\text{distance}_{\text{km}}))$, and by an additive (in dB) multipath fading effect which is modelled by means of 5000-TTI traces for the 10 users. To model the fact that the radio links between a given user and the 37 cells in the considered network are characterized by different multipath fading effects, the multipath fading for each user,srb trace were reused. For the radio link between user m and cell b, for each SRB, at TTI $(135 \times b + 1)$, $(5000 - 135 \times b)$ values were taken until the end of the (user, SRB)-specific trace, and then to that, the first $(135 \times b)$ values from the beginning of that trace were appended in order to end up with a 5000-TTI trace for each (user, SRB, cell) tuple.

2 TASK 1 - SINR and Attainable BitRates for User 0

In this section, all SRB and TTI resources were assigned to each user and their SINR and attainable bit rates were derived as detailed in the procedure below.

The distance for each user to the cells were derived using the euclidean distance from each user's coordinates to each cell's coordinate. The distance based path gain was then added to each multipath fading tracings for the users, cells and SRBs. Given as:

$$G = \text{path gain} + \text{multipath fading}$$

The gain in watts calculated as:

$$G_{\text{Watts}} = 10^{\frac{G}{10}}$$

The Signal-to-Interference-plus-Noise Ratio (SINR) for each user and SRB calculated as:

$$\text{SINR}_{\text{Watts}} = \frac{P_{\text{tx}}(i) \cdot G(i)}{\sum_{\substack{j=1 \\ j \neq i}}^{n} P_{\text{tx}}(j) \cdot G(j) + \text{thermal noise}}$$

where:

- $P_{\text{tx}}(i)$ is the transmitted power of cell 0 and $P_{\text{tx}}(j)$ the tx power of all other cells for the user, srb under consideration. Both equal to 20/50.
- $G(i)$ is the gain for cell 0 and $G(j)$ the gain for other cells for the user, srb under consideration.
- n is the total number of cells excluding cell 0.
- The thermal noise is given by kTB, where:
  - k is the Boltzmann constant (1.380649e-23).
  - T is the temperature in Kelvin (290K).
  - B is the SRB bandwidth(180 kHz).

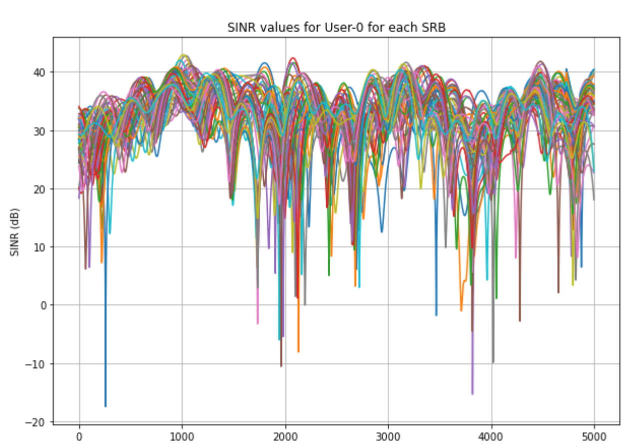
These SINR values were then converted to dB and the chart for User 0 is shown in Figure 2a.
The SINR values in dB were converted to the attainable bit rates using:

$$R = B \log_2 \left(1 + 10^{\frac{\text{SINR(dB)}}{10}}\right)$$

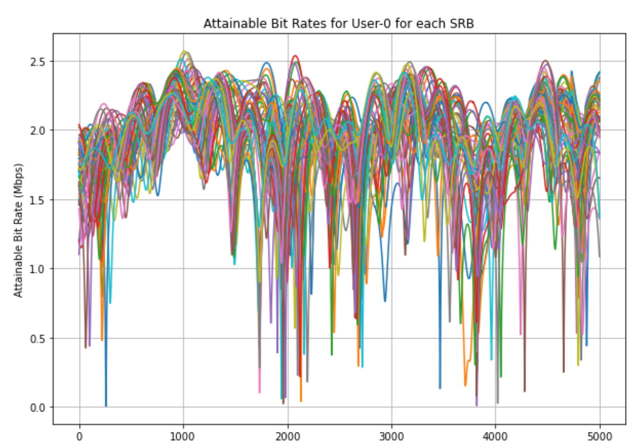
where:

- R is the attainable bit rate.
- B is the bandwidth(180KHz).
- SINR(dB) is the SINR value in decibels.

The attainable bit rates are reported in MBps in figure 2b. The bitrates were summed over all the SRBs across each TTI and the values reported in figure 3. Finally, the time-averaged experienced aggregate bit rate over the 5000 TTIs was derived for user 0 and determined to be 97.883Mbps in 3 decimal places.



(a) SINR(dB) for User 0



(b) Attainable Bitrate for User 0

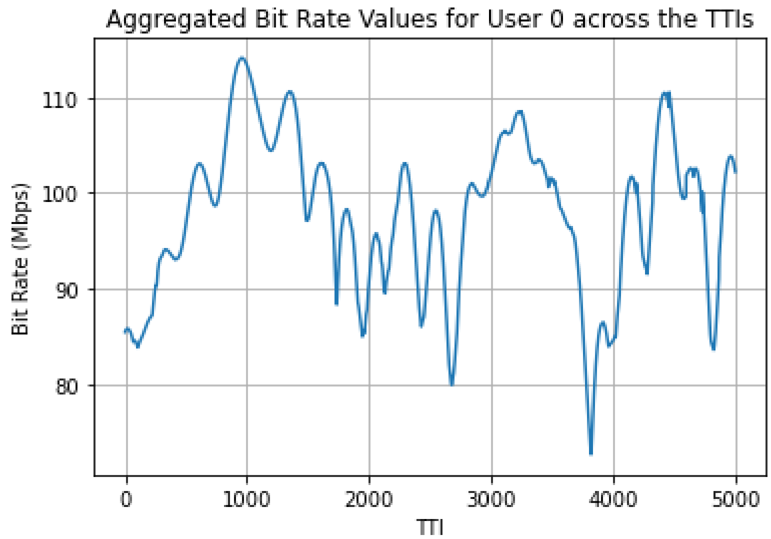


Figure 3: Aggregate bitrate for user 0 across the SRBs

The charts in figures 2a, 2b and 3 show the different channel conditions for User 0 across the TTIs and SRBs, showing peaks where the SINR/attainable bit rate is high indicating favourable channel conditions, and dips where the effects of multipath fading and interference are increased, indicating a degradation in quality.

3 TASK 2 - SINR and Attainable BitRates for Users 0-9

The steps in task 1 were repeated for the other users 1-9 and the aggregated bitrates(over the 50 SRBs) for all 10 users are shown in figure 4. The table showing the ten time-averaged aggregate bit rates for the ten users are shown in table 1.

Users	0	1	2	3	4	5	6	7	8	9
Time-Averaged Bit rate (MBps)	97.883	64.282	46.371	34.428	24.655	18.022	12.801	9.194	6.237	4.493

Table 1: Time-Averaged Aggregate BitRates for all 10 users

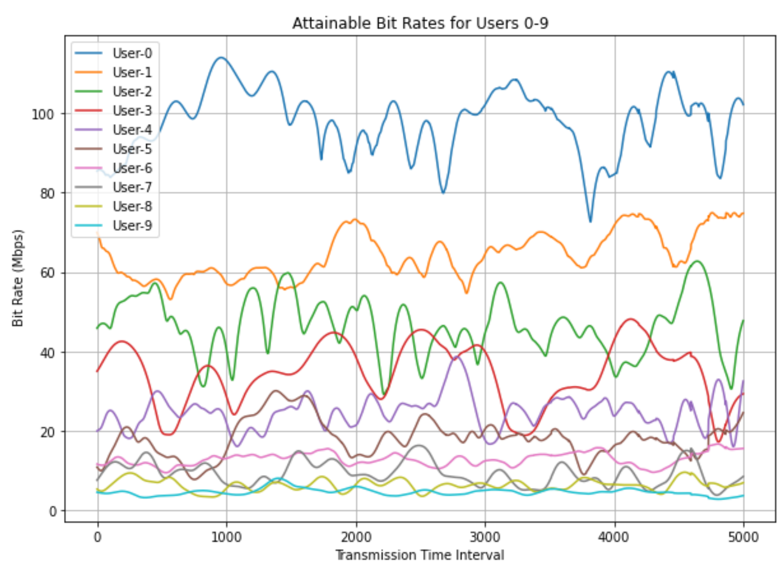


Figure 4: Attainable bitrates for all 10 users

From the observed attainable bit rates across the TTIs(figure 4) and the time averaged bitrates for all the users (table 1), it is evident that the user closest to the base station(user 0) has the highest attainable bit rates with an average of 97.883Mbps. This degrades as the users are positioned further away from the base station with the cell edge user(user 9), having the worst bit rate. This is because the signal strength closest to the base station is the highest and this signal attenuates as it gets further away from the base station. Additionally, the effect due to path loss increases as the user is farther away from the base station and users closer to the cell edge face more interference from neighbouring cells. However, there are few instances where users farther away from the base station temporarily achieve better bit rates than those closer to it. At these instances, the users closer to the base station, were likely more severely affected by multipath fading and increased interfering signals causing the severe dips at those instances.

4 TASK 3: PACKET SCHEDULING

In this section, packet scheduling is done for the 8-9 users first, then the 7-8-9 users,then 6-7-8-9, then 5-6-7-8-9, etc, all the way to the final case where the presence of all users is assumed. Packet scheduling is done using Time domain-only scheduling, using Round Robin(RR), Time domain-only scheduling, using 'Maximum Rate'(MR) scheduling, Time domain-only scheduling, using 'Proportional Fair'(PR) scheduling, and then all types repeated using Time/frequency-domain.

- Time domain-only scheduling, using Round Robin: For this scheduler, all SRBs in each TTI were assigned sequentially to a single user in a repeating pattern. That is; 8-9-8-9-8-9 for the 8-9 case.
- Time domain-only scheduling, using Maximum Rate: For this scheduler, all SRBs in each TTI were assigned to the user with the maximum aggregate bit rate (over all SRBs) at that TTI.
- Time domain-only scheduling, using Proportional Fair: For this scheduler, all SRBs were assigned to a single user, whose ratio of aggregate bitrate (over a specific TTI) to the time-averaged bit rate for that specific user is the highest for that TTI.
- Time frequency domain scheduling, using Round Robin: This scheduler utilizes both the time and frequency domains. Unlike time-domain scheduling where all SRBs at a specific TTI are assigned to a single user, here each SRB is sequentially assigned to every user in a repeating pattern.
- Time frequency domain scheduling, using Maximum Rate: In a given SRB and TTI, the scheduler assigns the resource to the user which, in that particular SRB has the highest bit rate.
- Time frequency domain scheduling, using proportional scheduling: In a given SRB and TTI, the scheduler assigns the resource to the user which, in that particular SRB has the highest ratio of the bit rate to the time-averaged bit rate of that particular user.

Metrics

- The average throughput for each user under each scheduling method was calculated by summing the throughput across all SRBs for each TTI and then dividing by the total number of TTIs.
- The cell throughput derived by aggregating the average throughput of each user.
- Jains fairness index was derived using the formula;

$$J = \frac{\left(\sum_{i=1}^{n} x_i\right)^2}{n \cdot \sum_{i=1}^{n} x_i^2}$$

  where x_i either denotes the average throughput allocated to the i-th user(throughput fairness) or the total count of times the user was allocated a resource (resource fairness) and n is the total number of users.

  - $J = 1$ represents perfect fairness, where all users receive equal throughput or resource allocation.
  - $J < 1$ indicates varying degrees of unfairness, with lower values indicating greater unfairness.

  The metrics were determined when users 8-9 were in the system for all scheduling algorithms and the results shown in section 4.1. Results for all other users in the system are shown in section 4.2.

4.1 Results for 8-9 users

Average Throughput (Mbps)	Time Domain			Time-Frequency Domain		
Users	Round Robin	Maximum Rate	Proportional Fair	Round Robin	Maximum Rate	Proportional Fair
8	3.118	5.340	3.796	3.123	5.084	4.555
9	2.247	1.063	2.385	2.254	2.802	3.250

Table 2: Average Throughput when users 8 and 9 are in the system for the different packet scheduling algorithms

Aggregate Cell Throughput(Mbps)	Time Domain			Time-Frequency Domain		
Users	Round Robin	Maximum Rate	Proportional Fair	Round Robin	Maximum Rate	Proportional Fair
8 - 9	5.365	6.403	6.181	5.377	7.886	7.805

Table 3: Cell Throughput when users 8 and 9 are in the system

Throughput fairness index	Time Domain			Time-Frequency Domain		
Users	Round Robin	Maximum Rate	Proportional Fair	Round Robin	Maximum Rate	Proportional Fair
8 - 9	0.974	0.692	0.95	0.975	0.923	0.973

Table 4: Throughput fairness when users 8 and 9 are in the system

Resource fairness index	Time Domain			Time-Frequency Domain		
Users	Round Robin	Maximum Rate	Proportional Fair	Round Robin	Maximum Rate	Proportional Fair
8 - 9	1	0.726	0.996	1	0.952	0.998

Table 5: Resource fairness when users 8 and 9 are in the system

4.2 Results for all other user combinations

The scheduling algorithms were run for all other user combinations, and the results are presented in Tables 6, 7, and 8 for Round Robin, Maximum Rate, and Proportional Fair scheduling, respectively. These tables also show the gains achieved by exploiting the frequency domain. Table 9 summarizes the gains for 2-user(8-9) and 10-user(0-1-2-3-4-5-6-7-8-9) scenarios across the scheduling algorithms. Additionally, Figures 5a, 5b, and 5 illustrate cell throughput, throughput fairness, and resource fairness for all scheduling algorithms. Finally, Figures 6a and 6b plot throughput fairness versus cell throughput and resource fairness versus cell throughput, respectively, for all (6 x 9) cases.

	Time Domain RR			Time Frequency Domain RR			Gains		
Num of Users	Cell Through-put(Mbps)	Throughput Fairness	Resource Fairness	Cell Through-put(Mbps)	Throughput Fairness	Resource Fairness	Cell Through-put(Mbps)	Throughput Fairness	Resource Fairness
2	5.365	0.974	1.000	5.377	0.975	1.000	0.229	0.024	0.000
3	6.641	0.921	1.000	6.641	0.921	1.000	-0.003	0.009	0.000
4	8.181	0.871	1.000	8.187	0.871	1.000	0.082	0.057	0.000
5	10.149	0.815	1.000	10.130	0.813	1.000	-0.191	-0.205	0.000
6	12.570	0.764	1.000	12.570	0.765	1.000	0.002	0.106	0.000
7	15.695	0.710	1.000	15.690	0.710	1.000	-0.028	0.058	0.000
8	19.525	0.667	1.000	19.530	0.667	1.000	0.025	0.016	0.000
9	24.511	0.620	1.000	24.498	0.620	1.000	-0.052	0.043	0.000
10	31.836	0.554	1.000	31.718	0.554	1.000	-0.369	0.017	0.000

Table 6: Results for Round Robin Scheduling

	Time Domain MR			Time Frequency Domain MR			Gains		
Num of Users	Cell Through-put(Mbps)	Throughput Fairness Index	Resource Fairness Index	Cell Through-put(Mbps)	Throughput Fairness Index	Resource Fairness Index	Cell Through-put(Mbps)	Throughput Fairness	Resource Fairness
2	6.403	0.692	0.726	7.886	0.923	0.952	23.148	33.436	31.157
3	9.364	0.429	0.473	11.605	0.738	0.818	23.935	71.948	72.971
4	13.048	0.328	0.322	16.173	0.581	0.653	23.951	76.803	102.992
5	18.367	0.251	0.272	21.748	0.447	0.499	18.405	77.841	83.040
6	25.284	0.234	0.238	28.887	0.343	0.384	14.252	46.660	61.013
7	35.214	0.179	0.191	38.687	0.261	0.287	9.862	45.717	50.424
8	47.244	0.161	0.164	50.670	0.214	0.231	7.251	33.328	41.249
9	64.350	0.116	0.117	67.610	0.165	0.176	5.065	41.411	50.235
10	97.883	0.100	0.100	98.612	0.110	0.113	0.745	10.058	12.758

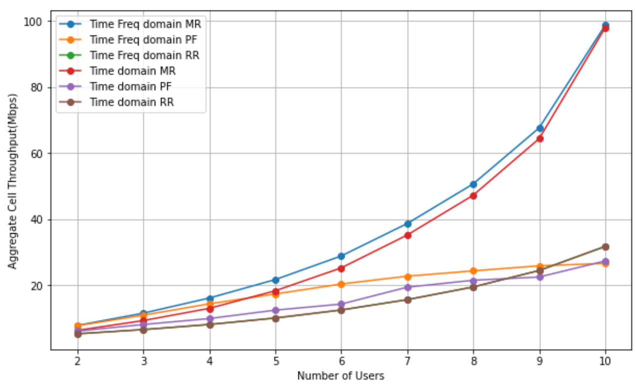
Table 7: Results for Maximum Rate Scheduling

	Time Domain PF			Time Frequency Domain PF			Gains		
Num of Users	Cell Through-put(Mbps)	Throughput Fairness Index	Resource Fairness Index	Cell Through-put(Mbps)	Throughput Fairness Index	Resource Fairness Index	Cell Through-put(Mbps)	Throughput Fairness	Resource Fairness
2	6.181	0.950	0.996	7.805	0.973	0.998	26.277	2.354	0.150
3	8.179	0.893	0.976	10.995	0.946	0.999	34.431	5.894	2.363
4	9.976	0.871	0.985	14.417	0.917	1.000	44.520	5.318	1.538
5	12.520	0.822	0.969	17.411	0.928	0.993	39.064	12.909	2.478
6	14.349	0.849	0.917	20.427	0.934	0.974	42.361	10.002	6.246
7	19.462	0.701	0.890	22.786	0.953	0.930	17.080	35.976	4.493
8	21.550	0.709	0.821	24.394	0.956	0.863	13.198	34.834	5.089
9	22.534	0.698	0.752	25.933	0.955	0.794	15.087	36.661	5.624
10	27.393	0.679	0.724	26.655	0.915	0.722	-2.693	34.712	-0.190

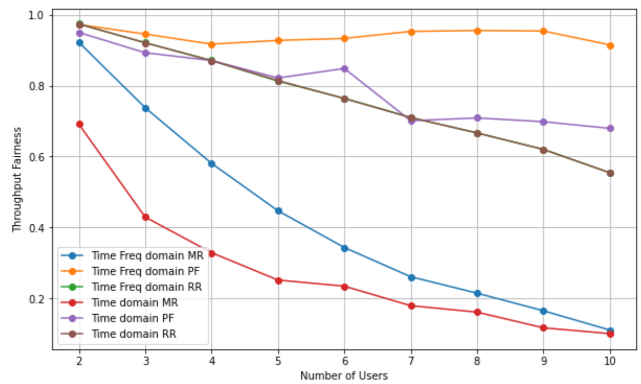
Table 8: Results for Proportional Fair scheduling

% Gain between 2 and 10 Users	Time Domain			Time Frequency Domain		
Scheduling Algorithm	Cell Throughput(Mbps)	Throughput Fairness	Resource Fairness	Cell Throughput(Mbps)	Throughput Fairness	Resource Fairness
Maximum Rate	1428.597	-85.539	-86.230	1150.508	-88.073	-88.162
Proportional Fair	343.190	-28.506	-27.338	241.513	-5.905	-27.585
Round Robin	493.417	-43.113	0.000	489.875	-43.117	0.000

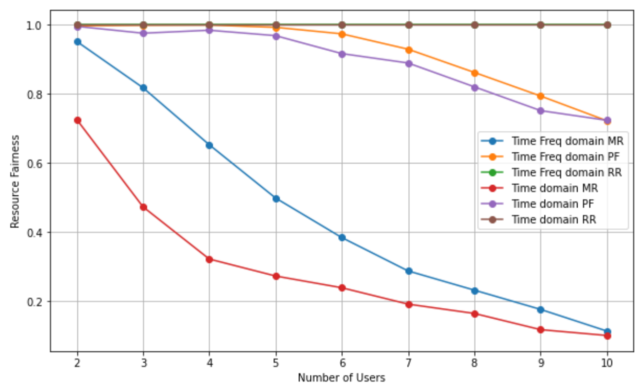
Table 9: % Gain when 2 users and 10 users are considered



(a) Cell throughput

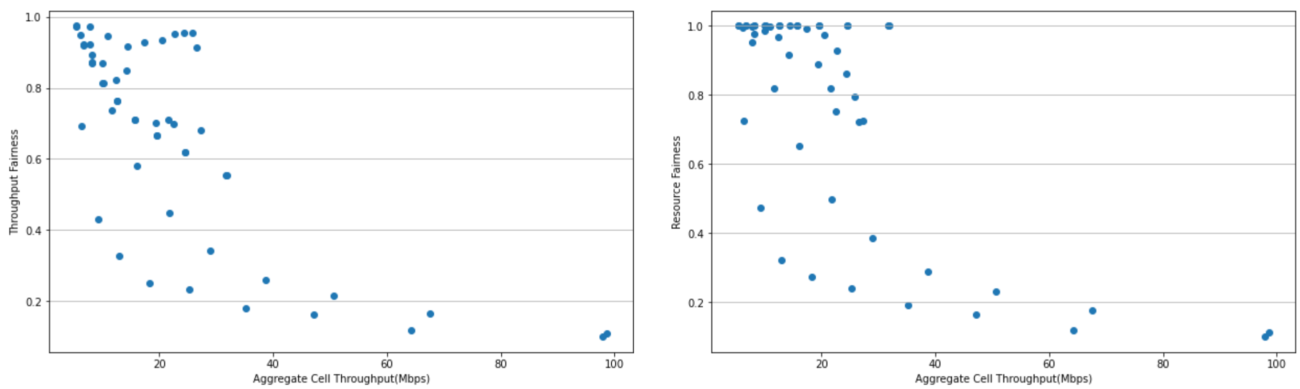


(b) Throughput fairness



(c) Resource fairness

Figure 5: Cell Throughput and Fairness across the different number of users for the scheduling algorithms



(a) Cell Throughput vs Throughput fairness

(b) Cell Throughput vs Resource fairness

Figure 6: Throughput vs Fairness for all 6 x 9 cases

5 DISCUSSION

5.1 Multi user gain

For all three scheduling algorithms, an increase in the number of users closer to the base station led to an increase in throughput, as users closer to the base station experience better channel conditions and thus achieve higher throughput. However, the Maximum Rate scheduling algorithm exhibits a significantly higher increase in aggregate cell throughput (showing a 1428.597% gain with 2 users compared to 10 users) compared to Proportional Fair (343.190% gain) and Round Robin (493.417% gain) as shown in Figure 5a, Tables 7 and 9. With 10 users, the throughput value is $\approx$ 97MBps with a very low throughput fairness and resource fairness, indicating that majority of the resources are allocated to the closest users to the base station. The Maximum Rate scheduling algorithm allocates resources to users with the highest bit rate at any given time. Therefore, adding more users closer to the base station results in a much higher throughput because resources are concentrated on the users with optimal channel conditions.

In contrast, the Proportional Fair algorithm allocates resources to the user whose instantaneous bit rate relative to their time-averaged bit rate is the highest. This ensures a fairer distribution of resources and throughput among all users while still trying to maximize throughput when compared to the Maximum Rate scheduling. However, it performs worse in terms of cell throughput than the Maximum Rate scheduling because it still assigns resources to users with poor channel conditions, even if their channel quality at that particular time relative to their average is favorable. It is also noted that Proportional Fair performs better than Round Robin until the number of users reaches 9-10. This might be because during this period, when comparing the PF ratios (instantaneous bit rate over the time-averaged bit rate) for each user, the users farther from the base station may have had higher ratios majority of the time, resulting in more resources being allocated to them and thus hindering users closest to the base station from getting resources. Unlike Proportional Fair, Round Robin allocates resources to all users in a fixed sequence, ensuring equal resource distribution regardless of channel conditions.

5.2 Frequency diversity

It is observed from tables 6, 7 and 8 that there is some gain when the time-frequency domain is considered, particularly in the Maximum Rate and Proportional Fair scheduling algorithms. The Maximum Rate, Proportional Fair and Round Robin have a cell throughput average gain of 14.06%, 25.48% and -0.03% respectively.

In the Maximum Rate scheduling algorithm, resources are allocated to users with the highest instantaneous bit rate. This would benefit from frequency diversity by selecting SRBs where the channel conditions are optimal. At certain SRBs, the channel experiences less fading and better signal quality, leading to higher bit rates. By assigning resources to the users with higher bit rates at better SRBs, Maximum Rate scheduling can improve overall throughput. This would allow the algorithm to take full advantage of the peaks in channel conditions across the different SRBs, ensuring that the users with the best possible conditions at any given moment are prioritized.

Likewise, the Proportional Fair scheduling algorithm selects users with best channel conditions at specific SRBs with respect to their time-averaged throughput. This increases the likelihood of assigning resources to SRBs with less fading, thus ensuring that users with instantaneous good bit rates compared to their average receive more resources, thereby improving the throughput while maintaining fairness over time. The Proportional Fair algorithm takes advantage of the variations in channel quality across the SRBs, providing a significant performance gain by using the best SRBs for each user. The % gain in Proportional Fair is higher than Maximum Rate possibly because a broader range of users (users 0-9) are likely to have highest PF ratios, resulting in a larger pool of SRBs being considered. In contrast to the Maximum Rate which focuses on users with the highest overall bit rates (those majorly closest to the base station) thus limiting its scope.

However, as seen in table 6, the Round Robin scheduling algorithm does not really benefit from frequency diversity in this scenario. As a result of assigning resources to users sequentially, the algorithm cannot take advantage of the peaks in channel quality at the different SRBs. Each user receives resources at regular intervals without considering the varying channel conditions across the SRBs, leading to similar results as the time domain.

5.3 Throughput and Resource Fairness vs Efficiency

Generally, as seen in figures 6a and 6b , higher cell throughput(efficiency) leads to lower throughput and resource fairness. It is observed that very high throughput values from above 28 Mbps, results in extremely low resource and throughput fairness values. This occurs because very high cell throughput values generally means resources are assigned to users with better channel conditions (those closer to the base station), depriving users farther from the base station (those near the cell edge) of resources as seen in Maximum Rate. It is also noted in figure 6a and 6b that some low throughput values have a low/average resource and throughput fairness. This typically occurs when there are fewer users under Maximum Rate scheduling. Those closer to the cell edge experience lower user throughput which results in lower cell throughput, but fairness issues persist because Maximum Rate scheduling prioritizes users with better channel conditions (those closer to the base station). Additionally, adding more users with better channel conditions significantly reduces the resource allocated to users with poorer channels which significantly reduces fairness. As seen in Table 9, with a cell throughput gain of 1428.597% when 2 users and 10 users were considered, throughput fairness and resource fairness reduced by 85.539% and 86.230% respectively.

In Round Robin scheduling, resource fairness remains consistently high as throughput increases, approximately 1 in all cases, because each user gets equal access to the resources. However, throughput fairness decreases as cell throughput increases, as seen in Figures 5b. This occurs because, as more users are added, they all receive equal access to resources, but users closer to the base station still achieve higher average throughput due to their better channel conditions. As seen in Table 9, with a cell throughput gain of 493.417% when 2 users and 10 users were considered, throughput fairness and resource fairness reduced by 43.113% and 0% respectively.

Although the throughput fairness of Proportional Fair in the time domain decreases with an increasing number of users, it outperforms other methods in terms of throughput fairness, with the time-frequency domain exhibiting the highest values (Figure 5b).This indicates that Proportional Fair effectively distributes resources among users, ensuring a fair share of throughput for all. While its resource fairness is lower than that of Round Robin, it is higher than that of Maximum Rate, striking a balance between throughput and resource allocation fairness. As seen in Table 9, with a cell throughput gain of 343.190% when 2 users and 10 users were considered, throughput fairness and resource fairness reduced by 28.506% and 27.336% respectively for the time domain while the throughput fairness decreased by only 5.905% for the time-frequency domain.

6 CONCLUSION

This report has comprehensively evaluated three scheduling algorithms - The Maximum Rate, Round Robin and Proportional Fairness. The results reveal that the Round Robin algorithm achieved the highest resource fairness but it is not as efficient as Maximum Rate because it assigns resources equally to all users. The Maximum Rate is the most efficient allowing the PRBs to be efficiently utilized and to transmit more bits across with an increase in users. However, it's resource and throughput fairness values were the poorest. Proportional Fair provides a balance between efficiency and fairness. PRBs are efficiently utilized while ensuring fairness between the users. It had the highest throughput fairness and although not as efficient as the Maximum Rate, it still achieved higher cell throughput than the Round Robin algorithm when 2-8 users were in the system. It is also not as resource fair as Round Robin, but it still exhibited higher resource fairness than Maximum Rate. Lastly, Proportional Fair and Maximum Rate both exhibited gains with respect to frequency diversity in contrast with Round Robin.

Estimated time it took - 12 hours