Task 1: Understanding the impact of throughput and delay achieved by UEs using three different MAC scheduling algorithms (e.g., Round Robin (RR), Proportional Fair (PF), and Maximum Rate (MR)). Use additional simulation parameters mentioned below for this task and fill the values in the table.

Part A:

i) Analysing average aggregate throughput, packet loss rate and packet delay for Full buffer case

Simulation Parameters

Numerology	1
NrMacScheduler	Tdma, Ofdma

Average Aggregate Throughput (Mb/s): Sum up individual UE throughputs given by the flow monitor to get aggregate throughput of 6 UEs in each experiment and take average of the aggregate throughputs after repeating it for 5 seeds (RngRuns)
runs : 13,14,15,16,17

RR -TDMA

seed	Throughput	packetLoss	Packdelay
13	4.060146	90.435944	1318.680111
14	4.145990	90.234562	1698.712803
15	4.149065	90.226215	1700.072115
16	4.374199	89.696154	1686.789378
17	4.587265	89.194265	1675.243218
Avg	4.263333	89.957428	1615.899525

OFDMA

seed	Throughput	packetLoss	Packdelay
13	3.426063	91.932219	1749.173903
14	3.613747	91.491893	1722.832980
15	3.627870	91.457459	1730.431212

16	3.744403	91.192429	1727.230608
17	3.928593	90.759406	1717.582736
Avg	3.6681352	91.3666812	1729.4502878

PF - TDMA

seed	Throughput	packetLoss	Packdelay
13	4.170421	90.176131	1309.697626
14	4.261150	89.978923	1689.286927
15	3.908067	90.794883	1729.908832
16	4.447987	89.538596	1680.021098
17	4.484817	89.436340	1684.437167
Avg	4.2544884	89.9849746	1618.67033

OFDMA

seed	Throughput	packetLoss	Packdelay
13	3.874474	90.875227	1635.352751
14	3.825153	90.992091	1727.152408
15	4.026909	90.516288	1688.061603
16	3.925247	90.756276	1725.131318
17	4.564469	89.266262	1713.222578
Avg	4.0432504	90.4812288	1697.7841316

MR-TDMA

seed	Throughput	packetLoss	Packdelay
13	21.396064	49.596194	380.199752
14	21.422500	49.534631	767.253613
15	21.528810	49.283165	372.946009
16	21.936206	48.323212	350.832568
17	22.476602	47.050231	321.200730

Avg	21.7520364	48.7574866	438.4865344

OFDMA

seed	Throughput	packetLoss	Packdelay
13	9.845343	76.811912	625.780933
14	10.754248	74.670799	567.949599
15	9.467696	77.698825	628.997172
16	10.641711	74.937916	576.865778
17	11.048508	73.976919	556.442435
Avg	10.3515012	75.6192742	591.2071834

	RR		PF		MR	
	TDMA	OFDMA	TDMA	OFDMA	TDMA	OFDMA
Average Aggregate Throughput (Mb/s)	4.263333	3.6681352	4.2544884	4.0432504	21.7520364	10.3515012
Average Packet Loss Rate	89.957428	91.3666812	89.9849746	90.4812288	48.7574866	75.6192742
Average Packet Delay	1615.899525	1729.4502878	1618.67033	1697.7841316	438.4865344	591.2071834

Q1. Based on the values measured, provide an analysis of the trends observed and quantify improvement in performance (i.e., throughput, loss and delay) for different scheduling algorithms studied.

Answer:

Average Aggregate Throughput:

More average throughput has been observed in MR than RR and PF. In TDMA, MR gave more than 5 times the average throughput than RR and PF. In OFDMA, MR has more than 2 times

that of RR and PF. This trend can be observed because MR prioritises the users with best channel strength which increases the average throughput but it's not fair in terms of resource allocation among all users.

Average Packet Loss:

Average Packet Loss is as expected from the throughput results. MR has around 20% less packet loss when compared to RR and PF in OFDMA. Whereas it has around 40-50% less packet loss in TDMA. And when observing the same scheduling schemes with different NrMacScheduler types, RR and PF have similar packet loss in both TDMA and OFDMA. But MR has significantly less average packet loss in TDMA compared to OFDMA.

Average Packet Delay:

MR has around 60% less packet delay when compared to RR and PF. And when observing the same scheduling schemes with different multiplexing schemes, RR and PF have similar packet delay in both TDMA and OFDMA. But MR has less average packet loss in TDMA compared to OFDMA.

ii) Repeat the above set of experiments for Non Full Buffer case and fill the measurements in the table (same as previous one)

RR - TDMA

seed	Throughput	packetLoss	Packdelay
13	4.060146	66.789855	775.068111
14	4.145991	66.090580	1143.709972
15	4.147547	66.072464	1147.862321
16	4.374200	64.221014	1101.157470
17	4.587265	62.478261	1061.083885
Avg	4.2630298	65.1304348	1045.7763518

OFDMA

seed	Throughput	packetLoss	Packdelay
13	3.475151	71.608696	1273.306854
14	3.706374	69.695652	1224.387049
15	3.619687	70.398551	1244.981241
16	3.813037	68.818841	1210.446678

17	3.961376	67.612319	1185.473055
Avg	3.715125	69.6268118	1227.7189754

PF-TDMA

seed	Throughput	packetLoss	Packdelay
13	4.170421	65.887681	751.311626
14	4.261150	65.202899	1119.746261
15	3.908067	68.036232	1205.817499
16	4.447987	63.673913	1085.441765
17	4.484817	63.318841	1083.166164
Avg	4.2544884	65.2239132	1049.096663

OFDMA

seed	Throughput	packetLoss	Packdelay
13	3.874474	68.315217	1111.880180
14	3.825153	68.721014	1215.224408
15	4.026909	67.068841	1140.769696
16	3.925247	67.902174	1198.037406
17	4.564469	62.728261	1096.509285
Avg	4.0432504	66.9471014	1152.484195

MR-TDMA

seed	Throughput	packetLoss	Packdelay
13	7.646844	37.449275	98.991666
14	7.636515	37.532609	486.317064
15	8.162061	33.242754	350.711742
16	8.968182	26.644928	235.341700
17	8.179466	33.101449	349.322118
Avg	8.1186136	33.594203	304.136858

OFDMA

seed	Throughput	packetLoss	Packdelay
13	6.514432	46.739130	315.928153
14	7.112351	41.826087	583.398696
15	6.608004	45.996377	663.981716
16	7.218411	41.014493	490.506374
17	7.675187	37.452899	453.778646
Avg	7.025677	42.6057972	501.518717

	RR		PF		MR	
	TDMA	OFDMA	TDMA	OFDMA	TDMA	OFDMA
Average Aggregate Throughput (Mb/s)	4.2630298	3.715125	4.2544884	4.0432504	8.1186136	7.025677
Average Packet Loss Rate	65.1304348	69.6268118	65.2239132	66.9471014	33.594203	42.6057972
Average Packet Delay	1045.7763518	1227.7189754	1049.096663	1152.484195	304.136858	501.518717

Q2. Based on the values measured for non full buffer case, provide an analysis of the trends observed and quantify improvement in performance (i.e., throughput and delay) for different scheduling algorithms studied.

Answer:

Average Aggregate Throughput:

More average throughput has been observed in MR than RR and PF. MR has around 2 times that of RR and PF. This trend can be observed because MR prioritises the users with best channel strength which increases the average throughput but it's not fair in terms of resource allocation among all users. The overall trend in average throughput is similar to full buffer case but the increase in average throughput in case of MR is not as aggressive as in full buffer case.

Average Packet Loss:

Average Packet Loss is as expected from the throughput results. MR has around 20% less packet loss when compared to RR and PF in OFDMA. Whereas it has around 50% less packet loss in TDMA. And when observing the same scheduling schemes with different NrMacScheduler types, RR and PF have similar packet loss in both TDMA and OFDMA. But MR has significantly less average packet loss in TDMA compared to OFDMA.

Average Packet Delay:

MR has around 60% less packet delay when compared to RR and PF. And when observing the same scheduling schemes with different multiplexing schemes, RR and PF have similar packet delay in both TDMA and OFDMA. But MR has less average packet loss in TDMA compared to OFDMA.

Part B: Analysing throughput, loss and delay achieved for each UE in Full Buffer Case by using the simulation parameters mentioned below and fill the values in the table.

Simulation Parameters

Numerology	1
#Seeds	1 (Set RngRun = “Last TWO DIGITS of one of your ROLL NUMBERS”)
NrMacScheduler	Tdma, Ofdma

Throughput (Mb/s), loss rate and delay (m/s): 13

NrMacScheduler = Tdma									
UE ID	RR			PF			MR		
	Throughput	Loss Rate	Delay	Throughput	Loss Rate	Delay	Throughput	Loss Rate	Delay
1	8.084173	80.955362173668	1870.345324	8.171999	80.748763538471	1859.878992	12.203518	0.173913	8.721708
2	7.675035	81.919489137932	1892.339573	8.169214	80.755024103174	1860.121737	12.203328	0.173913	8.793331
3	0.517746	98.785450447643	2278.907592	0.512352	98.797971577036	2277.486994	9.271653	24.1522	567.375944
4	8.08392	80.9553	1870.	8.1689	80.755	1860.6	12.2025	0.19565	9.059

	2	6217366	488180	60	024103174	98032	66	2	015
5	0.517728	98.78545052	2279.050273	0.512332	98.79797158	2278.146033	0	100	0
6	0	100	0	0	100	0	0	100	0

NrMacScheduler = Ofdma									
UE ID	RR			PF			MR		
	Throughput	Loss Rate	Delay	Throughput	Loss Rate	Delay	Throughput	Loss Rate	Delay
1	6.557831	84.555186877856	1961.277757	7.555679	82.201214549552	1901.204566	12.202566	0.195652	10.024109
2	6.810362	83.960433231077	1948.366040	7.547706	82.219996243661	1902.197753	12.201224	0.26087	11.906564
3	0.389413	99.085957553371	2335.925825	0.563665	98.672760282978	2269.829708	2.480236	79.7826	1863.595733
4	6.557831	84.555186877856	1961.277757	7.555679	82.201214549552	1901.003056	12.202566	0.195652	10.042515
5	0.240943	99.436549176736	2288.196037	0.024113	99.956176047079	1837.881424	0	100	0
6	0	100	0	0	100	0	0	100	0

Q3. Based on the values reported in above tables, provide an analysis of the trends observed and quantify improvement in performance (i.e., throughput, loss and delay) for different scheduling algorithms studied. Also, comment on the impact of NrMacScheduler type on the results obtained.

Answer:

We can observe that RR and PF are similar in average throughput in most of the cases, but MR has significantly more average throughput when compared to them. But when we observe each UE's throughput separately in MR, UE 5 and UE 6 have 0 throughput as their channel

bandwidth is lower when compared to other UEs. So the scheduler doesn't allocate packets to these UEs because they are farther away from the gNB. But in RR each UE gets an equal time slice which is not exactly fair in the context of throughput but is fair in time allocation. In PF, each UE is given a time allocation such that their average throughput is maintained fairly. This is why MR has more average throughput than RR and PF since MR always favors the UE with maximum channel strength. Some UEs like UE 5 and 6 are too far from gNB, which makes their throughput 0. TDMA has more throughput than OFDMA. Packet loss rate also follows the same trend as we observed previously.

Task 2: Understanding the impact of different Numerologies (0 to 3) in Full Buffer Case. Use the additional simulation parameters mentioned below and fill the values in the table.

Simulation Parameters

Part A:

Numerologies	0,1,2,3
NrMacScheduler	TdmaPF

Average Aggregate Throughput (Mb/s):

	Numerology 0	Numerology 1	Numerology 2	Numerology 3
Average Aggregate Throughput (Mb/s)	14.891969	4.170421	4.038725	3.930319
Average Loss Rate	64.919969	90.176131	90.487072	90.743755
Average Delay	347.700632	1309.697626	1307.409795	1324.818554

Q4: Based on the values measured provide an analysis of the trends observed and quantify improvement in performance (i.e., throughput, loss rate and delay) for different Numerologies. Which numerology is more suitable for time-sensitive traffic?

Answer:

We can observe that the average throughput, average packet loss and average packet delay are mostly similar for numerology 1,2,3. But numerology 0 has almost 3-4 times more average throughput when compared to other numerologies. Average packet loss of numerology 0 is almost 30% less when compared to numerology 1,2,3. Average packet delay of numerology is also observed to be 70-75% less when compared to others. So numerology 0 is most suitable for time-sensitive traffic for its low average packet delay.

Part B: Analysing throughput, loss rate, and delay achieved for each UE for different numerologies in Full Buffer Case . Use the simulation parameters mentioned below and fill the values in the table.

Numerology	0,1,2, 3
NrMacScheduler	TdmaPF
#Seeds	1 (Set RngRun = “Last TWO DIGITS of one of your ROLL NUMBERS”)

Throughput (Mb/s), loss rate and delay (m/s):

NrMacScheduler = TdmaPF									
UE	Numerology 0			Numerology 1			Numerology 2		
	Throughput	Loss Rate	Delay	Throughput	Loss Rate	Delay	Throughput	Loss Rate	Delay
1	42.357186	0.21911976460277	10.212979	8.171999	80.748763538471	1859.878992	7.928026	81.32473549114 1	1859.334401
2	42.359159	0.21911976460277	9.942455	8.169214	80.755024103174	1860.121737	7.930161	81.31847492643 8	1860.357063
3	4.635469	89.081575158079	2066.048359	0.512352	98.797971577036	2277.486994	0.451605	98.94196456520 4	2264.498235
4	0	100	0	8.168960	80.755024103174	1860.698032	7.922557	81.33725662054 7	1860.269073
5	0	100	0	0	100	0	0	100	0
6	0	100	0	0	100	0	0	100	0

	Numerology 3		
UE	Throughput	Loss Rate	Delay
1	8.205148	80.6736	1868.439894

2	6.666158	84.2985	1942.179673
3	0.392564	99.0797	2287.417832
4	8.318042	80.4107	1850.873927
5	0	100	0
6	0	100	0

Q5: Based on the values measured provide an analysis of the trends observed and quantify improvement in performance (i.e., throughput, loss rate and delay) for different numerologies. Comment on how fair is PF.

Answer:

As we observed from the previous values, numerology 0 has better throughput when compared to numerology 1,2,3. Numerology 1,2,3 have similar throughputs, packet loss and delays. And we can observe that UEs which are positioned farther from the gNB have more packet loss and delays.

- UE 1 gets 5 times the throughput when it uses numerology 0 over numerology 1,2,3.
- UE 2 gets 5 times the throughput when it uses numerology 0 over numerology 1,2,3.
- UE 3 gets 9-10 times the throughput when it uses numerology 0 over numerology 1,2,3. But when compared to that of UE 1,2 throughput is drastically less and even packet loss and delay are significantly higher for UE3 when compared to that of UE 1,2.
- UE 4 received no throughput when using numerology 0 and the same as UE 1,2 when using numerology 1,2,3. This is because UE 4 is very close to gNB at (-10,0).
- UE 5,6 didn't receive any packets in any numerology as they are located very far from gNB and in the opposite direction to the directional gNB antenna. This can clearly be observed in the SINR plot in question 7.

Fairness provided by PF is great compared to other schemes. This can be observed from the throughput values of UE 1 and UE 2 which are located at (10,0) and (1000,0) respectively. But still getting a similar throughput is commendable.

Task 3. Understanding the impact of Mobility in Full Buffer Case. Refer here to know more about these RandomWalk2d Mobility Model. Using the simulation parameters mentioned below and fill the values in the table.

Simulation Parameters

Numerology	1
NrMacSchedulerTdma	PF
Simulation Time	20 Seconds
UE mobility model	RandomWalk2d Mobility
Speeds	10 m/s, 50 m/s
Seeds	5

Average Aggregate Throughput (Mb/s):

Speed (meter/s)	RR	PF	MR
10	3.6172026	4.3983586	20.7890315
50	3.3474226	4.3624058	18.3829576

Avg Loss Rate :

Speed (meter/s)	RR	PF	MR
10	94.6248678	93.022315	56.5085618
50	95.1265132	93.2665744	59.8311684

Avg. Delay (ms):

Speed (meter/s)	RR	PF	MR
10	4208.7772172	4352.280706	1136.7716728
50	3943.5362472	4189.7627816	1554.0029996

Q6: Based on the values measured, provide an analysis of the trends observed and quantify improvement/loss in performance (i.e., throughput, loss rate and delay) for different mobile scenarios. Compare these results with that of the static scenario.

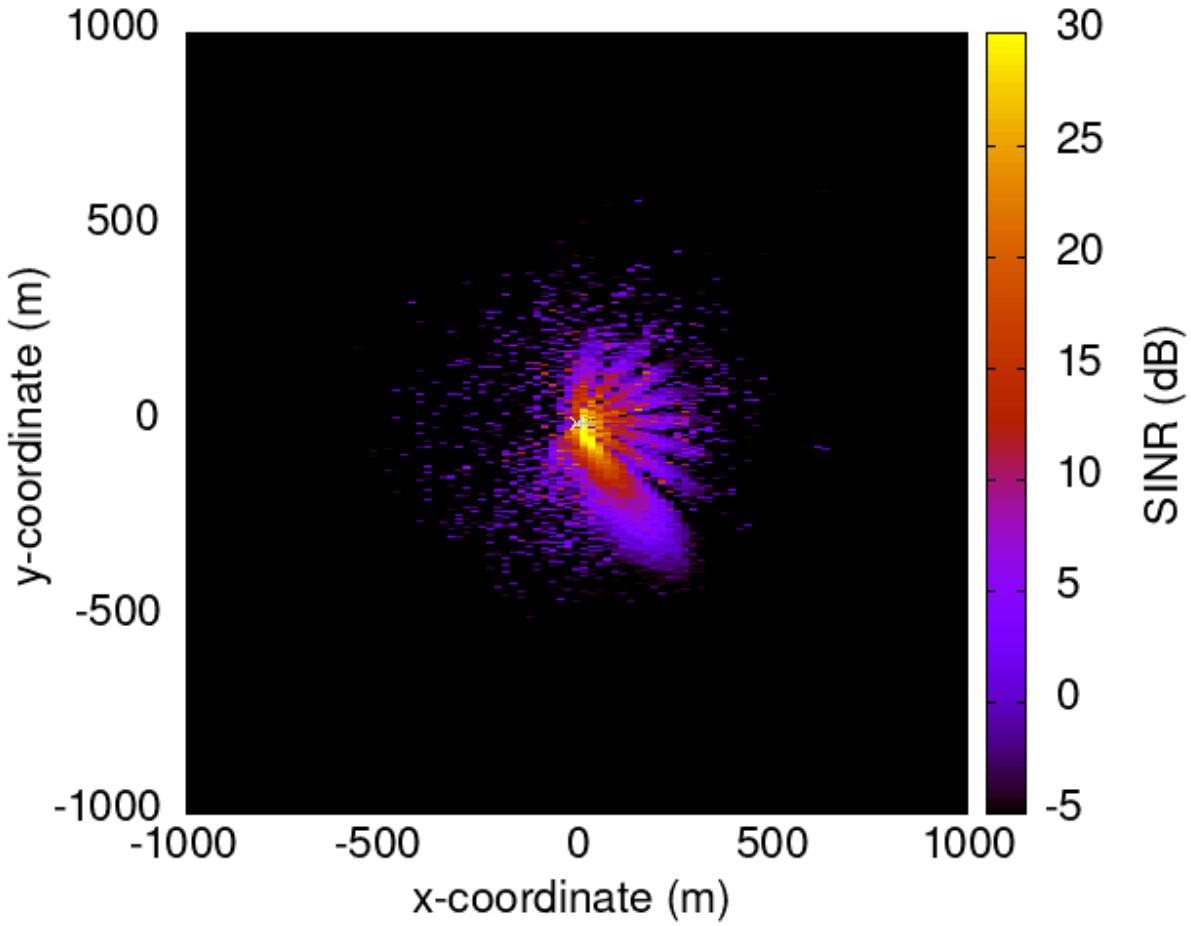
Ans.

More average throughput has been observed in MR than PF and RR. In TDMA, MR gave more than 5-6 times the average throughput than RR and PF. This tendency can be seen since MR prioritises users with the best channel strength leads to increase in average throughput but not being fair in resource distribution among all users.

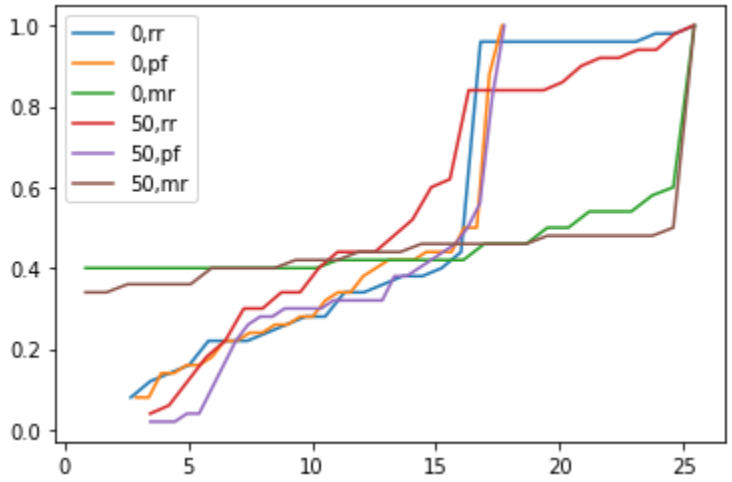
Lesser Average loss rate has been observed in MR than PF and RR because most of the resources are given to the users with higher channel strength, so the loss rate for users with higher channel strength will be less which leads to a lesser average loss rate compared to PF and RR.

Task 4: Also, you need to turn in the following graphs

Q7: Plot Graph 1: SINR Radio Environment Map (REM) plots of single-cell topology given above. Note: refere to *Rem-beam-example.cc* example program in 5G NR module.



Q8: Plot Graph 2: Throughput CDF plot for different TDMA schedulers at Speeds (0,50) m/s for full buffer scenario for 20 secs for 5 seeds; One curve each for 0 m/s (static case) and 50 m/s (mobile case). Scheduling algorithms need to be evaluated with 20 UEs. Location of the UEs can be set between (10,0) to (3000,0) randomly. Set numerology to 1. Note that here you need not to do any averaging. Have a list of per UE throughputs across in all different runs by varying the seed value and use them for plotting CDF. Report your observations from the plot.

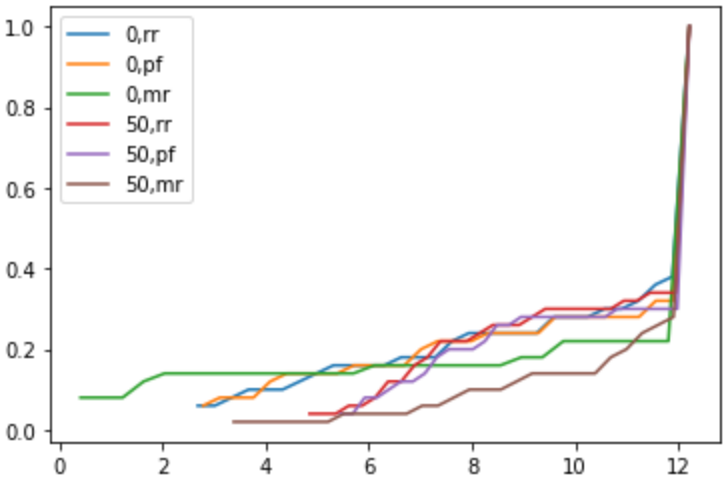


For Static case, In MR 40% of all the flows in the simulation have throughput value less than 1. We can also see there are no flows having throughput values from 1-10 and 11-15 in the case of MR . For all scheduling algorithms 40% of the flows have lesser throughput than 15. We can also observe there are more flows with threshold value less than 15 in MR compared to PF and RR. There are more flows in PF and RR having throughput values more than 15 in comparison with MR. Both PF and RR have almost the same threshold values. 90% the flows of PF and RR schedulers have throughput value less than 18.

We can observe similar trends of respective schedulers in both the mobile and static case.

We can see all the flows of all schedulers have a threshold value less than 25.

Q9: Plot Graph 3: Throughput CDF plot for different TDMA schedulers at Speeds (0,50) m/s for non buffer scenario for 20 secs for 5 seeds; One curve each for 0 m/s (static case) and 50 m/s (mobile case). Set numerology to 1 and number of users to 20 (set UE positions as above). Report your observations from the plot.



For Static case, All the scheduling algorithms throughput is less than 12 and also all the scheduling algorithms 15% of the flows have a throughput value less than 6. In MR, there are no flows with throughput values from 2-5.7, 6-8.3, and 10-12, whereas in other scheduling algorithms we can observe all flows have throughput values from 3-12. We can see 40% of all the flows have a threshold value less than 12, and the rest have a throughput value of 12.

PLAGIARISM STATEMENT

I certify that this assignment/report is our own work, based on our personal study and/or research on our personal/lab equipment and that we have acknowledged all material and sources used in its preparation, whether they be books, articles, reports, lecture notes, and any other kind of document, electronic or personal communication. We also certify that this assignment/report has not previously been submitted for assessment in any other course, except where specific permission has been granted from all course instructors involved, or at any other time in this course, and that we have not copied in part or whole or otherwise plagiarised the work of other students and/or persons. We pledge to uphold the principles of honesty and responsibility at CSE@IITH. In addition, We understand our responsibility to report honour violations by other students if we become aware of it.

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