SCHEDULING ALGORITHMS FOR 5G NR

A Project Report

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THESIS CERTIFICATE

This is to certify that the thesis titled **SCHEDULING ALGORITHMS FOR 5G NR**, submitted by **BODAGALA VISWA CHAITANYA**, to the Indian Institute of Technology, Madras, for the award of the degree of **BACHELOR OF TECHNOLOGY**, is a bona fide record of the research work done by him under our supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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ABSTRACT

KEYWORDS: 5G, Scheduler, Proportional Fair, Max Age, Throughput, Delay;

The Increasing number of users in the recent times has given a new problem to solve in telecommunications which led to the development of 5G NR. One of the key problem is the resource allocation to users by a base station which is the key part in measuring the delay and data throughput that is received by a user. Our aim is to design and implement a scheduler with an efficient scheduling algorithms for assigning the resources to a user while considering the throughput and delay optimality. We introduce a new metric called Age of Information to develop the algorithms for scheduling. Later we will be implementing the different scheduling policies and use the simulation results to find the delay and throughput for different users with different parameters by including Mobility Model.

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ABBREVIATIONS

IITM	Indian Institute of Technology, Madras
BS	Base Station
MA	Max Age policy
MW	Max Weight Policy
PF	Proportional Fair Policy
RP	Randomized Policy
UE	User Equipment
MATP	Max Age Policy with Throughput constraints
AoI	Age of Information

CHAPTER 1

INTRODUCTION

Increasing number of users demanding wireless Internet access and a growing number of wireless applications require high speed transmission and efficient utilization of system resources such as power and bandwidth. Within orthogonal frequency division multiplexing access (OFDMA) framework, the resource allocated to the users comes in three dimensions: Time slots, frequency, and power. We plan to develop scheduling algorithms for Scheduling the UEs efficiently based on its requirements. The main goal or objective is to find the optimal scheduling policy that minimizes the Average Peak Age of UEs in a system with and without Throughput constraint Devices that generate eMBB Traffic, when the mobility model is included i.e., the Users UEs are mobile, moving from one cell to the other cell.

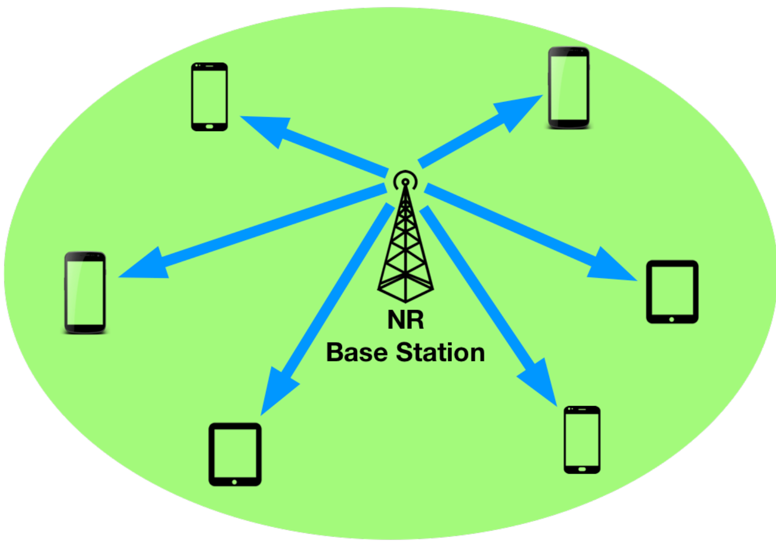

Figure 1.1: BS Users

1.1 Introduction to 38.211 series

1.1.1 Frame Structure

The 5G NR is quite similar to LTE standards but mainly differ in terms of frame stucture and the slots. 5G NR Supports two frequency ranges FR1 (Sub 6GHz) and FR2 (millimeter wave range, 24.25 to 52.6 GHz). NR uses flexible subcarrier spacing derived from basic 15 KHz subcarrier spacing used in LTE. A frame has duration of 10 ms which consists of 10 subframes having 1ms duration each similar to LTE technology. Each subfame can have 2^{μ} slots. Each slot typically consists of 14 OFDM symbols. The radio frame of 10 ms are transmitted continuously as per TDD topology one after the other. Subframe is of fixed duration (i.e. 1ms) where as slot length varies based on subcarrier spacing and number of slots per subframe. As shown below, it is 1 ms for 15 KHz, 500 μs for 30 KHz and so on. Sub-carrier spacing of 15 KHz occupy 1 slot per sub-frame, sub-carrier spacing of 30 KHz occupy 2 slots per sub-frame and so on. Each slot occupies either 14 OFDM symbols or 12 OFDM symbols based on normal CP and extended CP respectively. Each 5G NR frame is divided into two equal size half frames with 5 sub-frames in each. Half frame-0 consists of sub-frames 0 to 4 and half frame-1 consists of sub-frames 5 to 9

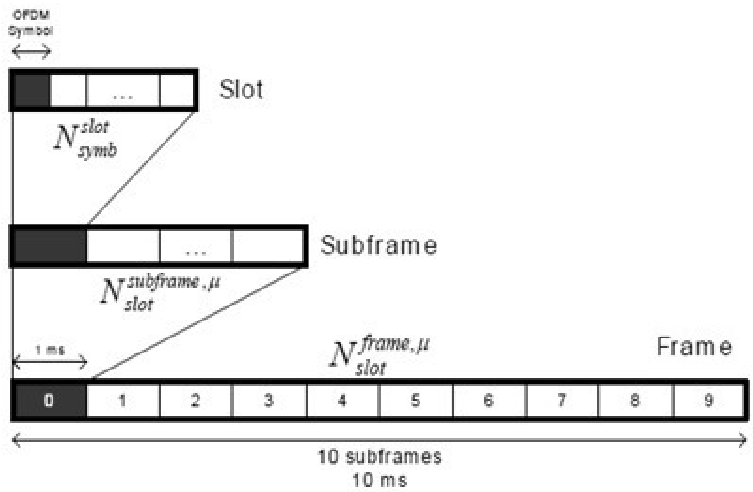

Figure 1.2: 5G-NR-Frame

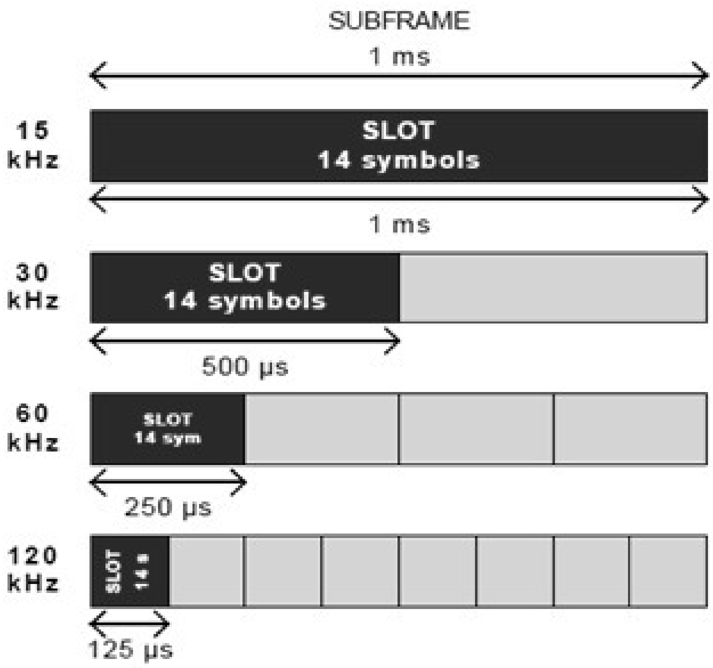

Figure 1.3: 5G-NR-slots-per-sub-frame

1.1.2 Slot Format

Slot Format indicates how each of symbols within a single slot is used. It defines which Symbols are used for uplink and which Symbols are used for downlink within a specific slot. In LTE TDD, if a sub-frame (equivalent to a Slot in NR) is configured for DL or UL, all of the symbols within the sub-frame should be used as DL or UL. But in NR, the symbols within a slot can be configured in various ways as follows. Various slot formats are used which shown below in the figure, to make NR scheduling flexible especially for TDD operation. By applying a slot format or combining different slot formats in sequence, we can implement various different types of scheduling.

• *We don't need to use every symbols within a slot (where only a part of sub-frames can be used for data transmission).*

• *Single slot can be divided into multiple segments of consecutive symbols that can be used for DL , UL or Flexible.*

Below is an example slot format taken from 38.211 series standard.

1.1.3 Resource Grid & Elements

A Resource Grid is the set of resource blocks or elements that is allocated to users by a base station. It is a frequency-time access where each element has different sub-

<38.213-Table 11.1.1-1: Slot formats for normal cyclic prefix>
D : Downlink, U : Uplink, F : Flexible

	Symbol Number in a slot													
Format	0	1	2	3	4	5	6	7	8	9	10	11	12	13
0	D	D	D	D	D	D	D	D	D	D	D	D	D	D
1	U	U	U	U	U	U	U	U	U	U	U	U	U	U
2	F	F	F	F	F	F	F	F	F	F	F	F	F	F
3	D	D	D	D	D	D	D	D	D	D	D	D	D	F
4	D	D	D	D	D	D	D	D	D	D	D	D	F	F
5	D	D	D	D	D	D	D	D	D	D	D	F	F	F
6	D	D	D	D	D	D	D	D	D	D	F	F	F	F
7	D	D	D	D	D	D	D	D	D	F	F	F	F	F
8	F	F	F	F	F	F	F	F	F	F	F	F	F	U
9	F	F	F	F	F	F	F	F	F	F	F	F	U	U
10	F	U	U	U	U	U	U	U	U	U	U	U	U	U
11	F	F	U	U	U	U	U	U	U	U	U	U	U	U
12	F	F	F	U	U	U	U	U	U	U	U	U	U	U
13	F	F	F	F	U	U	U	U	U	U	U	U	U	U
14	F	F	F	F	F	U	U	U	U	U	U	U	U	U
15	F	F	F	F	F	F	U	U	U	U	U	U	U	U
16	D	F	F	F	F	F	F	F	F	F	F	F	F	F
17	D	D	F	F	F	F	F	F	F	F	F	F	F	F
18	D	D	D	F	F	F	F	F	F	F	F	F	F	F
19	D	F	F	F	F	F	F	F	F	F	F	F	F	U
20	D	D	F	F	F	F	F	F	F	F	F	F	F	U
21	D	D	D	F	F	F	F	F	F	F	F	F	F	U
22	D	F	F	F	F	F	F	F	F	F	F	F	U	U
23	D	D	F	F	F	F	F	F	F	F	F	F	U	U

Figure 1.4: Slot-Formats

carrier frequency on different time slot. The general Nomenclature of 38.211 standards is $N_{grid,x}^{size,\mu} N_{sc}^{RB}$ sub-carriers and $N_{symbols}^{subframe,\mu}$ OFDM Symbols is defined, Starting at a common resource block $N_{grid}^{Start,\mu}$. According to 38.211 standards, the Maximum and Minimum number of resource blocks for Down-link and Up-link is defined below.

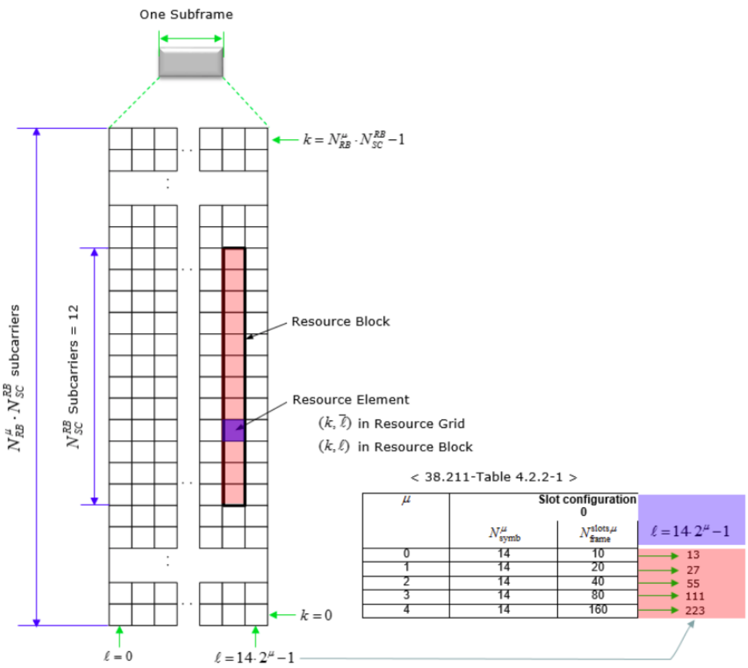

Figure 1.5: ResourceGrid

< 38.211 v1.0.0 Table 4.4.2-1: Minimum and maximum number of resource blocks.>

μ	$N^{min,\mu}_{RB,DL}$	$N^{max,\mu}_{RB,DL}$	$N^{min,\mu}_{RB,UL}$	$N^{max,\mu}_{RB,UL}$
0	24	275	24	275
1	24	275	24	275
2	24	275	24	275
3	24	275	24	275
4	24	138	24	138

Figure 1.6: Resource Block UL and DL config.

1.2 Introduction to System Model

A single hop wireless network with a Base station(BS) is considered which serves the User(UE) or also called Nodes. Let Us consider M nodes are present in network that are active receiving time-sensitive information. Our assumptions are that time is slotted and only one packet can be transmitted in a given slot i.e., in each slot BS either selects a node in {1,2,......, m} or be Idles for each transmission. Let $u_i(k)$ be an indicator function which equals 1 if a packet is transmitted to BS in time slot k by the node i otherwise 0. The probability of that packet from i is successfully received by the BS is $p(i)$ and the probability of transmission error will be $1 - p(i)$ where $p(i)$ is less than 1. Let $d_i(k)$ be the random variable that indicates when a packet from node i is delivered to the BS. If node i transmits a packet during slot k, i.e. $u_i(k)$ = 1, then $d_i(k)$ = 1 with probability $p(i)$ and $d_i(k)$ = 0 with probability $1 - p(i)$. On the other hand, if node i does not transmit, i.e., $u_i(k)$ = 0, then $d_i(k)$ = 0 with probability one.The channel interference constraints written below associated with the wireless channel imposes that any scheduling policy can select at-most one node for transmission**[1]**.

$$\sum_{i=1}^{M} u_i(k) \leq 1$$

We introduce a new metric called Age of Information (AoI) which represents how old the information from perspective of BS. The more the value of AoI for a particular UE, the UE is more outdated at that time. Hence this metric can be key in scheduling the UEs based on how long a UE is outdated till that time. Since our objective is to Minimize the Overall Peak AoI of the system, this metric is the key for scheduling a UE. Let $h_i(k)$ be the positive integer that represents the AoI associated with node i at the beginning of slot k. If the BS does not receive a packet from node i during slot k, then $h_i(k + 1) = h_i(k) + 1$, because there was no information that was sent in that slot. The Average AoI of node i during the first K slots is calculated by $E[\sum_{k=1}^{K} h_i(k)]/K$.

we then maintain a vector of size M which contains Average AoI when a scheduling policy π is employed. For measuring the freshness of the information of entire network when policy π is employed, we use the Expected Weighted Sum AoI,

$$\mathbb{E}[J_K^\pi] = \frac{1}{KM}\mathbb{E}\left[\sum_{k=1}^{K}\sum_{i=1}^{M} \alpha_i h_i^\pi(k)\right]$$

The Scheduling policy which results from the below constraints assuming the above system model is refered as *AoI-Optimal*.

According to [1],

AoI Optimization

$$\text{OPT}^* = \min_{\pi\in\Pi}\left\{\lim_{K\to\infty}\frac{1}{KM}\mathbb{E}\left[\sum_{k=1}^{K}\sum_{i=1}^{M}\alpha_i h_i(k)\right]\right\} \quad (8a)$$

$$\text{s.t.} \;\; \hat{q}_i^\pi \geq q_i \;, \forall i \;; \quad (8b)$$

$$\textstyle\sum_{i=1}^{M} u_i(k) \leq 1 \;, \forall k \;. \quad (8c)$$

For a given Network setup, the optimality ratio η is given by $\psi^\eta = \frac{OPT_\eta}{OPT}^*$, we say that policy η is ψ^η optimal . The closer the value to 1 the better AoI performance of policy η.

1.3 Delay Optimality

One of our main priority and requirement for developing 5G NR is to decrease the latency or delay with which the packets reach a user from base station(BS). Our main objective is to minimize the Peak average Age of Information of **URLLC**(***Ultra reliable Low Latency communications***) using different low complexity scheduling policies in the case of mobility model. The Delay constrained UEs with URLLC type traffic, such as control information updates for intelligent transportation require low latency communications, so it is important to schedule a policy that is sensitive to the delay in other words, we need to minimize the Overall Average Peak AoI of a system. According to [2], The Mathematical equation for the Delay Optimality we would like to achieve is given below,

$$\mathbb{E}\left[J_K^{\pi}\right] = \frac{1}{KM}\mathbb{E}\left[\sum_{k=1}^{K}\sum_{i=1}^{M}\alpha_i h_i(k) \,\Big|\, \vec{h}(1)\right]$$

where $\vec{h} = [h_1(1), ..., h_M(1)]^T$ is the vector of initial AoI in and $\alpha(i) > 0$ is the weight of node i. For simplicity, we assume that $h_i(1) = 1, \forall i$, and omit $\vec{h}(1)$ henceforth. In other words, For the case of Non-Mobility Model the above problem is formally derived as according to [3],

At a given slot t, define $h_{max}(t) \equiv max_{i=1}^{N} h_i(t)$ to be the peak instantaneous Age of Information among all N users. Our objective is to design a scheduling policy which minimizes the time-averaged expected peak-AoI. More formally, we consider the following stochastic control problem P_{sched}:

$$\lambda^* = \inf_{\pi\in\Pi} \limsup_{T\to\infty} \frac{1}{T}\sum_{t=1}^{T}\mathbb{E}(\max_i h_i(t)),$$

subject to the constraint that at most one user may be scheduled at any slot. We will be simulating different policies and compare them by including Mobility model.

1.4 Throughput Optimality

Similar to delay optimality, we need more throughput for every user depending on the type of UE. This is both dependent on the architecture of the 5G and also how efficient the resource allocation is done by the base station. For example, if one of the user is idle and an another user is making a data call, unlike the basic round robin scheduler which gives equal priority to all the users, we need to schedule UE using a different scheduling algorithm inorder to provide more resource to the user who is making data call thereby increasing the throughput. In case of ***eMBB(Enhanced Moblie Broadband)*** traffic generated by throughput constrained devices such as HD multimedia streaming, it is critical that we need to maximize the overall average throughput of these devices along with delay optimality of URLLC devices which are delay sensitive. We simulate all the policies and check for the mobility model which can provide maximum overall average throughput in the presence of URLLC Devices.

According to [1], the system model we've considered the long term throughput of node i, Using the random variable $d_i^{\pi}(k)$ the Long-Term Throughput of node i is when a policy belongs to π is used for scheduling is given by,

$$\hat{q}_i^{\pi} := \lim_{K \to \infty} \frac{1}{K} \sum_{k=1}^{K} \mathbb{E}[d_i^{\pi}(k)] \, .$$

We then express the minimum throughput constraints of each individual node i as

$$\hat{q}_i^{\pi} \geq q_i \, , \forall i \in \{1, \cdots, M\}$$

assuming that there exists a feasibility set $\{q_i\}_{i=1}^{M}$ for the policies we use for scheduling along with the strict inequality $\sum_{i=1}^{M} \frac{q_i}{p_i} \leq 1$ that is necessary and sufficient condition for the feasibility set mentioned above.

CHAPTER 2

Theoretical proofs and Research

2.1 Scheduling policies

We'll be simulating the Following scheduling policies and also modify them by changing certain parameters(which will be discussed in later parts) to achieve our low latency and high throughput requirement and also compare them to find the best scheduling policy.

For a given Network Setup the policy is said to be η optimal if the ratio of Expected weighted sum of AoI using the non-anticipative and low complexity policies is η times the Expected Weighted sum of optimal policy. If the η is close to 1 the policy is also closed to optimal.

(a)Proportional Fair;

(b) Optimal Stationary Randomized policy;

(c) MaxWeight policy;

(d) Drift-Plus-Penalty policy;

(e) Whittle's Index policy.

2.1.1 Proportional Fair Scheduling

It is a basic compromise-based scheduling algorithm to maintain balance between the users to maximize overall throughput. This is done by maintaining calculating the ratio of data rate of each user over overall average throughput of users until that point of time. The more the throughput of an user *i* the more the priority given to *i* in resource allocation with maintaining the least rate (non-zero) to other users. This can be achieved by means of "***weighted fair queuing***" by setting the scheduling weights of data flow to inverse of number of resources consumed per data bit.

Mathematically according to [6], It is proven in by Tse that a proportional fair allocation for a single carrier system also ***maximizes the sum of the logarithms of average user rates*** $\sum_{i=1}^{N} logR_i$ where N is the number of users and R_i is the average received rate of user i. In a single carrier system proportional fairness is achieved by scheduling at each slot t, a user i^* according to:

$$i^* = \arg\max_i \frac{r_i(t)}{R_i(t)}.$$

Here $r_i(t)$ is the instantaneous transmittable rate to user i at the current frame. $R_i(t)$ is the average data rate that user i receives over time.

The BS using this Policy Schedules the UE maximizing the metric $p(i)/R(i)$. Here, The $R(i)$ is the exponentially-smoothed average rate, which is updated at every time slot as: $R_i(t+1) = R_i(t) + \epsilon y_i(t)$ where $y_i(t)$ is the instantaneous throughput to the UE_i at slot t. The value of ϵ is taken to be 0.1 for our entire simulations.

2.1.2 Optimal Stationary Randomized policy

This policy is 2-optimal policy with respect to the optimality ratio ψ^n that was considered in our system model mentioned in the previous section. Each time slot the UEs are mobile around the BS moving from one cell to another cell. The BS in one cell schedules a UE from the corresponding Cell randomly with uniform distribution i.e., chooses every UE with equal probability which lies between $(0, 1)$.

2.1.3 MaxWeight policy

It uses Lyapunov Optimization technique along with our AoI optimisation . This policy keeps the network in desirable states when the positive drift of Lyapunav function is very large when compared to the required AoI or Less throughout. Even in the case of mobility the BS chooses the UE that has Maximum $p(i) * (h(i)^2)$ metric where $h(i)$ is the Age of Information of User i till previous time slot.
Mathematically,

Lyapunov Function: $L(k) := \frac{1}{2}\sum_{i=1}^{M}(\alpha_i h_i(k)^2 + V[x_i^+(k)^2])$

Lyapunov Drift: $\Delta(k) := E\{L(k+1) - L(k)|(h_i(k), x_i(k))_{i=1}^{M}\}$

The Lyapunov drift that need to be minimized is:

$$\Delta(k) \leq -\sum_{i=1}^{M} E\{u_i(k)|(h_i(k), x_i(k))_{i=1}^{M}\}W_i(k) + B_i(k)$$

From the above Policy, in each slot k, the BS should schedule the UE that has highest value of $W_i(k)$, where,

$$W_i(k) = \frac{\alpha_i p_i}{2} h_i(k)[h_i(k) + 2] + V p_i(k) x_i^+(k)$$

From the above euqation, the most dominating term is $p(i) * (h(i)^2)$, Hence, in this policy **BS schedules the UE that has highest $p(i)h(i)^2$ metric**.

2.1.4 Max Age Policy

This Policy is independent of channel charachteristics which is in our model is simulated using $p(i)$. In simple words, the BS schedules the UE in it's corresponding Cell which has Highest AoI which in our case is $h(i)$ for a User i. The Max Age Policy mentioned above is when there are only URLLC Devices.
Another Variant of this policy is slightly similar to the above mentioned policy, when there are Delay Constrained UEs. The URLCC devices and eMBB devices are divided

into two sets. Type-I UEs are the URLLC devices and Type-II UEs are the eMBB devices. We Introduce a new penalty function $g(i)$ for every User i which is dependent on a New Non-Negative Tuning Parameter called β.

The $g(i)$ is defined as follows for User i :

$$g(i) = \begin{cases} \beta & \text{if } i \in \{\textbf{Type-I}\ UEIndexes\} \\ \beta(1 - p(i)) & \text{if } i \in \{\textbf{Type-II}\ UEIndexes\} \end{cases}$$

The above equation is obtained by using bellman equation[3], $g(i)$ denotes the expected cost when a UE, which receives eMBB traffic, does not successfully receive a packet at time slot t.

This policy is called as **MATP** Policy where, At any time slot t, **The BS then Schedules the UE that has maximum value of** $h_i(t) - g(i)$ where $g(i)$ is mentioned in the above function. In case of non-mobilty model,The MATP policy strikes a balance between minimizing the peak-AoI,$h_i(t)$ while also ensuring sufficient throughput to the eMBB user (through the second term $g(i)$. As β is increased, it gradually dominates the AoI term, which, in turn, facilitates scheduling the eMBB user. We now simulate and check the results for the case of Mobility Model.

2.1.5 Drift-Plus-Penalty policy

This Policy is 2-optimal with respect to the optimality ratio ψ^n . This policy is quite similar to Max Weight Policy but we optimize it by adding one more constraint called Penalty to the Lyapunov drift function.

Based on the AoI minimization[2], we define the Penalty Function as follows,

$$P'(S_k) := \frac{1}{2}\sum_{i=1}^{M} \beta_i \mathbb{E}[h_i(k+1)|S_k]$$

where $S_k = (h_i(k), x_i^+(k))_{i=1}^M$ is the network state at the beginning of the time slot k, where β_i is some positive value associated with node *i*.

We define the Lyapunov drift as below:

$$\Delta'(S_k) := \mathbb{E}\left\{L'\left(S_{k+1}\right) - L'\left(S_k\right)|S_k\right\}$$

which is associated with lyapunov function given below:

$$L'(S_k) := \frac{V'}{2}\sum_{i=1}^{M}\left[x_i^+(k)\right]^2$$

where $V^{'}$ is strictly positive value representing the throughput constraints. Here, the AoI values of UE i at slot t, $h_i(t)$ are involved in the above mentioned penalty function.

2.1.6 Whittle's Index policy

This is an Index based policy similar to MaxWeight policy which uses Relaxed Restless Multi-Armed Bandit(***RMAB***) and AoI Optimization. This policy is 8-optimal with respect to the optimality ratio ψ^n.

Below are some previous results without Mobility model taken from [4],

Scheduling Policy	Technique	Optimality Ratio	Simulation Result
Optimal Stationary Randomized Policy	Renewal Theory	2-optimal	**~ 2-optimal**
Max-Weight Policy	Lyapunov Optimization	4-optimal	**close to optimal**
Whittle's Index Policy	RMAB Framework	8-optimal	**close to optimal**

CHAPTER 3

Simulation results

3.1 CEWiT Simulator Architecture

The simulator used in our implementation of Scheduler Algorithms is developed by CEWiT. The Schedular part of the simulator is where we implement the algorithms.

3.1.1 Scheduler Interface

The Simulator developed by CEWiT is developed to simulate a real life scenario of BS serving Users considering all practical aspects. The part I've worked on is Developing the Different Scheduling Policies[1] for Scheduling the Users by Improving the already existing Round-Robin Schedular which gives equal priority to all users irrespective of channel and throughput of users. I've implemented Proportional Fair scheduling policy using Age of Information(AoI), which requires calculation of PF metric using Instant and average throughput of users.

Flowchart and Function calls in Simulator

BWSIM.events is the main event function call that starts the function call. Our part schedular interface has a custom schedular code which is enabled from **"mytraces.txt"** file in **config folder** and also in **"myL2Support.txt"** Scheduler Info should be modified for the simulator to run our custom scheduling policies. In case of PF schedular, The Custom scheduler part contains a function call which is used to find the UE that has best PF metric. The "LinkAdaptation()" function call is the one that calculates **Instant MCS rate** and the variable "**mUEavgrate**" in main schedular class is always updated in background after every time slot. A Vector of Containing **AoI values** are maintained by which a BS schedules the UE in its corresponding cell. Although we haven't got any desired results the flow of the simulator is mentioned above. **We will use MATLAB simulations to check which policy is better optimal in the later sections.**

3.1.2 CQI and CSI

CQI is Channel Quality Indicator. PMI stands for Pre-coding Matrix Indicator, and RI is Rank Indicator. These three values are computed on the fly in LTE systems and used to try to optimize resource allocation among the various UEs that are requesting service. The ***CQI*** and ***CSI*** is "***Channel Quality Indicator***" and "***Channel State Information***" which is the key part for measuring the channel capacity. The CQI is usually suggests the transport block size.

3.1.3 PMI and RI

It is called "***precoding matrix indiactor***". It is used in setting the weights for precoding which is an important part in Link Adaptaion. The UE selects the maximum PMI to maximize the SNR ratio at its reciever.The PMI is reported only on certain transmission modes according to 3GPP references: TS 36.211, TS 36.212. The PMI can be used by the eNodeB when selecting the precoding weights for multi-user MIMO The precoding is usually done according to a Precoding Matrix ***"W"*** which is equal to Identity Matrix (I) in case of non-codebook based transmission and in case of codebook transmission, it is calculated by ***"TPMI"*** index obtained from Downlink Control Information scheduling the up-link transmission or the higher layer parameters according to procedure mention in [6, TS 38.214]. The Rank Indicator(RI) provides the eNodeB with a recommended number of layers.

3.2 $MATLAB$ Simulations with Mobility Model

One of the practical scenarios to consider for calculating Age of Information of each User is when Users are Mobile around the BS. We try to setup a model and simulate it for calculating Average Age of Information with and without Throughput Constraints. The Mobility model we have used is that UEs will be moving from one cell to other every time slot. We assume that only one UE gets scheduled per time slot.

Mobility Model Setup:

To simulate the Mobility Model, we use S Base Stations and N UEs which are of two types, Type-I, and Type-II which will be discussed in later parts. Each UEs cahnnel is modeled by a paramenter called Probability of success denoted by $p(i)$ for user i which is the probability of a packet getting delivered successfully from BS to the UE when it is scheduled in that particular time slot. We will be simulating this with three diferrent setups of Base Staions and UEs along with their Probability of Success $p(i)$. The values N, BS are configurable which can be changed accoriding to our requirements.

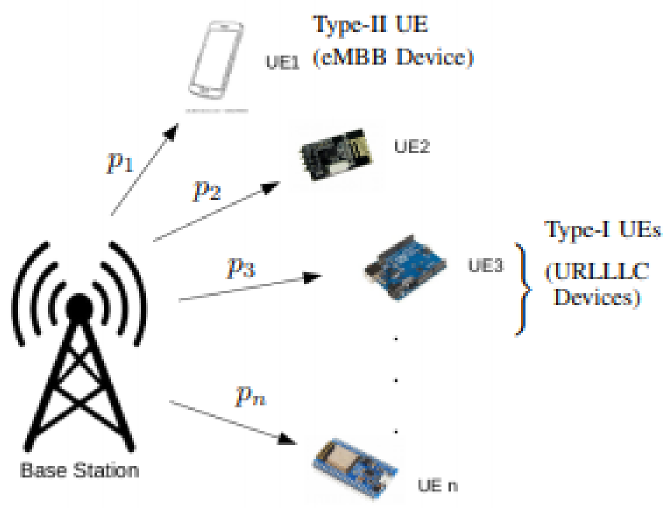

Figure 3.1: An Example BS in a random cell with different UEs taken from [3]

Setup-I

We assume that each UE has constant Probability of Success which denoted by $p(i)$, irrespective of it's current cell in which it is located, every time slot. The values for $p(i)$ is generated from a uniformly random number generator which lies between 0 and 1. For all time slots, t, the probability of success in all the cells is given by:

$$p(i) = l, where\ \ l \in (0,1) \text{ and } l \text{ is constant } \forall\ \ t\ \&\ \forall i \in \{1, 2, ...N\}$$

Setup-II

In this setup, we assume each UE has constant Probability of Success in a cell but it varies when UE moves to another cell in the next time slot. Simply the values $p(i)$ is constant in a cell but different across the cells when the UE moves. Assuming there are S Base-Stations which implies there are S cells, then For all time slots, t, the probability of success in a particular cell S for a UE i is given by:

$p_s(i) \in$ (0,1) is the Probability of success of UE i in Cell $s \in$ {1, 2, ..., S}

$$p_s(i) = l, where\ \ l \in (0,1) \text{ and } l \text{ is constant } \forall\ \ t\ \ \&\ \forall i \in \{1, 2, ...N\}$$

Setup-III

This setup is similar to setup-II but UE can move only to the Cell that is connected to the current cell. This is modelled as a graph where the BS are nodes and the UE chooses to move from current cell to another cell among the connected cells, with equal probability, in other words Uniformly distributed random variable. The Probability of choosing a Connected BS is the inverse of degree of the current BS, $degree_{BS(i)}$ which equals to , $\frac{1}{total\ no.of\ connected\ BS\ to\ current\ BS}$

Assumptions: As we are considering that at-most only one UE can be scheduled in one cell, we simulate by the assumption that on average only 5-10 users are present at any given time slot, so that the Max Peak age will not be constant and saturated because, if the number of users get increased there will always be a user with max Peak AoI which will be constant throughout the simulation. Hence we take S to be 50 and N ranging from 200 to 300.

3.3 *Simulations for Various Setups:*

3.3.1 Simulations for Setup-I

In this setup we've considered $S = 50$ and N ranging from 100 to 150. Only Type-II UEs that are URLLC devices are simulated as our objective in this setup is to find out the Optimal Policy in case of Mobility to minimize the Overall Average Peak AoI.

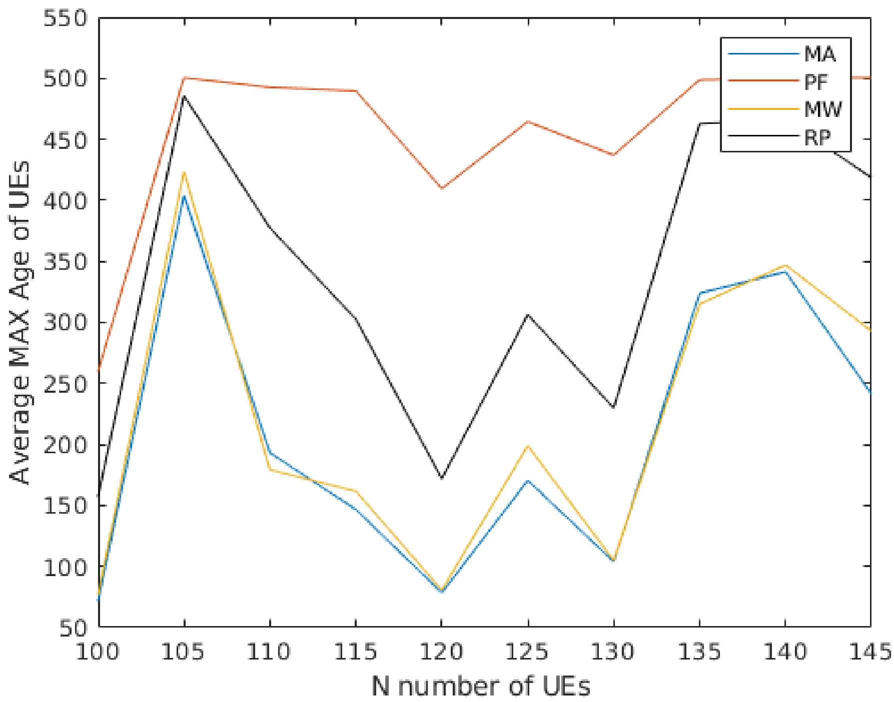

Figure 3.2: Average Peak AoI Setup-I

Conclusion: We could observe that Average Peak AoI is minimum for all N in case of MaxAge and MaxWeight Policies. Hence we conclude that even in the case of Mobility model the ***MaxAge and Max Weight are Optimal*** compared to PF and Randomized Policies.

3.3.2 Simulations for Setup-II

The setup is similar to Setup-I but here as mentioned above, we consider constant $p(i)$ in a cell but varies when it moves to other cell. The value of N varies from 200 to 300 for the rest of the simulations.

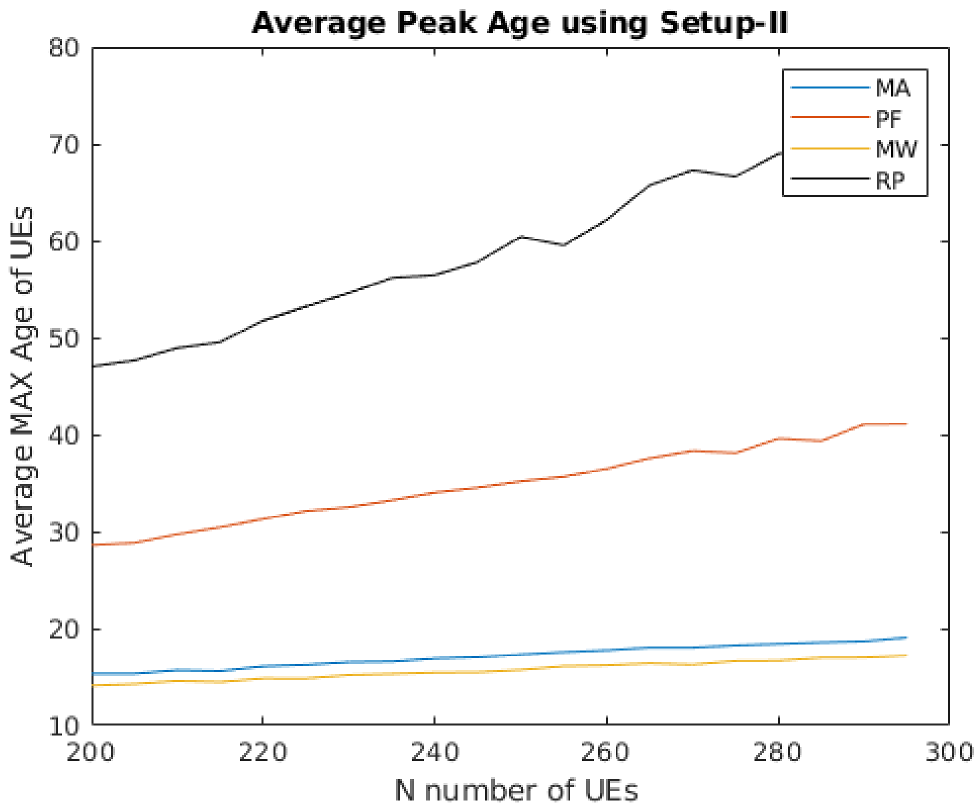

Figure 3.3: Average Peak AoI Using Setup-II

Conclusion: In this setup, contrary to Non-Mobility Model where the Max-Age Policy is Optimal when compared to nearly Optimal Max-Weight Poilcy, the Max-Weight Policy turns out to be better optimal than Max-Age Policy. Moreover the PF Policy which is worst in setup-I turns out to be better optimal compared to the Randomized Policy in the Setup-II. The Overall Avg Peak AoI is also Increasing when Number of UEs are Increased, it can be intuitively explained as, when the number of UEs get increased per Cell the Number of Contending Users seen by the BS in that particular Cell is also Increased which lead to the Increase in Age of Non-Scheduled UEs every time slot as atmost only one UE can be scheduled in one time slot.

3.3.3 Markov Mobility Mobility Model

The Moblity Model in this setup is constrained in terms of Mobility of a UE to another cell. In previous setups, we simulated for **Complete Graph while assuming BS as Nodes in the Graph**. In case of Markovian Mobility Model, We Generate a Connected Graph but not complete Graph by using Uniform random generator Matrix that contains Rows which are ***Adjacency lists of the connected Cells to the Current BS***. The UE moves to the next Cell by choosing randomly with equal Probability from the Connected Cells i.e., Adjacency List of the Cuurent BS/Cell. An example of the above Model is shown in the Figure Below.

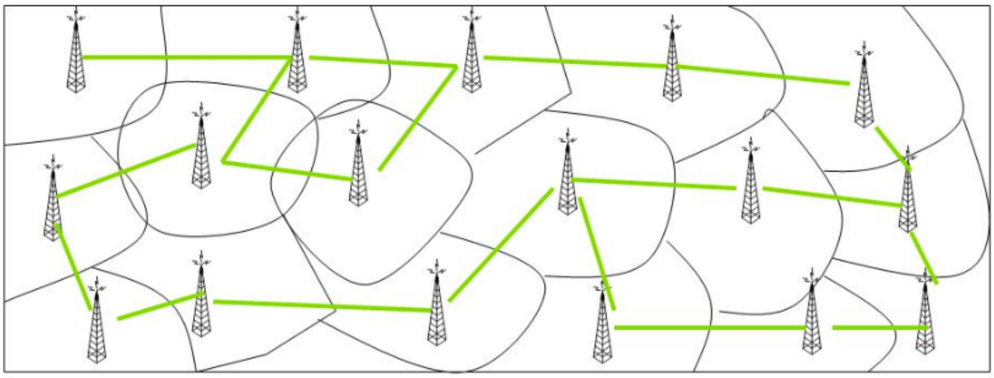

Figure 3.4: Example of Base Stations as connected Graphs taken from google images

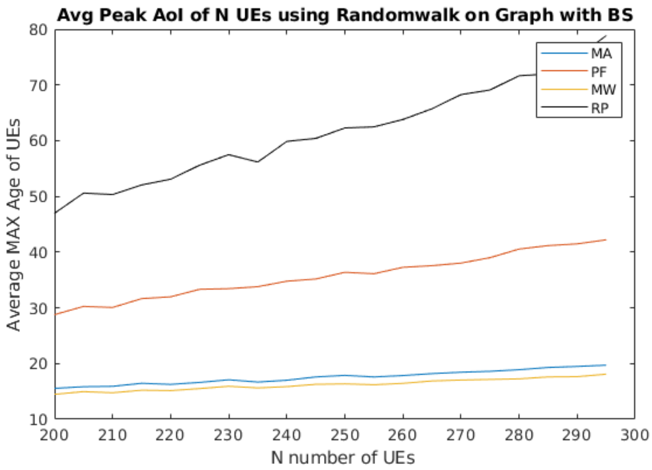

Figure 3.5: Average Peak AoI using Random walk Markov Model

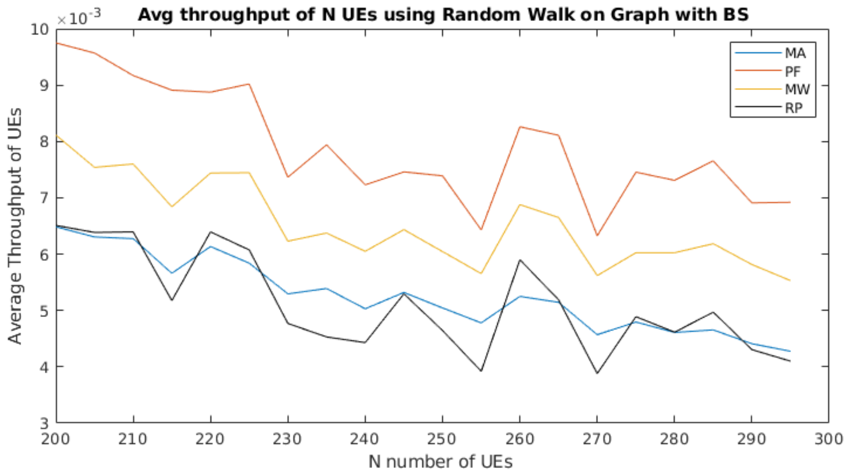

Figure 3.6: Average Throughput using Random walk Markov Model

Conclusion: The Above Simulated model is similar to the case of Setup-II where we have used the fully connected graph. In terms of Optimal Policy the Max-Weight is more optimal over Max-Age because of inclusion of Model. Also we could see that the Overall Avg Throughput is Higher when PF policy is used. The Overall Avg-Age is increased when N is increased which is due to the same reason as mentioned in the setup-II conclusion.

3.3.4 Max Age Policy With Throughput Constraints

This setup contains UEs of both Type-I (URLLC devices) and Type-II (eMBB Devices) where We simulate all the Policies by Including Mobility Model with **setup-II configuration** that would Minimize the Overall Average Peak AoI of Type-I UEs and Maximize the Overall Average Throughput of Type-II UEs with a different Values of β that is a Non-Negative tuning parameter for a penalty function that is used in MATP policy that is mentioned above. We will simulate the Overall Average Throughput of Type-I UEs along with Type-II UEs using **MATP Policy** and compare it with the Throughput of eMBB UEs without remaining policies including the MA policy without throughput constraints. The Plots are obtained for a β value of 1000.

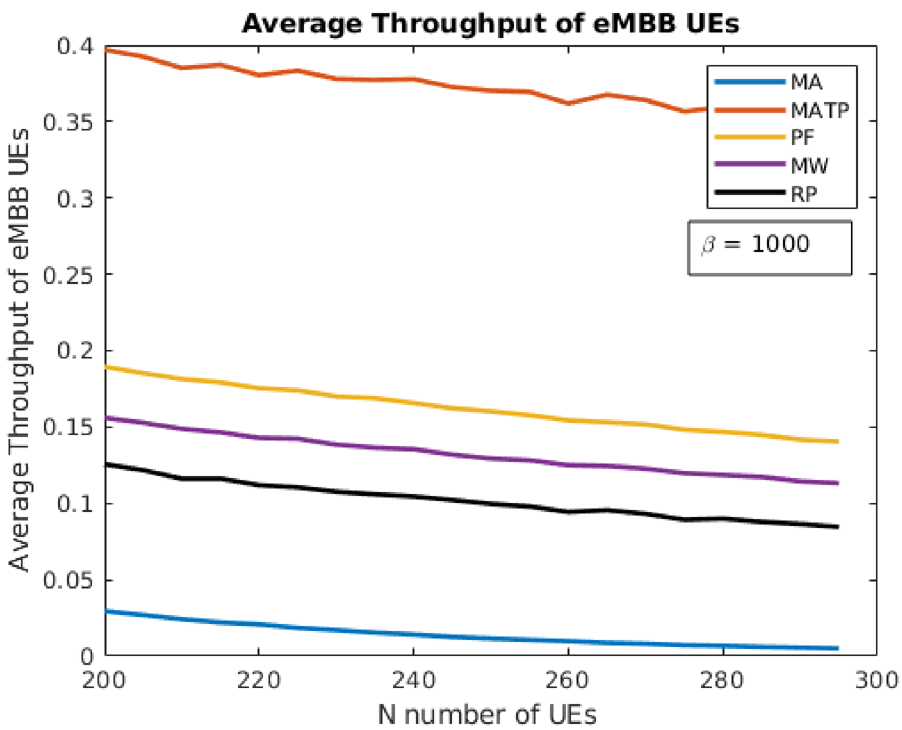

Figure 3.7: Average Throughput of eMBB UEs using all policies

The below plots concludes that ***MATP policy provides more Average throughput*** for the eMBB (throughput Constraint UEs) over URLLC devices even in the case of Mobility.

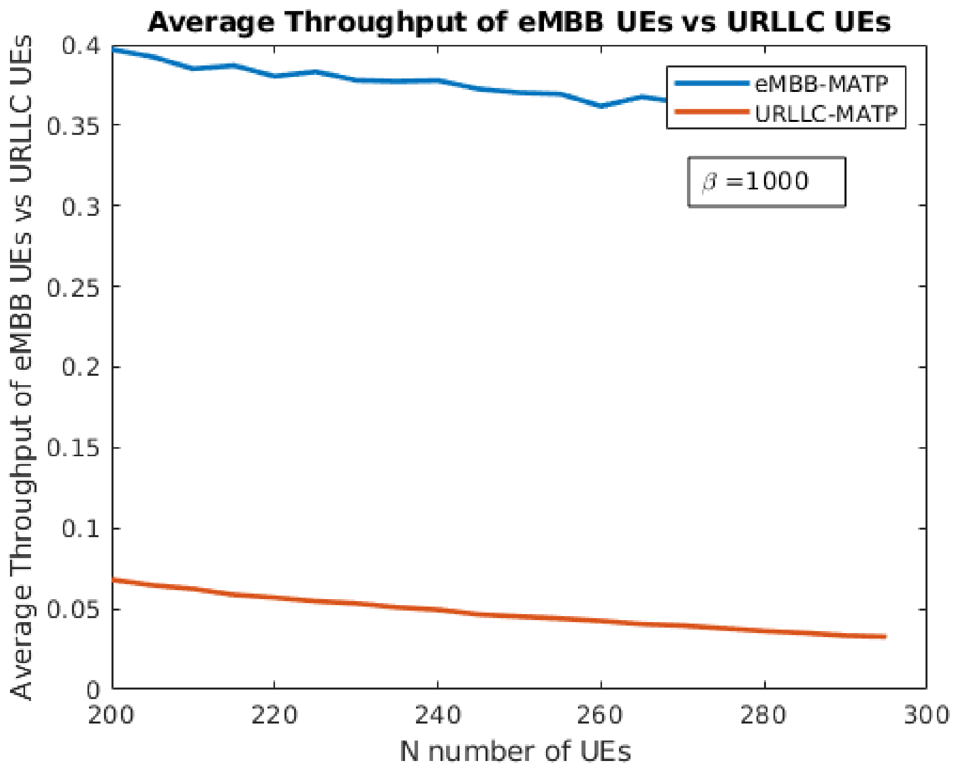

Figure 3.8: Average Throughput of eMBB vs URLLC UEs

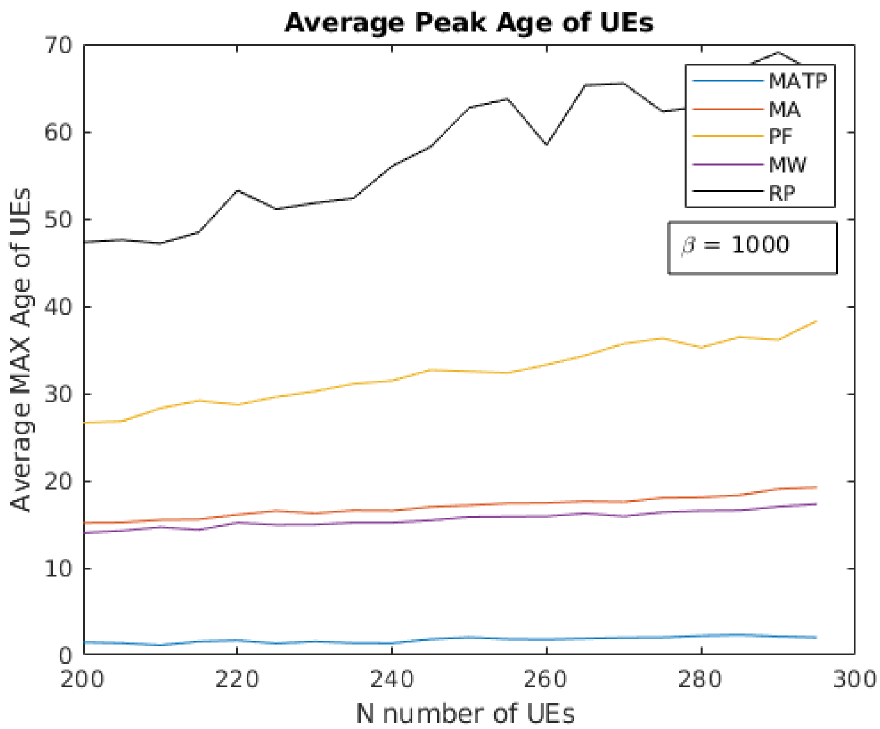

Figure 3.9: Average Peak AoI for all Policies

The Average Throughput of UEs when β is varied after including mobility model is simulated for S=50 and N=200 by varying β from 0.001 to 10^6 in the log scale of 10.

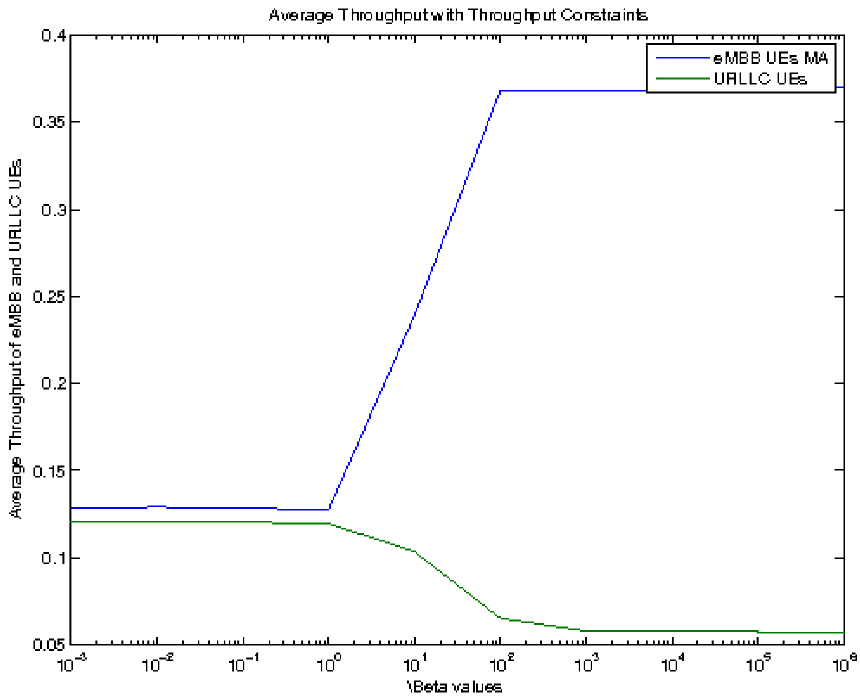

Figure 3.10: Average Throughput of eMBB UEs with varying β values

Conclusion: We could see that even in the case of Mobility Model, the MATP Policy is Optimal as the average throughput of eMBB UEs are Increased while the Throughput of URLLC devices are decreased simultaneously when MATP Policy is used. Also the Average Peak Age is minimum in case of MATP policy, which supports the fact that MATP is the Optimal Policy in terms of Maximizing the Throughput and Minimizing the Average Peak AoI.

CHAPTER 4

Conclusions and Future work

We conclude that from the above obtained plots the Max-Weight and Max-Age are Optimal Policies with Max-Weight being better Optimal compared to Max-Age Policy without throughput constraint UEs which is contrary to the previous results which are obtained without Mobility Model. The MATP policy is the better Policy in case of Throughput constraint UEs which outperforms the PF Policy that is meant to Maximize the Overall Average Throughput in the system.

In terms of implementing the Policies in practical life, the Max-Age is easy to implement over Max-Weight because Max-Weight needs a continuous feedback of Channel State Information, which in our simulations is modeled as $p(i)$ in our simulations,when the users are mobile where as Max-Age Policy needs to keep track of only the AoI metric.

In terms of adding more functionalities to the $MATLAB$ simulation, We could include the re-transmissions model for a UE when a packet is not delivered successfully from BS, even though it has an excellent channel for the next few time slots.Including this model would add more practical scenarios and might give a bit more accurate results.

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