Downlink Resource Allocation and Packet Scheduling in Multi-Numerology Wireless Systems

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***Abstract*—5G New Radio (NR) is moving towards flexibility and adaptability and is expected to provide optimized support for diverse 5G use case categories. With the introduction of flexible waveforms and numerologies in 5G, there is a need for new scheduling and resource allocation techniques. Using different non-orthogonal numerologies in the network complicates the resource allocation process since it introduces numerology multiplexing. In this paper, we propose a channel quality and Quality of Service (QoS) aware resource allocation scheme for multi-numerology 5G networks. We implement a frequency domain packet scheduler which allocates packets to Resource Blocks to achieve higher spectral efficiency, maintain fairness, and satisfying the QoS requirements of users with different non-orthogonal numerologies. The results show that our algorithm achieves high throughput in different traffic mixes with different numerology QoS requirements over varying number of users.**

***Index Terms*—Resource Allocation, Packet Scheduling, 5G, NR, Numerology, Waveforms, Numerology multiplexing.**

I. Introduction

THE increase in the demands and application of cellular communication requires the proposal of 5G New Radio (NR) technology. The NR technology is part of the ever-growing mobile broadband evolution and would be an upgrade for the Long Term Evolution (LTE) standard. The usage pattern of 5G (IMT 2020) is not just limited to mobile broadband but constitutes diverse use cases like Enhanced mobile broadband (eMBB), Ultra-reliable and low latency communications (URLLC), and Massive machine type communications (mMTC) [1]. The traffic pattern of these cases has not yet been fully characterized. However, we do know that these use cases would introduce a very large number of devices in the network and would, therefore, require a larger spectrum with flexible and adaptable network parameters.

5G is currently working on a new radio interface where different users would have different numerologies, which is the waveform parameterization [2], [3]. Users employing different waveforms or numerologies would no longer be orthogonal in the frequency domain. If two users with non-orthogonal numerologies are assigned next to each other, they would cause interference and considerable degradation in each other's performance. Therefore, the traditional resource block allocation techniques become obsolete in a multi-numerology system. In this paper, we propose resource allocation and packet scheduling using numerology multiplexing for 5G NR technology. We assume that all our users are synchronized with the evolved NodeBs (eNBs).

Considerable amount of work has been done in resource allocation for LTE systems. In [4], the authors formulate the problem of resource allocation for device-to-device communication as a mixed integer nonlinear programming (MINLP). They further present a greedy heuristic to decrease the complexity and utilize the channel gain information efficiently. In [5], the authors present a frequency domain scheduler for LTE uplink that maintains fairness among different users by employing proportional fair in the uplink. In [6], the authors present an optimization model for multi-user frequency selective scheduling in the downlink for LTE system. However, the authors also show that the optimal solution is much complex and not real-time solution. We can observe that the optimal solution has a considerable advantage over a completely greedy algorithm. In [7], the authors show that dividing the schedulers into two layers. One for time domain and one for frequency domain achieves faster convergence and achieves better results. The paper also deals with inter-user fairness problem arising in LTE systems. However, as we have already discussed, these LTE schedulers cannot be employed in a non-orthogonal multi-numerology network. Nevertheless, they can still become a good starting point in understanding packet scheduling and how it can be employed for multi-numerology systems.

There has been considerable amount of work done on Non-Orthogonal Multiple Access (NOMA) [8] for future technologies. However, most of the work focuses on single-carrier and even when they do tend to work on multi-carrier, they concentrate on power allocation schemes. In [9], the authors propose a resource allocation scheme for heterogeneous networks which is energy efficient. In [10], the authors show that dynamic resource allocation should be used in 5G NR in order to tackle the issues of different transmission time intervals (TTI). Resource allocation for URLLC using signal strength has also been proposed [11]. In [12], the authors measure the performance of flexible utilization of spectrum for 5G heterogeneous networks. However, in all these works the authors do not consider the issue of multiple numerologies resulting in non-orthogonality between different resource blocks.

In this paper we tackle the resource allocation problem for the non-orthogonal multi-numerology systems. We assume synchronization among different numerology UEs and the eNB. We model the resource allocation and packet scheduling problem for multi-numerology systems and propose an Adaptive Numerology Resource Allocation (ANRA) algorithm which performs numerology multiplexing as well as resource allocation. The algorithm is both channel quality and QoS aware and also assures fairness. The rest of the paper is organized as follows. Section II describes the system model for our problem. Section III explains the packet scheduling techniques and considerations. Section IV formulates the problem mathematically in order to achieve an optimal solution. Section V explains our proposed solution to the problem. Section VI simulates our proposed solution in different scenarios and analyze the results. Section VII concludes our paper.

II. System Model

A. LTE System

LTE uses Orthogonal Frequency Division Multiplexing (OFDM) scheme as a radio access technique for downlink (DL) and utilizes Single Carrier Frequency Division Multiple Access (SC-FDMA) for energy efficiency in uplink (UL). SC-FDMA assigns contiguous sets of subcarriers as UEs can only use adjacent sub-carriers in uplink whereas OFDM can exploit the subcarriers distributed throughout the spectrum. LTE physical resource is defined in both time as well as frequency domain. A Resource Block (RB) has a duration of 0.5 ms and 180 kHz, consisting of 12 subcarriers and 6 or 7 OFDM symbols. A RB is the minimum scheduling size for UL and DL scheduling. The time domain is divided into Transmission Time Interval (TTI) of 1 ms that forms a subframe. An LTE frame consists of 10 subframes and is of a 10 ms duration. A set of Quality of Service (QoS) parameters are associated with each flow depending on the application [13]. In LTE standard, QoS Class Identifier (QCI) is identified to differentiate among flows. Once a link is established, channel quality is estimated by measuring Signal to Interference plus Noise Ratio (SINR). Using SINR, Channel Quality Indicator (CQI) is estimated and reported back to the eNB. The CQI value helps identify the Modulation and Coding Scheme (MCS) to use.

B. 5G and Beyond Systems

The current proposals of 5G intend to use OFDMA and variants of OFDMA in the uplink as well as downlink [3], [14], [15]. 5G intends to also cater for much diverse use cases which would not just be limited to mobile broadband but would also include: eMBB, mMTC, and URLLC [1]. Introducing flexible numerologies are a key feature to satisfy the stringent requirements of 5G NR for reliability, latency, and data rate. These numerologies would differ in subcarrier spacing, the number of symbols per TTI, Cyclic prefix (CP) length, TTI length etc. The requirements for numerology [16], [17] as well as frame structure [18] could be based on: Service type (eMBB, URLLC, and mMTC), Link type (uplink, downlink, sidelink, and backhaul), and User based (UE environment and requirements). The numerologies tend to be non-orthogonal to each other and hence assigning resource blocks distributed through the spectrum like in LTE downlink would cause interference between RB resulting in considerable performance degradation. Assigning users with the same numerology in a specific frequency band and having a guard band between different numerologies would be one way of resolving excessive interference.

III. Packet Scheduling

Scheduling techniques generally can be categorized as Channel unaware schedulers, Channel aware schedulers, and Channel and QoS aware schedulers. The key design consideration for future wireless systems should account for: *Complexity and Scalability* confirming that schedulers can work with the granularity of a millisecond. *Spectral Efficiency* to use the spectrum effectively, *Fairness* among users and applications, *QoS Provisioning* to make sure the QoS requirements are met, and *Energy Consumption* since each user has a limited amount of energy to spend. In LTE, resources are usually allocated based on a comparison of per-RB metrics: the j-th user is assigned resource block k if its metric $m_{j,k}$ is the largest one compared to other users for that particular RB. This metric is usually calculated based on the desired performance requirement using a combination of information like transmission queue size, Channel Quality Indicator, historical throughput, buffer state, and QoS requirement. Some common techniques for resource allocation in LTE are:

1) Maximum Throughput: This algorithm aims to maximize the overall throughput of the cell. Each user's metric is calculated based on their channel quality alone.

$$m_{i,k} = d_k^i(t) \tag{1}$$

Where $d_k^i(t)$ is the achieveable throughput expected for user i at the t-th TTI over RB k. Maximum throughput algorithm does maximize the spectral efficiency of the system. However, the resources are allocated very unfairly with the users having the best channel quality getting the most RBs.

2) Proportional Fair: Proportional Fair [19] algorithm gives a trade-off between fairness and spectral efficiency.

$$m_{i,k} = d_k^i(t)/R^i(t-1) \tag{2}$$

where $R^i(t-1)$ is the past average throughput of the user.

3) Maximum Largest Weighted Delay First: (M-LWDF) [20] is efficient in scheduling real time users with different QoS requirements catering to their delay requirements.

$$m_{i,k} = \alpha_i D_{HOL,i} \cdot \frac{d_k^i(t)}{R^i(t-1)} \tag{3}$$

Where $D_{HOL,i}$ is the delay of the head of the line (HOL) packet and $\alpha_i = -\frac{log\delta_i}{\tau_i}$. Where δ_i is the packet loss rate and τ_i is the delay threshold of flow i ver RB k.

IV. Problem Formulation

We assume that each numerology has its own QoS parameters for delay budget and packet error loss rate. The goal of our optimization problem is to increase cell throughput, maintain fairness, and minimize the delay and packet loss. This problem would become a multi-objective optimization problem with the following objective functions:

$$max \sum_{i=1}^{u} \sum_{k \in RB^i} r_{i,k} \tag{4}$$

$$\forall i \in U : \lim_{t \to \infty} r_i(t) \geq \phi_i \bar{r} \quad (5)$$

$$\forall i \in U : min(l_i) \text{ and } min(d_i) \quad (6)$$

subject to:

$$\forall i, j \in U, \;\; i \neq j : RB^i \cap RB^j = \emptyset \quad (7)$$

$$\forall i \in U, \;\; x \in N : \;\; d_{i_x} < D_x \quad (8)$$

$$\forall i \in U, \;\; x \in N : \;\; l_{i_x} < L_x \quad (9)$$

$$\forall i \in U, \;\; x \in N : \;\; RB^i \subset RB^x \quad (10)$$

$$\forall a, b \in K, \; a = b + 1 \;\text{ and }\; \forall x, y \in N, \; x \neq y : RB_a^x \neq RB_b^y \quad (11)$$

where $i \in U = \{1, 2, ..., u\}$ denotes the index of different flows that have packets to transmit. RB^i where $i \in U$ are the set of resource blocks assigned to ith flow, RB^x where $x \in N$ are the set of resource blocks using numerology x and RB_k^x denotes that k-th resource block is assigned to numerology x. $r_{i,k}$ is the achieved throughput of user i over k-th resource block. $r_i(t)$ is the average throughput of user i uptill time t and $\bar{r}$ is the average total throughput. ϕ_i is the mimum fractional throughput of the total average throughput, required by user i with $\sum_{i=1}^{u} \phi_i \leq 1$. d_{i_x} and l_{i_x} is the delay and loss of user i using numerology x respectively. D_x and L_x are the maximal delay budget and maximal loss target for numerology x. N denotes the set of available numerology.

The objective functions include maximizing the system throughput, assuring fairness, and minimizing the delay and packet loss rate per user expressed by Equation (4), (5), and (6). Equation (7) insures that a single resource block is not assigned to two users. Equation (8) and (9) makes sure that the QoS requirements for the numerology are met. Equation (10) ensures that each user utilizes only one single numerology. Equation (11) makes sure that no two different numerologies are assigned resource blocks next to each other. The guard band between different numerologies is assumed as one RB.

V. Proposed Algorithm

We propose an Adaptive Numerology Resource Allocation (ANRA) algorithm to cater for the multi-numerology requirements of 5G networks. The eNB calculates the metric $m_{j,k}$ for each user over all available resource blocks. ANRA is flexible in the sense it can use any of the available metrics from the literature or a new metric specifically developed for the diverse use cases of 5G networks. ANRA further calculates a metric for each numerology based on the metric values of all the users in that particular numerology. ANRA maintains flexibility and can allow the calculation of a numerology metric based on mean, mode, median, maximum, etc depending on the use case. In our algorithm and simulations, we are using the average (mean) of all user metrics to calculate the numerology metric as shown in the equation:

$$N_i\text{-}RB_k = \frac{1}{n} \sum_{j=1}^{n} m_{j,k} \qquad \forall j \in N_i \quad (12)$$

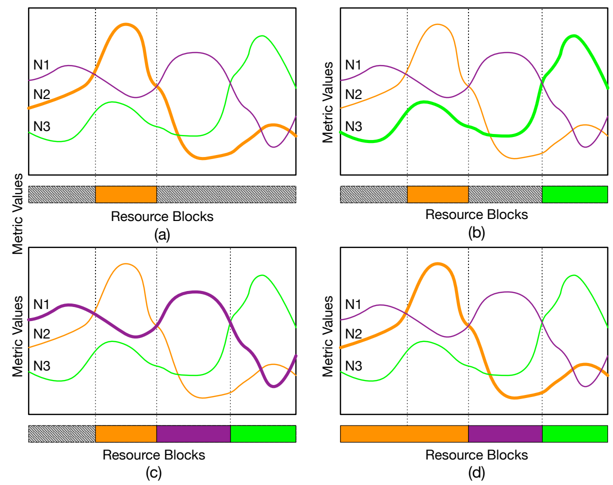

Fig. 1. Example of resource allocation with 3 numerologies using ANRA.

Where N_i-RB_k is the average metric value over RB k of all flows j employing numerology i.

The steps of the algorithm, exemplified in Fig. 1, are as follows:

1) Calculate the metric for each numerology N-RB.
2) Search within each numerology metric, the numerology i and RB k with the highest metric value (N_i-RB_k) and allocate RB k to numerology i.
3) Expand the bandwidth of numerology i in the direction of higher metric value until one of the following conditions are met on both sides:
   a) Another numerology has a higher metric value. (Fig. 1(a))
   b) The expansion has reached physical constraints.
   c) All UEs data has been assigned to the RBs.
4) Temporarily exclude numerology i and its metric values.
5) Repeat step 2-4 for the remaining numerologies, until all numerologies are assigned or until there's no more RBs left. (Fig. 1(b),(c))
6) Re-admit temporarily excluded numerologies to see if any of them can be expanded. (Fig. 1(d))
7) If there are still any RBs left and there are numerologies in which UEs have data to send, repeat steps 2-5 for the remaining RBs using remaining numerology metric.

Fig. 1 shows in detail on how the resources are assigned in a three numerology system. N_2 has the highest metric value and hence is assigned the resources first until another numerology has a higher metric value (Fig. 1(a)). Afterwards, N_3 has the highest value and hence is assigned the resources until another numerology has a higher metric on one side and physical constraints are reached on the other side (Fig. 1(b)). N_1 is assigned the resource blocks thereafter until physical constraints are reached on both sides (Fig. 1(c)). Next, following Step 6, the numerologies that can be expanded are expanded (Fig. 1(d)). We assume a guard band between different numerologies is added.

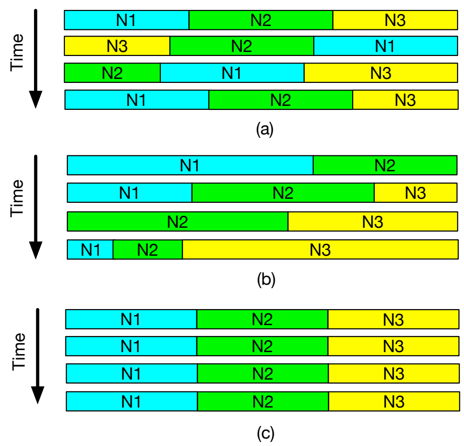

Fig. 2. Resource allocation for 3 numerologies over multiple TTI. (a) Resource allocation for ANRA. (b) Resource allocation for PBNA. (c) Resource allocation for CB.

In order to compare our algorithm, we proposed two other intuitive algorithms. We proposed a *Priority Based Numerology Allocation* (PBNA) algorithm where RBs are assigned to the numerology with the highest priority first before serving other numerologies. The higher numerology is served until it has no more data to send or the RBs are all occupied. The RBs are assigned in a serial manner. The priority of the numerology is decided based on the QCI value of its users. We also proposed *Constant Band* (CB) algorithm where each numerology is assigned a specific band calculated based on the number of UEs in the numerology. This band is fixed and the users in this numerology can only use RBs within this band. Fig. 2 shows the resource allocation of these three algorithms.

VI. Performance Evaluation

We developed a multi-numerology system level simulator environment. The performance of the scheduling algorithm is evaluated in terms of aggregate downlink throughput. The experiments are performed in a single cell environment with one eNB and multiple UE in an LTE environment. Since the architecture and parameters for 5G have not been finalized, and would probably be an extension of LTE, we chose to simulate in an LTE like environment. For this paper, we have limited our analysis to throughput alone. The delay and fairness analysis would depend on the parameters, architecture, and the application usage of the 5G network and would be included in the extension of this paper. The schedulers are implemented every TTI for the duration of the simulation. For macroscopic propagation model, we used a typical urban setup path loss model [21]. For microscopic channel model, we implemented a tapped delay line model [22] with each UE having 6 to 12 tap power delay profile. We assume that the nodes are synchronized with the eNB. We further assume a guard band of 96 kHz in between different numerologies to assure minimum interference. Table I summarizes the simulation parameters discussed above.

TABLE I
System Simulation Parameters

Cellular Layout	Single-Cell with Omnidirectional Antenna
System Bandwidth	3 MHz
Carrier Frequency	2 GHz
Number of RBs	15
TTI Duration	1 ms
Path Loss Model	128.1 + 3.76*10*$\log_{10}$(d[km])
Minimum distance	200 m
Mobility	Half UEs are mobile with random speed in range 10 to 100 km/h
Power Delay Profile	6 to 12 tap channel
Channel Estimation	Ideal
eNB Antenna Gain	18 dBi
UE Antenna Gain	0 dBi
UE Noisefigure	7 dB
eNB Transmit Power	46 dBm
Simulation Time	10000 TTI

TABLE II
Parameters for Traffic Model

Traffic	Numerology #	QCI #	PDB (ms)	GBR (kbps)
VoIP	N1	1	50	12.2
Video Streaming	N2	2	100	64
FTP	N3	6	300	10

TABLE III
Simulation A : The Effect of Traffic Mix Ratios - Parameters

Parameter	**Value**
Number of UEs	15
UE Ratios (VoIP : Video : FTP)	1:1:3, 1:2:2, 1:3:1, 2:2:1, 3:1:1

A. Traffic Model

The traffic models for our experiment has been adopted from LTE [23] and summarized in Table II. To better evaluate the schedulers, we assume that each UE is carrying a single type of traffic throughout the duration of the simulation.

VoIP Traffic: Highest priority traffic in our model. We assume a continuously active VoIP source generating a packet of 40 bytes every 20 ms [23] running at a bit rate of 16 kbps.

Video Streaming: We model it as a low quality video stream running at a bit rate of 64 kbps. 1 video frame is generated every 100 ms. Each video frame is divided into 8 packets where the size and the arrival time of the packets follow a pareto distribution [23].

FTP: We use this as a best effort traffic having the lowest priority and highest data available. A constant packet size of 256 bytes arrives every 16 ms.

B. Simulation Results

1) Simulation A: The Effect of Different Traffic Mixes on System Performance: The purpose of this simulation is to examine the scheduler's performance in different traffic conditions. We assign a different numerology to each application type with the parameters listed in Table III. We analyze the results for *ANRA* and *PBNA* algorithms using metric values of *PF*, *M-LWDF*, and *MT*. It does not make sense to perform

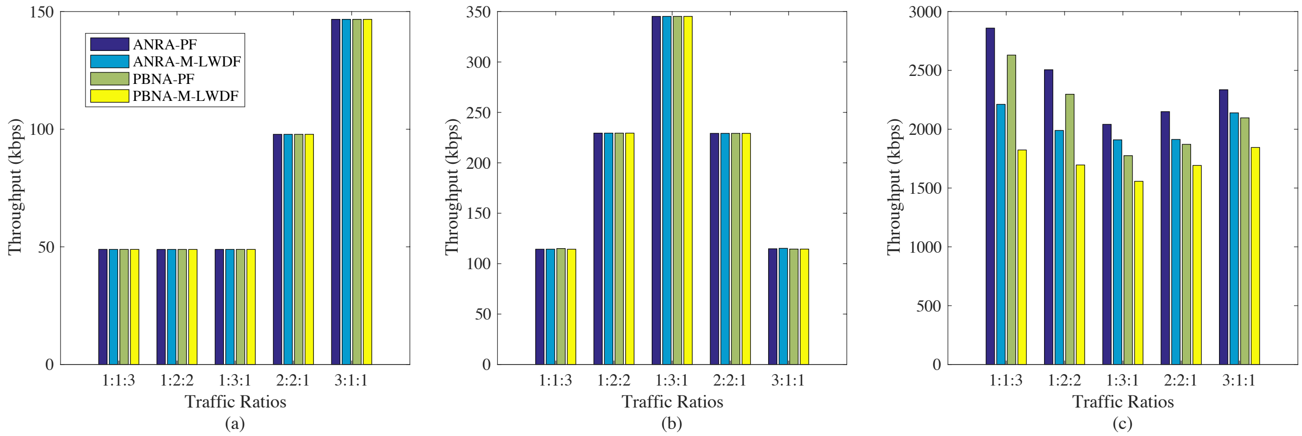

Fig. 3. Simulation A: Aggregate Throughput of each Numerology under different trafic ratios.

TABLE IV
SIMULATION B : VARRYING NUMBER OF UES - PARAMETERS

Parameter	Value
Number of UEs	10, 20, 30, 40, 50
UE Ratios (VoIP : Video : FTP)	4:3:3

TABLE V
SIMULATION C : DIFFERENT NUMEROLOGY WITH SAME PRIORITY

Parameter	Value
Number of UEs	12, 24, 36, 48, 60
UE Ratios (FTP : FTP : FTP)	1:1:1

the simulation for *CB* algorithm since numerology 1 and numerology 2 have limited amount of data and is not reaching saturation. Therefore, assigning a fixed band would mean a lot of the bandwidth would go empty.

Fig. 3 (a), (b), and (c) show the results of *ANRA* and *PBNA* algorithm with metric values of *PF* and *M-LWDF* for each numerology. Since Numerology 1 and 2 have a higher priority and low amount of data to send, we can see in the figures that these numerologies are able to send all of their available data while the best effort traffic i.e. Numerology 3 gets the least priority and faces congestion. In a multi QoS traffic systems, the flows with the least priority suffers the most degradation because of limited resources. In order to evaluate the throughput performance of these schedulers, we have to look at the performance of Numerology 3. From the figures, we can see that metric *PF* performs better than *M-LWDF*. We also see that our proposed algorithm *ANRA* performs much better in all scenarios compared to *PBNA* algorithm. Fig. 4 (a) show the effects *MT* metric in the throughput of Numerology 3. However, this assignment is highly unfair with the best UEs getting the most RBs and starving the other users. We can see that our algorithm *ANRA* still performs much better than *PBNA* algorithm. Since *MT* is unfair and unrealistic, we decided to not include it in the rest of our simulations.

2) Simulation B: Varrying the number of UEs: In this simulation, we keep the traffic ratio of *4:3:3* while increasing the number of UEs steadily. As we increase the number of UEs in the cell, the competition among the UEs over limited RBs increases, which decreases the chances of transmission for each UE. We assign a different numerology to each application type with the parameters shown in Table IV. The results of the simulation are shown only for the best effort flows (Numerology 3) in Fig. 4 (b). As we increase the number of UEs, more and more RBs are occupied by Numerology 1 and 2 whereas Numerology 3 suffers. However, we can see that our algorithm *ANRA* performs much better than *PBNA*. We still see that *PF* performs better than *M-LWDF*.

3) Simulation C: Different Numerologies with Same Priority: The purpose of this simulation is to compare different numerologies having the same QoS requirements and hence the same QCI index. We performed this simulation for *ANRA* and *CB* with *PF* and *M-LWDF* metrics with parameters shown in Table V. It does not make sense to use *PBNA* algorithm since each numerology has the same priority. Fig. 4 (c) shows the total aggregated cell throughput of all three numerologies. *ANRA* performs considerably well compared to *CB*. We can see that with an increase of the number of UEs, the throughput also increases. However, After reaching a certain number of UEs, the system is saturated with the maximum throughput achieved.

VII. CONCLUSION

5G NR intends to implement flexible waveforms and numerologies in their network forming a multi-numerology system. These numerologies would not be orthogonal and hence there's a need to find ways of scheduling different non-orthogonal numerologies without adding excessive guard band. In our quest for joint resource allocation and numerology multiplexing while maintaining high spectral efficiency, we propose an Adaptive Numerology Resource Allocation (ANRA) algorithm. ANRA allocates flows with the same numerology in the same frequency band and adds a guard band between different non-orthogonal numerologies. ANRA

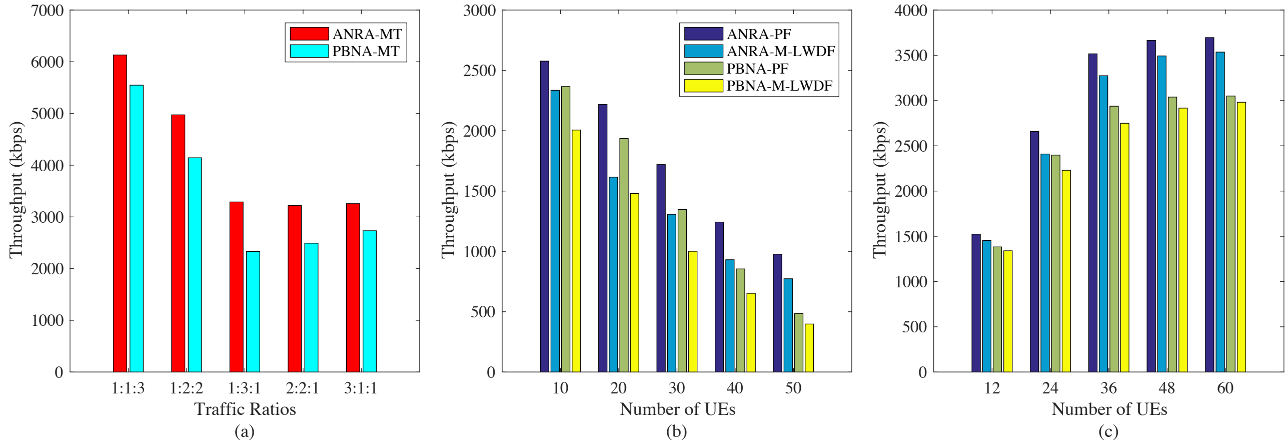

Fig. 4. (a) Simulation A: Aggregate Throughput of Numerology 3 with different traffic ratios using MT. (b) Simulation B: Aggregate Throughput of Numerology 3 under varrying number of UEs. (c) Simulation C: Total aggregate cell throughput under varrying number of UEs.

is fairly flexible and performs numerology multiplexing by calculating a metric for each numerology. We show in our simulations that ANRA performs considerably better than other intuitive algorithm.

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