QoS guaranteed radio resource scheduling in stand-alone unlicensed MulteFire

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***Abstract*—Increase in voice and data traffic has recently prompted cellular operators to consider deploying LTE-like systems in the unlicensed spectrum as an option to meet their customer requirements. This has led to industry-proposed specifications for unlicensed band access, namely LTE enhanced Licensed Assisted Access (LTE-eLAA), LTE Unlicensed (LTE-U)/MulteFire (MF). In this paper we focus on MF, which is an extension to the LTE specification that operates entirely in the unlicensed band. It employs a flexible frame format that enables adaptive allocation of subframes for uplink and downlink resources, unlike the rigid (or) fixed frame format used in eLAA. We study and evaluate the potential of a MF network in terms of its flexible resource allocation to ensure Quality of Service (QoS) guarantees to users. Exploiting MF's flexible allocation, we propose a scheduling model that utilizes a satisfaction function which guarantees transmission opportunities to users that are close to their deadline (*i.e.*, reward to users transmitting closer to their deadlines and penalty to users transmitting after their deadlines). Compared to eLAA our proposed MF scheduling algorithm achieves better performance for a dense user deployment. We corroborate the analysis by performing system level simulations in ns-3 and demonstrate good agreement between analysis and simulation with respect to latency and packet-drop metrics.**

I. INTRODUCTION

In recent years there has been an exponential growth in cellular traffic both indoors and outdoors leading to cellular operators investigating deployments in unlicensed spectrum. User traffic has also grown more diverse (*e.g.*, voice, video, online-gaming) leading to varying data rate and latency requirements. LTE enhanced Licensed Assisted Access (eLAA) [1] and LTE unlicensed (LTE-U) [2] are two candidate technologies developed for use in unlicensed spectrum. LTE-eLAA, which was proposed by 3GPP [1] in Release 14, uses the unlicensed spectrum for both uplink and downlink transmission, unlike LTE-LAA which only used the unlicensed spectrum for downlink transmission while all uplink transmission took place over the licensed carrier. In order to fairly coexist with Wi-Fi, eLAA uses a listen before talk (LBT) mechanism that is similar to Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) in Wi-Fi. LTE-U, another standard developed by industry, operates on the unlicensed carrier only for downlink transmission, while its uplink transmission uses licensed carrier. It coexists with Wi-Fi in the unlicensed band by following a duty cycle approach, which is a periodic ON and OFF state. Table I shows a summary of different types of channel access and spectrum utilization approaches currently used in the unlicensed bands.

TABLE I: Different Types of Unlicensed Technologies

Methods	Channel Access	Spectrum Utilization
LTE-U	Duty Cycled	Licensed (UL) & Unlicensed (DL)
LAA	LBT	Licensed (UL) & Unlicensed (DL)
eLAA	LBT	Licensed (UL) & Unlicensed (UL & DL)
MF	LBT	Unlicensed (UL & DL)
Wi-Fi	CSMA/CA	Unlicensed (UL & DL)

Recently, Qualcomm proposed a stand-alone unlicensed technology called MulteFire (MF) [3]. MF is a LTE-based technology operating exclusively in the unlicensed spectrum without the need for a licensed anchor channel. In a sense, MF operates similarly to Wi-Fi in that it uses a channel access access mechanism similar to CSMA/CA in Wi-Fi, but also uses the LTE protocol stack that allows MF to have flexibility in terms of resource allocation, re-transmission mechanisms, power control procedures, etc. The key specifications of MF are closely aligned with 3GPP Rel-13 and Rel-14 standards and could be potentially very advantageous to the future standalone new radio (NR) based small-cell deployments in unlicensed 6 GHz spectrum [4]. This novel technology is augmented with Listen Before Talk (LBT) based procedures to fairly co-exist with other complementary technologies such as Wi-Fi and encompasses the benefits from eLAA without a licensed anchor.

In eLAA, there is a restriction on Time Division Duplex (TDD) frame con-figuration as it supports only seven fixed UL/DL TDD frame configurations. But, in MF, any sub-frame can be UL or DL because it uses the new frame structure, type-3 [3], [5]. Thus, in MF, all UL and DL combinations are feasible. The motivation for designing and developing cost-efficient networks using MF [6] is to realize a simple and ubiquitous deployment similar to Wi-Fi, but offering users an improved Quality of Service (QoS) like LTE. Hence, it adopts features from both LTE and Wi-Fi in order to coexist fairly with Wi-Fi in the unlicensed spectrum while offering users a level of QoS not available with Wi-Fi. In this paper, we evaluate the potential of stand-alone MF in terms of flexible uplink/downlink frame resource allocation as compared to eLAA's fixed allocation. Towards this end, we propose a satisfaction function which is defined in terms of users' reward and penalty. This method guarantees Quality of Service (QoS) in terms of satisfying user's delay requirements. We validate the proposed model in a ns-3 based network simulator [7], by implementing an LTE scheduler that accepts inputs from our model.

II. RELATED WORK

Unlicensed spectrum is inherently ”unmanaged” meaning that there is no central control that manages channel access between all competing systems in the band. Hence, a robust radio resource scheduling scheme can lead to better coexistence between different systems that may be deployed in this band. In this section, we briefly discuss some of the existing literature on LTE-LAA and MF. In a traditional LTE network operating over a licensed channel, the scheduling of radio resources is based on SINR, buffer status, channel aware and per user throughput fairness. A few papers focus on QoS or delay guaranteed based resource allocation. In [8] the authors propose a cross layer solution for real-time traffic that allocates spectrum for different services in order to meet their QoS requirements. This approach utilizes the instantaneous downlink SINR and QoS information to determine when to allocate the spectrum to a real-time service. In [9], the authors proposed a new scheduling algorithm for the downlink based on delay to increase the throughput for real-time video traffic. Authors in [10] proposed a channel aware service discipline for guaranteed bit rate (GBR) bearers which is able to fulfill not only GBR but also the packet delay budget. Additionally the algorithm will take care of prioritizing the GBR and non-GBR bearers from different QoS services. The proposed algorithm in [11] minimizes the delay of the real-time traffic while still offering a good level of QoS. Also, this paper effectively analyzed the queue buffer of each user and prioritized the flow in terms of delay. Similarly, in [12], the author proposed a LAA enabled LTE base station that fully controls the shared environment by dynamically adjusting the time allocation for both Wi-Fi and LAA technologies. In [13], the authors explored LBT category 4 scheme and developed a model for the distribution of MAC delay experienced by the Wi-Fi packets and LTE frames.

In [6] the authors provided an overview of the regulatory requirements in the 5 GHz unlicensed band, the radio challenges (channel access procedure, frame structure, mobility, etc), solutions and performance of MF and the required modifications to the MF specifications. Most of the above work considers only the fixed frame format for LTE-LAA resource allocation, while in this paper, we consider a dynamic ratio of uplink and downlink transmission opportunity to schedule the users in such a way that the QoS is maximized.

III. FRAME FORMAT: FIXED VERSUS FLEXIBLE

In LTE, each Radio Resource Block (RB) is 180 KHz in bandwidth consisting of 12 sub-carriers and 7 Orthogonal Frequency Division Multiplexing (OFDM) symbols. Each RB consists of 84 (*i.e.,* 12*7) resource elements. The number of bits that can be carried in each resource element is calculated based on the chosen modulation-coding-scheme. Resources are allocated in the frame format at a sub-frame level, where each frame and sub-frame has the duration of 10 ms and 1 ms, respectively. The TDD mode in LTE has seven different configurations of uplink and downlink sub-frame structures and each configuration has a different allotment of uplink and downlink slots. Based on the traffic demand, the operator can choose one of these fixed eLAA TDD configurations. Fig. 1 shows the fixed and flexible format of the frame structure.

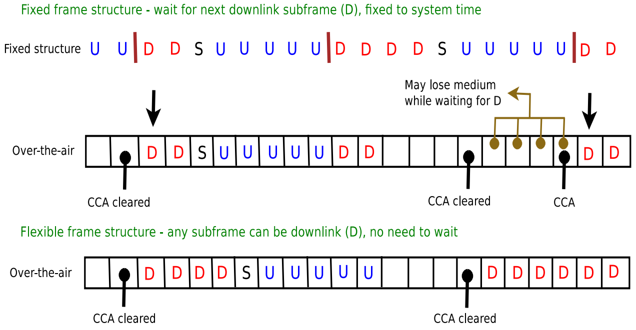

Fig. 1: Frame structure: Fixed versus Flexible

Consider a situation where the eLAA operator chooses a fixed configuration format [”D”,”S”,”U”,”U”,”U”,”D”,”D”,”D”,”D”,”D”], when the demand for downlink D is high in the network. After the Clear Channel Assessment (CCA), if the eLAA occupies the medium in the uplink slot, then it needs to wait for the downlink slot (D), which may be inefficient. With the fixed frame format, the operator does not have the flexibility to change the slot (within the frame) in the air-medium from uplink to downlink and vice-versa. The flexible frame allocation feature in MF can overcome this challenge of fixed frame allocation by allocating the radio resource dynamically based on the user request. Hence, the operator will not waste the medium for downlink (D), rather it will allocate the downlink slots as needed. This approach will be able to better guarantee the QoS for the users.

IV. PROPOSED WORK

In this section, we present the system model that we consider in this paper and the definition for the satisfaction function used in the proposed MF optimization model.

A. *MulteFire System Model*

The MF network utilizes the unlicensed spectrum for both uplink and downlink transmission. To maintain a fair comparison, we assume that eLAA will operate only on unlicensed carrier (*i.e.,* no licensed anchor). The channel access mechanisms like Physical Broadcast Control Channel (PBCCH), Physical Downlink Control Channel (PDCCH), Physical Downlink Shared Channel (PDSCH), Physical Uplink Control Channel (PUCCH) and Physical Uplink Shared Channel (PUSCH) in MF are similar to eLAA as specified in Release 13 and Release 14. To visualize the potential of flexible frame allocation, we consider only one BS (either MF or eLAA) in the network as shown in Fig. 2 (where red color circle represents DL users and blue color circle represents UL users). Hence, there is no impact of collisions or contention. Also, we assume that the uplink and downlink traffic will vary dynamically over time. We assume the number of downlink users is high compared to the uplink. We consider different delays for different traffic such as voice, video, online-gaming, etc.

We propose a satisfaction function based method that ensures QoS by giving higher rewards to users transmitting closer to their deadlines and penalties to users transmitting after their deadlines. This ensures QoS by giving transmission priority to the user with the closest deadline while discouraging late transmissions. The detailed explanation of the profit and loss calculation is explained next.

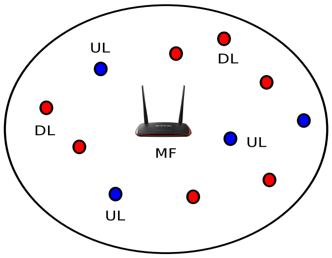

Fig. 2: Experiment Deployment Scenario

B. Satisfaction Function

The definition of the satisfaction function considered in this paper is shown in Fig. 3. The *reward (R)* for device d is guaranteed when the satisfaction function increases linearly until the delay is less than the allowable delay ($\hat{D}_d$) and the *penalty* ($\bar{R}_d$) for device d is applied once the allowable delay is exceeded and is equal to $-\hat{D}_d$. This satisfaction function leverages the allowable delay to ensure that:

- A device with lower allowable delay is served frequently
- A device with higher allowable delay has fewer missed requests

Let us consider the following two extreme cases with respect to allowable delay of two users (namely User 1 and User 2) to understand the behavior of the satisfaction function.

1) When the delay values are close to $\hat{D}$: As shown in Fig. 4, consider the case when the delay value of the users are closer to their respective allowable delays. Clearly, only one user out of the two can be scheduled within the allowable delay. Since User 2 has a higher penalty, User 2 will be scheduled. Hence, this ensures that the packet drop rate is lower for user 2 which is the device with a higher allowable delay.

2) When the delay values are same: As shown in Fig. 5, consider the case when the delay values of User 1 and User 2 are the same. Clearly, scheduling User 1 has more advantage than User 2 since the delay of User 1 is closer to its allowable delay. Since User 1 has a higher reward than User 2, User 1 will be scheduled. Hence, this ensures that the device with less allowable delay is served more frequently.

C. Proposed MF Optimization Model

The notations and definitions for the problem formulation are illustrated in Table II. The goal is to maximize the system satisfaction in each MF frame and is given by:

TABLE II: List of notations used in the problem formulations.

Notation	**Definition**
D	Number of devices
T	Number of timeslots (subframes) in a frame
$\hat{D}_d$	Maximum allowable delay for device d.
x_{dt}	1 if device d gets the latest scheduled packet at timeslot t; 0 otherwise.
D_{dt}	Delay of device d at timeslot t.
α_{dt}	1 if the packet received by device d at timeslot t does not exceed the allowable delay $\hat{D}_d$; 0 otherwise.
β_{dt}	1 if the packet received by device d at timeslot t exceeds the allowable delay $\hat{D}_d$; 0 otherwise.
R_{dt}	Reward for device d for receiving the packet at timeslot t.
P_d	1 if the delay of the latest packet exceeds the allowable delay at the end of the frame; 0 otherwise
$\bar{R}_d$	Penalty for device d at the end of the frame

$$\max \sum_{d=1}^{D}\sum_{t=1}^{T} R_{dt} + \sum_{d=1}^{D} \bar{R}_d$$

Constraints: Equation (1) ensures that exactly one MF device will access the channel at each time slot.

$$\sum_{d=1}^{D} x_{dt} \leq 1 \qquad \forall t \in [T] \tag{1}$$

where $[T] = \{1, 2, \ldots, T\}$. The following three constraints (equation (2) (3) and (4)) classify whether the delay of a packet received by device d at timeslot t ($x_{dt} = 1$) exceeds ($\alpha_{dt} = 1$) or does not exceed ($\beta_{dt} = 1$) the allowable delay $\hat{D}_d$.

$$\alpha_{dt} + \beta_{dt} = x_{dt} \qquad \forall d \in \mathcal{D}, t \in \mathcal{T} \tag{2}$$

$$\hat{D}_d - 1 + \bar{D}(1 - \alpha_{dt}) \geq D_{d,t-1} \qquad \forall d \in [D], t \in [T] \tag{3}$$

$$\bar{D}(1 - \beta_{dt}) + D_{d,t-1} \geq \hat{D}_d \qquad \forall d \in [D], t \in [T] \tag{4}$$

where $[D] = \{1, 2, \ldots, D\}$ and $\bar{D}$ is a large value. As discussed in the previous section, the reward R_{dt} for device d at timeslot t is calculated as,

$$R_{d,t} = \begin{cases} 0, & \text{if } \alpha_{dt} = \beta_{dt} = 0 \\ \frac{1+D_{d,t-1}}{\hat{D}_d}, & \text{if } \alpha_{dt} = 1 \\ 0, & \text{if } \beta_{dt} = 1 \end{cases}$$

In the proposed model, we have provided 0 reward when a packet is received after the allowable delay (we only penalize when a packet exceeds allowable delay at the end of a frame, as shown in equations (7) and (8)). However, the model can be easily extended to consider any reward/penalty when $\beta_{dt} = 1$. The following constraint in equation (5) models the reward for device d at timeslot t,

$$R_{dt} = \alpha_{dt}\left(\frac{1 + D_{d,t-1}}{\hat{D}_d}\right) + \beta_{dt}(0), \; \forall d \in [D], t \in [T] \tag{5}$$

Delay for the latest packet scheduled for device d at timeslot t is,

$$D_{d,t} = \begin{cases} D_{d,t-1} + 1, & \text{if } x_{dt} = 0 \\ 0, & \text{otherwise} \end{cases}$$

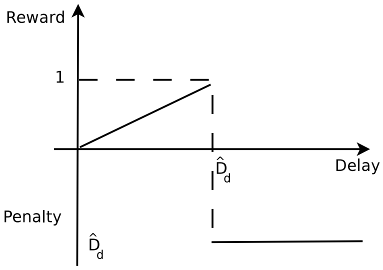

Fig. 3: Satisfaction Function: Reward & Penalty

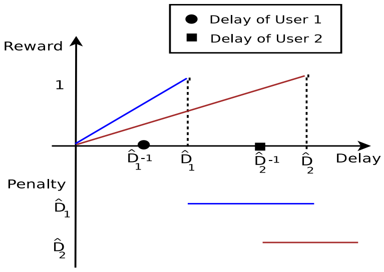

Fig. 4: Reward & Penalty (delay close to $\hat{D}$)

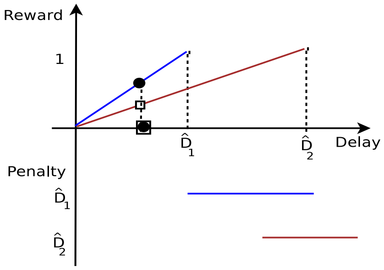

Fig. 5: Reward & Penalty (same delay for device d)

TABLE III: LTE eLAA DL-UL Configurations

Configurations	UL/DL Slots
eLAA Conf.1	[”D”,”S”,”U”,”U”,”U”,”D”,”S”,”U”,”U”,”U”]
eLAA Conf.2	[”D”,”S”,”U”,”U”,”D”,”D”,”S”,”U”,”U”,”D”]
eLAA Conf.3	[”D”,”S”,”U”,”D”,”D”,”D”,”S”,”U”,”D”,”D”]
eLAA Conf.4	[”D”,”S”,”U”,”U”,”U”,”D”,”D”,”D”,”D”,”D”]
eLAA Conf.5	[”D”,”S”,”U”,”U”,”D”,”D”,”D”,”D”,”D”,”D”]
eLAA Conf.6	[”D”,”S”,”U”,”D”,”D”,”D”,”D”,”D”,”D”,”D”]
eLAA Conf.7	[”D”,”S”,”U”,”U”,”U”,”D”,”S”,”U”,”U”,”D”]

TABLE IV: Simulation Parameters

Parameter	**Value**
Number of UEs	5, 10, 15, 20, 25, 30 (per BS)
Transmission Power	23 dBm
Traffic Class	Voice, Video and Online gaming
Load	Full Buffer
Channel Bandwidth	20 MHz
LTE-eLAA Scheduling	Proportional Fair
Traffic Flow	Downlink and Uplink

The following constraint in equation (6) models the delay for device d at timeslot t,

$$D_{d,t} = (D_{d,t-1} + 1)(1 - x_{dt}), \; \forall d \in [D], t \in [T] \tag{6}$$

The following constraints (in equation (7) and (8)) model the penalty assigned to a device if the device's latest packet exceeds the allowable delay at the end of the frame.

$$M \times P_d \geq \frac{D_{d,T}}{\hat{D}_d - 1} - 1, \; \forall d \in [D] \tag{7}$$

$$\bar{R}_d = -\hat{D}_d P_d, \; \forall d \in [D] \tag{8}$$

where M is a large value.

$$x, \alpha, \beta \in \{0,1\}^{D \times T}, (D, R \quad \in R^{D \times T}), P \in \{0,1\}^D, \bar{R} \in R^D$$

D. *Linearizing the above model*

Bilinear product $x_{dt} D_{dt-1}$ makes the above model non-linear. Hence, we linearlize the model as follows,

$$\bar{D}(1 - x_{dt}) + y_{dt} \geq D_{d,t-1} \tag{9}$$

$$y_{dt} \leq \bar{D} x_{dt} \tag{10}$$

$$y_{dt} \leq D_{d,t-1} \tag{11}$$

The above three constraints (in equation (9), (10) and (11)) together ensure that $y_{dt} = x_{dt} D_{d,t-1}$. Hence, the bi-linear term $x_{dt} D_{d,t-1}$ can be replaced with y_{dt} subject to adding the above set of constraints. Similarly, we also linearize the bilinear term $\alpha_{dt} D_{dt-1}$. The above linear optimization model can be solved using commercial solvers such as CPLEX and GUROBI.

V. EVALUATION

We evaluate the performance of the MF Optimization Model analytically by establishing simulation parameters, scheduling packets by solving the model's linear function, and calculating the theoretical performance in terms of latency (or delay), and packet drop. We then run an ns-3 simulation using the same parameters and compare the performance result with the model.

A. *NS-3 Experiment Setup*

In our experiment, we deploy a mix of both UL and downlink DL users. Each user will have a maximum allowable delay ($\hat{D}_d$) based on the type of traffic (voice, video and online gaming). Based on the delay requirement of the traffic, the packet transmission is considered as a success or failure. Once the user deadline exceeds $\hat{D}$ in the experiment, we do not allow the packet to re-transmit (for example: online streaming traffic). In the simulation, we assume that the transmission opportunity (TxOP) is continuous for each BS in its UL and DL transmission. The simulation parameters are described in Table IV. We consider the total number of devices as 5, 10, 15, 20, and 25 respectively and the maximum allowable delay (ms) for those users are $\hat{D}$ (Let's assume for 15 users the delay $\hat{D}$ = [5, 10, 30, 15, 40, 5, 10, 20, 35, 10, 50, 15, 50, 5, 10]) and the achievable throughput (Mbps) for those users which are uniformly randomized between the values of [5, 10, 15, 20, 30]. We set these delay values according to the allowable delay values subject to various type of traffic taken from the QCI 3GPP table [1], but proportionally reducing it as there is no contention or collision in the model. The total number of frames considered in the experimental setup is 100. The number of DL and number of UL users are varied based

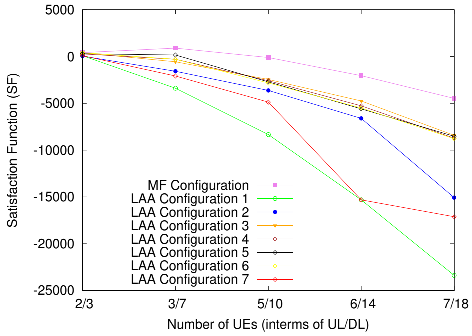

Fig. 6: Satisfaction Fun: MF & eLAA

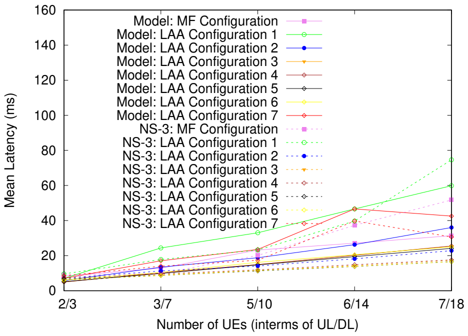

Fig. 7: Avg. Delay: MF & eLAA

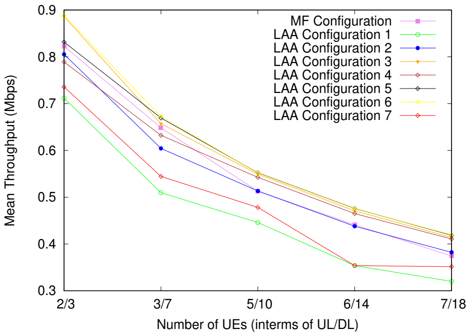

Fig. 8: Avg. Throughput: MF & eLAA

on the total number of users. The configuration used in the experiment for LTE-eLAA is shown in Table III.

We implement the model in ns-3 with some modifications. As there is no contention/co-channel interference in the system and distance between the transmitter and receiver is fixed, the path loss will be constant. Hence, in the simulation we assume that all uplink devices can use their configuration in a downlink device (*i.e.,* uplink devices are treated as downlink devices). The scheduling information is obtained from the MF model and fed to the ns-3 simulation as an input, along with UE's configuration parameters (*i.e.,* allowable delay, achievable throughput, number of UE). We run the simulation over multiple schedulers (*i.e.,* MF, and eLAA-Optimal configuration 1 to 7), multiple number of UE (*i.e.,* 5, 10, 15, 20, 25), and 10 random seeds that randomize each UE's achievable throughput. We observed the throughput, latency, and application-level packet drop (*i.e.,* packet dropped because of application-level latency $>$ allowable delay) of each UE.

B. Experiment Results

1) Satisfaction Function: Fig. 6 shows the benefits in terms of satisfaction function.In our experiment the UL and DL ratios (UL/DL) are 2/3, 3/7, 5/10, 6/14 and 7/18 respectively (as shown in the X-axis). From the result, it is evident that MF has higher reward and less penalty as compared to the seven different LTE-eLAA configurations. This is because of the fact that the satisfaction function is based on the on the delay guarantees. We efficiently used the deadline of the maximum delay ($\hat{D}$) for a MF user in such a way that the minimum delay users can be served.

2) Number of Users Vs Delay, Packet Drop and Throughput: Fig. 7 shows the average delay for total number of UL/DL users in MF and eLAA. We observe that MF has higher delay than eLAA, other than eLAA Conf. 1 and 7. This is because the satisfaction function for the proposed MF is defined in such a way that it utilizes each user's maximum deadline. Each user's deadline is used efficiently in MF, in the sense that each user is served based on its closeness to its deadline, satisfying the deadline requirement to avoid packet drop, and we will see this in the packet statistics. The reason for the higher delay in the eLAA Conf. 1 & 7 is due to the larger allocation of uplink slot than the downlink slot (as shown in Table. III). This in turn increased the waiting time for the downlink users to get downlink slot in Conf. 1 & 7 and leads to increased transmission delay and packet drop. Also, we observe good agreement between model and ns-3 simulation. In ns-3, the latency is calculated slightly differently: the model calculates latency from the time of transmit to time of receive (*i.e.,* PHY latency), while ns-3 counts latency from the time the packet is generated on the application to time of receive. This leads to a slight difference in ns-3 latency as compared to the model but the overall trend remains same.

Table V shows the number of requests or successful packet transmissions for 25 UEs in MF & eLAA. We focus on this specific scenario to see how the scheduler performs in the scenario with largest contention. We observe the received-to-sent packet ratio in the model & ns-3, where we define successful reception to be when the packet is received with delay less than the deadline. The maximum utilization of the delay in MF leads to a larger received-to-sent ratio and the under utilization of delay in eLAA leads to a lower received-to-sent ratio (*i.e.,* higher packet drop). We can clearly see that there is a good agreement between MF model and ns-3 simulation for packet ratio. The MF model has a 92% successful transmission while the ns-3 simulation has a 81% successful transmission, and we can observe a similar trend in each of the eLAA configuration. This shows that the high ratio of successful transmission in MF leads to fair access for all users in the system. Since we are interested in the full protocol stack (*i.e.,* from physical to application layer) throughput, we capture the ns-3 throughput performance in Fig. 8. *Observation Note:* When compared to the traditional 20 MHz system (where the maximum achievable rate for all users are same in the network) the obtained mean throughput in the MF is less. This is due to different achievable throughput for each user in the network. Because in a realistic scenario, we can expect this kind of configuration based on the user data plan and nature of traffic. From Fig. 7 and Fig. 8 we observe higher delay and lower throughput for the eLAA Conf. 1 & 7.

3) Traffic Deadline Time Vs Delay, Packet Drop and Throughput: To explain the performance increase of MF optimization model, we explain it in terms of the average delay (Fig. 9) vs. successful transmission (Fig. 10) for each users

Configuration	Received-to-sent packets ratio	
	Model	**NS-3**
MF Dynamic Conf.	0.92	0.81
eLAA Conf. 1	0.31	0.28
eLAA Conf. 2	0.41	0.37
eLAA Conf. 3	0.43	0.40
eLAA Conf. 4	0.45	0.41
eLAA Conf. 5	0.47	0.44
eLAA Conf. 6	0.45	0.40
eLAA Conf. 7	0.38	0.39

TABLE V: 25 UEs Packet Information for MF & eLAA Configuration

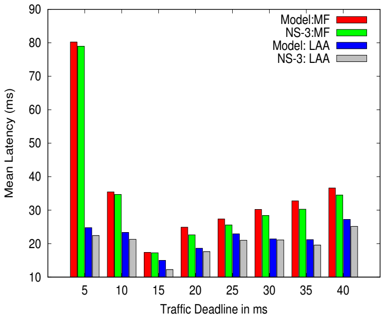

Fig. 9: Avg. Delay grouped by $\hat{D}$, for MF & eLAA Conf. 6

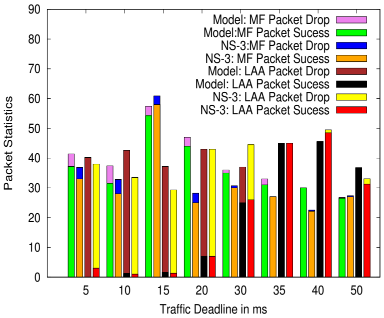

Fig. 10: Packet Statistics grouped by $\hat{D}$, for MF & eLAA Conf. 6

grouped by its allowable deadline for the 25-user scenario. For brevity, we only show eLAA configuration 6, since it delivers the highest overall throughput performance (as shown in Fig. 7). The allowable delay $\hat{D}$ for 25 users are [5. 10, 30, 15, 40, 5, 10, 20, 35, 10, 50, 15, 50, 5, 10, 15, 40, 5, 30, 15, 50, 15, 50, 5, 10]. The DL and UL users are in the ratio of 18:7. First, we observe that there is a good agreement for average delay between the model analysis and the simulation (Fig. 9). In Fig. 10, we observe that group of users with deadline of 5 and 10 ms has the highest latency in the MF model/ns-3 compared to the eLAA model/ns-3. Yet from Fig. 10, we observe a high packet success rate for MF, and no successful packet transmission for eLAA in those groups. This is because all of eLAA packets in it shows lower average delay, yet exceeds beyond the allowable deadline $\hat{D}$. In the case of MF simulation, for users with $\hat{D} = 5$ ms, we observed 94.05% of packet transmission have delay less than 5 ms, while the rest of 4.32% packets is larger 60 ms, with the largest delay of 313 ms, skewing the average delay to 79 ms. It shows that while average delay of MF users are higher than eLAA, most of packets are received within the allowable delay, and the rest of dropped packets has delay large enough to skew its average delay to be higher. As the allowable delay increased on Fig. 10, successful packet transmission rate of eLAA also increased, while its average deadline shown on Fig. 9 remain unchanged. This shows that eLAA aims to have a smaller average latency performance, but does not consider each users' allowable delay. On the other hand, the average delay of MF users are increased as the allowable delay increased, showing that the scheduler can assign the users with higher allowable delay with more freedom, while still retain its successful transmission performance.

VI. CONCLUSION

In this paper, we analyzed the performance of the flexible radio resources allocation scheme in MF and compared it to eLAA, both analytically and via system level ns-3 simulations. We carefully designed a scheduling model that takes advantage of the flexible allocation, and created an LTE scheduler in ns-3 to confirm the correctness of the model in a system-level simulation. We observed improvement of successful packet ratio in MF compared to eLAA in our analysis, meaning that MF guarantees fair scheduling for all users. Further, our ns-3 simulation results validated the model by showing a very good agreement between the model and the simulation. We observed that both in model and simulation, while MF shows higher delay than eLAA, it shows higher successful packet transmission ratio thus better QoS guarantee. In the latest iteration of Wi-Fi, 802.11ax, an OFDMA scheduling scheme similar to LTE is adopted for its radio resources scheduling. Hence, in future we are interested in studying and comparing the performance of MF, eLAA, and Wi-Fi IEEE 802.11ax, which will potentially be the three technologies that will be deployed in the unlicensed spectrum.

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