Joint Time and Power Allocation for 5G NR Unlicensed Systems

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Abstract—The fifth-generation (5G) and beyond networks are designed to efficiently utilize the spectrum resources to meet various quality of service (QoS) requirements. The unlicensed frequency bands used by WiFi are mainly deployed for indoor applications and are not always fully occupied. The cellular industry has been working to enable cellular and WiFi coexistence. In particular, 5G New Radio in unlicensed channel spectrum (NR-U) supports the uplink and downlink transmission on the maximum channel occupation time (MCOT) duration. In this paper, we consider maximizing the total throughput of both downlink and uplink in NR-U by jointly optimizing the time and power allocation during MCOT while ensuring fair coexistence with WiFi. Fairness is guaranteed in two steps: 1) tuning the access related parameters of NR-U to achieve proportional fairness, and 2) including 3GPP fairness from the throughput perspective as a constraint in NR-U throughput maximization. Numerical analysis and simulation have demonstrated the superior performance of the proposed resource allocation algorithm compared to conventional deployment strategies.

Index Terms—5G NR-U, spectrum sharing, resource management, cellular, WiFi, iterative algorithm.

I. INTRODUCTION

THe fifth-generation (5G) networks are being fast deployed all over the world with many underlying technologies as critical integral parts. The exponentially growing mobile data traffic and new applications have tremendously pushed the use of the spectrum resource to the limit and hence many new frequency bands, e.g., millimeter wave (mmWave) bands are being adopted for both cellular and WiFi usage [1]. Meanwhile, spectrum sharing is another promising approach to address the high demands of data traffic. The 3GPP has been actively seeking to use the unlicensed spectrum since the LTE age. In particular, licensed assisted access (LAA) and LTE-unlicensed (LTE-U) are two protocols proposed to co-exist with WiFi in unlicensed bands. The LTE-U developed in 3GPP Releases 10/11/12 allocates a fraction of a duty cycle for the LTE system and another portion for the WiFi system, which enables the base stations (eNodeB) to offload part of their traffic to the WiFi network [2]. However, there is no carrier sensing before LTE-U transmission, which will degrade the performance of the WiFi system [3]. On the other hand, the contention-based LAA performs carrier sensing before any transmission. In [4], the authors proposed a cellular-WiFi co-enabled design at the user equipment (UE) end to

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solve the hardware resource competition issue between the two standards in [3]. In 5G new radio, the coexistence between NR-unlicensed (NR-U) and WiFi has become a potential technology to boost the throughput of the NR system and improve the quality of service (QoS).

Nevertheless, how to accommodate cellular networks to operate in an unlicensed spectrum and ensure a fair and harmonious coexistence with other unlicensed systems is a challenging problem. According to the NR-U fairness defined by 3GPP TR 38.899 sub 7 GHz [5], assuming two independent networks are deployed in the same area (e.g., NR-U+WiFi and WiFi+WiFi), the fairness criterion is defined as the NR-U network not degrading the WiFi 802.11n network performance when they are deployed in the area, compared to the case where two WiFi 802.11n networks are deployed, similar to the definition in 3GPP 36.889 [6]. 3GPP TR 36.889 [6] has provided a paradigm for fairly evaluating the coexistence between two radio access technologies. That is, evaluate two WiFi systems coexisting in a given scenario and then replace one WiFi with LAA for a group of eNBs and UE. Accordingly, there are two types of fairness evaluation methods in the literature. The first type strictly follows the evaluation method [6]–[10]. For example, Gao *et al.* in [7], [8] investigate the fair coexistence between WiFi-WiFi systems, then use eNodeB to replace one WiFi AP, and derive the optimal duty circle and initial contention window size to satisfy the fairness requirement, respectively. The second type firstly considers a WiFi-LTE coexistence scenario, uses an equivalent WiFi system to replace the LTE system, and then adjusts some parameters to satisfy the fairness requirement [11]. Furthermore, a virtual WiFi network is created to replace the LTE system and compete with the real WiFi network, where the virtual WiFi network is assumed to obtain the same level of throughput as the LTE system to imitate the impact of eNodeB on a WiFi network in [12], [13].

Although the aforementioned fairness evaluation scenarios are defined, the fairness metrics are still up for discussion. Normally airtime and throughput are the two metrics for fairness consideration. The proportional fairness in LTE-WiFi coexistence in [14]–[16] considers the equal airtime and equal throughput per node. However, airtime fairness cannot always guarantee the throughput fairness, as there is a trade-off between throughput and airtime fairness when only adjusting the contention window size [17]. The throughput fairness in [7], [8], [11] only considers the successful airtime to satisfy the 3GPP fairness constraint given the physical data rate. However, the physical data rate of the licensed system usually is obtained by adjusting its transmission parameters. 3GPP TR 38.899 [5] recommends that Category-4 listen-before-talk (LBT) should

be adopted for 5G new radio base station (gNB) to access the unlicensed channels. The authors in [15] investigated different LBT categories proposed by LTE Release 13 and showed that the proposed LAA LBT cannot always make the WiFi system and LTE system proportionally coexist. Additional operation needs to be taken, such as adjusting the initial contention window size or sending duration of the LTE system. This suggests that parameters in 5G NR-U will also need to be optimized. On the other hand, for the NR-U frame, there are two operation modes of the MCOT, i.e., MCOT with a single or multiple downlink (DL)/uplink (UL) switching point(s) [9]. It was recommended in [18] that the maximum number of DL/UL switching points within one MCOT initiated by gNB should be one to reduce the communication latency, which is different from the LTE-U frame where the MCOT is usually used for downlink transmission or uplink transmission. NR-U adopts the frame structure Type 3, similar to the LTE time division duplex (TDD). How to allocate the time slots in gNB initiated MCOT for uplink and downlink to enable fair coexistence with WiFi and maximize the total throughput of the NR system on the unlicensed channels has not been studied in the literature.

In this paper, we consider the 5G NR-U coexistence with WiFi. Based on the access procedure of the NR-U and WiFi system, we calculate the throughput for the WiFi systems and the uplink and downlink throughput for NR users. To maximize the total throughput on the unlicensed channels and satisfy the fairness constraint between the two systems, we need to allocate the time and power for the uplink and downlink transmission. The main contributions of this paper are summarized as follows:

- We propose a new analytical model for NR-U and WiFi fair coexistence, which involves the NR-U frame structure including DL/UL transmission in COT and access procedures of NR-U and WiFi. Fairness is taken into account in two steps. First, to guarantee the proportional fairness of the two systems in terms of airtime, we derive the optimal initial contention window size for NR-U when it adopts LBT to compete for the unlicensed band. Second, throughput fairness is included as constraints in the subsequent NR-U resource allocation optimization.
- To maximize the DL and UL throughput of cellular users on the unlicensed channels while satisfy the throughput fairness constraints, the time and power allocation problem of NR-U is formulated and converted into a convex problem. A low-complexity iterative algorithm is developed to solve this problem.

The reaming part of this paper is organized as follows. In Section II, we survey the coexistence techniques for the NR and WiFi systems. In Section III, we model the unlicensed and licensed access probability, the throughput for both systems, the fairness and power constraints, and the uplink and downlink time duration constraints. In Section VI, the throughput maximization of the NR-U gNB is formulated, and then converted into a convex problem. In Section VII, we use the Lagrange multiplier to relax the problem and then decompose it into two subproblems, which are solved by the Karush-Kuhn-Tucker (KKT) conditions. In Section VIII, simulation is conducted to verify the proposed model and algorithm. Finally, Section IX concludes the paper and presents possible future work.

II. RELATED WORKS

A. Resource Allocation for Unlicensed Spectrum

LTE coexistence with the WiFi system has been widely researched. Liu *et al.* in [19] investigated comprehensive resource management scenarios in LTE-U systems, which includes single small base stations (SBS), multiple SBSs, device-to-device (D2D) network, vehicular ad hoc network, and unmanned aerial vehicle (UAV) systems. Liu *et al.* in [20] researched user association and resource allocation in unlicensed channels. The unlicensed time slots shared by the WiFi access point (AP) are assumed to be equal to the LTE-U users' to guarantee fairness, which provides airtime fairness for two systems. For the 5G NR-U system, Shi *et al.* [21] investigated the unlicensed spectrum resource sharing between NR-U and WiFi system, and proposed a distributed channel access mechanism to decide the optimal unlicensed channel for NR-U user offloading traffic. In [22], Song *et al.* proposed to use the cooperative LBT and $(N + 3)$-state semi-Markovian to characterize the effective capacity of NR-U with cooperative communications in unlicensed channels, but they did not consider the improvement of throughput for DL and UL transmission on unlicensed channels due to new NR-U frame.

B. Access Control and NR-U Frame on Unlicensed Channels

The 3GPP Release 16 [5] points out that the Category-4 LBT should be used to access the unlicensed channels for gNB initiated MCOT. Wang *et al.* in [23] proposed a network adaptive LAA-LBT strategy which includes a partially-randomized initial clear channel assessment (ICCA) scheme and adaptive-contention-window-size-adjustment scheme, enabling the Category-4 access method. In [24], the authors studied NR-U with Category-4 LBT at gNBs and Category-2 LBT at the UEs. Zheng *et al.* in [25] proposed a 3-D Markov chain to model a LAA Category-4 LBT procedure with a gap period and 3-D Markov chain to model an 802.11e enhanced distributed channel access (EDCA) procedure. Both of them considered transmission priorities, and then derived the normalized throughput and average channel access delay when N_L LAA eNodeBs contended an unlicensed spectrum with N_W WiFi systems. Additionally, Pei *et al.* in [26] derived an explicit expression of the access probability for the Category-4 LBT with both linear and binary exponential backoff mechanism, and fixed contention window size.

C. Fairness between the Two Radio Access Technologies

There are several precedent work about the fairness between LTE-U and WiFi systems. Max-min fairness that maximizes the minimum average throughput achievable by users from both LTE-U and WiFi networks is adopted in [27], [28]. Jain's
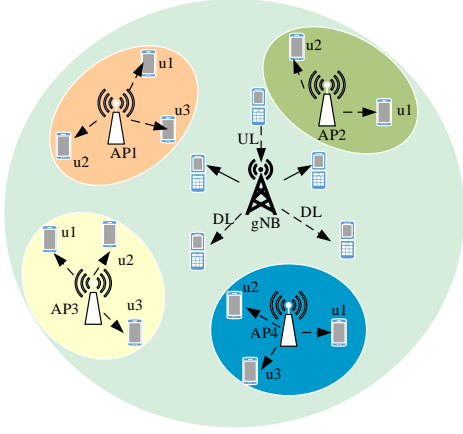
Fig. 1: Network model.

fairness index is widely used to characterize the throughput-fairness tradeoff [18], [29]. The larger the Jain's fairness index is, the fairer the system is. The maximum Jain's fairness index can be achieved when the two systems have the same throughput. Proportional fairness usually refers to equal node airtime or equal throughput per node between the two systems [14]–[16], which intuitively seems a fair opportunity for both systems to access the unlicensed band. In [15], [30], the authors applied the 3GPP fairness constraint in terms of throughput for the WiFi system. All these methods obtain fairness between WiFi and LTE system through adjusting the access parameters, such as initial backoff window size, the number of sensing slots. Wang *et al.* in [12], [13] proposed to maximize the throughput on the unlicensed spectrum and ensure the fairness between SBS and WiFi systems, and proposed a virtual WiFi system to imitate the impact of eNodeB on a WiFi network, which provides a new approach to fairness.

III. SYSTEM MODEL

As shown in Fig. 1, we assume that there is a gNB station with N_u cellular user equipment, and there are K WiFi systems. Besides, each WiFi system k consisting of N_k WiFi nodes (including one WiFi AP and $N_k - 1$ WiFi stations) utilizes a unique unlicensed channel f_k to avoid interference among K WiFi systems similar to [13]. When the data traffic of some cellular UEs cannot be satisfied, gNB and UEs can offload the data via unlicensed channels to increase the data rate of the UEs. The uplink and downlink UEs can be denoted as $\mathcal{U}$ with U users and $\mathcal{D}$ with D users respectively, and $\mathcal{N}_u = \mathcal{D} \cup \mathcal{U}$, and $\mathcal{D} \cap \mathcal{U} = \varnothing$, and $|\mathcal{N}_u| = N_u$. We assume that each node can detect other nodes on the same unlicensed carrier with carrier sensing, node buffers are full and there is no hidden terminal. In our proposed model, we mainly consider the standalone unlicensed band NR-U scenario to align with the 3GPP specification 3GPP TR 38.889 [5]. Note that the system model includes two stages: airtime competition and joint power and time allocation for transmission. Here, we assume that gNB competes with the N_k WiFi nodes in the unlicensed channel f_k used by the WiFi network k. In total there are K unlicensed channels for gNB to coexist with K

WiFi networks. The notations in this paper are specified in Table I.

IV. ACCESS PROCEDURE OF WiFi AND gNB AND PROPORTIONAL FAIRNESS

A. WiFi Access on Unlicensed Channels

Under the coverage of the kth WiFi AP, there are N_k WiFi nodes to share the same unlicensed channel with gNB, and we assume that standard WiFi is 802.11n and the bandwidth is set to 20 MHz. WiFi nodes will compete with gNB to access the unlicensed channel by adopting an exponential backoff scheme, and here we consider a saturated NR-WiFi coexisting network, i.e., each node in the network always has packets to transmit. Let τ_k^w denote the channel access probability of WiFi nodes in WiFi system k in a randomly chosen slot given by [31], [32]

$$\tau_k^w = \frac{2(1 - 2p_k^w)}{(1 - 2p_k^w)(W_w + 1) + p_k^w W_w (1 - (2p_k^w)^{m_w})}, \quad (1)$$

where p_k^w is the collision probability for WiFi nodes transmission on the channel f_k, m_w is the maximum backoff stage, and W_w is the minimum contention window size for WiFi nodes.

For the WiFi nodes, the collision occurs when at least one of the remaining $N_k - 1$ WiFi nodes or gNB access the same unlicensed channel simultaneously with a WiFi user. The collision probability thus is expressed as

$$p_k^w = 1 - (1 - \tau_k^w)^{N_k - 1}(1 - \tau_k^l), \quad (2)$$

where τ_k^l is the access success probability of gNB, and it is different from τ_k^w because gNB accesses the unlicensed band by adopting different access parameters. Furthermore, the probability that there is at least one WiFi user transmission during a time slot is $P_{tr,w}$; and the probability when only one WiFi user successfully transmits a packet under the condition that at least one WiFi user transmits a packet is $P_{s,w}$, given by

$$P_{tr,w} = 1 - (1 - \tau_k^w)^{N_k},$$
$$P_{s,w} = \frac{N_k \tau_k^w (1 - \tau_k^w)^{N_k - 1}}{P_{tr,w}}. \quad (3)$$

B. 5G NR Access on the Unlicensed Spectrum

According to the 3GPP [5], NR-U enables both uplink and downlink operation in unlicensed channels with multiple switching points or single switching point in the MCOT. Category-4 LBT channel access can be used for gNB or UE to initiate a COT for normal data transmissions, and it is recommended for the DL and UL switching gap of up to 16 μs. To reduce the overhead, 3GPP [18] has proposed that the maximum number of DL/UL switching points within a MCOT for a UE-initiated transmission is 2, and the maximum number of switching points for gNB is 1. Once gNB successfully occupies the unlicensed channel f_k, it is allowed to use the maximum time duration up to MCOT for transmission. In this paper, we consider data offloading for NR on unlicensed

TABLE I: Notation Definition.

Parameter	Definition	Parameter	Definition
$\mathcal{D}(\mathcal{U})$	set of downlink (uplink) users	$\mathbb{E}(PL)$	mean payload of WiFi
$m_w(m_l)$	WiFi (gNB) maximum backoff stage	N_k	number of WiFi nodes under the coverage of WiFi AP_k
$W_w(W_l)$	WiFi (gNB) minimum contention window	$MCOT$	maximum channel occupation time
$\tau_k^w(\tau_k^l)$	access probability of WiFi nodes (gNB)	$P_{tr,w}(P_{tr,l})$	WiFi (gNB) transmission probability
$p_k^w(p_k^l)$	collision probability of WiFi nodes (gNB)	$P_{s,w}(P_{s,l})$	WiFi (gNB) success transmission probability
T_σ	WiFi slot time/CCA slot time	$T_k^{s,w}(T_k^{s,l})$	success transmission duration of WiFi (gNB)
T_d	gNB defer time duration	$T_k^{c,w}(T_k^{c,l})$	collision transmission duration of WiFi (gNB)
ACK	Acknowledgment length	$T_k^{l,w}$	collision duration between WiFi nodes and gNB
DIFS	distributed interframe space	T_k^{slot}	total average time duration
SIFS	short interframe space	$t_{d,k}(t_{u,k})$	time duration for downlink (uplink) transmission
RTS/CTS	request to send (clear to send)	$p_{d,k}(p_{u,k})$	transmit power for downlink (uplink)
δ	propagation delay	N_u	number of licensed users in NR
$\mathbb{E}(PL_{k'})$	mean payload of virtual WiFi system k'	T_{gNB}	time slot of NR system
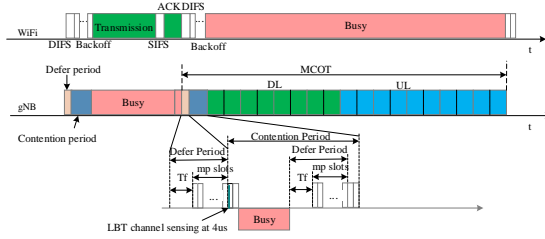
(a) Timing graph of the access procedure for NR and WiFi.
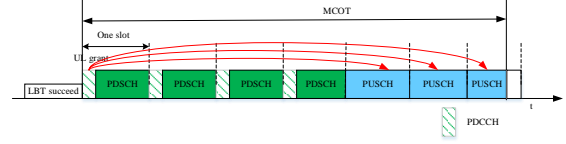
(b) NR-U DL/UL frames in MCOT.

Fig. 2: Timing graph of access procedure and frame structure for MCOT.

channels during MCOT initiated by gNB, and correspondingly the switching point during the MCOT is set to 1.

The procedure for gNB and WiFi competing an unlicensed channel for transmission is depicted in Fig. (2a) according to [33], [34]. WiFi nodes perform the carrier sense multiple access with collision detection (CSMA/CA) channel sense procedure while gNB performs the LBT Category-4 procedure to access the unlicensed channel. If a WiFi node wins the competition after DIFS and backoff procedure, it can transmit the data immediately. After successfully receiving data, the WiFi receiver transmits the ACK message back to the transmitter. After a DIFS period, the WiFi will compete with gNB for the unlicensed channel again.

On the other hand, the access procedure for gNB is composed of two time periods, the defer period (ICCA stage), the contention period (ECCA stage). The defer period (ICCA) is $T_d = T_f + m_p * T_\sigma$, where T_f is the silent period, T_σ is the length of a CCA slot (time slot of gNB system), and the value m_p depends on the LBT access priority p as shown in Table II. If the channel keeps idle during the ICCA period, gNB will transmit data immediately. Otherwise, gNB will proceed to the ECCA period to compete for the unlicensed channel with WiFi nodes. In the ECCA period, a backoff counter

with contention window size W_i is started in each backoff stage, where $W_i \in [0, 2^i * W_l - 1]$, $i \in (0, m_l - 1)$ is the backoff stage, m_l is the maximum backoff stage, and W_l is the initial contention window size for gNB. If the backoff stage reaches its maximum value, it will drop the packet. Otherwise, it will perform the channel sensing procedure. If the channel is sensed idle during ECCA defer period, the backoff procedure is started, otherwise, it will continue to sense the channel for ECCA defer period until the channel is idle. The backoff counter will decrease by one each time when the channel is sensed idle in a CCA slot. If the backoff counter reaches zero, gNB will transmit data immediately. If the channel is sensed busy before the counter reaches zero in a backoff stage, gNB will freeze the backoff counter and continue to sense the channel for ECCA defer period. If the channel is sensed idle during ECCA defer period again, gNB will recover the backoff counter and sense the channel in the next CCA slot. Otherwise, it will sense the channel for another ECCA defer duration until the channel is idle. This sensing procedure will repeat until the data is successfully transmitted or dropped.

The frame structure of NR-U during MCOT is the same as the Type-3 frame defined in 3GPP Release 13, and the

TABLE II: Category for NR-U LBT [5].

LBT access priority p	CW_{min}	CW_{max}	m_p	MCOT	Initial window size
1	3	7	1	2 ms	3,7
2	7	15	1	3 ms	7,15
3	15	63	3	8 ms or 10 ms	15,31,63
4	15	1023	7	8 ms or 10 ms	15,31,63,127,255,511,1023

frames including DL/UL are shown in Fig. (2b) [35], [36]. If gNB wins the competition, gNB can transmit data during COT which is composed of up to 10 subframes, and each subframe usually contains two NR time slots. The MCOT is divided into DL (green square) and UL (blue square) burst, each of which is composed of multiple subframes (or time slots). Each DL time slot is composed of PDCCH and PDSCH, and the first PDCCH will provide a UL grant (red line) for the subsequent UL transmission.

Following the work in [26] on LTE and WiFi coexistence, the access probability of gNB on the unlicensed channel of WiFi k network is given by

$$\tau_k^l = \frac{2p_k^l(1-2p_k^l)[1+(1-p_k^l)^L]}{[2-2(1-p_k^l)^L](1-3p_k^l+2(p_k^l)^2)+p_k^l H_1},$$
(4)
$$H_1 = (2W_l+1)(1-2p_k^l)+2p_k^l W_l[1-2(2p_k^l)^{(m_l-1)}],$$

where p_k^l is the conditional collision probability detailed below, W_l is the minimum (i.e., initial) contention window and m_l is the maximum backoff stage, and L is number of CCA time slots in the ICCA duration, i.e., $L = \lfloor \frac{T_d}{T_\sigma} \rfloor$ of gNB.

gNB shares the unlicensed channel of WiFi system k with N_k WiFi nodes. In this scenario, the collision probability of gNB competing with at least one WiFi node in the WiFi system k is calculated as

$$p_k^l = 1 - (1-\tau_k^w)^{N_k}.$$
(5)

The probability of at least one gNB accessing the unlicensed channel of WiFi system k and the success probability of just one gNB accessing the unlicensed channel under the condition that at least one gNB transmits packets are $P_{tr,l}$, $P_{s,l}$, respectively

$$P_{tr,l} = 1 - (1-\tau_k^l)^1 = \tau_k^l,$$
$$P_{s,l} = \tau_k^l/\tau_k^l = 1.$$
(6)

C. Average Time Slot Duration

1) Idle slot: the average duration of the backoff state (idle slot) is calculated as

$$\overline{T_k^{idle}} = (1-\tau_k^l)(1-\tau_k^w)^{N_k}T_\sigma,$$
(7)

where T_σ is the CCA time slot for the WiFi system and assumed to be the same for gNB.

2) Average time duration for WiFi successful transmission: the probability of success transmission for a WiFi user in the WiFi system k during a WiFi slot is $N_k\tau_k^w(1-\tau_k^w)^{N_k-1}(1-\tau_k^l)$. The average success transmission duration of the WiFi AP is

$$\overline{T_k^{s,w}} = N_k\tau_k^w(1-\tau_k^w)^{N_k-1}(1-\tau_k^l)T_k^{s,w},$$
(8)

where $T_k^{s,w}$ is the time duration for success transmission of the WiFi user expressed as [31]

$$T_k^{s,w} = (RTS+CTS+H+\mathbb{E}(PL_w)+ACK)/r_w$$
$$+ 3SIFS + DIFS + 4\delta,$$
(9)

where RTS, CTS are the size of the handshake messages, r_w is the transmission rate of the WiFi AP. Moreover,

$H, \mathbb{E}(PL_w), ACK$ stand for the size of the header, the payload of the WiFi frame, and the size of acknowledgment (ACK) message, respectively. $SIFS$ and $DIFS$ represent the shortest inter-frame spacing and time duration of the distributed inter-frame spacing, and δ is the propagation time.

3) Average time duration for a gNB success transmission: the success transmission probability of gNB with N_k WiFi nodes is $\tau_k^l(1-\tau_k^w)^{N_k}$. Correspondingly, the average success time duration is

$$\overline{T_k^{s,l}} = \tau_k^l(1-\tau_k^w)^{N_k}T_k^{s,l},$$
(10)

where $T_k^{s,l} = MCOT+T_{gNB}$ is the success transmission time for gNB on the unlicensed channel, and T_{gNB} is the NR slot as a gNB node will not transmit until the beginning of the next gNB slot [15], [37].

4) Average time duration for the failed transmission due to the conflict among WiFi nodes: the conflict is caused by at least two WiFi nodes that transmit in the WiFi system k at the same time, and the conflict probability is $(1-(1-\tau_k^w)^{N_k} - N_k\tau_k^w(1-\tau_k^w)^{N_k-1})(1-\tau_k^l)$. Therefore, the average failure duration for WiFi nodes is given by

$$\overline{T_k^{c,w}} = (1-(1-\tau_k^w)^{N_k}-N_k\tau_k^w(1-\tau_k^w)^{N_k-1})(1-\tau_k^l)T_k^{c,w},$$
(11)

where $T_k^{c,w} = \frac{RTS}{r_w} + DIFS + \delta$.

5) Average time duration of the failed transmission due to gNB and WiFi nodes: the conflict probability between a gNB and at least one WiFi user transmitting at the same time is $\tau_k^l(1-(1-\tau_k^w)^{N_k})$, and the average time duration for the conflict between gNB and the WiFi nodes is given by

$$\overline{T_k^{l,w}} = \tau_k^l(1-(1-\tau_k^w)^{N_k})T_k^{l,w},$$
(12)

where $T_k^{l,w} = max(T_k^{c,w}, T_k^{c,l})$ is the collision duration between the WiFi nodes and gNB node, and the failed transmission duration for gNB is $T_k^{c,l} = MCOT+T_{gNB}$.

The average time spent on each state on the unlicensed channel of WiFi system k can thus be calculated as

$$\overline{T_k^{slot}} = \overline{T_k^{idle}} + \overline{T_k^{s,w}} + \overline{T_k^{s,l}} + \overline{T_k^{c,w}} + \overline{T_k^{l,w}}.$$
(13)

D. Proportional Fairness between the Two Systems

The Category-4 LBT proposed in 3GPP [5] enables gNB and WiFi coexistence but it cannot guarantee fair coexistence between the two systems when there exists an aggressive node that occupies most of the unlicensed channel [15]. To make the two systems fairly coexist on the unlicensed channel, the most intuitive measure is to equalize the successful airtime ratio that the two systems used to successfully transmit on the unlicensed channel. The access parameters of both systems, such as the initial backoff window sizes, the numbers of sensing slots, the maximum backoff stages, and the retry limits and transmission opportunities, can be adjusted to achieve the desired airtime ratio [15]. In this paper, we consider adjusting the initial contention window size of the NR system as in [15],

[17]. The successful airtime ratios for NR and one WiFi node are given by

$$r_{gNB,s} = \frac{P_{s,l}P_{tr,l}(1-P_{tr,w})T_k^{s,l}}{\overline{T_k^{slot}}}$$

$$r_{w,s} = \frac{P_{s,w}P_{tr,w}(1-P_{tr,1})T_k^{s,w}}{\overline{T_k^{slot}}N_k}. \tag{14}$$

Proportional fairness between gNB and WiFi is achieved when each node achieves an identical (or a desired) fraction of time over the unlicensed channel, e.g., $r_{gNB,s} = r_{w,s}$, we can obtain

$$\tau_k^l(W_l) = \frac{\tau_k^w T_k^{s,w}}{T_k^{s,l} - \tau_k^w \cdot T_k^{s,l} + \tau_k^w \cdot T_k^{s,w}}. \tag{15}$$

The optimal initial contention window size of gNB is

$$W_l^* = \tau_k^{l^{-1}}(\frac{\tau_k^w T_k^{s,w}}{T_k^{s,l} - \tau_k^w \cdot T_k^{s,l} + \tau_k^w \cdot T_k^{s,w}}), \tag{16}$$

where $\tau_k^{l^{-1}}$ is the inverse function of τ_k^l. In the following context, the optimal initial contention window size W_l^* is set as the default value in our proposed method.

V. THROUGHPUT FAIRNESS AND OPTIMAL TIME AND POWER ALLOCATION

The throughput and time fairness cannot be obtained simultaneously by adjusting the contention window size alone [17]. Thus, we first obtain the throughput of the two systems when they coexist on a single unlicensed band, and then make the two systems satisfy throughput fairness.

A. Data Rate Analysis for WiFi and NR Systems

1) WiFi Data Rate: For WiFi systems, the normalized system data rate is a ratio of the successful transmission of information packets in a slot and the average duration of a slot time [32], [37]. Therefore, the normalized data rate for the WiFi system k is defined as

$$R_k^W = \frac{P_{tr,w}P_{s,w}(1-P_{tr,l})\mathbb{E}(PL_k)}{\overline{T_k^{slot}}}$$

$$= \frac{N_k\tau_k^w(1-\tau_k^w)^{N_k-1}(1-\tau_k^l)\mathbb{E}(PL_k)}{\overline{T_k^{slot}}}, \forall k \in \mathcal{K}. \tag{17}$$

2) NR Data Rate: The effective downlink data rate for each cellular user by using the unlicensed channel of the WiFi system k is given by

$$R_{d,k} = \frac{P_{tr,l}P_{s,l}(1-P_{tr,w})t_{d,k}}{\overline{T_k^{slot}}}B_k \log_2(1+\frac{p_{d,k}|h_{d,k}|^2}{\sigma^2})$$

$$= \frac{\tau_k^l(1-\tau_k^w)^{N_k}t_{d,k}}{\overline{T_k^{slot}}}B_k \log_2(1+\frac{p_{d,k}|h_{d,k}|^2}{\sigma^2}), \tag{18}$$

where $p_{d,k}$ is the transmit power from gNB to cellular UE d by using the WiFi system k, $h_{d,k}$ is the channel coefficient from gNB to the user d, σ^2 is the noise power, $t_{d,k}$ is time for gNB downlink transmission to cellular UE, and B_k is the
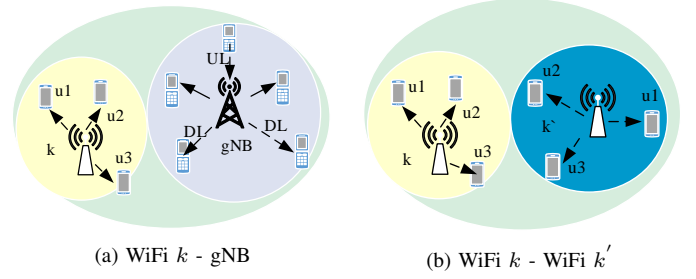

(a) WiFi k - gNB

(b) WiFi k - WiFi k'

Fig. 3: Coexistence of WiFi-gNB and WiFi-WiFi.

bandwidth. Similarly, the uplink data rate from user $u \in \mathcal{U}$ to gNB on the unlicensed channel of WiFi system k is

$$R_{u,k} = \frac{\tau_k^l(1-\tau_k^w)^{N_k}t_{u,k}}{\overline{T_k^{slot}}}B_k \log_2(1+\frac{p_{u,k}|h_{u,k}|^2}{\sigma^2}), \tag{19}$$

where $p_{u,k}$ is the transmit power of cellular UE $u \in \mathcal{U}$ to gNB by using the unlicensed channel f_k, $t_{u,k}$ is the time for cellular UE $u \in \mathcal{U}$ uplink transmission, and $h_{u,k}$ is the channel coefficient from the cellular user u to gNB.

Furthermore, the uplink data rate for each user $u \in \mathcal{U}$ and the downlink data rate for each user $d \in \mathcal{D}$ by using the unlicensed channel f_k are calculated as

$$R_k^U = \sum_{u \in \mathcal{U}} R_{u,k}, \forall k \in \mathcal{K},$$

$$R_k^D = \sum_{d \in \mathcal{D}} R_{d,k}, \forall k \in \mathcal{K}. \tag{20}$$

B. Fairness Constraints between Different RATs

Following the 3GPP fairness definition, Fig. (3a) represents the coexistence between WiFi system k and the NR system, and Fig. (3b) indicates the coexistence between the WiFi system k and a replaced virtual WiFi system k'. According to the definition to make gNB and WiFi fairly coexist, the data rate of WiFi nodes in the WiFi system k influenced by gNB should not be larger than the data rate of the WiFi system k influenced by a virtual WiFi system k' supporting the same level of traffic load [12], [13], [38], [39]. Firstly, we need to calculate the data rate of the WiFi system k coexisted with the WiFi system k'. To imitate the effect of gNB on WiFi system k, WiFi system k' is assumed to have the same data rate and the number of users as the NR system. The two WiFi systems will compete for the unlicensed channel f_k, and WiFi system k' is assumed to have similar parameters as the WiFi system k except the average payload. After replacement, each WiFi system k will just compete with one virtual WiFi system k'. WiFi system k' with N_u nodes can set its payload size to achieve the same data rate as what a gNB can obtain when a gNB coexists with the WiFi system k.

1) Payload of WiFi System k': To achieve the same data rate as what a gNB can obtain when a gNB coexists with WiFi system k, WiFi system k' with N_u nodes can set its payload size. Note that the data rate of the NR system includes uplink and downlink rates. That is,

$$\frac{P_s^{k'} P_{tr}^{k'} \mathbb{E}(PL_{k'})}{\left(1 - P_{tr}^{k'}\right)\sigma + P_{tr}^{k'} P_s^{k'} T_s^{k'} + P_{tr}^{k'}\left(1 - P_s^{k'}\right) T_c^{k'}} = R_k^D + R_k^U \quad (21)$$

where

$$\tau_{k'} = \frac{2}{1 + W_k + p_{k'} W_k \sum_{t=0}^{m_w-1}(2p_{k'})^t},$$
$$p_{k'} = 1 - (1 - \tau_{k'})^{N_u-1},$$
$$P_{tr}^{k'} = 1 - (1 - \tau_{k'})^{N_u},$$
$$P_s^{k'} = \frac{N_u \tau_{k'}(1 - \tau_{k'})^{N_u-1}}{P_{tr}^{k'}},$$
$$T_s^{k'} = \frac{RTS + CTS + (H + \mathbb{E}(PL_{k'}) + ACK}{r_w} + 3SIFS$$
$$+ DIFS + 4\delta,$$
$$T_c^{k'} = \frac{RTS}{r_w} + DIFS + \delta. \quad (22)$$

Thus, the average size of the payload of the WiFi system k' is

$$\mathbb{E}(PL_{k'}) =$$
$$\frac{((1 - P_{tr}^{k'})T_\sigma + P_{tr}^{k'}(1 - P_s^{k'})T_c^{k'} + YP_{tr}^{k'}P_s^{k'})r_w(R_k^D + R_k^U)}{P_{tr}^{k'}P_s^{k'}(r_w - (R_k^D + R_k^U))}, \quad (23)$$

where $Y = \frac{RTS+CTS+H+ACK}{r_w} + 3SIFS + DIFS + 4\delta$.

2) WiFi-WiFi System: The initial backoff window size and the maximum backoff stage of WiFi k' are set to W_w and m_w, respectively, which are identical to the parameters in Section IV-A. As the two WiFi systems k and k' adopt the same access parameters, the hybrid network can be regarded as a single WiFi network with $N_k + N_u$ WiFi nodes to access the unlicensed channel f_k. The data rate of the hybrid network is

$$R_{con} =$$
$$\frac{P_{tr}^{con} P_s^{con} \mathbb{E}(PL_{con})}{(1 - P_{tr}^{con})T_\sigma + P_{tr}^{con} P_s^{con} T_s^{con} + P_{tr}^{con}(1 - P_s^{con})T_c^{con}}, \quad (24)$$

where

$$\tau_k^{con} = \frac{2}{1 + W_w + p_k^{con} W_w \sum_{t=0}^{m_w-1}(2p_k^{con})^t},$$
$$p_k^{con} = 1 - (1 - \tau_k^{con})^{N_u+N_k-1},$$
$$P_{tr}^{con} = 1 - (1 - \tau_k^{con})^{N_u+N_k},$$
$$P_s^{con} = \frac{(N_u + N_k)\tau_k^{con}(1 - \tau_k^{con})^{N_k+N_u-1}}{P_{tr}^{con}},$$
$$T_s^{con} = \frac{RTS + CTS + (H + \mathbb{E}(PL_{con})) + ACK}{r_w} + 3SIFS$$
$$+ DIFS + 4\delta,$$
$$T_c^{con} = \frac{RTS}{r_w} + DIFS + \delta,$$
$$\mathbb{E}(PL_{con}) = \frac{N_k \mathbb{E}(PL_k) + N_u \mathbb{E}(PL_{k'})}{N_k + N_u}. \quad (25)$$

Then, the average data rate that the WiFi system k coexisted with the virtual WiFi system k' is given by equation (26).

For fair coexistence in term of throughput, the rate relationship must satisfy

$$R_k^{k'} \leq R_k^W. \quad (27)$$

C. DL and UL Time Fraction Constraints

According to the frame structure of the MCOT, the total downlink time duration $t_{d,k}$ and uplink time duration $t_{u,k}$ for occupying the unlicensed channel of WiFi system k should not be more than MCOT are given by

$$\sum_{d \in \mathcal{D}} t_{d,k} + \sum_{u \in \mathcal{U}} t_{u,k} \leq MCOT, \forall k \in \mathcal{K}. \quad (28)$$

D. Power Constraint

The average uplink power for each cellular users $u \in \mathcal{U}$ and total downlink power for all users $d \in \mathcal{D}$ on all unlicensed channels during the MCOT should be smaller than the threshold P_{avg}, P_{gNB}^{max}, respectively. That is,

$$\frac{1}{U} \sum_{u \in \mathcal{U}} \sum_{k \in K} \frac{t_{u,k}}{MCOT} \cdot p_{u,k} \leq P_{avg}, \forall u \in \mathcal{U}, \quad (29)$$

$$\sum_{d \in \mathcal{D}} \sum_{k \in K} \frac{t_{d,k}}{MCOT} \cdot p_{d,k} \leq P_{gNB}^{max}, \quad (30)$$

where P_{avg} and $P_{d,k}^{max}$ are the average maximum transmit power of each user $u \in \mathcal{U}$ and total maximum transmit power for all users $d \in \mathcal{D}$ on all unlicensed channels.

The downlink transmit power for each cellular user $d \in \mathcal{D}$ by gNB in each unlicensed channel f_k by gNB should be smaller than $P_{d,k}^{max}$. That is,

$$p_{d,k} \leq P_{d,k}^{max}, \forall d \in \mathcal{D}, k \in \mathcal{K}, \quad (31)$$

where $P_{d,k}^{max}$ is the maximum downlink transmit power for each user on each unlicensed channel.

VI. NR-U THROUGHPUT MAXIMIZATION PROBLEM FORMULATION

To improve the unlicensed channel utilization, the problem is formulated to maximize the downlink and uplink throughputs of NR-U on all available unlicensed channels, with both time duration and power constraints considered. That is,

$$P1 : \max_{t_d, t_u, p_d, p_u} \sum_{d \in D} \sum_{k \in \mathcal{K}} R_{d,k} + \sum_{u \in U} \sum_{k \in \mathcal{K}} R_{u,k}$$
$$\text{s.t. } (27), (28), (29), (30), (31),$$
$$t_{d,k}, t_{u,k}, p_{u,k}, q_{u,k} \geq 0, \forall d \in \mathcal{D}, u \in \mathcal{U}, k \in \mathcal{K}, \quad (32)$$

where the variables are $t_d = \{t_{d,k}\}_{d \in \mathcal{D}, k \in \mathcal{K}}$, $t_u = \{t_{u,k}\}_{u \in \mathcal{U}, k \in \mathcal{K}}$, $p_u = \{p_{u,k}\}_{u \in \mathcal{U}, k \in \mathcal{K}}$, and $p_d = \{p_{d,k}\}_{d \in \mathcal{D}, k \in \mathcal{K}}$.

To make the problem more tractable, we transform the variables as $q = \{q_{d,k} = p_{d,k}\frac{t_{d,k}}{MCOT}\}_{k \in \mathcal{K}, d \in \mathcal{D}}$, $\overline{q} = \{q_{u,k} =$

$$R_k^{k'} = \frac{N_k \mathbb{E}(PL_k)R_{con}}{N_k \mathbb{E}(PL_k) + N_u \mathbb{E}(PL_{k'})} = \frac{N_k P_{tr}^{con} P_s^{con} \mathbb{E}(PL_k)}{(N_k + N_u)((1 - P_{tr}^{con})T_\sigma + P_{tr}^{con} P^{con} T_s^{con} + P_{tr}^{con}(1 - P_s^{con})T_c^{con})}. \tag{26}$$

$p_{u,k} \frac{t_{u,k}}{MCOT}\}_{k \in \mathcal{K}, u \in \mathcal{U}}$, and let $\frac{\tau_k^l(1-\tau_k^w)^{N_k}}{T_k^{slot}} = p_k$. Then the problem is reformulated as

$$P2 : \max_{\boldsymbol{t_d}, \boldsymbol{t_u}, \boldsymbol{q}, \bar{\boldsymbol{q}}} \sum_{d \in D} \sum_{k \in \mathcal{K}} R_{d,k} + \sum_{u \in U} \sum_{k \in \mathcal{K}} R_{u,k} \tag{33a}$$

$$\text{s.t.} \quad (27), (28), \tag{33b}$$

$$\frac{1}{U} \sum_{u \in \mathcal{U}} \sum_{k \in K} q_{u,k} \le P_{avg}, \tag{33c}$$

$$\sum_{d \in \mathcal{D}} \sum_{k \in K} q_{d,k} \le P_{gNB}^{max}, \tag{33d}$$

$$q_{d,k} \le \frac{t_{d,k}}{MCOT} \cdot P_{d,k}^{max}, \forall d \in \mathcal{D}, k \in \mathcal{K}, \tag{33e}$$

$$t_{d,k}, t_{u,k}, q_{d,k}, q_{u,k} \ge 0, \forall d \in \mathcal{D}, u \in \mathcal{U}, k \in \mathcal{K}, \tag{33f}$$

where

$$R_{d,k} = p_k t_{d,k} B_k \log_2(1 + \frac{MCOT \cdot q_{d,k}|h_{d,k}|^2}{\sigma^2 t_{d,k}}), \tag{34a}$$

$$R_{u,k} = p_k t_{u,k} B_k \log_2(1 + \frac{MCOT \cdot q_{u,k}|h_{u,k}|^2}{\sigma^2 t_{u,k}}). \tag{34b}$$

Equation (27) can be rewritten as

$$\frac{R_k^D + R_k^U}{r_w - (R_k^D + R_k^U)} \ge$$
$$\frac{r_w Z - r_w(N_k + N_u)(Q + Y) - N_k \mathbb{E}(PL_k)}{N_u s_k}, \tag{35}$$

where $s_k = \frac{((1-P_{tr}^{k'})T_\sigma + P_{tr}^{k'}(1-P_s^{k'})T_c^{k'} + Y P_{tr}^{k'} P_s^{k'})r_w}{P_{tr}^{k'} P_s^{k'}}$, $Q = \frac{(1-P_{tr}^{con})T_\sigma + P_{tr}^{con}(1-P_s^{con})T_c^{con}}{P_{tr}^{con} P_s^{con}}$, and $Z = \frac{T_k^{slot}}{\tau_k^w(1-\tau_k^w)^{N_k-1}(1-\tau_k^l)}$. Afterwards, we transform (27) to

$$R_k^D + R_k^U = \sum_{d \in \mathcal{D}} R_{d,k} + \sum_{u \in \mathcal{U}} R_{u,k} \ge \frac{\phi r_w}{1 + \phi}, \tag{36}$$

where

$$\phi = \frac{r_w Z - r_w(N_k + N_u)(Q + Y) - N_k \mathbb{E}(PL_k)}{N_u s_k}. \tag{37}$$

Theorem 1: The objective function of problem (33) is convex with respect to (w.r.t) $(\boldsymbol{t_u}, \boldsymbol{t_d}, \boldsymbol{q_d}, \boldsymbol{q_u})$.

Proof 1: Please refer to appendix A.

Lemma 1: The equality of the second constraint should be held.

Proof 2: Please refer to appendix B.

VII. OPTIMAL TIME AND POWER ALLOCATION

A. Optimal Time Allocation for Uplink and Downlink Transmission

According to the basic principle of successive convex approximation (SCA), $P2$ can be divided into two problems, the optimal time allocation problem P3 given power allocation and the optimal power allocation problem P4 given time allocation. Problem $P3$ is formulated as

$$P3 : \max_{\boldsymbol{t_d}, \boldsymbol{t_u}} \sum_{d \in \mathcal{D}} \sum_{k \in \mathcal{K}} R_{d,k} + \sum_{u \in U} \sum_{k \in \mathcal{K}} R_{u,k} \tag{38a}$$

$$\text{s.t.} \quad (36), (28), (33e) \tag{38b}$$

$$t_{d,k}, t_{u,k} \ge 0, \forall d \in \mathcal{D}, u \in \mathcal{U}, k \in \mathcal{K}. \tag{38c}$$

The Lagrange function of problem P3 is given by

$$L_1(\boldsymbol{t_d}, \boldsymbol{t_u}, \boldsymbol{\alpha}, \boldsymbol{\beta}, \boldsymbol{\xi}, \boldsymbol{\epsilon}, \boldsymbol{\eta}) = \sum_{k \in \mathcal{K}} \sum_{d \in \mathcal{D}} R_{d,k} + \sum_{u \in U} \sum_{k \in \mathcal{K}} R_{u,k}$$
$$+ \sum_{k \in \mathcal{K}} \alpha_k(\sum_{d \in \mathcal{D}} R_{d,k} + \sum_{u \in \mathcal{U}} R_{u,k} - \frac{\phi r_w}{1 + \phi})$$
$$+ \sum_{k \in \mathcal{K}} \beta_k(MCOT - (\sum_{d \in \mathcal{D}} t_{d,k} + \sum_{u \in \mathcal{U}} t_{u,k}))$$
$$+ \sum_{k \in \mathcal{K}} \sum_{d \in D} \xi_{d,k}(\frac{t_{d,k}}{MCOT} \cdot P_{d,k}^{max} - q_{d,k})$$
$$+ \sum_{u \in \mathcal{U}} \sum_{k \in \mathcal{K}} \epsilon_{u,k} t_{u,k} + \sum_{d \in \mathcal{D}} \sum_{k \in \mathcal{K}} \eta_{d,k} t_{d,k}, \tag{39}$$

where $\boldsymbol{\alpha} = \{\alpha_k\}_{k \in \mathcal{K}}, \boldsymbol{\beta} = \{\beta_k\}_{k \in \mathcal{K}}, \boldsymbol{\xi} = \{\xi_{d,k}\}_{d \in \mathcal{D}, k \in \mathcal{K}}, \boldsymbol{\epsilon} = \{\epsilon_{u,k}\}_{u \in \mathcal{U}, k \in \mathcal{K}}, \boldsymbol{\eta} = \{\eta_{d,k}\}_{d \in \mathcal{D}, k \in \mathcal{K}}$ are the non-negative Lagrangian multipliers. The dual problem can be written as

$$\min_{\boldsymbol{\alpha}, \boldsymbol{\beta}, \boldsymbol{\xi}, \boldsymbol{\epsilon}, \boldsymbol{\eta}} D(\boldsymbol{\alpha}, \boldsymbol{\beta}, \boldsymbol{\xi}, \boldsymbol{\epsilon}, \boldsymbol{\eta}), \tag{40}$$

where the dual function of problem (32) is denoted as

$$D(\boldsymbol{\alpha}, \boldsymbol{\beta}, \boldsymbol{\xi}, \boldsymbol{\epsilon}, \boldsymbol{\eta}) = \max_{\boldsymbol{t_d}, \boldsymbol{t_u}} L_1(\boldsymbol{t_u}, \boldsymbol{t_d}, \boldsymbol{\alpha}, \boldsymbol{\beta}, \boldsymbol{\xi}, \boldsymbol{\epsilon}, \boldsymbol{\eta}). \tag{41}$$

According to the KKT conditions, and the corresponding constraints of $P3$, the optimal solution of problem $P3$ should satisfy

$$\frac{\partial L_1}{\partial t_{d,k}} = (1 + \alpha_k)\frac{\partial R_{d,k}}{\partial t_{d,k}} - \beta_k + \xi_{d,k}\frac{P_{d,k}^{max}}{MCOT} + \eta_{d,k}$$
$$= 0, \tag{42a}$$

$$\frac{\partial L_1}{\partial t_{u,k}} = (1 + \alpha_k)\frac{\partial R_{u,k}}{\partial t_{u,k}} - \beta_k + \epsilon_{u,k} = 0, \tag{42b}$$

where

$$\frac{\partial R_{d,k}}{\partial t_{d,k}} = B_k p_k \left(\frac{\ln(1 + \frac{MCOT \cdot q_{d,k}|h_{d,k}|^2}{\sigma^2 t_{d,k}})}{\ln 2} - \frac{MCOT \cdot q_{d,k}|h_{d,k}|^2}{(\sigma^2 t_{d,k} + MCOT \cdot q_{d,k}|h_{d,k}|^2)\ln 2} \right). \tag{43}$$

Define function $h(x)$ as

$$h(x) = \frac{\ln(1 + x)}{\ln 2} - \frac{x}{(\ln 2)(1 + x)}, \tag{44}$$

and the derivative of the uplink and downlink data rate can be written as

$$\frac{\partial R_{d,k}}{\partial t_{d,k}} = B_k p_k h(\frac{MCOT \cdot q_{d,k}|h_{d,k}|^2}{\sigma^2 t_{d,k}})$$
$$= \frac{\beta_k - \xi_{d,k}\frac{P_{d,k}^{max}}{MCOT} + \eta_{d,k}}{1 + \alpha_k}, \qquad (45a)$$

$$\frac{\partial R_{u,k}}{\partial t_{u,k}} = B_k p_k h(\frac{MCOT \cdot q_{u,k}|h_{u,k}|^2}{\sigma^2 t_{u,k}}) = \frac{\beta_k - \epsilon_{u,k}}{1 + \alpha_k}. \qquad (45b)$$

It is found that $t_{d,k} = 0$ if and only if $q_{d,k} = 0$, and $t_{u,k} = 0$ if and only if $q_{u,k} = 0$. According to the complementary slackness conditions, $\eta_{d,k} = \epsilon_{u,k} = 0$. According to Lemma 1, it can be found that $\sum_{d\in\mathcal{D}} t_{d,k} + \sum_{u\in\mathcal{U}} t_{u,k} = MCOT$.

If $\xi_{d,k} > 0$, $q_{d,k} = \frac{t_{d,k}}{MCOT} \cdot P_{d,k}^{max}$, which cannot be equal to the given value, thus $\xi_{d,k} = 0$. Therefore, from (45a) and (45b), we can obtain

$$\frac{\partial R_{d,k}}{\partial t_{d,k}} = \frac{\partial R_{u,k}}{\partial t_{u,k}} = \frac{\beta_k}{1 + \alpha_k}. \qquad (46)$$

According to (46), we can use the Lambert W function to denote the uplink time duration and downlink time duration as

$$t_{d,k} = -\frac{MCOT \cdot q_{d,k}|h_{d,k}|^2}{\sigma^2(1 + \frac{1}{W(-e^{-(\frac{\beta_k \ln 2}{(1+\alpha_k)B_k p_k}+1)})})}\Bigg|_{\frac{MCOT \cdot q_{d,k}}{P_{d,k}^{max}}},$$

$$t_{u,k} = -\frac{MCOT \cdot q_{u,k}|h_{u,k}|^2}{\sigma^2(1 + \frac{1}{W(-e^{-(\frac{\beta_k \ln 2}{(1+\alpha_k)B_k p_k}+1)})})}\Bigg|_0, \qquad (47)$$

where $W(.)$ is Lambert W function, $a|_b = max(a, b)$. According to (66), β_k is the solution of

$$\sum_{d\in\mathcal{D}} -\frac{MCOT \cdot q_{d,k}|h_{d,k}|^2}{\sigma^2(1 + \frac{1}{W(-e^{-(\frac{\beta_k \ln 2}{B_k p_k}+1)})})}\Bigg|_{\frac{MCOT \cdot q_{d,k}}{P_{d,k}^{max}}}$$

$$+ \sum_{u\in\mathcal{U}} -\frac{MCOT \cdot q_{u,k}|h_{u,k}|^2}{\sigma^2(1 + \frac{1}{W(-e^{-(\frac{\beta_k \ln 2}{B_k p_k}+1)})})}\Bigg|_0 = MCOT, \qquad (48)$$

which can be solved by the bisection method.

Next, we can use the sub-gradient to update the Lagrangian multiplier α_k as

$$\alpha_k(t+1) = \left[\alpha_k(t) - s_1(t)(\sum_{d\in\mathcal{D}} R_{d,k} + \sum_{u\in\mathcal{U}} R_{u,k} - \frac{\phi r_w}{1 + \phi})\right]^+, \qquad (49)$$

where $s_1(t)$ is the step size and $[x]^+ \triangleq max(0, x)$.

B. Optimal Power Allocation for Uplink and Downlink Transmission

Given the time duration for DL and UL allocation $(\boldsymbol{t_u}, \boldsymbol{t_d})$, the problem $P4$ can be reformulated as

$$P4 : \max_{\boldsymbol{q_d}, \boldsymbol{q_u}} \sum_{d\in D}\sum_{k\in\mathcal{K}} R_{d,k} + \sum_{u\in U}\sum_{k\in\mathcal{K}} R_{u,k}$$
$$\text{s.t. } (36), (33c), (33d), (33e), \qquad (50)$$
$$q_{d,k}, q_{u,k} \geq 0, \forall u \in \mathcal{U}, d \in \mathcal{D}, k \in \mathcal{K}.$$

Similarly, the Lagrangian function of (P4) is given by

$$L_2(\boldsymbol{q_d}, \boldsymbol{q_u}, \boldsymbol{\alpha}, \boldsymbol{\theta}, \boldsymbol{\gamma}, \boldsymbol{\xi}, \boldsymbol{\psi}, \boldsymbol{\omega}) = \sum_{d\in D}\sum_{k\in\mathcal{K}} R_{d,k} + \sum_{u\in\mathcal{U}}\sum_{k\in\mathcal{K}} R_{u,k}$$

$$+ \sum_{k\in\mathcal{K}} \alpha_k(\sum_{d\in\mathcal{D}} R_{d,k} + \sum_{u\in U} R_{u,k} - \frac{\phi r_w}{1 + \phi})$$

$$+ \theta(P_{avg} - \frac{1}{U}\sum_{u\in\mathcal{U}}\sum_{k\in K} q_{u,k}) + \gamma(P_{gNB}^{max} - \sum_{k\in\mathcal{K}}\sum_{d\in D} q_{d,k})$$

$$+ \sum_{k\in\mathcal{K}}\sum_{d\in D} \xi_{d,k}(\frac{t_{d,k}}{MCOT}.P_{d,k}^{max} - q_{d,k})$$

$$+ \sum_{k\in\mathcal{K}}\sum_{u\in U} \psi_{u,k} q_{u,k} + \sum_{k\in\mathcal{K}}\sum_{d\in D} \omega_{d,k} q_{d,k}, \qquad (51)$$

where $\boldsymbol{\alpha} = \{\alpha_k\}_{k\in\mathcal{K}}, \boldsymbol{\theta}, \boldsymbol{\gamma}, \boldsymbol{\xi} = \{\xi_{d,k}\}_{d\in\mathcal{D},k\in\mathcal{K}}, \boldsymbol{\psi} = \{\psi_{u,k}\}_{u\in\mathcal{U},k\in\mathcal{K}}, \boldsymbol{\omega} = \{\omega_{d,k}\}_{d\in\mathcal{D},k\in\mathcal{K}}$ are non-negative Lagrange multiplier. According to the KKT conditions and the complementary slackness conditions, the optimal solution with fixed $(\boldsymbol{q_d}, \boldsymbol{q_u})$ should satisfy

$$\frac{\partial L_2}{\partial q_{d,k}} = (1 + \alpha_k)\frac{\partial R_{d,k}}{\partial q_{d,k}} - \gamma - \xi_{d,k} + \omega_{d,k} = 0, \qquad (52a)$$

$$\frac{\partial L_2}{\partial q_{u,k}} = (1 + \alpha_k)\frac{\partial R_{u,k}}{\partial q_{u,k}} - \frac{\theta}{U} + \psi_{u,k} = 0, \qquad (52b)$$

where

$$\frac{\partial R_{d,k}}{q_{d,k}} = \frac{MCOT \cdot B_k p_k t_{d,k}|h_{d,k}|^2}{(\sigma^2 t_{d,k} + MCOT \cdot q_{d,k}|h_{d,k}|^2)\ln 2}$$
$$= \frac{\gamma + \xi_{d,k} - \omega_{d,k}}{1 + \alpha_k}, \qquad (53a)$$

$$\frac{\partial R_{u,k}}{q_{u,k}} = \frac{MCOT \cdot B_k p_k t_{u,k}|h_{u,k}|^2}{(\sigma^2 t_{u,k} + MCOT \cdot q_{u,k}|h_{u,k}|^2)\ln 2} = \frac{\frac{\theta}{U} - \psi_{u,k}}{1 + \alpha_k}. \qquad (53b)$$

According to the complementary slackness conditions, we can find that $q_{d,k} = 0$ and $q_{u,k} = 0$ if and only if $t_{d,k} = 0$ and $t_{u,k} = 0$ for $(u \in \mathcal{U}, d \in \mathcal{D}, k \in \mathcal{K})$. As we assume $t_{d,k}$ and $t_{u,k}$ are given, $\psi_{u,k} = \omega_{d,k} = 0$ can be held. From (53b), if $\theta = 0$, $(1 + \alpha_k)\frac{\partial R_{u,k}}{\partial q_{u,k}} = 0$, that is, $q_{u,k} = 0$ and $t_{u,k} = 0$, which makes the fraction $\frac{\partial R_{u,k}}{\partial q_{u,k}}$ meaningless; According to the complementary slackness conditions, $\theta > 0$ and $P_{avg} - \frac{1}{U}\sum_{u\in\mathcal{U}}\sum_{k\in K} q_{u,k} = 0$. Furthermore, $\xi_{d,k} = 0$ similar to the previous assumption. According to (53b) and $P_{avg} = \frac{1}{U}\sum_{u\in\mathcal{U}}\sum_{k\in K} q_{u,k} = 0$, we can obtain

$$q_{u,k} = t_{u,k}(\frac{B_k p_k(1 + \alpha_k)U}{\theta \ln 2} - \frac{\sigma^2}{MCOT \cdot |h_{u,k}|^2})\Bigg|_0, \qquad (54)$$

where Lagrangian multiplier θ is written as

$$\theta = \frac{U \cdot \sum_{k\in\mathcal{K}}\sum_{u\in\mathcal{U}} t_{u,k} B_k p_k(1 + \alpha_k)}{\ln 2(\frac{\sigma^2}{MCOT}\sum_{k\in\mathcal{K}}\sum_{u\in\mathcal{U}} t_{u,k}/h_{u,k}^2 + U \cdot P_{avg})}. \qquad (55)$$

According to (53a) and the complementary slackness conditions, if $\gamma + \xi_{d,k} = 0$, i.e., $\gamma = \xi_{d,k} = 0$, then $\frac{\partial R_{d,k}}{\partial q_{d,k}} = 0$, $t_{d,k} = 0$ and $q_{d,k} = 0$, which makes $\frac{\partial R_{d,k}}{\partial q_{d,k}}$ meaningless. If $\gamma + \xi_{d,k} > 0$, we can obtain $q_{d,k}$ as follows.

$$q_{d,k} = \begin{cases} t_{d,k}\Big(\frac{B_k p_k(1+\alpha_k)}{(\gamma+\xi_{d,k})\ln 2} - \frac{\sigma^2}{MCOT\cdot|h_{d,k}|^2}\Big)\Big|_0^{\frac{t_{d,k}}{MCOT}\cdot P_{d,k}^{max}} & \text{with (57)}, \quad \xi_{d,k} > 0 \text{ and } \gamma \geq 0, \\ t_{d,k}\Big(\frac{B_k p_k(1+\alpha_k)}{\gamma\ln 2} - \frac{\sigma^2}{MCOT\cdot|h_{d,k}|^2}\Big)\Big|_0^{\frac{t_{d,k}}{MCOT}\cdot P_{d,k}^{max}} & \text{with (59)}, \quad \xi_{d,k} = 0 \text{ and } \gamma > 0. \end{cases} \tag{60}$$

- If $\xi_{d,k} > 0$ and $\gamma \geq 0$, according to (53a) and $\frac{t_{d,k}}{MCOT}\cdot P_{d,k}^{max} = q_{d,k}$, we have $q_{d,k}$ as

$$q_{d,k} = t_{d,k}\Big(\frac{B_k p_k(1+\alpha_k)}{(\gamma+\xi_{d,k})\ln 2} - \frac{\sigma^2}{MCOT\cdot|h_{d,k}|^2}\Big)\Big|_0^{\frac{t_{d,k}}{MCOT}\cdot P_{d,k}^{max}} \tag{56}$$

where the Lagrange multiplier $\gamma + \xi_{d,k}$ is written as

$$\gamma + \xi_{d,k} = \frac{B_k p_k(1+\alpha_k)}{\ln 2\big(\frac{\sigma^2}{MCOT\cdot|h_{d,k}^2|} + \frac{P_{d,k}^{max}}{MCOT}\big)}, \tag{57}$$

and $a|_b^c = min(max(a,b),c)$.

- If $\xi_{d,k} = 0$ and $\gamma > 0$, then $\frac{\partial R_{d,k}}{\partial q_{d,k}} = \frac{\gamma}{1+\alpha_k}$ and $P_{gNB}^{max} = \sum_{k\in\mathcal{K}}\sum_{d\in D} q_{d,k}$, and thus we can obtain

$$q_{d,k} = t_{d,k}\Big(\frac{B_k p_k(1+\alpha_k)}{\gamma\ln 2} - \frac{\sigma^2}{MCOT\cdot|h_{d,k}|^2}\Big)\Big|_0^{\frac{t_{d,k}}{MCOT}\cdot P_{d,k}^{max}} \tag{58}$$

where Lagrange multiplier γ can be written as

$$\gamma = \frac{\sum_{k\in\mathcal{K}}\sum_{d\in\mathcal{D}} t_{d,k} B_k p_k(1+\alpha_k)}{\ln 2\big(\frac{\sigma^2}{MCOT}\sum_{k\in\mathcal{K}}\sum_{d\in\mathcal{D}} t_{d,k}/h_{d,k}^2 + P_{gNB}^{max}\big)}. \tag{59}$$

The download power allocation (multiplied by time) $q_{d,k}$ for gNB is summarized as equation (60).

Lastly, the Lagrangian multiplier is updated by sub-gradient as

$$\xi_{d,k}(t+1) = \Big[\xi_{d,k}(t) - s_2(t)\big(\frac{t_{d,k}}{MCOT}\cdot P_{d,k}^{max} - q_{d,k}\big)\Big]^+,$$

$$\gamma(t+1) = \Big[\gamma(t) - s_3(t)\big(P_{gNB}^{max} - \sum_{k\in\mathcal{K}}\sum_{d\in D} q_{d,k}\big)\Big]^+, \tag{61}$$

where $s_i(t), i = 1,2,3$, are the step sizes subject to

$$\sum_{t=1}^{\infty} s_i(t)^2 < \infty \text{ and } \sum_{t=1}^{\infty} s_i(t) = \infty, i = 1,2,3. \tag{62}$$

The overall algorithm is summarized in Algorithm 1.

VIII. PERFORMANCE ANALYSIS, SIMULATION AND DISCUSSION

In this section, we first compare the successful access probability and airtime ratio of our proposed method with the other two methods. Then the performance of the proposed algorithm under the influence of the payload, the maximum downlink power, the length of MCOT, and the number of WiFi nodes is evaluated.

Algorithm 1: Resource Allocation Algorithm for UL and DL on Unlicensed Channels

```
/* Unlicensed Access Procedure        */
```
1 Initialize $k = 1, \boldsymbol{\alpha}, \gamma, \boldsymbol{\xi}$, set $s_i(i = 1,2,3)$;
2 **repeat**
3   Calculate the WiFi access probability τ_k^w and gNB access probability τ_k^l according to (1) and (4);
4   Calculate the average time slot $\overline{T_k^{slot}}$ and WiFi throughput R_k^W according to (13) and (17), respectively;
5   Calculate the $p_k = \frac{\tau_k^l(1-\tau_k^w)^{N_k}}{T_k^{slot}}$;
```
    /* Resource Allocation on
       unlicensed channel            */
```
6   **repeat**
7   With fixed $\{q_{u,k}\}_{u\in\mathcal{U}}, \{q_{d,k}\}_{d\in\mathcal{D}}$, obtain the β_k according to (48), and then obtain the optimal value $\{t_{u,k}, t_{d,k}\}_{u\in\mathcal{U},d\in\mathcal{D}}$ according to (47);
8   Obtain the optimal value $\{q_{u,k}\}_{u\in\mathcal{U}}$ according to (54), and obtain the optimal $\{q_{d,k}\}_{d\in\mathcal{D}}$ according to (60) with fixed $\{t_{u,k}, t_{d,k}\}_{u\in\mathcal{U},d\in\mathcal{D}}$;
9   **until** *The objective function of (33) converges*
10   Update the Lagrangian multiplier α_k as (49);
11   Update the Lagrangian multiplier $\xi_{d,k}$ and γ as (61);
12    $k = k + 1$;
13 **until** $k > K$


A. System Parameter Setting

The simulation parameters of WiFi and NR-U (sub 7 GHz) are presented in Table III. The DL and UL channels in NR-U experience Rayleigh fading and the UMi-street Canyon path loss model is adopted [40] as given by

$$PL = \begin{cases} 32.4 + 21\log_{10}(\bar{d}) + 20\log_{10}(f_c), 10\text{ m} \leq \bar{d} \leq d_{BP}', \\ 32.4 + 40\log_{10}(\bar{d}) + 20\log_{10}(f_c) - 9.5\log_{10}((d_{BP}')^2 \\ \quad + (h_{BS} - h_{UT})^2), d_{BP}' < \bar{d} \leq 5\text{ km}, \end{cases} \tag{63}$$

where $h_{BB}' = h_{BS} - h_E$, $h_{UT}' = h_{UT} - h_E$, $h_E = 1$ m, $h_{BS} = 10$ m, $h_{UT} = 1.5$ m, $f_c = 5$ GHz, $c = 3*10^8$ m/s, $d_{BP}' = 4h_{BB}'h_{UT}'f_c/c = 300$ m, and $\bar{d}$ is the distance between UE and gNB uniformly chosen from 10 to 2000 m. The noise power density is $N_0 = -174$ dBm/Hz, and the noise power is $-174 + 10\log_{10}(B_k)$ dBm. The simulation is run 100 times, and the result is the average of all runs. Without loss of generality, we assume that there is one WiFi network and hence one unlicensed channel, the number of WiFi nodes varies from 5 to 30, increasing by 5 in each scenario.

TABLE III: Simulation parameters.

WiFi System (IEEE 802.11n)		NR-U System (sub 7GHz)	
Parameter	Value	Parameter	Value
H	400 bits	MCOT	8-10 ms
ACK	364 bits	U	5
SIFS	16 μs	D	5
PIFS	25 μs	Subcarrier Spacing (SCS)	60 KHz
DIFS	34 μs	T_f	16 μs
r_w	54 Mbps	T_d	$T_f + m_p * T_\sigma$
RTS	288 bits	N_u	10
CTS	352 bits	L	8
$\mathbb{E}(PL_k)$	800-2048 Bytes	P_{gNB}^{max}	35 dBm
T_σ	9 μs	P_{dk}^{max}	23-35 dBm
δ	0.1 μs	P_{avg}	23 dBm
Carrier Bandwidth B_k	20 MHz	$\bar{d}$ (distance between user and gNB)	10-2000 m
W_w	16	m_l	6
m_w	6	T_{gNB}	0.25 ms
K	6	N_k	5-30
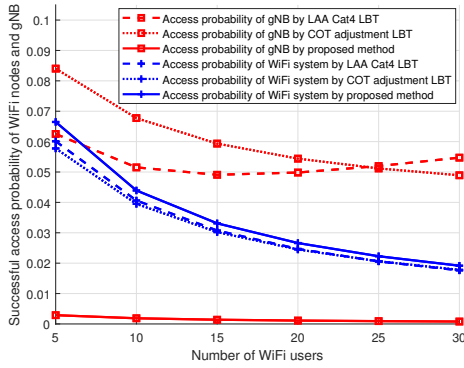
(a) Successful access probability.
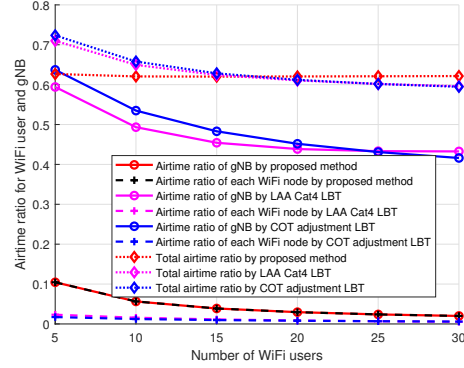
(b) Airtime ratio.

Fig. 4: Successful access probability and airtime ratio for NR and WiFi system.

B. Access Probability and Airtime Ratio

In this simulation, we evaluate and compare Cat4 LBT in [26] (Category-4 LBT with the initial contention window size 16), and COT adjustment LBT [13] with our proposed method in terms of successful access probability, airtime ratio as shown in Fig. (4a) and Fig. (4b). In Fig. (4a), we can find that almost in all methods the successful access probability of gNB and WiFi decreases with the increase of the number of WiFi nodes, as expected. Because when more WiFi nodes compete for unlicensed channels, the successful access probability for each node will decrease. It is also observed that the access probability of gNB in our proposed setting is smaller than that of Cat4 LBT and COT adjustment LBT, while the successful access probability for WiFi is slightly improved than the other two methods. The reason gNB has a much smaller access probability than WiFi is that gNB usually has a much larger channel occupation time than WiFi and to ensure an equal airtime ratio per WiFi node to that of gNB, the optimized initial window size of gNB tends to be large to protect the WiFi system.

In Fig. (4b), we compared the airtime ratio per node (successful transmission time ratio) with different methods. Our proposed method can achieve the equal airtime ratio per

node when gNB adopts the optimal initial contention window W_l^*, which gives the two systems an equal chance to access the unlicensed channel. Note that when the number of WiFi nodes is large, the airtime ratio per WiFi node (lower) and the airtime ratio of the gNB (higher) can be tuned to balance the coexistence, achieving proportional fairness. When gNB adopts the Cat4 LBT and COT adjustment LBT, we find that the airtime ratio of gNB is larger than that of each WiFi node for these two methods, which make the WiFi nodes have little chance to access the unlicensed channel. On the other hand, the total airtime ratio for all nodes of Cat4 LBT and COT adjustment LBT decrease with the increase of the number of WiFi nodes, while the proposed method keeps almost constant since the proposed method can adjust the initial contention window size according to the number of WiFi nodes to keep the total airtime ratio constant but the airtime ratio of each node will decrease with the number of WiFi nodes.

C. Throughput Fairness and WiFi Throughput with Different Methods

In Fig. (5a), Fig. (5b), Fig. (5c) we compare and validate the fairness under different maximum downlink power, WiFi payload, and MCOT. It can be easily that our proposed
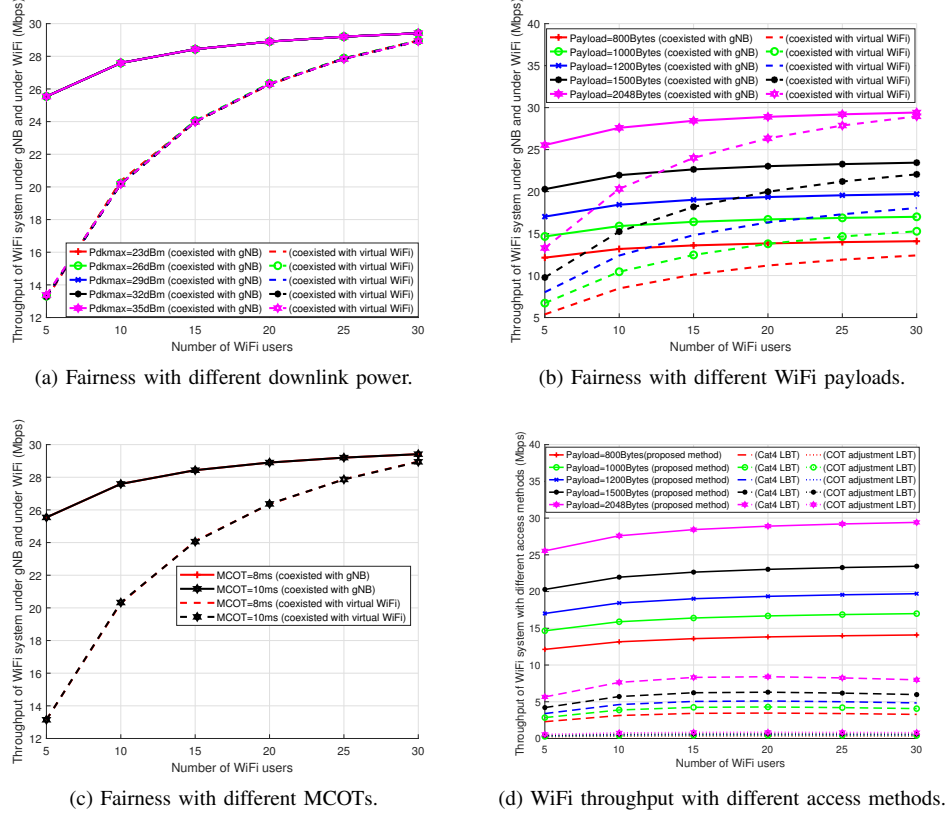
(a) Fairness with different downlink power.

(b) Fairness with different WiFi payloads.

(c) Fairness with different MCOTs.

(d) WiFi throughput with different access methods.

Fig. 5: Throughput fairness and WiFi throughput with different methods.

method can obtain throughput fairness under different power, WiFi payload, MOCT. It is also observed that the maximum downlink power and MCOT have little influence on the throughput of the WiFi system, whether coexisting with a gNB system or a virtual WiFi system, while they are deeply influenced by the WiFi payload. Since gNB obtains a small successful access probability in our proposed method, and thus, the successful and failed access time $MCOT + T_{gNB}$ have little impact on the WiFi throughput coexisted with NR (under gNB) or coexisted with a virtual WiFi network (under WiFi). The maximum downlink power has no influence on WiFi throughput under gNB and has little impact on the WiFi system under a virtual WiFi system. From Fig. (5b), we can find that the WiFi throughput under gNB and under WiFi will increase with the increasing of WiFi payload, and the fairness can be always satisfied with different payloads. In Fig. (5d), we compare the WiFi throughput coexisted with NR with Cat4 LBT [26] and COT adjustment LBT [13]. It is observed that the WiFi throughput coexisted with NR in the proposed method is larger than that of Cat4 LBT and COT adjustment LBT whatever the payload is.

D. NR Throughput under Affected Parameters with Different Methods

In this simulation, we compare the NR throughput by the proposed method with equal time allocation and equal power allocation (ETEP) [41], equal time allocation and optimal

power allocation (ETOP) [41], and optimal time allocation and equal power allocation (OTEP).

1) Impact of Maximum Downlink Power: Fig. (6a) compares the total NR throughput of the proposed method with ETEP, ETOP, OTEP methods under different maximum downlink power of gNB. It is easily observed that the proposed method can achieve a larger throughput than other methods. Furthermore, the larger the maximum downlink power is, the larger the total NR throughput is. The methods, OTEP and ETEP, achieve the lower throughput than our proposed method and ETOP, since these two methods adopt average equal power $p_{dk} = \frac{1}{2}P_{d,k}^{max}$. It means that power allocation has more influence on NR throughout than time allocation.

2) Impact of the WiFi Payloads: Fig. (6b) shows the NR throughput with different methods and different WiFi payloads, where the maximum downlink power is set as $P_{d,k}^{max} = 23$ dBm. We can find that our proposed method can achieve the largest throughput compared to ETOP, OTEP, and ETEP. Furthermore, the larger payload of the WiFi system will yield slightly lower NR throughput, since more WiFi payload means WiFi will occupy the unlicensed channel for a longer time to transmit data, and gNB will be given less time to transmit on the unlicensed channel. Besides, the throughput of NR decreases with the increase of the number of WiFi nodes, since the successful access probability of gNB will become small when there are more WiFi nodes as shown in Fig. (4a).

3) Impact of Length of the MCOT: From Fig. (6c), we can find that the total NR throughput of the proposed method is
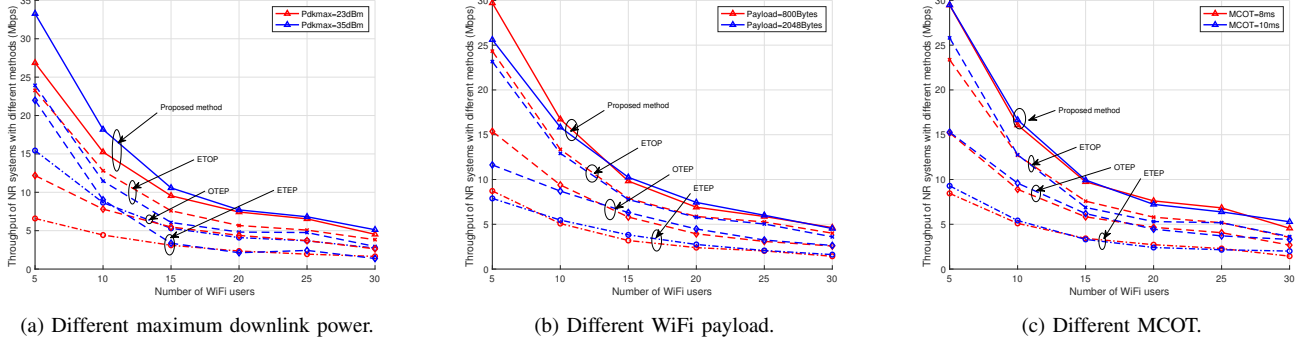
Fig. 6: Throughput of NR system under affected parameters with different methods.

larger than that of other methods. The method ETEP achieves the lowest NR throughput since it adopts the average power and time allocation, which cannot guarantee the maximum NR throughput. The throughput of OTEP and ETOP is larger than that of ETEP, which means that the influence of time allocation on the NR throughput is smaller than that of power allocation. Besides, it is also observed that the larger the MCOT is, the larger the total NR throughput is, as expected. Since more time for uplink and downlink transmission is the larger throughput for the NR system.

IX. CONCLUSION

In this paper, we have considered coexistence between NR-U and WiFi systems under 7 GHz, and proposed a coexistence model on unlicensed channels where the MCOT of gNB is divided into two parts, one for uplink transmission and the other for downlink transmission. Our proposed equal airtime access method can make WiFi nodes and gNB obtain fair access opportunities. Furthermore, the proposed method can realize throughput fairness with different WiFi payloads, maximum downlink power and MCOTs, and achieve the largest WiFi throughput under gNB compared to Cat4 LBT and COT adjustment LBT. The optimization of time and power allocation has demonstrated superior performance over the method ETEP, ETOP, OTEP. We also find that the larger maximum downlink power, smaller WiFi payload, and larger MCOT can improve the NR throughput.

For 5G use of unlicensed bands at higher frequencies, NR-U will need to coexist with WiGig at mmWave. The current unlicensed channel access method for mmWave unlicensed coexistence may not work well, because beamforming is necessary for directional transmission in high path loss mmWave channels, which increases the chance of coexistence in a spatial domain. In this case, directional LBT should be considered at the transmitter, or hybrid with omni-directional LBT. There are a number of studies in the literature on the coexistence of NR-U and 802.11ad. The receiver-assisted LBT, that is, listen before received (LBR), is an auxiliary method to improve the access performance, and the combination of transmitter LBT and receiver LBR usually can provide significant enhancements in interference management. All these potential unlicensed access methods provide a path for our

future research on NR-U and WiGig coexistence. We will extend the proposed methodology to the coexistence study at mmWave bands as future work.

X. APPENDIX

APPENDIX A
CONVEXITY PROOF OF THE FORMULATION

Proof 3: It is well known that the Shannon formula $f(q_{d,k}) = \log_2(1 + \frac{MCOT \cdot q_{d,k}|h_{d,k}|^2}{\sigma^2})$ is concave with respect to (w.r.t.) $q_{d,k}$, and $t_{d,k}f(q_{d,k}) = t_{d,k}\log_2(1 + \frac{MCOT \cdot q_{d,k}|h_{d,k}|^2}{t_{d,k}\sigma^2})$ is also concave w.r.t $(t_{d,k}, q_{d,k})$ as stated in [42]. Thus, the first part of the objective function ($R_{d,k} = p_k t_{d,k} f(q_{d,k})$) in (33) is also concave as the coefficient of the sum is positive w.r.t. (t_k, q). Similarly, we can find that $t_{u,k}\log_2(1 + \frac{MCOT \cdot q_{u,k}|h_{u,k}|^2}{\sigma^2 t_{u,k}})$ is also concave w.r.t. $(t_{u,k}, q_{u,k})$, and thus the second part of the objective function, $R_{u,k} = p_k t_{u,k} f(q_{u,k})$, is also a concave function. Since the objective function is a concave function and all the constraints are affine, the maximum-concave problem is a convex problem.

APPENDIX B
PROOF OF MAXIMUM VALUE FOR THE SECOND CONSTRAINT

Proof 4: Define

$$U_{i,k} = \begin{cases} B_k p_k \log_2(1 + \frac{MCOT \cdot q_{d,k}|h_{d,k}|^2}{\sigma^2 t_{d,k}}) & , i \in \mathcal{D}. \\ B_k p_k \log_2(1 + \frac{MCOT \cdot q_{u,k}|h_{u,k}|^2}{\sigma^2 t_{u,k}}) & , i \in \mathcal{U}. \end{cases} \quad (64)$$

Thus the objective function can rewritten as

$$\sum_{k \in \mathcal{K}}(\sum_{i \in \mathcal{D}} t_{i,k}U_{i,k} + \sum_{i \in \mathcal{U}} t_{i,k}U_{i,k}) = \sum_{k \in \mathcal{K}}\sum_{i \in \mathcal{U}\cup\mathcal{D}} t_{i,k}U_{i,k}. \quad (65)$$

As can be seen from (65), the objective function is an increasing function with $t_{i,k}, i \in \mathcal{U} \cup \mathcal{D}$. To maximize the objective function, the equation of the second constraint of problem (33) should be held, i.e.,

$$\sum_{i \in \mathcal{D}\cup U} t_{i,k} = \sum_{d \in \mathcal{D}} t_{d,k} + \sum_{u \in \mathcal{U}} t_{u,k} = MCOT, \forall k \in \mathcal{K}. \quad (66)$$

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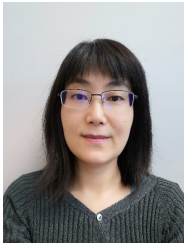
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