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3GPP Fairness Constrained Throughput Optimization for 5G NR-U and WiFi Coexistence in the Unlicensed Spectrum

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***Abstract*—5G New Radio Unlicensed (5G NR-U) and WiFi are considered to be the two most representative radio access technologies in the newly released 6 GHz unlicensed bands, and thus their efficient and fair coexistence becomes crucial. In this paper, we study the coexistence performance of 5G NR-U and WiFi by accounting the new physical layer (PHY) enhancements in 5G NR including flexible numerologies and mini-slot scheduling. Consider the 3GPP notion of fairness as the requirement, we further study how to maximize the total network effective throughput of the WiFi and NR-U coexisting network. Explicit expressions of the maximum total network effective throughput and the corresponding optimal initial backoff window sizes of WiFi and NR-U nodes are derived, and verified by simulation results. The analysis shows that if the transmission opportunity (TXOP) value of NR-U nodes exceeds a certain threshold, then a win-win coexistence can be achieved, where both the WiFi and 5G NR-U network can perform no worse than the case when two WiFi networks coexist. In this case, the maximum total network effective throughput steadily grows as the time slot length of NR-U nodes decreases, indicating the PHY enhancement in 5G NR can benefit the coexistence performance of 5G NR-U and WiFi in the unlicensed spectrum.**

***Index Terms*—5G New Radio Unlicensed (5G NR-U), WiFi, coexistence, 3GPP fairness**

I. INTRODUCTION

Due to the scarcity of the licensed spectrum, the unlicensed spectrum sharing has gained significant attention in recent years due to its free-to-use nature. Regulators in the US and Europe are opening up to 1.2 GHz additional spectrum in the 6 GHz bands for unlicensed radio access technologies (RATs) [1], including the incumbent WiFi [2] and the recently-released 5G New Radio Unlicensed (5G NR-U) [3]. Ensuring the efficient and fair coexistence for WiFi and 5G NR-U is thus of signficant importance.

To support harmonious coexistence with WiFi, the medium access control (MAC) layer of 5G NR-U is based on its predecessor Long Term Evolution Licensed Assisted Access (LTE-LAA) [4], which follows a Listen-before-Talk (LBT) scheme similar to WiFi. The coexistence of LTE-LAA and WiFi in unlicensed spectrum has been extensively studied [5]–[9] under distinct notions of fairness such as proportional fairness [6], [9] and 3GPP fairness [8]. Although 5G NR-U and LTE-LAA share a similar MAC scheme, their PHY layer derives from 5G NR-U and LTE, respectively. In contrast to LTE-LAA which has fixed time slot structure and subframe-based synchronization, 5G NR-U will adopt flexible numerologies and mini-slot scheduling. A few studies on the coexistence of 5G NR-U and WiFi have put the focus on spatial reuse [10], [11] and power allocation [12]. Little work, nevertheless, can be found on how the PHY layer enhancements in 5G NR would affect the coexistence performance of 5G NR-U and WiFi in the unlicensed spectrum.

In this paper, we address the above open questions by comparing the network performance of two coexistence scenarios in the unlicensed spectrum: 1) a WiFi network coexists with another WiFi network and 2) a WiFi network coexists with a 5G NR-U network. By extending an analytical framework proposed for LTE-LAA and WiFi coexistence in our recent work [9], the maximum total network effective throughput of a coexisting WiFi and NR-U network under 3GPP fairness constraint is derived as an explicit function of system parameters.

The analysis shows that when the TXOP value of the 5G NR-U network is large enough, it is a preferable neighbor of a pre-installed WiFi network over another WiFi network, as not only 3GPP fairness can be achieved, the total network can maintain a higher maximum effective throughput. The performance limit can be further boosted if the time slot length of NR-U nodes becomes smaller. To achieve it, the initial backoff window sizes of both NR-U and WiFi networks need to be jointly tuned according to the number of nodes in both networks.

The rest of the paper is organized as follows. The system model and preliminary analysis are presented in Section II. Section III presents how to optimize the total network effective throughput under the constraint of 3GPP fairness, which is verified by simulation results in Section IV. Finally, concluding remarks are summarized in Section V.

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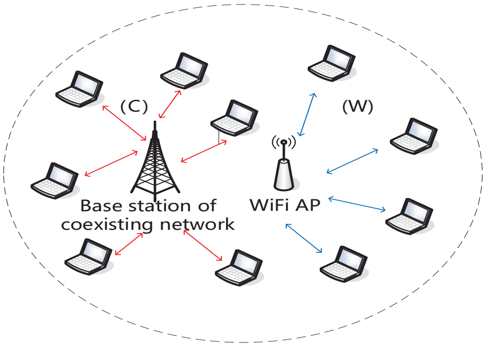


Fig. 1. The network scenario of the coexistence with a WiFi network in the unlicensed spectrum.

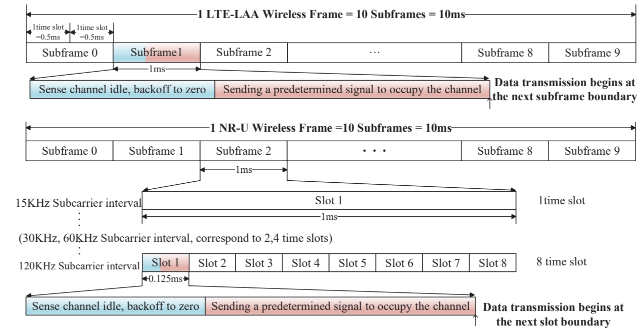


Fig. 2. Graphic illustration of frame structure and time slot length of NR-U and LTE Licensed Assisted Access (LTE-LAA).

II. SYSTEM MODEL AND PROBLEM FORMULATION

To support fair coexistence between cellular systems and WiFi networks in the unlicensed spectrum, 3GPP proposed a fairness definition in Release 13 for LAA: "*the LAA design should target fair coexistence with existing WiFi networks to not impact WiFi services more than an additional WiFi network on the same carrier, with respect to throughput and latency*" [4]. In this paper, we follow the 3GPP notion of fairness for 5G NR-U and WiFi coexistence. Therefore, let us consider the network scenario as shown in Fig. 1, where a WiFi network and a coexisting network operate at the same unlicensed channel for both downlink and uplink transmissions.

For the WiFi network, one WiFi access point (AP) and $n^{(W)}-1$ WiFi stations (STAs) make transmissions following the IEEE 802.11 distributed coordination function (DCF) protocol. Assume that each node (including the WiFi AP and STAs) adopts identical backoff parameters, i.e., initial backoff window size $W^{(W)}$, maximum backoff stage $K^{(W)}$ and retry limit $m^{(W)}$. For the coexisting network, it consists of one base station and $n^{(C)}-1$ nodes. When a node accesses to the channel, it will transmit a packet payload of $PL^{(W)}$ bits with a physical layer (PHY) transmission rate $R^{(W)}$ Mbps. According to the notion of 3GPP fairness, the coexistence scenario can be further divided into two cases:

1) *The WiFi network coexists with another WiFi network*: In this case, the coexisting network is also a WiFi network, which consists of a WiFi AP and $n^{(C)}-1$ WiFi STAs. All the WiFi nodes adopt the same backoff and transmission parameters.

2) *The WiFi network coexists with a 5G NR-U network*: In this case, one 5G NR-U gNodeB (gNB) and $n^{(C)}-1$ User Equipments (UEs) are transmitting over the unlicensed band. 5G NR-U follows a similar access scheme to its predecessor LTE-LAA by adopting an LBT-based scheme. 3GPP defines four access priority for NR-U [3], each of which has different initial backoff window sizes $W^{(NR)}$, maximum backoff stage $K^{(NR)}$ and retry limit $m^{(NR)}$. When an NR-U node accesses to the channel, it is allowed to transmit for a TXOP duration $T^{(NR)}$ μs. For the simplicity, we assume that all the 5G NR-U transmissions are within the same access priority in this paper.

In contrast to LTE-LAA, 5G NR-U derives its physical layer from 5G NR, and thus can benefit from leveraging PHY layer enhancements made in 5G NR, including the flexible numerologies and mini-slot scheduling. Fig. 2 illustrates the comparison of frame structure and time slot length between LTE-LAA and 5G NR-U. In contrast to the fixed slot length of 500 μs for LTE-LAA, the slot length of NR-U is variable, denoted as $\sigma^{(NR)}\mu$s, which varies from 1000, 500, 250, 125 μs. Moreover, the use of mini-slot scheduling in NR-U allows each NR-U transmission to begin at the next slot boundary, which minimizes the reservation signals used in LTE-LAA to reserve the channel after an LTE-LAA node gains access to the channel, as LTE-LAA transmissions are required to be synchronized with the subframe boundaries.

A. Problem Formulation

As both 5G NR-U and WiFi adopt LBT-based random access scheme, the number of successfully decoded packets varies from time to time. Therefore, to evaluate the access performance, the average number of successfully decoded packets per time slot is an important performance metric, which is referred to as the *network effective throughput*. In this paper, the classical collision model is adopted, where a packet transmission is successful if and only if there are no concurrent transmissions; otherwise, a collision occurs and none of the packets can be successfully decoded. Therefore, the network effective throughput is also the percentage of the time that a network has a successful packet transmission, which reflects the access efficiency.

In this paper, we focus on the network effective throughput performance. Denote the effective throughput of the WiFi network and the coexisting network as $\eta^{(W)}_{\text{WiFi+NR-U}}$ and $\eta^{(C)}_{\text{WiFi+NR-U}}$, respectively, when the coexisting network is a 5G NR-U network; that of the WiFi network and the coexisting network as $\eta^{(W)}_{\text{WiFi+WiFi}}$ and $\eta^{(C)}_{\text{WiFi+WiFi}}$, respectively, when the coexisting network is another WiFi network.

To achieve 3GPP fairness, we need to guarantee that the effective throughput of the WiFi network when it coexists with a 5G NR-U network is no lower than that when it coexists with another WiFi network, i.e., $\eta^{(W)}_{\text{WiFi+NR-U}} \geq \max\ \eta^{(W)}_{\text{WiFi+WiFi}} = \frac{n^{(W)}}{n^{(W)}+n^{(NR)}}\eta^{(W)}_{\text{max, WiFi+WiFi}}$, as each WiFi node achieves the same share of the total network effective throughput. Consider the optimization problem of maximizing the total network throughput of a coexisting NR-U and WiFi network with the 3GPP fairness constraint, which can be formulated as

$$\eta^{3GPP}_{\max,\text{ WiFi+NR-U}} = \max_{W^{(NR)},\, W^{(W)}} \quad \eta^{(W)}_{\text{WiFi+NR-U}} + \eta^{(C)}_{\text{WiFi+NR-U}},$$

$$s.t. \quad \eta^{(W)}_{\text{WiFi+NR-U}} \geq \frac{n^{(W)}}{n^{(W)} + n^{(NR)}} \cdot \eta^{(W)}_{\max,\text{ WiFi+WiFi}}. \tag{1}$$

B. System Model

In [9], an analytical model was proposed to model the state transition of the Head-of-Line (HOL) packets for a LTE-LAA and WiFi coexisting network. That paper considered proportional fairness, not network performance optimization, and the new PHY enhancements in 5G NR-U will be taken into account in new study. In this paper, the model will be further extended to a coexisting network with two types of nodes $g = W,\ C$, i.e., WiFi nodes and Coexisting nodes (can be WiFi or 5G NR-U). By following a similar derivation in [9], the network steady-state operating point p_A can be characterized as the non-zero root of the fixed-point equation of the limiting probability of successful transmission given that the channel is idle, p, which is given by

$$p \approx \exp\left(\sum_g \frac{\frac{-2n^{(g)}}{W^{(g)}}\left(1-(1-p)^{K^{(g)}+m^{(g)}+1}\right)}{\frac{p}{2p-1}+(2-2p)^{K^{(g)}+1}\left(\frac{1}{2}-\frac{p}{2p-1}-\frac{(1-p)^{m^{(g)}}}{2}\right)}\right), \tag{2}$$

In this paper, we focus on the effective throughput, which is defined as the average number of successfully decoded packets per time slot. By following a similar derivation in [9], for the type of nodes g, its network effective throughput $\eta^{(g)}$ is then given by

$$\eta^{(g)} = \frac{p_A \xi^{(g)} \tau_T^{(g)} n^{(g)} e^{(g)}}{1+\tau_F-\tau_F p_A-\left(\frac{\sum \tau_T^{(g)} n^{(g)} e^{(g)}}{\sum n^{(g)} e^{(g)}}-\tau_F\right) p_A \ln p_A}, \tag{3}$$

$g = W, C$, where $\xi^{(g)}$ denotes the percentage of time for packet transmission in a successful transmission of nodes in Group g, which is given by

$$\xi^{(W)} = \frac{PL^{(W)}}{\sigma R^{(W)} \tau_T^{(W)}}, \tag{4}$$

and

$$\xi^{(C)} = \begin{cases} \frac{T^{(NR)}}{\sigma \tau_T^{(NR)}}, & \text{if the coexisting network is 5G NR-U} \\ \xi^{(W)}, & \text{if the coexisting network is WiFi,} \end{cases} \tag{5}$$

$e^{(g)}$ is given by

$$e^{(g)} = \frac{\frac{-2}{W^{(g)}}\left(1-(1-p_A)^{K^{(g)}+m^{(g)}+1}\right)}{\frac{p_A}{2p_A-1}+(2-2p_A)^{K^{(g)}+1}\left(\frac{1}{2}-\frac{p_A}{2p_A-1}-\frac{(1-p_A)^{m^{(g)}}}{2}\right)}. \tag{6}$$

Moreover, $\tau_T^{(g)}$ and τ_F denote the holding time of successful transmission and collision of nodes in Group $g = W, C$ in unit of slots, respectively. For WiFi nodes, we have

$$\tau_T^{(W)} = \frac{PL^{(W)}}{R^{(W)}\sigma} + OH, \tag{7}$$

where σ denotes the time slot length of WiFi and OH denotes the overhead (in unit of time slots) including the PHY header, RTS, CTS, ACK frames that are transmitted with a fixed basic rate R_B Mbps and several interframe spaces, which can be written as

$$OH = \frac{(\text{phyH+RTS+CTS+ACK})/R_B + \text{DIFS+3SIFS}}{\sigma}. \tag{8}$$

For a 5G NR-U node, once successfully accessing to the channel, it will send a reservation signal on the channel until the beginning of the next time slot, and then occupy the channel for a TXOP $T^{(NR)}$ μs. We then have

$$\tau_T^{(NR)} = \frac{T^{(NR)} + \sigma^{(NR)}/2}{\sigma}. \tag{9}$$

Note that the collision time depends on the specific protocol that determines how each WiFi AP/node and NR-U gNB/UE get aware of the collision. For the sake of simplicity, we assume that the collision time is identical for both NR-U and WiFi nodes, which is given by

$$\tau_F = \frac{\text{RTS}/R_B + \text{DIFS}}{\sigma}. \tag{10}$$

Now let us consider the network effective throughput performance in the two coexisting cases:

1) *The WiFi network coexists with another WiFi network*: In this case, all the nodes in the two WiFi networks have identical parameters. By combining (2)-(6), the total network effective throughput of the WiFi and WiFi coexisting network can be written as

$$\eta_{\text{WiFi+WiFi}} = \frac{-\frac{PL^{(W)}}{\sigma R^{(W)}} \cdot p_A \ln p_A}{1+\tau_F-\tau_F p_A-\left(\tau_T^{(W)}-\tau_F\right) p_A \ln p_A}. \tag{11}$$

The maximum effective network throughput of the WiFi and WiFi coexisting network is then given by [13]

$$\eta_{\max,\text{WiFi+WiFi}} = \frac{-\frac{PL^{(W)}}{\sigma R^{(W)}} \cdot \hat{\mathbb{W}}}{\tau_F - \left(\tau_T^{(W)} - \tau_F\right)\hat{\mathbb{W}}}, \tag{12}$$

where $\hat{\mathbb{W}} = \mathbb{W}_0\left(\frac{-1}{e(1+1/\tau_F)}\right)$, $\mathbb{W}_0$ is the Lambert W Function [14].

2) *The WiFi network coexists with a 5G NR-U network*: In this case, by combining (2)-(6), the total network effective throughput of the WiFi and NR-U coexisting network can be written as

$$\begin{aligned} \eta_{\text{WiFi+NR-U}} &= \eta^{(C)}_{\text{WiFi+NR-U}} + \eta^{(W)}_{\text{WiFi+NR-U}} \\ &= \frac{-\frac{\sum n^{(g)} \tau_T^{(g)} e^{(g)} \xi^{(g)}}{\sum n^{(g)} e^{(g)}} p_A \ln p_A}{1+\tau_F-\tau_F p_A-\left(\frac{\sum n^{(g)} \tau_T^{(g)} e^{(g)}}{\sum n^{(g)} e^{(g)}}-\tau_F\right) p_A \ln p_A}. \end{aligned} \tag{13}$$

III. 3GPP FAIRNESS-CONSTRAINED MAXIMUM EFFECTIVE THROUGHPUT FOR NR-U AND WIFI COEXISTING NETWORKS

In this section, we will demonstrate how to optimize the network effective throughput of the NR-U-WiFi-coexisting network under the 3GPP fairness constraint.

A. 3GPP Fairness-Constrained Maximum Effective Throughput

By substituting (2)-(6) and (12)-(13) into (1), Theorem 1 presents the optimal solution $\{W_m^{(W)}, W_m^{(NR)}\}$ of (1).

TABLE I
SYSTEM PARAMETER SETTING

PHY header	20 μs
MAC header	36 B
ACK	14 B+PHY header
RTS	20 B+PHY header
CTS	14 B+PHY header
Slot Length σ	9 μs
SIFS	16 μs
DIFS	34 μs
R_B	6 Mbps

Theorem 1: For a saturated 5G NR-U and WiFi coexisting network, if $\gamma^* > 1$, where

$$\gamma^* = \frac{T^{(NR)} R^{(W)}}{PL^{(W)}} \cdot \frac{\tau_F - (\tau_T^{(W)} - \tau_F)\hat{\mathbb{W}}}{\tau_F - (\tau_T^{(NR)} - \tau_F)\hat{\mathbb{W}}}, \tag{14}$$

the optimal solution of (1) is given by

$$W_m^{(g)} = \frac{-2\left(n^{(\hat{g})} \cdot \frac{\tau_F - (\tau_T^{(g)} - \tau_F)\hat{\mathbb{W}}}{\tau_F - (\tau_T^{(\hat{g})} - \tau_F)\hat{\mathbb{W}}} + n^{(g)}\right)\left(1 - (1 - p_A^*)^{K^{(g)} + m^{(g)} + 1}\right)}{\ln p_A^* \left(\frac{p_A^*}{2p_A^* - 1} + \left(\frac{1}{2} - \frac{p_A^*}{2p_A^* - 1} - \frac{(1 - p_A^*)^{m^{(g)}}}{2}\right)(2 - 2p_A^*)^{K^{(g)} + 1}\right)}, \tag{15}$$

$g, \hat{g} = W, C$, $\hat{g} \neq g$, where $p_A^* = -(1 - 1/\tau_F)\mathbb{W}\left(-\frac{1}{e(1 + 1/\tau_F)}\right)$, with which the maximum total network effective throughput $\eta^{3GPP}_{\text{max, WiFi+NR-U}}$ is given by

$$\eta^{3GPP}_{\text{max, WiFi+NR-U}} = \frac{n^{(W)} + \gamma^* \cdot n^{(C)}}{n^{(W)} + n^{(C)}} \cdot \eta_{\text{max, WiFi+WiFi}}. \tag{16}$$

Otherwise, the optimal solution of (1) is given by

$$W_m^{(W)} = \frac{-\frac{2n^{(W)}}{\ln p_A^*}\left(1 - (1 - p_A^*)^{K^{(g)} + m^{(g)} + 1}\right)}{\frac{p_A^*}{2p_A^* - 1} + \left(\frac{1}{2} - \frac{p_A^*}{2p_A^* - 1} - \frac{(1 - p_A^*)^{m^{(g)}}}{2}\right)(2 - 2p_A^*)^{K^{(g)} + 1}} \tag{17}$$

and

$$W_m^{(NR)} = \infty, \tag{18}$$

with which the maximum total network effective throughput $\eta^{3GPP}_{\text{max, WiFi+NR-U}}$ is given by

$$\eta^{3GPP}_{\text{max, WiFi+NR-U}} = \eta_{\text{max, WiFi+WiFi}}. \tag{19}$$

Theorem 1 shows that the optimal solution is closely dependent on the holding time τ_F of HOL packets in collision state and the overhead OH in successful transmissions of WiFi nodes. In this paper, we use the system parameters adopted in IEEE 802.11ac standard [2], which are listed in Table I. According to Table I, we can obtain that $\tau_F^{(W)} = 9.07$ time slots and $OH = 26.15$ time slots. (14), (15) and (17) can then be obtained as

$$\gamma^* = \frac{\left(19.49 R^{(W)} + 0.07 PL^{(W)}\right) T^{(NR)}}{\left(3.54 + 0.07 T^{(NR)} + 0.03 \sigma^{(NR)}\right) PL^{(W)}}, \tag{20}$$

TABLE II
SYSTEM PARAMETER SETTING

Access Priority Class of NR-U AC	**1**	**2**	**3**	**4**
Maximum Backoff Stage of NR-U $K^{(NR)}$	1	1	2	6
Retry Limit of NR-U $m^{(NR)}$	4	4	4	4
TXOP of NR-U (ms)	2	3	8	8

$$W_m^{(g)} = \frac{5.13\left(n^{(\hat{g})} \cdot \frac{3.54 + \tau_T^{(g)}}{3.54 + \tau_T^{(\hat{g})}} + n^{(g)}\right)\left(1 - 0.32^{K^{(g)} + m^{(g)} + 1}\right)}{1.89 - \left(1.39 + \frac{0.32^{m^{(g)}}}{2}\right) 0.64^{K^{(g)}}}, \tag{21}$$

and

$$W_m^{(W)} = 2.81 n^{(W)}. \tag{22}$$

B. Criteria for a Win-Win Coexistence

We can clearly see from Theorem 1 that when the WiFi network coexists with a 5G NR-U network, the maximum total network effective throughput $\eta^{3GPP}_{\text{max, } WiFi+NR-U}$ under 3GPP fairness constraint is closely dependent on the value of γ^*, which is determined by the TXOP $T^{(NR)}$ and the slot length $\sigma^{(NR)}$ of 5G NR-U nodes, the packet payload length $PL^{(W)}$ and the data transmission rate $R^{(W)}$ of WiFi nodes.

Specifically, with $\gamma^* > 1$, the NR-U-WiFi-coexisting network can always achieve a higher maximum network effective throughput than the WiFi-WiFi-coexisting case, i.e., we always have $\eta^{3GPP}_{\text{max, WiFi+NR-U}} > \eta_{\text{max, WiFi+WiFi}}$. The corresponding effective throughput of the WiFi network and the NR-U network are given by

$$\eta^{(W)}_{\text{WiFi+NR-U}} = \frac{n^{(W)}}{n^{(W)} + n^{(C)}} \cdot \eta_{\text{max, WiFi+WiFi}}, \tag{23}$$

and

$$\eta^{(C)}_{\text{WiFi+NR-U}} = \frac{\gamma^* \cdot n^{(C)}}{n^{(W)} + n^{(C)}} \cdot \eta_{\text{max, WiFi+WiFi}}, \tag{24}$$

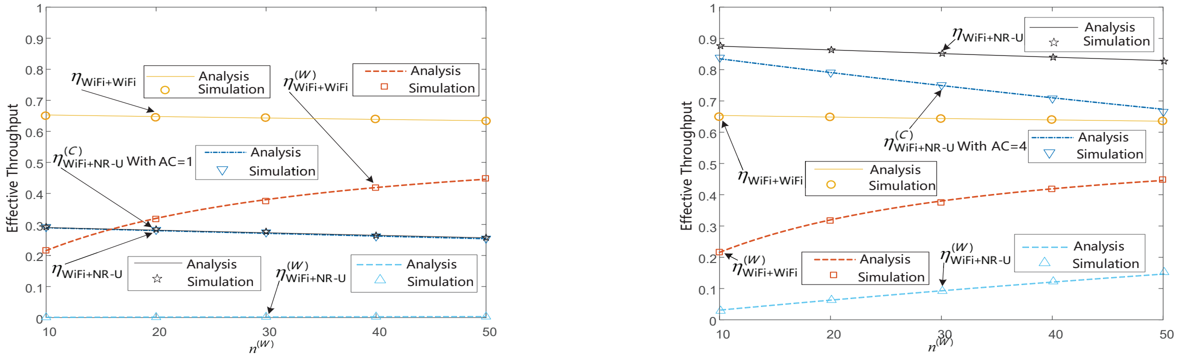
respectively. As shown in (23) and (24), when $\gamma^* > 1$, the pre-installed WiFi network achieves an identical effective throughput when it coexists with the NR-U network and another WiFi network, where the 3GPP fairness is satisfied. On the other hand, when the coexisting network is 5G NR-U, it can achieve an effective throughput γ^* times higher than the case when it is another WiFi network. It is clear that a win-win solution exists for 5G NR-U to coexist with WiFi when $\gamma^* > 1$. We can obtain from (14) that if and only if the following inequality of TXOP value $T^{(NR)}$ (in unit of μs) of NR-U nodes holds:

$$T^{(NR)} > \frac{PL^{(W)}\left(\tau_F - \left(\frac{\sigma^{(NR)}}{2\sigma} - \tau_F\right)\hat{\mathbb{W}}\right)}{R^{(W)}\left(\tau_F - (OH - \tau_F)\hat{\mathbb{W}}\right)} \tag{25}$$

By substituting $\tau_F^{(W)} = 9.07$ time slots and $OH = 26.15$ time slots into (25), we have

$$T^{(NR)} > \frac{PL^{(W)}}{R^{(W)}}\left(0.18 + 1.54 \times 10^{-3} \sigma^{(NR)}\right). \tag{26}$$

Eq. (26) indicates that for 5G NR-U and WiFi coexistence in unlicensed spectrum, if the TXOP value exceeds a certain



(a) (b)

Fig. 3. Effective network throughput of WiFi network and the coexisting network versus the number of nodes $n^{(W)}$ of the WiFi network in a 5G NR-U and WiFi coexisting network and a WiFi and WiFi coexisting network with the standard setting. $n^{(C)} = 20$. $\sigma^{(NR)} = 1$ ms. $PL^{(W)} = 32000$ bits. $R^{(W)} = 54$ Mbps. (a) NR-U access priority class $AC = 1$. $W^{(NR)} = 4$. $W^{(W)} = 16$. (b) NR-U access priority class $AC = 4$. $W^{(NR)} = 16$. $W^{(W)} = 16$

threshold, not only 3GPP fairness can be guaranteed, both the NR-U network and the total network can outperform that of a WiFi-WiFi-coexisting network. The threshold is closely dependent on the time slot length $\sigma^{(NR)}$ of NR-U nodes, as well as the packet payload length $PL^{(W)}$ and data rate $R^{(W)}$ of WiFi nodes.

IV. SIMULATION RESULTS

In this section, we will present simulation results to verify the analysis presented in Section II and III. The values of system parameters in the simulations are summarized in Table II.

A. Standard Setting

Fig. 3a and Fig. 3b present the effective throughput performance with standard parameter setting where 5G NR-U adopts different access priorities $AC = 1$ and $AC = 4$, respectively. When $AC = 1$, the throughput of WiFi network $\eta^{(W)}_{\text{WiFi+NR-U}}$ is close to zero, indicating that WiFi nodes tend to be starved when coexisting with high-priority NR-U nodes. When $AC = 4$, $\eta^{(W)}_{\text{WiFi+NR-U}}$ is still lower than $\eta^{(W)}_{\text{WiFi+WiFi}}$, i.e., the impact of the NR-U network on the WiFi network is stronger than another WiFi network, indicating that 3GPP fairness is not satisfied.

B. Optimal Setting

To maximize the total network effective throughput while maintaining 3GPP fairness in a NR-U-WiFi-coexisting network, both the initial backoff window sizes of WiFi and NR-U nodes should be carefully adjusted. Fig. 4 presents the effective throughput performance with optimal setting.

If AC=1 and $R^{(W)}$=5.4 Mbps, by substituting the prioritized parameters into (14), we have γ^{*}=0.69, and the corresponding optimal initial backoff window sizes of 5G NR-U and WiFi are given in (17) and (18), respectively. In this case, Fig. 4a clearly shows that the network throughput of the WiFi network $\eta^{(W)}_{\text{WiFi+NR-U}}$ in the NR-U and WiFi coexisting network is equal to the maximum effective throughput, which is much higher than that of $\eta^{(W)}_{\text{WiFi+WiFi}}$ in the WiFi and WiFi coexisting network, indicating 3GPP fairness is achieved. It is, nevertheless, at the cost of the coexisting 5G NR-U network, which is forbidden to transmit in order to maximizing the total network throughput. It implies that 3GPP fairness is biased to WiFi, which could be harmful to 5G NR-U nodes.

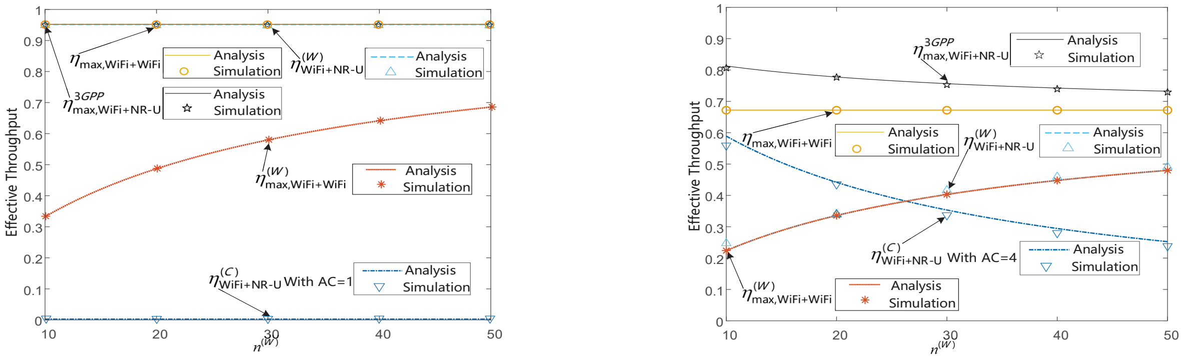
If AC=4 and $R^{(W)}$=54 Mbps, by substituting the prioritized parameters into (14), we have γ^{*}=1.32, and the corresponding optimal initial backoff window sizes are given in (15). We can clearly see from Fig. 4b that the WiFi network achieves the same network effective throughput no matter it coexists with the NR-U network or another WiFi network, which satisfies the 3GPP fairness requirement. Moreover, the total maximum effective throughput $\eta^{3GPP}_{\text{max, WiFi+NR-U}}$ of the NR-U and WiFi coexisting network is higher than that of a WiFi and WiFi coexisting network. In this case, the coexisting network achieves the win-win solution of maximizing network effective throughput and satisfying 3GPP fairness.

C. NR-U Slot Length Setting

In this subsection, we further study how the flexible slot length of 5G NR-U affects the coexisting performance, which is shown in Fig. 5. It can be clearly seen that the maximum effective throughput performance steadily increases as the slot length $\sigma^{(NR)}$ of 5G NR-U declines from 1000 μs to 125 μs. The reason is that with a smaller slot length, the average overhead in a successful transmission of NR-U decreases, leading to a higher maximum effective throughput. Compared to the fixed slot length in LTE-LAA, the flexible time slot length of NR-U is beneficial for coexisting performance limit in the unlicensed spectrum.

V. CONCLUSION

In this paper, the maximum effective throughput performance of coexisting WiFi and 5G NR-U networks under 3GPP fairness is characterized by considering the new PHY enhancements in 5G NR-U and a finite retry limit. The analysis shows that when the TXOP value of 5G NR-U nodes exceeds a certain threshold, a win-win coexistence can be achieved for 5G NR-U and WiFi, that is, not only 3GPP fairness is guaranteed, i.e., the WiFi network achieves the same throughput



(a)

(b)

Fig. 4. Effective network throughput of WiFi network and the coexisting network versus the number of nodes $n^{(W)}$ of the WiFi network in a 5G NR-U and WiFi coexisting network and a WiFi and WiFi coexisting network with the optimal setting. $n^{(C)} = 20$. $\sigma^{(NR)} = 1$ ms. $PL^{(W)} = 32000$ bits. (a) NR-U: $AC = 1$. WiFi: $R^{(W)} = 5.4$ Mbps. (b) NR-U: $AC = 4$. WiFi: $R^{(W)} = 54$ Mbps. $W^{(NR)} = W_m^{(NR)}$. $W^{(W)} = W_m^{(W)}$.

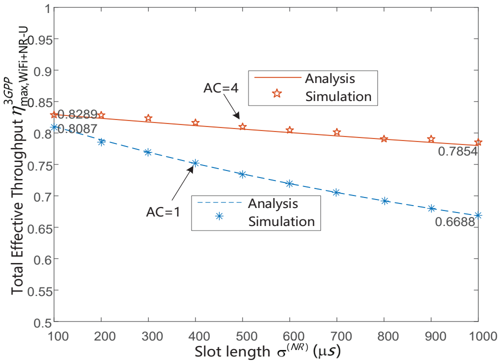


Fig. 5. Total network effective throughput versus the slot length of 5G NR-U $\sigma^{(NR)}$ in an 5G NR-U and WiFi coexisting network with the optimal setting. $n^{(W)} = n^{(C)} = 20$. $PL^{(W)} = 32000$ bits. $R^{(W)} = 54$ Mbps. $W^{(W)} = W_m^{(W)}$. $W^{(NR)} = W_m^{(NR)}$.

no matter it coexists with the 5G NR-U network or another WiFi network, but the coexisting WiFi and NR-U network can achieve a higher total throughput than a coexisting WiFi and WiFi network. The maximum effective throughput steadily increases as the slot length of NR-U nodes declines, which can outperform its predecessor LTE-LAA, indicating that the flexible numerologies and mini-slot scheduling introduced in 5G NR can benefit the coexistence performance of 5G NR-U and WiFi in the unlicensed spectrum.

This paper sheds important light on practical network design for WiFi and 5G NR-U coexistence. Explicit expressions of the optimal initial backoff window sizes of WiFi and NR-U nodes are also obtained, which show that to achieve the 3GPP fairness and the maximum total effective throughput, the initial backoff window sizes of both networks should be jointly tuned. The analysis shows that with the standard setting, WiFi nodes tend to be starved especially when they coexist with high-priority NR-U access category, which is much worse than the case when they coexist with other WiFi nodes, and the 3GPP fairness cannot be satisfied. With the optimal tuning of backoff parameters, on the other hand, 3GPP fairness can always be achieved, and the total network effective throughput is further maximized, indicating that 5G NR-U is a good candidate to support efficient and fair coexistence with WiFi in the 6 GHz unlicensed spectrum in near future.

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