# Optimal Coexistence of NR-U with Wi-Fi under 3GPP Fairness Constraint

Feifan Luo*, Xinghua Sun*, Yayu Gao†, Wen Zhan*, Peng Liu‡ and Ziyang Guo‡

*School of Electronics and Communication Engineering, Shenzhen Campus of Sun Yat-sen University
†School of Electronic Information and Communications, Huazhong University of Science and Technology
‡Huawei Technologies Co., Ltd.
luoff6@mail2.sysu.edu.cn, sunxinghua@mail.sysu.edu.cn, yayugao@hust.edu.cn, zhanw6@mail.sysu.edu.cn,
{jeremy.liupeng, guoziyang}@huawei.com

ICC 2022 - IEEE International Conference on Communications | 978-1-5386-8347-7/22/$31.00 ©2022 IEEE | DOI: 10.1109/ICC45855.2022.9838972

*Abstract*—**The deployment of 5G New Radio in unlicensed spectrum is a promising solution to alleviate the spectrum crunch for cellular networks. With the openness of unlicensed spectrum, 5G New Radio Unlicensed (NR-U) will coexist with the incumbent Wi-Fi networks. It is therefore important to study how to maintain harmonious coexistence with the Wi-Fi network. To address this issue, this paper considers two alternative throughput optimization strategies under the 3GPP fairness by adjusting the access parameter: one is to maximize the total throughput of coexisting scenario, and the other is to maximize the throughput of NR-U network. It is shown that the throughput gain of both optimization strategies are related to the initial backoff window size and the network size of Wi-Fi. Moreover, the first strategy can maximize the total throughput yet it may be unfair to the NR-U network while the second strategy can maximize NR-U throughput yet may be harmful to the total throughput. In practical scenario where the IEEE 802.11 EDCA protocol is adopted in Wi-Fi, the performance of NR-U cannot be guaranteed when optimizing the total throughput, and thus optimizing the throughput of NR-U is suggested for fair coexistence.**

## I. INTRODUCTION

With the long-standing problem of spectrum scarcity, the attention of the communication community has increasingly shifted to the unlicensed bands in recent years. Traditionally, it has been widely occupied by the increment Wi-Fi systems based on the IEEE 802.11 protocol, including 2.4GHz and 5GHz. Recently, 3GPP has taken its effect to extend 5G New Radio [1] to unlicensed spectrum. With the increasing demand for unlicensed bands, Federal Communications Commission (FCC) has opened up 6 GHz for unlicensed access. Meanwhile, both Wi-Fi based on IEEE 802.11ax and 5G New Radio Unlicensed (NR-U), are expected to be deployed at the newly developed 6GHz [2]. Therefore, it is a critical issue to ensure the harmonious coexistence of NR-U and Wi-Fi.

There are a few studies on the coexistence of NR-U and Wi-Fi focusing on detection threshold adjustment [3] and spatial multiplexing [4]. However, few work can be found on how to optimize the coexistence performance of NR-U and Wi-Fi from the medium access control (MAC) layer perspective. As the successor of Long Term Evolution Licensed Assisted Access (LTE-LAA), the MAC layer of NR-U is on the basis of LTE-LAA [5], following a Listen Before Talk (LBT) scheme similar to Wi-Fi. Differently, NR-U owns flexible numerologies and mini-slot scheduling, which enhances access efficiency of NR-U. However, due to adopting similar access scheme, the insights from the studies of the coexistence of LTE-LAA and Wi-Fi can still be used to orchestrate efficient coexistence of NR-U and Wi-Fi [6].

The problem of optimizing total throughput of LTE-LAA and Wi-Fi by adjusting the initial backoff window size has been studied in [7], [8]. To protect the increment Wi-Fi, 3GPP has defined a fairness constraint called 3GPP fairness, which requires that cellular network has less or equal impact on an existing Wi-Fi network compared with an additional Wi-Fi network in the same unlicensed channel [9]. Specifically, under 3GPP fairness, [8] investigated the joint adjustment of the initial backoff window size of Wi-Fi and LTE-LAA to maximize the total throughput. Unfortunately, in many cases, the incumbent Wi-Fi cannot adjust its access parameters, which makes the joint adjustment of the access parameters of both networks infeasible. In [7], the initial backoff window size of LTE-LAA was adjusted to maximize the total throughput of both networks with a constraint that the performance of an individual node in LTE-LAA and Wi-Fi coexistence scenario is not worse than that in Wi-Fi and Wi-Fi coexistence scenario. However, the implicit nature of the adopted model makes it hard to further characterize the optimal throughput performance.

In this paper, we aim to study optimal coexistence of NR-U and Wi-Fi under 3GPP fairness. To make a thorough analysis, we study two optimization objectives: one is altruistic, i.e., maximizing the overall network throughput; the other is self-interested, i.e., solely maximizing the throughput of NR-U networks. Since the incumbent Wi-Fi networks usually have fixed access parameters, we focus on adjusting the initial backoff window size of NR-U to achieve the two optimization objectives. The main contributions are summarized as follows:

---

The work of X. Sun was supported in part by the Key-Area Research and Development Program of Guangdong Province under Grant 2020B0101120003, and in part by the Huawei Development Fund under Grant YBN2020095065. The work of Y. Gao was supported by Natural Science Foundation of Hubei Province under Grant 2020CFB680 and Key Research and Development Project of Hubei Province under Grant 2020BAA02. The work of W. Zhan was supported by the Science, Technology and Innovation Commission of Shenzhen Municipality under Grant 2021A04.

- We derive the optimal access parameters (initial windows) of NR-U for both optimization objectives, which are aligned with simulation results.
- The analysis shows that the optimal setting and the optimization results of both strategies closely depend on the initial backoff window size and the network size of Wi-Fi. And setting the initial windows to the analytical optimum can boost throughput for both optimization objectives.
- To achieve the altruistic optimization objective, NR-U has to extremely degrade its performance, which is thus not recommended in practical implementation. Instead, both NR-U and Wi-Fi can achieve fairly good throughput in the case of self-interested optimization goal.

## II. SYSTEM MODEL AND PRELIMINARY ANALYSIS

As shown in Fig. 1, we consider a $n^{(NR)}$-node NR-U network coexisting with a $n^{(W)}$-node Wi-Fi network. Each node contends with others to access the channel for uplink transmissions. We focus on saturated scenario, where nodes in both networks always have packets to transmit. The LBT mechanism is adopt by NR-U network to keep a fair and friendly coexistence with Wi-Fi. By this way, each node will defer its transmission once the channel is sensed busy. NR-U and Wi-Fi nodes have identical sensing time, i.e., which is defined as the mini-slot time $\sigma = 9\mu s$ [10].

To access the channel, Wi-Fi network adopts IEEE 802.11 EDCA protocol, based on which Binary Exponential Backoff (BEB) scheme is performed. There are four access priority defined in IEEE 802.11 EDCA protocol, each of which has the different initial backoff window size $W^{(W)}$ (i.e., minimum contention window) and the cutoff phase $K^{(W)}$ (i.e., maximum backoff stage). For the access category AC_BK and AC_BE, only one packet can be transmitted once a node accesses the channel. For the other two access category AC_VI and AC_VO, it can transmit for a transmission opportunity (TXOP) duration. Here we use $\tau_T^{(W)}$ and $\tau_F^{(W)}$ (in unit of mini-slots) to denote the channel occupation time in successful transmission and in collision, respectively (referred to as $T_s$ and $T_c$ in [11], respectively).

For the NR-U network, on the other hand, each node makes transmissions following Type 1 channel access procedures defined by 3GPP [10], which is similar to the LBT scheme in Wi-Fi. Denote $W^{(NR)}$ the initial backoff window size and $K^{(NR)}$ the cutoff phase of NR-U network. Without loss of generality, we assume $K^{(W)} = K^{(NR)} = K$. For the PHY layer, NR-U has flexible numerologies and time slot scheduling, with which each NR-U transmission can only begin at the next slot boundary. Therefore, the channel occupation time of one access is determined by both a TXOP duration and the slot time. For simplicity, we assume that NR-U has the same channel occupation time in successful transmission and in collision as Wi-Fi, i.e., we have $\tau_T^{(NR)} = \tau_T^{(W)} = \tau_T$ and $\tau_F^{(NR)} = \tau_F^{(W)} = \tau_F$.

In this paper, to optimize the throughput performance of the coexisting scenario under the 3GPP fairness, an analytical model in [12] based classic collision model for heterogeneous Wi-Fi networks will be extended to the considered coexisting scenario. In the following, we will first summarize key analytical results.

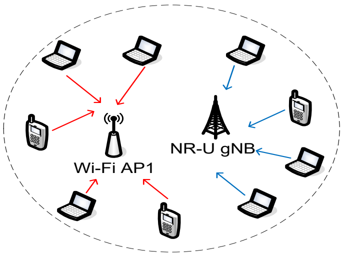

Fig. 1. Wi-Fi and NR-U coexistence scenario.

The probability of successful transmission given the channel is idle is denotes as $p$ (hereafter referred to as steady-state point). According to the equation (22) in [12], it can be characterized by the fixed-point equation

$$g(p) = \frac{n^{(W)}}{W^{(W)}} + \frac{n^{(NR)}}{W^{(NR)}}, \tag{1}$$

where $g(p)$ is given by

$$g(p) = -\frac{\ln p}{2}\left(\frac{p}{2p-1} + (1-\frac{p}{2p-1})(2-2p)^K\right). \tag{2}$$

And according to the equation (45) in [12], the throughput of Wi-Fi and NR-U, which is defined as the proportion of time occupied by successful packet transmissions, can be obtained as

$$\hat{\lambda}^{(g)}_{\text{W+NR}} = \frac{n^{(g)}}{W^{(g)}} \cdot f(p), \tag{3}$$

where $g \in \{W, NR\}$ and $f(p)$ is given by

$$\begin{aligned} f(p) =& \tau_T p / \Bigg\{ (\frac{p}{2p-1} + (1-\frac{p}{2p-1})(2-2p)^K) \times \\ & \frac{1}{2}(1+\tau_F - \tau_F p - (\tau_T - \tau_F) p \ln p) \Bigg\}, \end{aligned} \tag{4}$$

The total throughput of Wi-Fi and NR-U can be given as

$$\hat{\lambda}_{\text{W+NR}} = \sum_{g\in\{W,NR\}} \hat{\lambda}^{(g)}_{\text{W+NR}} = \frac{-\tau_T p \ln p}{1+\tau_F - \tau_F p - (\tau_T - \tau_F) p \ln p}. \tag{5}$$

Without any constraint, the maximum total throughput of NR-U and Wi-Fi coexisting network, can be obtained as [12]

$$\hat{\lambda}^{\max}_{\text{W+NR}} = \frac{-\mathbb{W}_0(-\frac{1}{e(1+1/\tau_F)})}{\tau_F/\tau_T - (1-\tau_F/\tau_T)\mathbb{W}_0(-\frac{1}{e(1+1/\tau_F)})} \tag{6}$$

which is achieved when the network operates at the optimal steady-state point

$$p^* = -(1+1/\tau_F)\mathbb{W}_0(-\frac{1}{e(1+1/\tau_F)}). \tag{7}$$

Note that $\mathbb{W}_0(\cdot)$ is a principal branch of the Lambert W function and $e$ is natural constant. (6) also equals the maximum throughput of a standalone Wi-Fi network.

## III. FAIRNESS-CONSTRAINED THROUGHPUT OPTIMIZATION

In this section, we will study how to optimize the throughput performance of the considered coexisting scenario under 3GPP fairness. 3GPP fairness requires that NR-U has less or

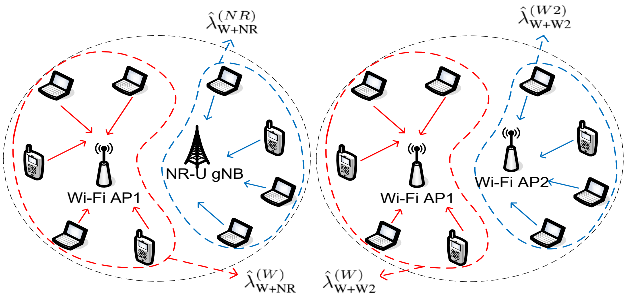

Fig. 2. 3GPP fairness: $\hat{\lambda}^{(W)}_{\text{W+NR}} \geq \hat{\lambda}^{(W)}_{\text{W+W2}}$.

equal impact on an existing Wi-Fi network compared with an addition Wi-Fi network in the same unlicensed channel. As illustrated in Fig. 2, 3GPP fairness is achieved when

$$\hat{\lambda}^{(W)}_{\text{W+NR}} \geq \hat{\lambda}^{(W)}_{\text{W+W2}}, \tag{8}$$

where $\hat{\lambda}^{(W)}_{\text{W+W2}}$ denotes the throughput of Wi-Fi 1 in a standalone Wi-Fi network. Here the network size of Wi-Fi 2 is denoted as $n^{(W2)}$. The throughput of Wi-Fi 2 is denoted as $\hat{\lambda}^{(W2)}_{\text{W+W2}}$.

NR-U network is developed to access the unlicensed bands occupied by the incumbent Wi-Fi networks. In order to establish harmonious coexistence with the Wi-Fi network, the access parameters of the NR-U nodes should be carefully tuned. According to (1-4), the throughput performance of both NR-U and Wi-Fi closely depends on the backoff window size of NR-U. Therefore, we focus on adjusting the initial backoff window size of NR-U to optimize the performance.

With 3GPP fairness, one optimization strategy is to maximize the total throughput of Wi-Fi and NR-U. 3GPP fairness can protect the performance of Wi-Fi network. However, without considering the performance of NR-U network, this strategy may make the NR-U network starved. Another optimization strategy is to maximize the throughput of NR-U network under 3GPP fairness. This strategy optimizes the performance of the NR-U network on the basis of 3GPP fairness. Intuitively, this strategy is more fair since it takes the performance of NR-U and Wi-Fi into account at the same time.

### *A. Optimization of Total Throughput*

To maximize the total throughput in Wi-Fi and NR-U under 3GPP fairness, the optimization problem can be formulated as

$$\begin{aligned} &\hat{\lambda}^{\max,\text{3GPP}}_{\text{W+NR}} = \max_{W^{(NR)}} \hat{\lambda}_{\text{W+NR}} \\ &s.t. \hat{\lambda}^{(W)}_{\text{W+NR}} \geq \hat{\lambda}^{(W)}_{\text{W+W2}}. \end{aligned} \tag{9}$$

The following theorem presents the maximum total throughput under 3GPP fairness and the corresponding optimal initial backoff window size of the NR-U network.

**Theorem 1.** *The maximum total throughput* $\hat{\lambda}^{\max,\mathit{3GPP}}_{W+NR}$ *of Wi-Fi and NR-U network under 3GPP fairness is given by (10), where* $p^* = -(1 + 1/\tau_F)\mathbb{W}_0(-\frac{1}{e(1+1/\tau_F)})$*. And* $p^{'}$ *and* $p^{''}$ *are the single root of* $g(p^{'}) = \frac{n^{(W)}+n^{(W2)}}{W^{(W)}}$ *and* $g(p^{''}) = \frac{n^{(W)}}{W^{(W)}}$*, respectively, where* $g(p) = -\frac{\ln p}{2}\left(\frac{p}{2p-1} + (1 - \frac{p}{2p-1})(2 - 2p)^K\right)$*.* $\hat{\lambda}^{\max,\mathit{3GPP}}_{W+NR}$ *is achieved when the initial backoff window size* $W^{(NR)}$ *of NR-U network is set to be*

$$W^{(NR),*} = \begin{cases} \infty & W^{(W)} \leq \frac{n^{(W)}}{g(p^*)} \\ \frac{n^{(NR)}}{g(p^*) - \frac{n^{(W)}}{W^{(W)}}} & \frac{n^{(W)}}{g(p^*)} < W^{(W)} \leq \frac{n^{(W)}+n^{(W2)}}{g(p^*)} \\ \frac{n^{(NR)}}{n^{(W2)}} W^{(W)} & W^{(W)} > \frac{n^{(W)}+n^{(W2)}}{g(p^*)}. \end{cases} \tag{11}$$

*Proof.* See Appendix A and B. ☐

Theorem 1 shows that the optimal total throughput under 3GPP fairness is divided into three cases, which is determined by the initial backoff window size $W^{(W)}$ of Wi-Fi. With a small $W^{(W)} \leq \frac{n^{(W)}}{g(p^*)}$, Wi-Fi itself suffers from severe competition, and the newly joined NR-U network will intensify the congestion. In this case, the total throughput is maximized when nodes in the NR-U network do not attempt to access the channel, i.e., the initial backoff window size of NR-U $W^{(NR)} \to \infty$. With a larger $W^{(W)}$, i.e., $\frac{n^{(W)}}{g(p^*)} < W^{(W)} \leq \frac{n^{(W)}+n^{(W2)}}{g(p^*)}$, the competition within Wi-Fi is alleviated. As a result, a carefully tuning of the initial backoff window size of NR-U $W^{(NR)}$ can make full use of the channel and the optimized total throughput equals that in (6), indicating that in this case, the maximum total throughput of NR-U and Wi-Fi coexisting network $\hat{\lambda}^{\max}_{\text{W+NR}}$ can be achieved. With a too large $W^{(W)} > \frac{n^{(W)}+n^{(W2)}}{g(p^*)}$, the channel is almost free and a small $W^{(NR)}$ can help NR-U achieve a higher throughput. Yet in this case, the tuning of $W^{(NR)}$ is constrained by the 3GPP fairness and thus the total throughput of NR-U and Wi-Fi can not achieve $\hat{\lambda}^{\max}_{\text{W+NR}}$ in (6) and is up to the throughput $\hat{\lambda}^{(W)}_{\text{W+W2}} + \hat{\lambda}^{(W2)}_{\text{W+W2}}$.

### *B. Optimization of NR-U Throughput*

In this subsection, we aim to maximize the throughput of NR-U network under 3GPP fairness in the coexistence of Wi-Fi and NR-U. The optimization problem can be formulated as

$$\begin{aligned} &\hat{\lambda}^{(NR),\max,\text{3GPP}}_{\text{W+NR}} = \max_{W^{(NR)}} \hat{\lambda}^{(NR)}_{\text{W+NR}} \\ &s.t. \quad \hat{\lambda}^{(W)}_{\text{W+NR}} \geq \hat{\lambda}^{(W)}_{\text{W+W2}}. \end{aligned} \tag{12}$$

According to (3) and Appendix A, the optimization problem (12) can be rewritten as

$$\begin{aligned} &\hat{\lambda}^{(NR),\max,\text{3GPP}}_{\text{W+NR}} = \max_{W^{(NR)}} \frac{n^{(NR)}}{W^{(NR)}} f(p) \\ &s.t. \quad W^{(NR)} \geq \frac{n^{(NR)}}{n^{(W2)}} W^{(W)}. \end{aligned} \tag{13}$$

Different from the total throughput in (5) that solely depends on $p$, it can be seen from (13) that the throughput of NR-U not only depends on $p$, but is also proportional to the number of nodes, and is inversely proportional to the initial backoff window size of NR-U network, which makes the optimization problem more complicated. While an explicit solution is unavailable, the optimal solution can be obtained numerically with a linear search of $W^{(NR)}$.

$$\hat{\lambda}_{\text{W+NR}}^{\text{max,3GPP}} = \begin{cases} \frac{-\tau_T p^{''} \ln p^{''}}{1+\tau_F-\tau_F p^{''}-(\tau_T-\tau_F)p^{''} \ln p^{''}} & W^{(W)} \le \frac{n^{(W)}}{g(p^*)} \\ \frac{-\mathbb{W}_0(-\frac{1}{e(1+1/\tau_F)})}{\tau_F/\tau_T-(1-\tau_F/\tau_T)\mathbb{W}_0(-\frac{1}{e(1+1/\tau_F)})} & \frac{n^{(W)}}{g(p^*)} < W^{(W)} \le \frac{n^{(W)}+n^{(W2)}}{g(p^*)} \\ \frac{-\tau_T p^{'} \ln p^{'}}{1+\tau_F-\tau_F p^{'}-(\tau_T-\tau_F)p^{'} \ln p^{'}} & W^{(W)} > \frac{n^{(W)}+n^{(W2)}}{g(p^*)}, \end{cases} \tag{10}$$

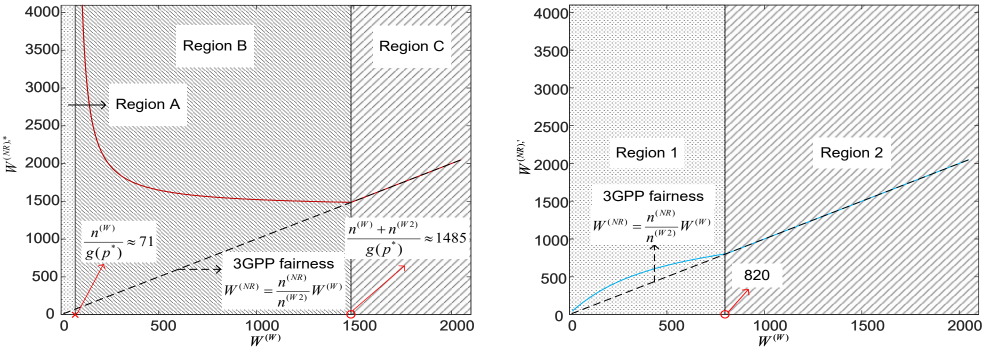

Fig. 3. Optimal setting of two optimization strategy versus the initial backoff window size of Wi-Fi network. $n^{(W)} = 5$, $n^{(NR)} = n^{(W2)} = 100$, $\tau_T = \tau_F = 121$, $K = 6$. (a) Optimizing the total throughput. (b) Optimizing the throughput of NR-U.

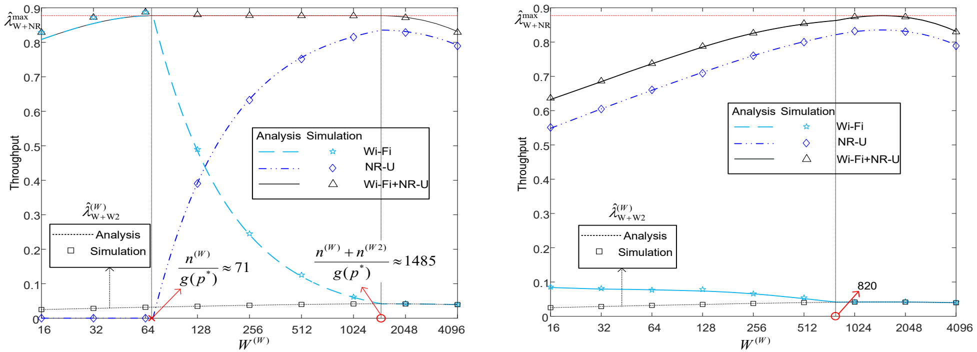

Fig. 4. The optimized throughput of two optimization strategies versus the initial backoff window size of Wi-Fi network. $n^{(W)} = 5$, $n^{(NR)} = n^{(W2)} = 100$, $\tau_T = \tau_F = 121$, $K = 6$. (a) Optimizing the total throughput. (b) Optimizing the throughput of NR-U.

To take a further look at how the optimal initial backoff window size of NR-U $W^{(NR)}$ vary with the initial backoff window size of Wi-Fi $W^{(W)}$, Fig. 3 presents the solution to both optimization problems (9) and (12). As shown in Fig. 3a, there are three regions, i.e., the Regions A, B and C for optimization of total throughput, which correspond to three cases in Theorem 1, respectively. They are divided by $W^{(W)} = \frac{n^{(W)}}{g(p^*)} \approx 71$ and $W^{(W)} = \frac{n^{(W)}+n^{(W2)}}{g(p^*)} \approx 1485$. Differently, there are only two regions, i.e., the Region 1 and Region 2, in Fig. 3b for throughput optimization of NR-U [1]. It can be seen from Fig. 3b that when $W^{(W)}$ falls in Region 1 i.e., $W^{(W)} \le 820$, the optimal backoff window size of NR-U $W^{(NR)} > \frac{n^{(NR)}}{n^{(W2)}} W^{(W)}$. In this case, the 3GPP fairness does not have any effect and it is equivalent to optimizing the throughput of NR-U without any constraint. Numerical results indicate that when $W^{(W)} \ge 820$, i.e., $W^{(W)}$ falls in Region 2, the optimal initial backoff window size of NR-U $W^{(NR)} = \frac{n^{(NR)}}{n^{(W2)}} W^{(W)}$. This case is the same as the case of the optimization of the total throughput in Region C. It implies that with a large initial backoff window size of Wi-Fi, optimizing the throughput of NR-U is equivalent to optimizing the total throughput due to the constraint of 3GPP fairness.

To implement the optimal configuration of both optimization strategies, it is necessary to have information of the network size and packet length of NR-U and Wi-Fi, the access parameters of Wi-Fi according to Theorem 1 and (13). In practical network, we could let NR-U gNB track the network size $n^{(NR)}$ of NR-U network and Wi-Fi AP track the network size $n^{(W)}$ and initial backoff window size $W^{(W)}$ of Wi-Fi. Besides, the packet length should also be captured to obtain the holding time in successful transmission $\tau_T$ and collision $\tau_F$. And then Wi-Fi AP broadcasts its captured information to NR-U gNB. Finally, NR-U gNB calculates the optimal setting and broadcasts it to each NR-U node.

## IV. SIMULATION RESULTS AND DISCUSSIONS

We have discussed the throughput optimization under 3GPP fairness based on two optimization strategies. In this section, we verify the analysis by simulations. The simulation setting is in accordance with the scenario presented in Section II.

Fig. 4 presents the throughput performance with optimal initial setting of two optimization strategies. It can be clearly seen from Fig. 4 that for both optimization strategies, the Wi-Fi throughput in the coexisting scenario is well protected and

---

[1] Note that through extensive experiments, we find that the Region 1 will vanish with a small $n^{(W2)}$. Therefore, we set $n^{(W2)} = 100$ to show all possible cases.

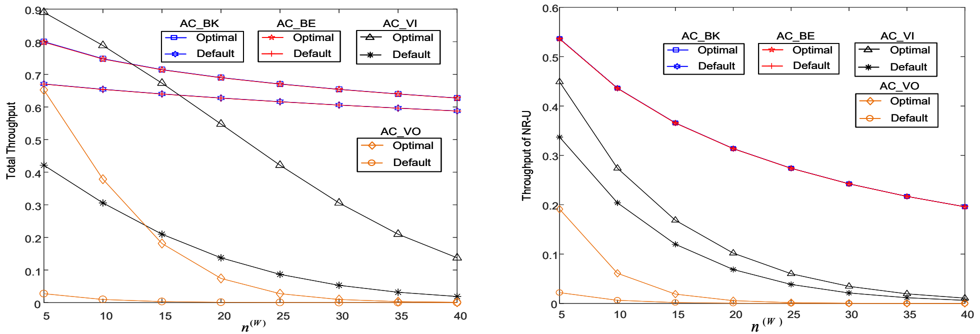

Fig. 5. Performance of two optimization strategies versus the Wi-Fi network size. $n^{(NR)} = n^{(W2)} = 20$, $W^{(NR)} = W^{(W)}$. (a) The optimization of the total throughput. (b) The optimization of NR-U network throughput.

TABLE I
SYSTEM PARAMETERS OF WI-FI NETWORK

| | |
|---|---|
| Packet payload | 4096*8 bits |
| MAC header | 288 bits |
| PHY header | 136 bits |
| ACK | 112 bits + PHY header |
| Channel Bit Rate | 54 Mbit/s |
| Slot Time | 9$\mu$s |
| SIFS | 16$\mu$s |

TABLE II
DEFAULT EDCA PARAMETERS FOR EACH AC

| AC | CWmin | CWmax | AIFSN | TXOPLimit |
|---|---|---|---|---|
| Background(AC_BK) | 16 | 1024 | 7 | 0 |
| Best Effort(AC_BE) | 16 | 1024 | 3 | 0 |
| Video(AC_VI) | 8 | 16 | 2 | 3.008ms |
| Voice(AC_VO) | 4 | 8 | 2 | 1.504ms |

higher than that in the standalone Wi-Fi network $\hat{\lambda}^{(W)}_{\text{W+W2}}$. It indicates that the 3GPP fairness is always achieved. Furthermore, when optimizing the total throughput of the NR-U and Wi-Fi coexisting network, the total throughput can approach the maximum total throughput of NR-U and Wi-Fi coexisting network $\hat{\lambda}^{\max}_{\text{W+NR}}$. However, when the initial backoff window size of Wi-Fi is lower than a certain threshold, the throughput of NR-U network is zero since NR-U nodes are not allowed to transmit. It implies that 3GPP fairness may be not enough to ensure harmonious coexistence due to lack of consideration of the performance of NR-U network. On the contrary, it can be seen from Fig. 4b that the NR-U network can always transmit. However, the total throughput when optimizing the throughput of NR-U is smaller than the maximum total throughput of NR-U and Wi-Fi coexisting network $\hat{\lambda}^{\max}_{\text{W+NR}}$. The gap is large especially with a small initial backoff window size of Wi-Fi.

To further examine the performance of both optimization strategies in practice, Fig. 5 presents the throughput performance when Wi-Fi adopts different access priorities of the IEEE 802.11 EDCA protocol. The simulation system parameters of Wi-Fi network are presented in Table I and the access parameters of four access priorities are summarized in Table II. The default initial backoff window size for NR-U is set to be $W^{(NR)} = W^{(W)}$ and other parameters settings are the same as those of Wi-Fi.

As shown in Fig. 5a, when optimizing the total throughput, the total throughput is greatly improved especially with a small number of Wi-Fi nodes. However, with the typical access parameters of four access priorities in IEEE 802.11 EDCA, the initial backoff window size $W^{(W)}$ always falls in Region A according to Theorem 1 and the NR-U network is not allowed to transmit. It implies that the performance of NR-U cannot be guaranteed with this optimization strategy in this scenario and thus it's not recommended in practical implementation.

By optimizing the throughput of NR-U, Fig. 5b illustrates that the throughput of the NR-U network with optimal setting is much higher than that with default setting when the network size of Wi-Fi is small with high-priority access category AC_VI and AC_VO. However, when AC_BK and AC_BE are adopted by the Wi-Fi network, the optimized throughput of NR-U has no improvement since $W^{(W)}$ falls in Region 2 and the optimal initial backoff window size of NR $W^{(NR)}$ is equal to $W^{(W)}$.

We can see from Fig. 5a and Fig. 5b that for both optimization strategies, the throughput gain decreases with the increment of the network size of Wi-Fi. In particular, when Wi-Fi adopts AC_VI and AC_VO, the total throughput of NR-U and Wi-Fi and the throughput of NR-U are close to zero with a large number of Wi-Fi nodes. It indicates that the optimization by solely adjusting the initial backoff window size of NR-U is not enough in the dense Wi-Fi coverage area due to extremely fierce competition among a large number of Wi-Fi nodes with a small initial backoff window size.

## V. CONCLUSIONS

In this paper, we have optimized the throughput of NR-U and Wi-Fi coexisting network under 3GPP fairness by tuning the initial backoff window size of NR-U nodes. We consider two optimization strategies: one is to maximize the total throughput, and the other is to maximize the throughput of NR-U. The analysis shows that the optimal setting and the optimization results of both strategies closely depends on the initial backoff window size and the network size of Wi-Fi. In practical scenario that Wi-Fi adopts IEEE 802.11 EDCA, both strategies can bring a certain performance gain especially when Wi-Fi with a small number of nodes adopts a high-priority access category. NR-U and Wi-Fi coexisting network with the first strategy achieves a higher total throughput than that with the second strategy. However, NR-U is starved when optimizing the total throughput. Therefore, we suggest optimizing the throughput of NR-U in practical scenario for fairness.

It should be noted that we assume that NR-U network has the same mean holding time in successful transmission and collision as Wi-Fi. In the further, the analysis can be extended to more practical assumptions including different mean holding

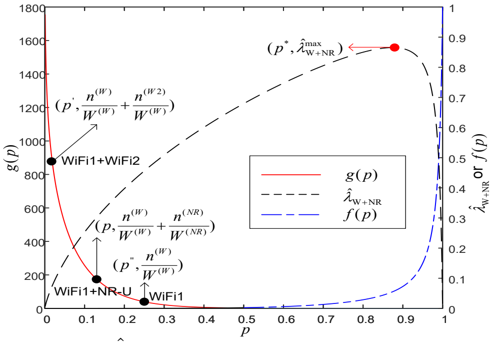

Fig. 6. Curve of $g(p)$, $\hat{\lambda}_{\text{W+NR}}$ and $f(p)$.

time in successful transmission and collision between Wi-Fi and NR-U.

## APPENDIX A
## DERIVATION OF SIMPLIFIED FORM OF 3GPP FAIRNESS

To derive the simplified form of 3GPP fairness in (8), we need to characterize the throughput of Wi-Fi 1 in the standalone Wi-Fi network. The standalone Wi-Fi network is a special case of Wi-Fi and NR-U coexistence scenario, where Wi-Fi 1 and Wi-Fi 2 has the same set of access parameters. Therefore, according to (1), the throughput of Wi-Fi 1 in the standalone Wi-Fi network can be written as

$$\hat{\lambda}^{(W)}_{\text{W+W2}} = \frac{n^{(W)}}{W^{(W)}} f(p^{'}), \tag{14}$$

where the steady-state operating point $p^{'}$ of the standalone Wi-Fi network is the single root of the following fixed equation

$$g(p^{'}) = \frac{n^{(W)} + n^{(W2)}}{W^{(W)}}. \tag{15}$$

Note that $n^{(W2)}$ denotes the number of nodes in Wi-Fi 2.

As illustrated in Fig. 6, $f(p)$ is monotonically increasing function of $p$. By substituting (3) and (14) into (8), the 3GPP fairness can be simplified as inequality $p \geq p^{'}$.

In fact, there is an implicit condition, i.e., $p < p^{''}$, where $p^{''}$ is the steady-state point of the standalone Wi-Fi 1 and can be obtained as the single root of the following fixed equation

$$g(p^{''}) = \frac{n^{(W)}}{W^{(W)}}. \tag{16}$$

The proof process is given below.

Fig. 6 shows the curve of $g(p)$, where three black points correspond to the standalone Wi-Fi with steady-state point $p^{'}$, the coexistence of Wi-Fi and NR-U with steady-state point $p$ and the standalone Wi-Fi 1 with steady-state point $p^{''}$, respectively. Note that the standalone Wi-Fi 1 is a special case of the coexistence of Wi-Fi and NR-U with the initial backoff window size of NR-U $W^{(NR)} \to \infty$, i.e., we can have $g(p^{''}) = \frac{n^{(W)}}{W^{(W)}}$. The values of $g(p)$ in these scenarios are obtained according to (1), (15) and (16), respectively. It is shown that $g(p)$ is a monotonically decreasing function of $p$. Due $\frac{n^{(W)}}{W^{(W)}} + \frac{n^{(NR)}}{W^{(NR)}} > \frac{n^{(W)}}{W^{(W)}}$, i.e., $g(p) > g(p^{''})$, we can have $p < p^{''}$.

Therefore, we can conclude that $p^{'} \leq p < p^{''}$. In fact, this constraint is equivalent to $W^{(NR)} \geq \frac{n^{(NR)}}{n^{(W2)}} W^{(W)}$ due to the monotonicity of $g(p)$.

## APPENDIX B
## PROOF OF THEOREM 1

Fig. 6 illustrates the curve of the sum throughput of the coexistence of Wi-Fi and NR-U $\hat{\lambda}_{\text{W+NR}}$, with a red point representing the optimal steady-state point $p^*$ to maximize the total throughput without any constraint.

In the following, we will present how to maximize the total throughput with 3GPP fairness.

According to Appendix A, the constraint can be simplified as $p^{'} \leq p < p^{''}$. By observing and comparing three black points on the curve of $g(p)$ and the red point on the curve of $\hat{\lambda}_{\text{W+NR}}$, we can easily obtain the following results:

*1)* If $p^* \geq p^{''}$, the total throughput of Wi-Fi and NR-U can be maximized when $p \to p^{''}$.

In this case, $g(p^*) \leq g(p^{''})$. According to (16), we can have $W^{(W)} < \frac{n^{(W)}}{g(p^*)}$.

*2)* If $p^{'} \leq p^* < p^{''}$, the total throughput of Wi-Fi and NR-U can be maximized when $p = p^*$.

In this case, $g(p^{'}) \geq g(p^*) > g(p^{''})$. According to (15) and (16), we can have $\frac{n^{(W)}}{g(p^*)} \leq W^{(W)} \leq \frac{n^{(W)}+n^{(W2)}}{g(p^*)}$.

*3)* If $p^{'} > p^*$, the total throughput of Wi-Fi and NR-U can be maximized when $p = p^{'}$.

In this case, $g(p^{'}) < g(p^*)$. According to (15), we can have $W^{(W)} > \frac{n^{(W)}+n^{(W2)}}{g(p^*)}$.

By substituting (1), (15) and (16) into above results, we can obtain the optimal initial backoff window size of NR-U $W^{(NR),*}$. And by combining (5) and the above results, we can obtain the maximum total throughput $\hat{\lambda}^{\max,\text{3GPP}}_{\text{W+NR}}$.

## REFERENCES

[1] 3rd Generation Partnership Project (3GPP), "Study on NR-based access to unlicensed spectrum," *3GPP TR 38.889 v16.0.0*, Dec. 2018.

[2] G. Naik and J.-M. J. Park, "Coexistence of Wi-Fi 6E and 5G NR-U: Can we do better in the 6 GHz bands?" *Proc. IEEE INFOCOM*, 2021.

[3] M. Hirzallah, "Protocols and algorithms for harmonious coexistence over unlicensed bands in next-generation wireless networks," Ph.D. dissertation, Univ. of Arizona, Tucson, Aug. 2020. [Online]. Available: https://repository.arizona.edu/handle/10150/645808

[4] Q. Chen, X. Xu and H. Jiang, "Spatial Multiplexing Based NR-U and WiFi Coexistence in Unlicensed Spectrum," in *IEEE 90th Veh. Technol. Conf. (VTC2019-Fall)*, pp. 1C5, 2019.

[5] 3GPP, "Technical Specification Group Radio Access Network; Study on Licensed-Assisted Access to Unlicensed Spectrum; (Release 13)", 3GPP TS 36.213, May. 2016.

[6] G. Naik, J.-M. Park, J. Ashdown, and W. Lehr, "Next generation Wi-Fi and 5G NR-U in the 6 GHz bands: Opportunities and challenges," *IEEE Access*, vol. 8, pp. 153027-153056, 2020.

[7] Y. Song, K. W. Sung and Y. Han, "Coexistence of Wi-Fi and Cellular With Listen-Before-Talk in Unlicensed Spectrum," *IEEE Commun. Lett.*, vol. 20, no. 1, pp. 161-164, 2016.

[8] X. Sun and L. Dai, "Towards fair and efficient spectrum sharing between LTE and WiFi in unlicensed bands: Fairness-constrained throughput maximization," *IEEE Trans. on Wireless Commun.*, vol. 19, no. 4, pp. 2713-2727, 2020.

[9] 3GPP, "NR-based Access to Unlicensed Spectrum," 3GPP RP-190706, 2019.

[10] 3GPP, "Physical Layer Procedures for Shared Spectrum Channel Access (Release 15)", 3GPP TS 37.213, Jul. 2018.

[11] G. Bianchi, "Performance analysis of the IEEE 802.11 distributed coordination function," *IEEE J. Selected Areas Comm.*, vol. 18, no. 3, pp. 535-547, 2000.

[12] Y. Gao, X. Sun, and L. Dai, "Throughput optimization of heterogeneous IEEE 802.11 DCF networks," *IEEE Trans. on Wireless Commun.*, vol. 12, no. 1, pp. 398-411, 2013.