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ORIGINAL RESEARCH

Spectrum sharing mechanisms in the unlicensed band: Performance limit and comparison

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Abstract
Deploying networks in unlicensed spectrum has been drawing significant attention, which serves to alleviate the increasing demands in licensed spectrum. However, the network coexistence in unlicensed channel may lead to throughput degradation and unfairness. An appropriate spectrum-sharing mechanism is therefore of great significance. In this paper, we study the performance limit of two representative mechanisms used in the coexistence with WiFi, including Duty Cycle (DC) and Listen-Before-Talk (LBT). In particular, both the throughputs of the coexisting network and WiFi under two mechanisms are derived as explicit expressions of system parameters, based on which the maximum total throughput of the coexisting network and WiFi is characterized under throughput fairness and 3GPP fairness, respectively. A systematic comparison between the optimal throughput performance of DC and LBT is conducted. It is found that if the coexisting network with LBT occupies the channel for a large period each time it successfully accesses the channel, then the maximum total throughput in LBT would be close to that in DC under both throughput fairness and 3GPP fairness. The optimal settings for DC and LBT mechanisms to achieve maximum total throughput are obtained, respectively, which sheds important light on the design of fair and efficient spectrum-sharing protocols.

1 | INTRODUCTION

The drastic growth of mobile data traffic makes it hard for licensed spectrum to satisfy the increasing demands. As a result, the proposal to enable networks to operate simultaneously in both licensed and unlicensed bands has attracted much attention [1]. The coexistence in unlicensed channel, nevertheless, faces the problems of performance degradation and unfairness due to the spectrum sharing. A proper mechanism is therefore of great significance to ensure an efficient and fair coexistence.

Currently, there are two main categories of spectrum-sharing regulations to guarantee a fair coexistence in unlicensed band, including Listen-Before-Talk (LBT) and Non-LBT. As a representative mechanism in the first category, Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) requires nodes to sense the channel before starting transmissions, which is defined in ETSI EN 300 328 standard [2] and EN 301 893 standard [3]. CSMA/CA is widely adopted in practical networks including WiFi [4, 5], New Radio-Unlicensed (NR-U) [6], MulteFire1.0, and LTE Licensed Assisted Access (LTE-LAA) [7]. Non-LBT, on the other hand, does not consider whether the channel is available for transmissions. One of the representative mechanisms is Duty Cycle (DC), with which the network schedules its transmissions according to an alternation of ON and OFF periods [8, 9]. As a mechanism without the requirement of sensing the channel before transmitting, DC mainly targets at certain markets like USA, Korean, and India, whereas LBT is an approach that complies with global regulation.

Since WiFi is the incumbent user of unlicensed band, there have been extensive studies on how to coexist with the WiFi network [10–18], which focused on the evaluation of throughput and fairness performance. Intuitively, DC mechanism might harm the performance of WiFi, since it is possible for the coexisting network to interrupt WiFi transmissions. In particular, it was found in [19–21] that when LTE adopts the DC mechanism, the coexistence is unfair to WiFi as it would experience performance degradation. As a result, LBT mechanism might be preferred to alleviate the unfairness and throughput degradation issues as it requires to regulate the access based on channel status. By mimicking WiFi distributed coordination function (DCF) protocol, LBT provides an effective way to minimize scheduling overhead instead of requiring centralized control. Various studies, nevertheless, have presented inconsistent conclusions in terms of the performance comparison between DC and LBT mechanisms. In particular, some studies claimed that when LTE and WiFi achieve proportional fair throughput allocation, the coexistence mechanism does not have an impact on the WiFi throughput while the LTE throughput varies with the mechanism adopted [22, 23]. Yet, it remains unclear the impact of coexistence mechanism on the throughput performance of both networks as a whole. Others pointed out that LBT outperforms DC since the WiFi network can achieve better throughput and latency performance[10, 24], but they did not verify whether such conclusion still holds when the network is optimized.

All of the aforementioned studies, nevertheless, evaluated network performance given system parameters. In this way, the comparison between DC and LBT mechanisms largely depends on the parameter configuration, and inconsistent observations might occur due to different settings. It is therefore necessary to make a more sound comparison based on performance limit, e.g., the maximum total throughput under the fairness constraint. In our previous work [25], an analytical model was proposed for the coexisting network and WiFi, where base stations (BSs) in the coexisting network adopt LBT mechanism, based on which the optimal total throughput with fairness constraints was further characterized. The optimal throughput performance under DC mechanism, nevertheless, still remains largely unknown. Such deficiency hinders a proper comparison between two mechanisms, and also impedes the realization of a fair and efficient coexistence.

In this work, we first characterize the throughputs of the coexisting network and WiFi when DC mechanism is adopted. In order to achieve a fair coexistence, the throughput fairness and 3GPP fairness are taken into account, respectively. Throughput fairness is defined as the throughput ratio of WiFi and coexisting network maintaining a certain value. On the other hand, with 3GPP fairness, the WiFi throughput in coexistence system is required to be no less than that in a stand-alone WiFi network. Under these fairness constraints, the maximum total throughput adopting DC mechanism is derived, respectively. Together with the results in [25], we thus draw a comparison between two coexistence mechanisms. It is found that if the coexisting network occupies the channel for a large

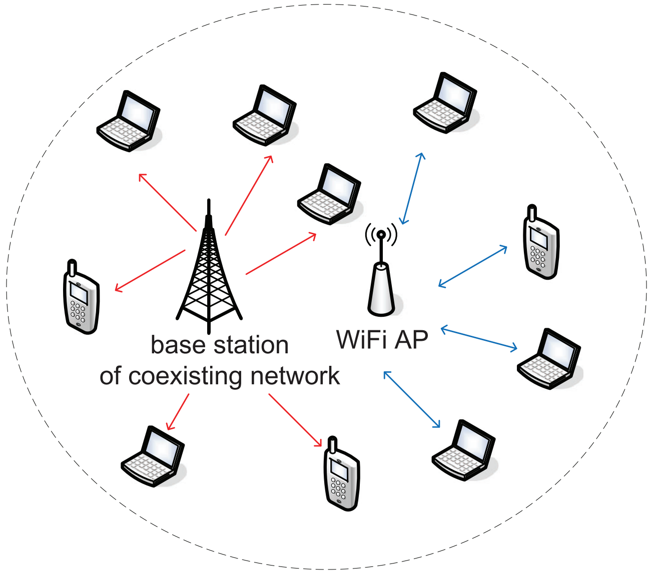

FIGURE 1 Scenario of the coexistence with a WiFi network.

period each time it successfully accesses the channel, the LBT mechanism could reach an optimal total throughput comparable to that with DC mechanism under both the throughput fairness and 3GPP fairness.

The contributions of this paper are summarized as:

- We characterize the maximum total throughputs of the coexisting and WiFi networks under throughput fairness and 3GPP fairness as explicit expressions, respectively, which can be achieved by jointly optimizing the system parameters of two networks.
- Based on the optimal throughput performance under fairness constraints, a comparison between DC and LBT mechanisms is conducted. It is shown that when LBT mechanism is adopted, a larger TXOP value, i.e., successful transmission time of the coexisting network, can effectively increase the maximum total throughput to a comparable level as that with DC mechanism. Such observation sheds important light on improving the coexistence performance in unlicensed band.

The rest of this paper is structured as follows: system model and preliminary analysis are presented in Section 2. The maximum total throughput of the coexisting network and WiFi network with throughput fairness constraint and that with 3GPP fairness constraint are characterized in Section 3. In Section 4, simulation results are given, and a comparison between DC and LBT mechanisms is drawn. Section 5 presents the conclusion.

2 | SYSTEM MODEL AND PRELIMINARY ANALYSIS

Consider the deployment scenario as Figure 1 shows, in which the coexisting network is composed of one cellular base station (BS) and $n^{(L)} - 1$ User Equipments (UEs). As what we did in previous work [25], here we consider that the coexisting network operates in the frequency division duplex (FDD) mode.

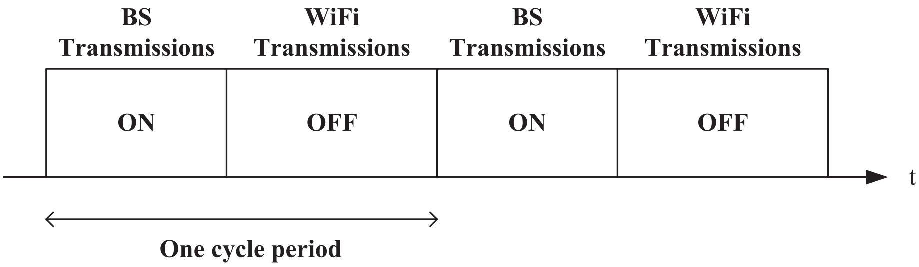

FIGURE 2 Graphic illustration of the channel with ON-OFF duty-cycling.

In particular, to cope with the shortage of licensed spectrum, the coexisting network allocates its downlink transmissions to a common unlicensed channel that the WiFi network uses, while its uplink transmissions are supported by licensed channel. Such allocation is introduced in 3GPP Release 13 [26], which has been widely used in previous studies [27–36]. For WiFi, on the other hand, both the downlink and uplink transmissions are considered, where one WiFi AP and $n^{(W)} - 1$ WiFi STAs make transmissions according to the IEEE 802.11 DCF protocol. Assume that each node (including WiFi AP and WiFi STAs) has identical backoff parameters. A noiseless channel is considered, and the classical collision model is adopted such that one packet transmission can only be successful when there are no simultaneous transmissions; otherwise, a collision would occur and none of the packets can be successfully decoded. In this paper, we use network throughput as the metric for efficiency, which is defined as the long-term time fraction of the channel that is used for successful packet transmissions.[1] In addition, suppose that all nodes can sense the ongoing transmission in unlicensed channel correctly based on the feedback from receiver. A saturated situation is assumed, i.e., each node always has packets to send.

In the following, protocol descriptions of the DC and LBT mechanisms will be presented in detail, respectively. The throughput performance of the coexisting network and WiFi under these two mechanisms will be characterized as well.

2.1 | Duty cycle mechanism

Let us first consider the DC mechanism. The duty-cycling approach alternates between ON and OFF periods, with which the BS is allowed to transmit only during the ON period, and the WiFi network, on the other hand, is left to transmit during the OFF period, as illustrated in Figure 2. In particular, during the ON period, BS would schedule its downlink transmissions to UEs, while each node in WiFi would transmit its packets independently following DCF protocol. Each WiFi node can only start transmission when it has sensed the channel available for a DCF Interframe Space (DIFS) time. The WiFi therefore would not transmit if it senses the BS is transmitting during this DIFS time. On the other hand, without such requirement of waiting for a certain period of time before transmission, BS can occupy the channel for the whole ON period, thus avoiding WiFi to access the channel [21, 33, 34]. As a result, no collision would occur during BS transmissions.[2]

The duty cycle fraction, which is defined as the ratio of ON period to one cycle period, is determined at the BS. Assume that the duty cycle fraction is β, i.e., a fraction β of time is assigned to the BS and a fraction $1-\beta$ of time is assigned to the WiFi in each cycle. Since the MAC layer of DC is centralized, no collisions would occur, and therefore the channel efficiency of BS is 1. As the BS always has packets to send, the throughput of the coexisting network in each cycle $\hat{\lambda}_{\text{out}}^{(BS),\,DC}$, which is defined as the fraction of time used for successful transmissions of the coexisting network in each cycle, is given by

$$\hat{\lambda}_{\text{out}}^{(BS),\,DC} = \beta. \tag{1}$$

For the WiFi network, on the other hand, when any node has a fresh Head-of-Line (HOL) packet to transmit, it would choose a value from $\{0, \dots, W^{(W)}\}$ at random, in which $W^{(W)}$ represents the initial backoff window size. This value diminishes by one at each idle time slot. When the counter counts down to zero and the channel is idle, the node would make a transmission request. Note that the transmission would fail if any other node in the coexisting or WiFi networks transmits concurrently. After the ith failure, the backoff window size of WiFi becomes $W_i^{(W)}$. Without loss of generality, it is assumed that

$$W_i^{(W)} = W^{(W)} \cdot \omega(i). \tag{2}$$

Normally, a cutoff phase is adopted in practice. Specifically, $\omega(i) = \omega(K^{(W)})$ if $i \geq K^{(W)}$, in which $K^{(W)}$ represents the cutoff phase of WiFi. With the widely adopted binary exponential backoff, we have $\omega(i) = \min\{2^i, 2^{K^{(W)}}\}, i = 0, 1, \dots$.

The throughput of WiFi in each cycle, $\hat{\lambda}_{\text{out}}^{(W),\,DC}$, is defined as the fraction of time that is used for successful transmissions of

[1] In classical collision model where concurrent transmissions would lead to collisions, transmission power of one node only affects its mean received signal-to-noise ratio (SNR), and would not influence transmission outcomes of other nodes. If the power control is adopted such that each node has an identical mean received SNR, then each node would have the same transmission rate. And network sum rate can then be simply obtained as the product of throughput and transmission rate, which is determined by the transmission power. In this case, the network throughput and sum rate performance can be optimized simultaneously, indicating that the optimization results in terms of network throughput in this paper can be applied if the goal is to maximize network sum rate.

[2] Note that at the end of a duty cycle where there is a transition from OFF to ON period, the transmission of WiFi nodes may be collided with BS's, known as the "edge effect". The edge effect is marginal and can be ignored when the time length of each duty cycle is sufficiently long.

WiFi in each cycle. It can be derived based on the unified analytical framework for IEEE 802.11 DCF network in our previous work [35, 36]. The main difference is that, in this circumstance WiFi can only transmit in a fraction $1-\beta$ of time, in which its transmissions would not be affected by the coexisting network. Because of this, $\hat{\lambda}_{\text{out}}^{(W),\,DC}$ should be multiplied by a factor of $1-\beta$, which is given by

$$\hat{\lambda}_{\text{out}}^{(W),\,DC}=\frac{-(1-\beta)\tau_T^{(W)}p_A\ln p_A}{1+\tau_F-\tau_F p_A-\left(\tau_T^{(W)}-\tau_F\right)p_A\ln p_A},\quad(3)$$

in which $\tau_T^{(W)}$ and τ_F represent the successful transmission time and the collision time of WiFi network. $\tau_T^{(W)}$ is determined by packet size, and the value of τ_F relies on the length of RTS frame when RTS/CTS scheme is adopted. p_A denotes the root of a fixed-point equation of the limiting probability p that HOL packets successfully transmit, which is derived as

$$p=\exp\left\{-\frac{2n^{(W)}}{1+W^{(W)}\left(\frac{p}{2p-1}-\left(\frac{p}{2p-1}-1\right)(2-2p)^{K^{(W)}}\right)}\right\}.\quad(4)$$

The total throughput of the coexisting network and WiFi when adopting DC mechanism, $\hat{\lambda}_{\text{out}}^{DC}$, is the sum of the throughputs of BS and WiFi network, which can be obtained as

$$\begin{aligned}\hat{\lambda}_{\text{out}}^{DC}&=\hat{\lambda}_{\text{out}}^{(BS),\,DC}+\hat{\lambda}_{\text{out}}^{(W),\,DC}\\&=\beta-\frac{(1-\beta)\tau_T^{(W)}p_A\ln p_A}{1+\tau_F-\tau_F p_A-\left(\tau_T^{(W)}-\tau_F\right)p_A\ln p_A},\end{aligned}\quad(5)$$

according to (1) and (3). It can be seen that the total throughput under DC mechanism is closely related to the duty cycle fraction β and the number of nodes $n^{(W)}$, the initial backoff window size $W^{(W)}$, and the cutoff phase $K^{(W)}$ of WiFi.

2.2 | LBT mechanism

With LBT mechanism, the coexisting network makes transmissions in a similar way to WiFi, i.e., the BS first sends a request when it has packet to transmit and then waits for feedback to see whether the channel is idle. As a result, the coexistence scenario can be regarded as a coexistence of two groups where the nodes in different groups may have different backoff and transmission parameters. In particular, $\tau_T^{(BS)}$ denotes the successful transmission time of coexisting network, which is determined by the value of TXOP, i.e., transmission opportunity, and τ_F represents the collision time of both the coexisting network and WiFi.

According to 3GPP's definition for LBT mechanism [26], a BS with a fresh HOL packet would choose a value from $\{0,\ldots,W^{(BS)}\}$ at random, in which $W^{(BS)}$ denotes the initial backoff window size of coexisting network. When the counter counts down to zero and the channel is idle, the BS would make a transmission request. After the ith failure, the backoff window size of coexisting network becomes $W_i^{(BS)}$. We assume that

$$W_i^{(BS)}=W^{(BS)}\cdot\zeta(i),\quad(6)$$

where $\zeta(i)=\zeta(K^{(BS)})$ if $i\geq K^{(BS)}$ and $K^{(BS)}$ is the cutoff phase of the coexisting network.

In our previous work [25], the throughput performance of the network coexistence under LBT mechanism has been characterized. The WiFi throughput includes the uplink throughput of all WiFi STAs and the downlink throughput of AP, which is obtained as [25]

$$\hat{\lambda}_{\text{out}}^{(W),\,LBT}=\frac{-\tau_T^{(W)}p^{(W)}\ln p^{(BS)}}{1+\tau_F+\left(\tau_T^{(BS)}-\tau_F\right)p^{(BS)}-\tau_T^{(BS)}p^{(W)}-\left(\tau_T^{(W)}-\tau_F\right)p^{(W)}\ln p^{(BS)}},\quad(7)$$

in which $p^{(BS)}$ and $p^{(W)}$ refer to the probabilities that HOL packets successfully transmit given that the channel is idle of coexisting network and WiFi, respectively. For the coexisting network, on the other hand, as we only consider the downlink transmissions of BS in the common unlicensed channel, its throughput equals the throughput of BS in the downlink, which is given by

$$\hat{\lambda}_{\text{out}}^{(BS),\,LBT}=\frac{\tau_T^{(BS)}\left(p^{(BS)}-p^{(W)}\right)}{1+\tau_F+\left(\tau_T^{(BS)}-\tau_F\right)p^{(BS)}-\tau_T^{(BS)}p^{(W)}-\left(\tau_T^{(W)}-\tau_F\right)p^{(W)}\ln p^{(BS)}}.\quad(8)$$

3 | FAIRNESS CONSTRAINED MAXIMUM THROUGHPUT

One of the most crucial issues of coexisting networks with WiFi in unlicensed spectrum is how to maintain harmonious coexistence. A common sense in the industry is that new user in unlicensed band should carefully select its access mechanism as well as access parameters to guarantee a certain fairness constraint with the WiFi network. Different notions of fairness have been considered for the network coexistence in unlicensed band. In this study, we consider two widely adopted concepts—throughput fairness and 3GPP fairness—as the indications of fair coexistence, respectively. In the following, we will optimize the total throughput of the coexisting network and WiFi under fairness constraints.

3.1 | Throughput fairness

Since two networks coexist in the unlicensed spectrum as two separate systems, the concept of "throughput fairness" is defined at the network level as the throughput ratio of WiFi and coexisting network maintaining a target value γ, i.e., $\frac{\hat{\lambda}_{\text{out}}^{(W)}}{\hat{\lambda}_{\text{out}}^{(BS)}} = \gamma$, where the value of γ can be selected according to the requirement in practical systems. Let $\hat{\lambda}_{\max}^{\gamma}$ denote the maximum total throughput under the throughput fairness constraint by optimally tuning the access parameters of coexistence system, which is given by

$$\hat{\lambda}_{\max}^{\gamma} = \max_{W^{(W)},\ \textit{network parameter}} \hat{\lambda}_{\text{out}} \tag{9}$$

$$s.t. \quad \frac{\hat{\lambda}_{\text{out}}^{(W)}}{\hat{\lambda}_{\text{out}}^{(BS)}} = \gamma. \tag{10}$$

The tuning parameter of WiFi is its initial backoff window size. On the other hand, the tuning parameter of the coexisting network is determined by the mechanism it chooses. In the following subsections, we will present solutions to the optimization problem in (9)-(10) for DC and LBT mechanisms, respectively.

3.1.1 | Duty cycle mechanism

With DC mechanism, the tuning parameter of the coexisting network is the duty cycle fraction β. The optimization problem in (9)-(10) can then be rewritten as

$$\hat{\lambda}_{\max}^{\gamma,\,DC} = \max_{W^{(W)},\ \beta} \hat{\lambda}_{\text{out}}^{DC} \tag{11}$$

$$s.t. \quad \frac{\hat{\lambda}_{\text{out}}^{(W),\,DC}}{\hat{\lambda}_{\text{out}}^{(BS),\,DC}} = \gamma. \tag{12}$$

The following theorem presents the solution to (11) and (12), in which the maximum total throughput of the coexistence system, the corresponding optimal duty cycle fraction and optimal initial backoff window size of WiFi are given.

Theorem 1. *With DC mechanism, the optimal total throughput of the coexisting network and WiFi under the throughput fairness can be written as*

$$\hat{\lambda}_{\max}^{\gamma,\,DC} = \frac{(1+\gamma)\tau_T^{(W)}}{(1+\gamma)\tau_T^{(W)} + \gamma\tau_F\left(-\frac{1}{\mathbb{W}_0\left(-\frac{1}{e(1+1/\tau_F)}\right)} - 1\right)}, \tag{13}$$

which is achieved when the duty cycle fraction is set to be

$$\beta^{\gamma,\,DC} = \frac{-\tau_T^{(W)}\mathbb{W}_0\left(-\frac{1}{e(1+1/\tau_F)}\right)}{\gamma\tau_F - \left((1+\gamma)\tau_T^{(W)} - \gamma\tau_F\right)\mathbb{W}_0\left(-\frac{1}{e(1+1/\tau_F)}\right)}, \tag{14}$$

and the initial backoff window size of each WiFi link is adjusted to be

$$W^{(W),\,DC} = \frac{2n^{(W)} + \ln p_A^*}{-\ln p_A^* \cdot \left(\frac{p_A^*}{2p_A^*-1} - \left(\frac{p_A^*}{2p_A^*-1} - 1\right)(2-2p_A^*)^{K^{(W)}}\right)}, \tag{15}$$

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

Proof. See Section A. □

It is shown in (13) that with throughput fairness constraint, the maximum total throughput in DC mechanism, $\hat{\lambda}_{\max}^{\gamma,\,DC}$, is solely determined by the target throughput ratio γ and the successful transmission time and collision time of the WiFi network, $\tau_T^{(W)}$ and τ_F.

3.1.2 | LBT mechanism

When it comes to LBT mechanism, the tuning parameter of coexisting network then becomes the initial backoff window size $W^{(BS)}$. Therefore, the optimization problem in (9)-(10) can be rewritten as

$$\hat{\lambda}_{\max}^{\gamma,LBT} = \max_{W^{(W)},\ W^{(BS)}} \hat{\lambda}_{\text{out}}^{LBT} \tag{16}$$

$$s.t. \quad \frac{\hat{\lambda}_{\text{out}}^{(W),\,LBT}}{\hat{\lambda}_{\text{out}}^{(BS),\,LBT}} = \gamma. \tag{17}$$

According to our previous study [25], the maximum total throughput is given by

$$\hat{\lambda}_{\max}^{\gamma,LBT} = \frac{1+\gamma}{\gamma} \cdot \frac{\tau_T^{(W)}}{\frac{1+\tau_F+(\tau_T^{(BS)}-\tau_F)p^{\gamma,(BS)}-\tau_T^{(BS)}p^{\gamma,(W)}}{-p^{\gamma,(W)}\ln p^{\gamma,(BS)}} + \tau_T^{(W)} - \tau_F}, \tag{18}$$

where $p^{\gamma,(BS)}$ is the single root of

$$-\gamma\tau_T^{(BS)}\tau_F p^{(BS)} + \gamma\tau_T^{(BS)}(1+\tau_F)(1+\ln p^{(BS)}) - \tau_T^{(W)} \cdot (1+\tau_F)(\ln p^{(BS)})^2 = 0, \tag{19}$$

and $p^{\gamma,(W)}$ is derived as

$$p^{\gamma,(W)} = \frac{\gamma\tau_T^{(BS)}p^{\gamma,(BS)}}{\gamma\tau_T^{(BS)} - \tau_T^{(W)}\ln p^{\gamma,(BS)}}. \tag{20}$$

$\hat{\lambda}_{\max}^{\gamma,LBT}$ can be reached when the initial backoff window size of BS is tuned to be

$$W^{\gamma,(BS)} = \frac{\frac{2\gamma\tau_T^{(BS)}}{-\tau_T^{(W)} \ln p^{\gamma,(BS)}} + 1}{\sum_{i=0}^{\infty} p^{\gamma,(BS)} \left(1 - p^{\gamma,(BS)}\right)^i \zeta(i)}, \tag{21}$$

and the initial backoff window size of each WiFi link is tuned to be

$$W^{\gamma,(W)} = \frac{\frac{2n^{(W)}}{-\ln p^{\gamma,(BS)}} - 1}{\sum_{i=0}^{\infty} p^{\gamma,(W)} \left(1 - p^{\gamma,(W)}\right)^i \omega(i)}. \tag{22}$$

3.2 | 3GPP fairness

To protect the throughput performance of WiFi when LTE shares a same unlicensed channel with it, 3GPP has proposed a definition for coexistence fairness in [26]. Particularly, here we adjust the concept to fit the scenario considered in this paper, and therefore 3GPP fairness means that the coexisting network should not influence WiFi throughput more than if it were a WiFi. As Figure 3 illustrates, we consider the scenario of a coexisting network and WiFi 1, and the scenario of a stand-alone WiFi network consisting of WiFi 1 and WiFi 2. To guarantee that the coexisting network would not harm the throughput performance of WiFi 1 more than WiFi 2, 3GPP fairness is defined as

$$\hat{\lambda}_{\text{out,BS+WiFi}}^{(W)} \geq \hat{\lambda}_{\text{out,WiFi+WiFi}}^{(W1)}. \tag{23}$$

To ensure that (23) can always hold, it is required that $\hat{\lambda}_{\text{out,BS+WiFi}}^{(W)} \geq \max \hat{\lambda}_{\text{out,WiFi+WiFi}}^{(W1)}$ should be reached, in which $\max \hat{\lambda}_{\text{out,WiFi+WiFi}}^{(W1)}$ is the optimal throughput of WiFi 1 in stand-alone WiFi network. Assume that WiFi 1 and WiFi 2 adopt the same parameter configuration, and they are able to sense the transmissions of each other. Then the throughput of each link in WiFi 1 is the same as that in WiFi 2. The total number of links in WiFi 1 is equivalent to $n^{(W)}$, and we denote the total number of links in WiFi 2 as n_2. We then have

$$\max \hat{\lambda}_{\text{out,WiFi+WiFi}}^{(W1)} = \frac{n^{(W)}}{n^{(W)} + n_2} \hat{\lambda}_{\text{max,WiFi+WiFi}}, \tag{24}$$

where $\hat{\lambda}_{\text{max,WiFi+WiFi}}$ is the maximum total throughput of the stand-alone WiFi network, which is given by

$$\hat{\lambda}_{\text{max,WiFi+WiFi}} = \max \left(\hat{\lambda}_{\text{out,WiFi+WiFi}}^{(W1)} + \hat{\lambda}_{\text{out,WiFi+WiFi}}^{(W2)} \right). \tag{25}$$

Denote the ratio between the number of links in WiFi 1 and that in WiFi 2 as η, i.e., $\eta = n^{(W)}/n_2$. The 3GPP fairness can then be guaranteed if

$$\hat{\lambda}_{\text{out,BS+WiFi}}^{(W)} \geq \max \hat{\lambda}_{\text{out,WiFi+WiFi}}^{(W1)} = \frac{\eta}{\eta + 1} \hat{\lambda}_{\text{max,WiFi+WiFi}}. \tag{26}$$

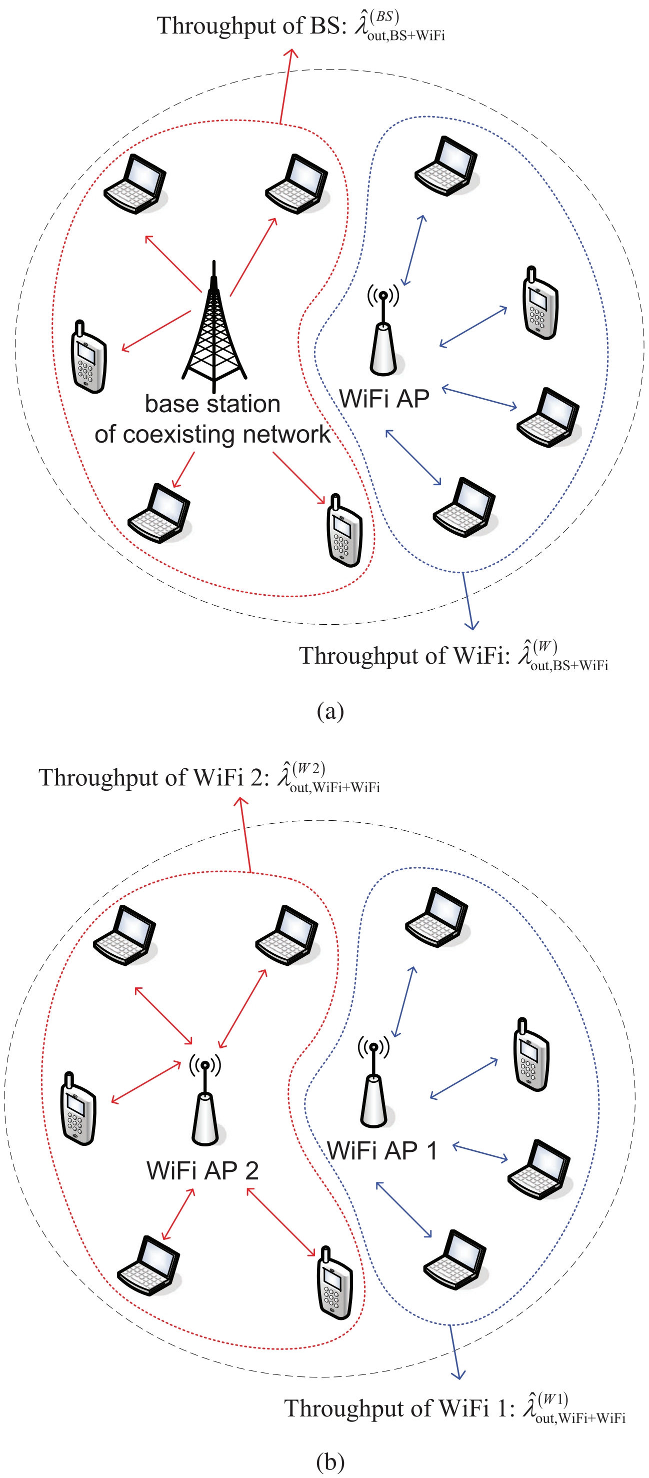

FIGURE 3 3GPP fairness illustration.

Let $\hat{\lambda}_{\max}^{3GPP}$ represent the maximum total throughput of the coexisting network and WiFi under the 3GPP fairness, and therefore the constrained optimization problem is written as

$$\hat{\lambda}_{\max}^{3GPP} = \max_{W^{(W)},\ network\ parameter} \hat{\lambda}_{\text{out}} \tag{27}$$

$$s.t. \quad \hat{\lambda}_{\text{out,BS+WiFi}}^{(W)} \geq \frac{\eta}{\eta+1} \hat{\lambda}_{\text{max,WiFi+WiFi}}. \tag{28}$$

In the following, we will give the solutions to the optimization problem in (27)-(28) under DC and LBT mechanisms, respectively.

3.2.1 | Duty cycle mechanism

Firstly, consider the stand-alone WiFi network, whose maximum throughput can be given by

$$\hat{\lambda}_{\text{max,WiFi+WiFi}} = \frac{-\tau_T^{(W)} \mathbb{W}_0\left(-\frac{1}{e(1+1/\tau_F)}\right)}{\tau_F - \left(\tau_T^{(W)} - \tau_F\right)\mathbb{W}_0\left(-\frac{1}{e(1+1/\tau_F)}\right)}. \tag{29}$$

With DC mechanism, the tuning parameter of the coexisting network is duty cycle fraction, β. Therefore, the constrained optimization problem in (27)-(28) can be rewritten as

$$\hat{\lambda}_{\max}^{3GPP,DC} = \max_{W^{(W)},\beta} \hat{\lambda}_{\text{out}}^{DC} \tag{30}$$

$$s.t. \quad \hat{\lambda}_{\text{out,BS+WiFi}}^{(W),DC} \geq \frac{\eta}{\eta+1} \hat{\lambda}_{\text{max,WiFi+WiFi}}. \tag{31}$$

The solution to problem in (30)-(31) is presented in the following theorem. Besides, the corresponding optimal duty cycle fraction and initial backoff window size of WiFi are also given as explicit expressions.

Theorem 2. *With DC mechanism, the maximum total throughput of the coexisting network and WiFi under 3GPP fairness is given by*

$$\hat{\lambda}_{\max}^{3GPP,DC} = -\frac{\gamma^{DC}+1}{\gamma^{DC}} \cdot \frac{\eta}{\eta+1} \cdot \frac{\tau_T^{(W)} \mathbb{W}_0\left(-\frac{1}{e(1+1/\tau_F)}\right)}{\tau_F - \left(\tau_T^{(W)} - \tau_F\right)\mathbb{W}_0\left(-\frac{1}{e(1+1/\tau_F)}\right)}, \tag{32}$$

where γ^{DC} is derived as

$$\gamma^{DC} = \frac{-\eta\tau_T^{(W)} \mathbb{W}_0\left(-\frac{1}{e(1+1/\tau_F)}\right)}{\tau_F - \left(\tau_T^{(W)} - \tau_F\right)\mathbb{W}_0\left(-\frac{1}{e(1+1/\tau_F)}\right)}. \tag{33}$$

$\hat{\lambda}_{\max}^{3GPP,DC}$ *is achieved when the duty cycle fraction is set to be*

$$\beta^{3GPP,DC} = \frac{-\tau_T^{(W)} \mathbb{W}_0\left(-\frac{1}{e(1+1/\tau_F)}\right)}{\gamma^{DC}\tau_F - \left((1+\gamma^{DC})\tau_T^{(W)} - \gamma^{DC}\tau_F\right)\mathbb{W}_0\left(-\frac{1}{e(1+1/\tau_F)}\right)}, \tag{34}$$

and the initial backoff window size of each WiFi link is tuned to be

$$W^{*,(W)} = -\frac{1}{\ln p_A^{*,3GPP}} \cdot \frac{2n^{(W)} + \ln p_A^{*,3GPP}}{\left(\frac{p_A^{*,3GPP}}{2p_A^{*,3GPP}-1} - \left(\frac{p_A^{*,3GPP}}{2p_A^{*,3GPP}-1} - 1\right)(2-2p_A^{*,3GPP})^{K^{(W)}}\right)}, \tag{35}$$

where $p_A^{*,3GPP} = -(1+1/\tau_F)\mathbb{W}_0(-\frac{1}{e(1+1/\tau_F)})$.

Proof. See Section B. □

3.2.2 | LBT mechanism

When adopting LBT mechanism, the tuning parameter of the coexisting network becomes its initial backoff window size. The optimization problem in (27)-(28) can then be rewritten as

$$\hat{\lambda}_{\max}^{3GPP,LBT} = \max_{W^{(W)},W^{(BS)}} \hat{\lambda}_{\text{out}}^{LBT} \tag{36}$$

$$s.t. \quad \hat{\lambda}_{\text{out,BS+WiFi}}^{(W),LBT} \geq \frac{\eta}{\eta+1} \hat{\lambda}_{\text{max,WiFi+WiFi}}. \tag{37}$$

According to our previous work [25], with LBT mechanism, the maximum total throughput of the coexisting network and WiFi under 3GPP fairness is obtained as

$$\hat{\lambda}_{\max}^{3GPP,LBT} = \begin{cases} \frac{1+\gamma^{LBT}}{\gamma^{LBT}} \cdot \frac{\eta}{1+\eta} \cdot \frac{\tau_T^{(W)}}{\tau_T^{(W)} + \tau_F\left(-\mathbb{W}_0^{-1}\left(-\frac{1}{e(1+1/\tau_F)}\right)-1\right)} & if\ \ \tau_T^{(BS)} \geq \bar{\tau}_T^{(BS)} \\ \frac{\tau_T^{(W)}}{\tau_T^{(W)} + \tau_F\left(-\mathbb{W}_0^{-1}\left(-\frac{1}{e(1+1/\tau_F)}\right)-1\right)} & otherwise, \end{cases} \tag{38}$$

where γ^{LBT} is the single root of

$$\frac{(1+\tau_F+(\tau_T^{(BS)}-\tau_F)p^{\gamma,(BS)})(\gamma\tau_T^{(BS)}-\tau_T^{(W)}\ln p^{\gamma,(BS)})}{-\gamma\tau_T^{(BS)}p^{\gamma,(BS)}\ln p^{\gamma,(BS)}} + \frac{\tau_T^{(BS)}}{\ln p^{\gamma,(BS)}} = \frac{1}{\eta}\left(\tau_T^{(W)} + \tau_F\right.$$

$$\times\left(-(\eta+1)\cdot\mathbb{W}_0^{-1}\left(-\frac{1}{e(1+1/\tau_F)}\right)-1\right)\Bigg), \tag{39}$$

and the threshold $\bar{\tau}_T^{(BS)}$ is the single root of

$$\frac{1+\tau_F+(\tau_T^{(BS)}-\tau_F)p^{\gamma=\eta,(BS)}-\tau_T^{(BS)}p^{\gamma=\eta,(W)}}{-p^{\gamma=\eta,(W)}\ln p^{\gamma=\eta,(BS)}} = \frac{1}{\eta}\left(\tau_T^{(W)}+\tau_F\left(-(\eta+1)\mathbb{W}_0^{-1}\left(-\frac{1}{e(1+1/\tau_F)}\right)-1\right)\right), \tag{40}$$

where $p^{\gamma=\eta,(BS)}$ and $p^{\gamma=\eta,(W)}$ are obtained by substituting $\gamma=\eta$ into (19) and (20), respectively. $\hat{\lambda}_{\max}^{3GPP,LBT}$ can be reached if the initial backoff window size of BS is tuned to be

$$W^{3GPP,(BS)} = \begin{cases} \dfrac{\frac{2\gamma^{LBT}\tau_T^{(BS)}}{-\tau_T^{(W)}\ln p^{\gamma=\gamma^{LBT},(BS)}}+1}{\sum_{i=0}^{\infty}p^{\gamma=\gamma^{LBT},(BS)}\left(1-p^{\gamma=\gamma^{LBT},(BS)}\right)^i\zeta(i)} & \text{if } \tau_T^{(BS)}\geq\bar{\tau}_T^{(BS)} \\ \infty & \text{otherwise,} \end{cases} \tag{41}$$

and the initial backoff window size of each WiFi link is tuned to be

$$W^{3GPP,(W)} = \begin{cases} \dfrac{\frac{2n^{(W)}}{-\ln p^{\gamma=\gamma^{LBT},(BS)}}-1}{\sum_{i=0}^{\infty}p^{\gamma=\gamma^{LBT},(W)}\left(1-p^{\gamma=\gamma^{LBT},(W)}\right)^i\omega(i)} & \text{if } \tau_T^{(BS)}\geq\bar{\tau}_T^{(BS)} \\ \dfrac{\frac{2n^{(W)}}{-\ln p^*}-1}{\sum_{i=0}^{\infty}p^*\left(1-p^*\right)^i\omega(i)} & \text{otherwise,} \end{cases} \tag{42}$$

where $p^{\gamma=\gamma^{LBT},(BS)}$ and $p^{\gamma=\gamma^{LBT},(W)}$ are obtained by substituting $\gamma=\gamma^{LBT}$ into (19) and (20), respectively, and p^* is given by

$$p^* = -(1+1/\tau_F)\mathbb{W}_0\left(-\frac{1}{e(1+1/\tau_F)}\right). \tag{43}$$

4 | SIMULATION RESULTS AND DISCUSSIONS

In previous section, the throughput performance of the coexistence system under DC and LBT mechanisms has been discussed respectively, based on which the maximum total throughputs under the fairness constraints in two mechanisms are further obtained. In the following, simulation results will be presented to validate the accuracy of preceding analysis.

Figure 4a illustrates the throughputs of the coexisting network and WiFi, $\lambda_{\text{out}}^{(BS)}$ and $\lambda_{\text{out}}^{(W)}$, in DC and LBT mechanisms, respectively. Case 1 and Case 2 of LBT have different backoff schemes as Case 1 adopts constant backoff window size while Case 2 adopts binary exponential backoff. When LBT mechanism is adopted, it is clearly shown in Figure 4a that as the initial backoff window size of WiFi $W^{(W)}$ increases, the WiFi throughput decreases while the BS throughput increases in both Case 1 and 2. It can also be observed that the WiFi throughput in Case 2 is always higher than that in Case 1. Note

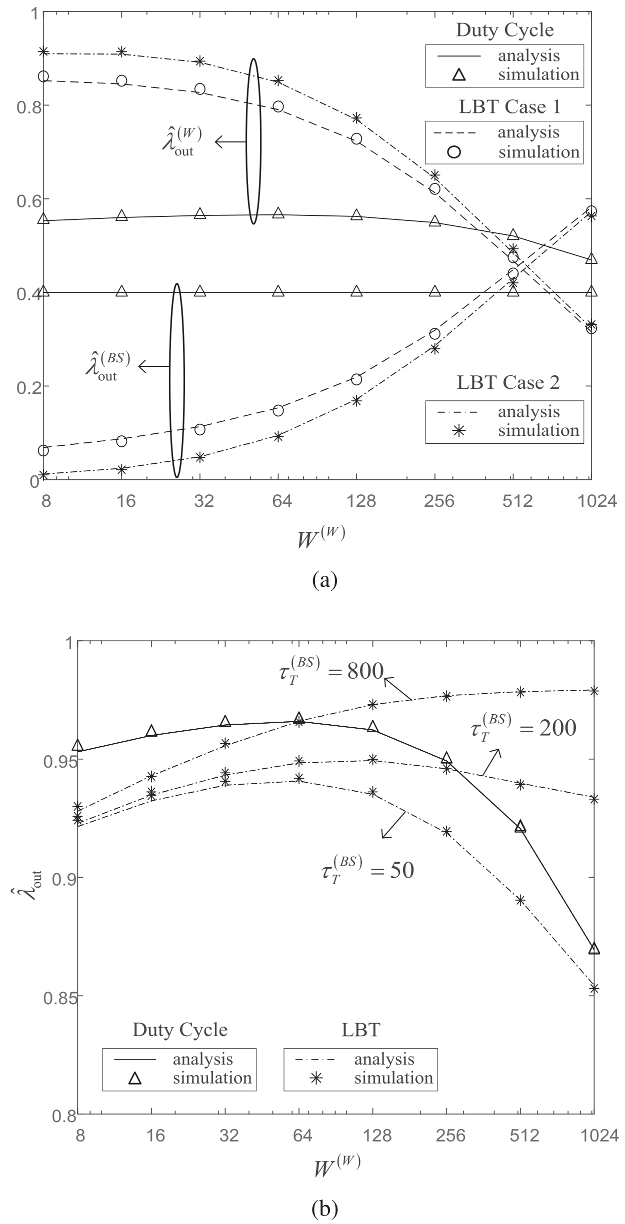

FIGURE 4 Throughput performance of coexistence system. (a) The throughputs of the coexisting network and WiFi, $\hat{\lambda}_{\text{out}}^{(BS)}$ and $\hat{\lambda}_{\text{out}}^{(W)}$, versus the initial backoff window size of WiFi network $W^{(W)}$. $\tau_T^{(BS)}=\tau_T^{(W)}=100$, $\tau_F=10$, and $n^{(W)}=20$. $W_i^{(W)}=W^{(W)}\cdot\omega(i)$, in which $\omega(i)=\min\{2^i, 2^{K^{(W)}}\}$ and $K^{(W)}=6$. For DC mechanism, $\beta=0.4$. For LBT mechanism, $W_i^{(BS)}=W^{(BS)}\cdot\zeta(i)$ where $W^{(BS)}=32$ and $\zeta(i)=1$ in Case 1; $W^{(BS)}=32$, $\zeta(i)=\min\{2^i,2^{K^{(BS)}}\}$ and $K^{(BS)}=6$ in Case 2. (b) The total throughput of the coexisting network and WiFi, $\hat{\lambda}_{\text{out}}$, versus $W^{(W)}$. $\tau_T^{(W)}=100$, $\tau_F=10$ and $n^{(W)}=20$. $W_i^{(W)}=W^{(W)}\cdot\omega(i)$ where $\omega(i)=\min\{2^i,2^{K^{(W)}}\}$ and $K^{(W)}=6$. For DC mechanism, $\beta=0.4$. For LBT mechanism, $W_i^{(BS)}=W^{(BS)}\cdot\zeta(i)$, in which $\zeta(i)=\min\{2^i,2^{K^{(BS)}}\}$ and $K^{(BS)}=6$.

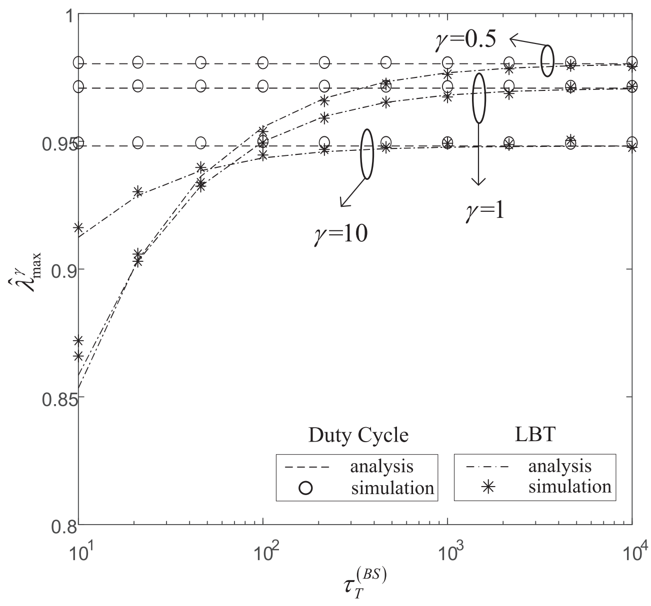

FIGURE 5 The maximum total throughput of the coexisting network and WiFi under the throughput fairness constraint, $\hat{\lambda}^{\gamma}_{\max}$, versus the successful transmission time of the coexisting network $\tau_T^{(BS)}$ (in unit of time slots). The throughput ratio constraint γ is set to be 0.5, 1, and 10, respectively. $\tau_T^{(W)} = 100$, $\tau_F = 10$ and $n^{(W)} = 20$. $W_i^{(W)} = W^{(W)} \cdot \omega(i)$, in which $\omega(i) = \min\{2^i, 2^{K^{(W)}}\}$ and $K^{(W)} = 6$. In LBT mechanism, $W_i^{(BS)} = W^{(BS)} \cdot \zeta(i)$ where $\zeta(i) = \min\{2^i, 2^{K^{(BS)}}\}$ and $K^{(BS)} = 6$.

that in Case 2, the backoff window of BS will be enlarged after collisions, which alleviates the contention from the coexisting network, thus leading to a better performance of WiFi and a worse performance of BS. Figure 4a also shows that with DC mechanism, the throughput of BS does not vary with the change of $W^{(W)}$. This is because at this time, the throughput of the coexisting network only depends on the duty cycle fraction, β, as (1) presents. Simulation results are in good agreement with the analysis.

Figure 4b presents the total throughput of the coexisting network and WiFi, $\hat{\lambda}_{\text{out}}$, in DC and LBT mechanisms, respectively. In particular, the successful transmission time of the coexisting network, $\tau_T^{(BS)}$, is tuned to have different values in order to illustrate the influence of $\tau_T^{(BS)}$ on coexistence system. As depicted in Figure 4b, when it comes to the coexistence scenario that is not optimized, both DC and LBT mechanisms have their own advantages, which relies on the selection of the initial backoff window size of WiFi $W^{(W)}$ and $\tau_T^{(BS)}$. With a small $W^{(W)}$, the total throughput in DC, $\hat{\lambda}^{DC}_{\text{out}}$, is larger than the total throughput in LBT, $\hat{\lambda}^{LBT}_{\text{out}}$. When $W^{(W)}$ is enlarged, however, $\hat{\lambda}^{LBT}_{\text{out}}$ gradually becomes larger than $\hat{\lambda}^{DC}_{\text{out}}$, and the crossing point is greatly affected by the value of $\tau_T^{(BS)}$. Therefore, by carefully tuning $W^{(W)}$ and $\tau_T^{(BS)}$, LBT mechanism can reach a better performance compared with DC mechanism.

Figure 5 illustrates the maximum total throughput of the coexisting network and WiFi under the throughput fairness constraint, $\hat{\lambda}^{\gamma}_{\max}$, where the target throughput ratio γ is set to be 0.5, 1, and 10, respectively. It is shown that as γ gets larger, the optimal total throughput in DC becomes smaller. Intuitively, with a larger γ, more time is allocated to WiFi transmissions, and thus more collisions might occur as there are multiple nodes in the WiFi network. As a result, the overall performance of the coexistence system would be impaired. We can also observe that the maximum total throughput in DC mechanism keeps the same without regard to successful transmission time of coexisting network $\tau_T^{(BS)}$, while the optimal total throughput increases as $\tau_T^{(BS)}$ increases in LBT mechanism. It is indicated in Figure 5 that the maximum total throughput in DC is larger than that in LBT, and the gap becomes smaller only when $\tau_T^{(BS)}$ gets larger.

In fact, we can prove that the maximum total throughputs with the throughput fairness constraint of DC and LBT tend to be the same when $\tau_T^{(BS)} \to \infty$. In particular, the maximum total throughput in LBT mechanism would be influenced by $\tau_T^{(BS)}$ according to (18). As $\tau_T^{(BS)} \to \infty$, the limit of the maximum total throughput in LBT is given by

$$\lim_{\tau_T^{(BS)} \to \infty} \hat{\lambda}^{\gamma,LBT}_{\max} = \frac{(1+\gamma)\tau_T^{(W)}}{(1+\gamma)\tau_T^{(W)} + \gamma\tau_F\left(\frac{1}{-\mathbb{W}_0\left(-\frac{1}{e(1+1/\tau_F)}\right)} - 1\right)}, \tag{44}$$

which is equal to the maximum total throughput in DC mechanism, as (13) shows. Therefore, under the throughput fairness, a higher optimal total throughput can be reached when DC mechanism is adopted, i.e.,

$$\hat{\lambda}^{\gamma,DC}_{\max} \geq \hat{\lambda}^{\gamma,LBT}_{\max}, \tag{45}$$

where the equivalence can be achieved if and only if $\tau_T^{(BS)} \to \infty$.

Figure 6 presents the maximum total throughput of the coexisting network and WiFi under the 3GPP fairness, $\hat{\lambda}^{3GPP}_{\max}$, where the ratio between the number of links in WiFi 1 and that in WiFi 2 η is set to be 0.5, 1, and 2, respectively. It is shown that the maximum total throughput in DC mechanism $\hat{\lambda}^{3GPP,DC}_{\max}$ becomes smaller as η gets larger. In fact, a larger η represents that WiFi 1 takes a larger proportion in the stand-alone WiFi network, and thus the WiFi throughput in coexistence system $\hat{\lambda}^{(W),DC}_{\text{out,BS+WiFi}}$ is required to be higher according to (23). As a result, the coexisting network faces fiercer competition, and therefore the throughput of BS $\hat{\lambda}^{(BS),DC}_{\text{out,BS+WiFi}}$ decreases. The deterioration of $\hat{\lambda}^{(BS),DC}_{\text{out,BS+WiFi}}$ outweighs the improvement of $\hat{\lambda}^{(W),DC}_{\text{out,BS+WiFi}}$, resulting in a decreasing trend of $\hat{\lambda}^{3GPP,DC}_{\max}$ as η increases.

Moreover, it is indicated in both Figure 6 and (38) that when the successful transmission time of coexisting network $\tau_T^{(BS)}$ is below the threshold $\bar{\tau}_T^{(BS)}$, the maximum total throughput in LBT $\hat{\lambda}^{3GPP,LBT}_{\max}$ does not vary with $\tau_T^{(BS)}$, which equals to the maximum total throughput of stand-alone WiFi network $\hat{\lambda}_{\max,\text{WiFi+WiFi}}$ according to (29). When $\tau_T^{(BS)} < \bar{\tau}_T^{(BS)}$, the optimal initial backoff window size of coexisting network

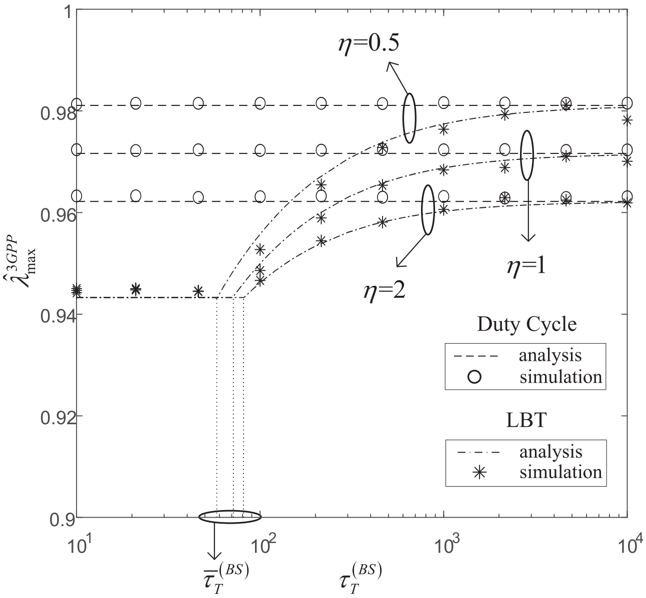

FIGURE 6 The maximum total throughput of the coexisting network and WiFi under the 3GPP fairness constraint, $\hat{\lambda}^{3GPP}_{\max}$, versus the successful transmission time of the coexisting network $\tau_T^{(BS)}$ (in unit of time slots). η is set to be 0.5, 1, and 2, respectively. $\tau_T^{(W)} = 100$, $\tau_F = 10$ and $n^{(W)} = 20$. $W_i^{(W)} = W^{(W)} \cdot \omega(i)$, in which $\omega(i) = \min\{2^i, 2^{K^{(W)}}\}$ and $K^{(W)} = 6$. In LBT mechanism, $W_i^{(BS)} = W^{(BS)} \cdot \zeta(i)$, where $\zeta(i) = \min\{2^i, 2^{K^{(BS)}}\}$ and $K^{(BS)} = 6$.

$W^{3GPP,(BS)}$ goes to infinity, and thus only WiFi links can access the channel. When $\tau_T^{(BS)} \geq \bar{\tau}_T^{(BS)}$, as Figure 6 illustrates, the maximum total throughput in LBT mechanism increases with the increment of $\tau_T^{(BS)}$. Similar to the observation under throughput fairness constraint, the maximum total throughput in DC is larger than that in LBT, and the gap becomes smaller only when $\tau_T^{(BS)}$ gets larger.

Likewise, it can be proved that the maximum total throughput under the 3GPP fairness in DC and that in LBT tend to be the same as $\tau_T^{(BS)} \to \infty$. In particular, when $\tau_T^{(BS)} \to \infty$, the maximum total throughput in LBT can be written as

$$\lim_{\tau_T^{(BS)} \to \infty} \hat{\lambda}^{3GPP,LBT}_{\max} = \frac{1 + \lim_{\tau_T^{(BS)} \to \infty} \gamma^{LBT}}{\lim_{\tau_T^{(BS)} \to \infty} \gamma^{LBT}} \cdot \frac{\eta}{1+\eta} \cdot \frac{\tau_T^{(W)}}{\tau_T^{(W)} + \tau_F \left(-\mathbb{W}_0^{-1}\left(-\frac{1}{e(1+1/\tau_F)} \right) - 1 \right)}, \tag{46}$$

where the limit of γ^{LBT} as $\tau_T^{(BS)} \to \infty$ is given by

$$\lim_{\tau_T^{(BS)} \to \infty} \gamma^{LBT} = \frac{-\eta \tau_T^{(W)} \mathbb{W}_0 \left(-\frac{1}{e(1+1/\tau_F)} \right)}{\tau_F - (\tau_T^{(W)} - \tau_F) \mathbb{W}_0 \left(-\frac{1}{e(1+1/\tau_F)} \right)}, \tag{47}$$

according to (39). By comparing (47) with (33), it can be found that $\lim_{\tau_T^{(BS)} \to \infty} \gamma^{LBT} = \gamma^{DC}$. Therefore, we have

$$\hat{\lambda}^{3GPP,DC}_{\max} \geq \hat{\lambda}^{3GPP,LBT}_{\max}, \tag{48}$$

according to (32) and (46), where the equivalence can be achieved if and only if $\tau_T^{(BS)} \to \infty$.

From previous discussions, we know that LBT could reach a comparable optimal throughput performance to that of DC when $\tau_T^{(BS)} \to \infty$. The reason lies in the MAC protocol of coexisting network, which refers to the difference between the centralized MAC with DC mechanism and the random access with LBT mechanism. With random access based protocol, WiFi network inevitably encounters collisions from the contention-based transmissions of the coexisting network, which thus leads to throughput degradation. With $\tau_T^{(BS)} \to \infty$ in LBT mechanism, the coexisting network occupies the channel for an infinite long period each time it successfully accesses the channel, which is asymptotically equivalent to the duty cycle case. This accounts for the observations that under both throughput fairness and 3GPP fairness constraints, the optimal total throughput in LBT would get close to that in DC as $\tau_T^{(BS)} \to \infty$. Therefore, in the regions and countries where LBT mechanism is mandatory and required, selecting a larger TXOP value can be an effective method to improve the optimal throughput performance of coexistence system.

5 | CONCLUSION

In this paper, we study the performance limit of DC and LBT mechanisms to achieve an efficient and fair coexistence in unlicensed channel. The maximum total throughputs under throughput fairness and 3GPP fairness with DC mechanism adopted are obtained as explicit expressions, respectively. By comparing the optimal throughput performance of DC and LBT mechanisms, it is indicated that TXOP value plays a pivotal role in the evaluation. In particular, with a large TXOP value, the gap between DC and LBT mechanisms in terms of maximum total throughput with fairness constraint becomes marginal. In other words, if the TXOP value is appropriately tuned, then LBT mechanism is capable of achieving a comparable performance limit to that with DC mechanism.

For the future work, it is meaningful to extend our proposed analytical framework to the case with capture model. The collision model considered in this work can be overly pessimistic in practice, since it rules out the possibility of concurrent transmissions. The capture model, on the other hand, allows multiple simultaneous transmissions to succeed as long as the received signal-to-interference-plus-noise ratio (SINR) exceeds a certain threshold. In such circumstance, transmission power plays a paramount role in network performance, since the transmission power of one node not only affects its transmission rate, but also influences the transmission outcomes of other nodes. In this case, network sum rate could be a more reasonable metric for efficiency, which is given as the product of network throughput and transmission rate. A fair and efficient coexistence can then be achieved by adjusting transmission power and other relevant system parameters.

AUTHOR CONTRIBUTIONS

Yingqi Lin: Conceptualization, formal analysis, methodology, software, validation, visualization, writing - original draft, writing - review and editing. Xinghua Sun: Conceptualization, methodology, project administration, software, supervision, writing - review and editing. Yayu Gao: Conceptualization, supervision, writing - review and editing. Wen Zhan: Conceptualization, supervision, writing - review and editing. Yitong Li: Supervision.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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APPENDIX A: PROOF OF THEOREM 1

Proof. By combining (1), (3), and (5), the optimization problem of (11)-(12) can be written as

$$\hat{\lambda}^{\gamma,DC}_{\max} = \max_{W^{(W)},\,\beta} \; (1+\gamma)\cdot\beta \tag{A1}$$

$$s.t. \quad \beta = \frac{1}{\gamma \cdot \frac{1+\tau_F-\tau_F p_A-(\tau_T^{(W)}-\tau_F)p_A \ln p_A}{-\tau_T^{(W)} p_A \ln p_A} + 1}. \tag{A2}$$

To maximize $\hat{\lambda}^{DC}_{\text{out}}$ is equivalent to maximize β. Let $f(p_A) = \frac{1+\tau_F-\tau_F p_A-(\tau_T^{(W)}-\tau_F)p_A \ln p_A}{-\tau_T^{(W)} p_A \ln p_A}$. For this problem, we make use of the first-order derivative, and derive the optimum by letting the derivative equal to 0. It can be easily shown that $\frac{df(p_A)}{dp_A} < 0$ if $p_A < p_A^*$, and $\frac{df(p_A)}{dp_A} > 0$ if $p_A > p_A^*$, where $p_A^* = -(1 + 1/\tau_F)\mathbb{W}_0(-\frac{1}{e(1+1/\tau_F)})$ is the single root of $\frac{df(p_A)}{dp_A} = 0$. Therefore, $f(p_A)$ is minimized when $p_A = p_A^*$, and the minimum value is given by

$$\min f(p_A) = \frac{\tau_F/\tau_T^{(W)} - \left(1-\tau_F/\tau_T^{(W)}\right)\mathbb{W}_0\left(-\frac{1}{e(1+1/\tau_F)}\right)}{-\mathbb{W}_0\left(-\frac{1}{e(1+1/\tau_F)}\right)}. \tag{A3}$$

(14) can then be obtained by combining (A3) and (A2). Substituting (14) into (A1) leads to (13). (15) can be derived by combining $p_A = p_A^*$ and (4). □

APPENDIX B: PROOF OF THEOREM 2

Proof. The proof of Theorem 2 builds upon Theorem 1. In particular, consider the coexistence scenario that one BS shares the unlicensed channel with WiFi network. Denote the ratio of WiFi throughput to BS throughput as γ, i.e.,

$$\gamma = \frac{\hat{\lambda}^{(W)}_{\text{out,BS+WiFi}}}{\hat{\lambda}^{(BS)}_{\text{out,BS+WiFi}}}. \tag{B1}$$

Then the optimization problem can be given by

$$\hat{\lambda}^{3GPP,DC}_{\max} = \max_{\gamma} \max_{W^{(W)},\beta} \hat{\lambda}^{DC}_{\text{out}} \tag{B2}$$

$$s.t. \quad \frac{\gamma}{\gamma+1}\hat{\lambda}^{DC}_{\text{out}} \geq \frac{\eta}{\eta+1}\hat{\lambda}_{\max,\text{WiFi+WiFi}}, \tag{B3}$$

where $\hat{\lambda}^{DC}_{\text{out}}$ denotes the total throughput of the coexisting network and WiFi, i.e., $\hat{\lambda}^{DC}_{\text{out}} = \hat{\lambda}^{(W)}_{\text{out,BS+WiFi}} + \hat{\lambda}^{(BS)}_{\text{out,BS+WiFi}}$. Note that in Theorem 1, given throughput ratio γ, the maximum total

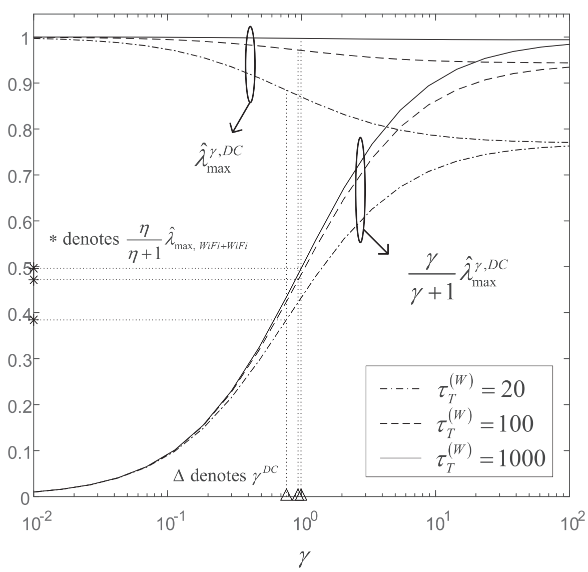

FIGURE B1 $\hat{\lambda}^{\gamma,DC}_{\max}$ and $\frac{\gamma}{\gamma+1}\hat{\lambda}^{\gamma,DC}_{\max}$ versus the throughput ratio γ. $\tau_F = 100$ and $\eta = 1$.

throughput is achieved by optimally tuning the duty cycle fraction β and the initial backoff window size of WiFi $\mathbb{W}^{(\mathbb{W})}$, i.e.,

$$\hat{\lambda}_{\max}^{\gamma,DC} = \max_{\mathbb{W}^{(\mathbb{W})},\beta} \hat{\lambda}_{\text{out}}^{DC}, \tag{B4}$$

and the optimal β and $\mathbb{W}^{(\mathbb{W})}$ are given in (14) and (15), respectively. Therefore we have

$$\hat{\lambda}_{\max}^{3GPP,DC} = \max_{\gamma} \hat{\lambda}_{\max}^{\gamma,DC} \tag{B5}$$

$$s.t. \quad \frac{\gamma}{\gamma+1}\hat{\lambda}_{\max}^{\gamma,DC} \geq \frac{\eta}{\eta+1}\hat{\lambda}_{\max,\text{WiFi+WiFi}}. \tag{B6}$$

It is found that both $\frac{\gamma}{\gamma+1}\hat{\lambda}_{\max}^{\gamma,DC}$ and $\hat{\lambda}_{\max}^{\gamma,DC}$ are monotonic functions in terms of γ. We then find out the optimum by using this property. In particular, as Figure B1 illustrates, $\frac{\gamma}{\gamma+1}\hat{\lambda}_{\max}^{\gamma,DC}$ is monotonically increasing with the increment of γ, so the constraint $\frac{\gamma}{\gamma+1}\hat{\lambda}_{\max}^{\gamma,DC} \geq \frac{\eta}{\eta+1}\hat{\lambda}_{\max,\text{WiFi+WiFi}}$ is equivalent to $\gamma \geq \gamma^{DC}$, in which γ^{DC} is the root of

$$\frac{\gamma}{\gamma+1}\hat{\lambda}_{\max}^{\gamma,DC} = \frac{\eta}{\eta+1}\hat{\lambda}_{\max,\text{WiFi+WiFi}}. \tag{B7}$$

Substituting (13) and (29) into (B7), and we can obtain (33).

It can be observed from Figure B1 that $\hat{\lambda}_{\max}^{\gamma,DC}$ is a monotonic decreasing function of γ. Since it is required that $\gamma \geq \gamma^{DC}$, the maximum total throughput under 3GPP fairness $\hat{\lambda}_{\max}^{3GPP,DC}$ can be achieved at $\gamma = \gamma^{DC}$, and $\hat{\lambda}_{\max}^{3GPP,DC}$ is written as

$$\hat{\lambda}_{\max}^{3GPP,DC} = \frac{\gamma^{DC}+1}{\gamma^{DC}} \cdot \frac{\eta}{\eta+1} \cdot \hat{\lambda}_{\max,\text{WiFi+WiFi}}. \tag{B8}$$

As a result, (32) can be obtained by substituting (29) and (33) into (B8). The optimal duty cycle fraction given in (34) is derived by combining (33) and (14). The corresponding initial backoff window size of WiFi given in (35) is the same as (15), since (15) does not vary with the throughput ratio γ. □