Novel Listen-Before-Talk Access Scheme with Adaptive Backoff Procedure for Uplink Centric Broadband Communication

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***Abstract*—To cater for the data-hungry Internet of Things (IoT) applications, Uplink Centric Broadband Communication (UCBC) has been identified as a new service class in the vision of 5.5G, where the unlicensed spectrum has been regarded as a promising solution to boost the uplink capacity. The New Radio Unlicensed (NR-U) network adopts Category-4 (Cat4) Listen Before Talk (LBT) access scheme to exploit the unlicensed spectrum and fairly coexist with the incumbent Wireless Fidelity (WiFi) network. However, the existing Cat4 LBT access scheme adopts single fixed energy detection (ED) threshold and Backoff speed, which cannot adapt to the sophisticated interference and achieve the expected uplink system throughput. To tackle this issue, in this paper, we develop a novel Cat4 LBT access scheme with adaptive Backoff procedure for UCBC, which includes instantaneous interference level quantification, instantaneous interference level sharing, and Backoff speed determination. The results have shown that our proposed adaptive Cat4 LBT scheme achieves over 70% uplink system throughput performance gain where cell throughput of NR-U network rises by over 100%, and cell throughput of WiFi network increases by 25%.**

***Index Terms*—Unlicensed spectrum, New Radio, UCBC, multiple ED thresholds, interference level, Backoff speed.**

I. Introduction

Data-hungry Internet of Things (IoT) applications have been widely deployed in our daily life, including high-definition (HD) video surveillance, and unmanned aerial vehicle (UAV) [1], [2], where the exponentially growing uplink traffic volume leads to a tremendously heavy burden on the existing downlink traffic-driven cellular network over scarce licensed spectrum. To provide high uplink throughput for the above IoT applications, Uplink Centric Broadband Communication (UCBC) has been identified as a new service class in the era of 5.5G [3], [4], which has identified the unlicensed spectrum as the promising solution to cope with the ever-increasing uplink traffic demand.

In particular, Long Term Evolution (LTE) based technologies including LTE licensed-assisted access (LTE-LAA) [5], [6] and enhanced LAA (eLAA) [7] have been standardized by Third Generation Partnership Project (3GPP) to exploit the unlicensed spectrum since Release 13. Recently, New Radio Unlicensed (NR-U) network has been further standardized to extend the applicability of New Radio (NR) to unlicensed spectrum in Release 16, which determines to support standalone operation mode over unlicensed spectrum [8]–[10].

As the unlicensed spectrum is accessible to any networks, no exclusive rights are granted to any networks over the unlicensed spectrum, which means the NR-U network needs to coexist with the incumbent Wireless Fidelity (WiFi) network [11]. To fairly and harmoniously coexist with the WiFi network, the NR-U network adopts the contention-based access scheme, called category-4 (Cat4) Listen Before Talk (LBT), to access the unlicensed spectrum, where the LBT scheme incorporates the Backoff procedure similar to the Carrier-sense multiple access with collision avoidance (CSMA/CA) scheme in WiFi network. The Backoff procedure aims to mitigate the collision among devices due to the lack of coordination function, where each device randomizes the transmission time via generating random number N. During the Backoff procedure, each device performs Clear Channel Assessment (CCA) to sense the ongoing transmissions over the unlicensed spectrum, where the sensed energy is compared with the single fixed Energy Detection (ED) threshold to determine whether the channel is idle or busy. When the channel is identified as idle, the random number N is decreased with fixed Backoff speed (i.e., $N = N - 1$). In other words, each device can only transmit when the random number N counts down to zero.

However, the single fixed ED threshold and Backoff speed setting cannot adapt to the fast-changing interference environment, and leads to uplink throughput degradation under the coexistence of NR-U and WiFi networks. Specifically, single fixed ED threshold may cause collisions due to hidden node (HN) problem, and low channel utilization due to exposed node (EN) problem [12]. Moreover, the existing NR-U network lacks reliable report mechanism for User Equipments (UEs) to share the experienced interference to the gNode (gNB), which further deteriorates the HN and EN issues. Furthermore, although the Backoff procedure mitigates the collision probability, the fixed Backoff speed prevents the device to access the channel efficiently when the interference decreases to low level, which leads to unnecessary overheads.

With the goal of improving the throughput over the unlicensed spectrum, the majority of efforts in previous works have been devoted to optimizing the access control parameters based on machine learning [13]–[18]. In [13], each device can decide to transmit or remain silent in every slot via Deep Reinforcement Learning (DRL) and Federated Learning (FL), where the NR-U network and HN problem are ignored for simplicity. In [14], the authors have proposed to utilize the DRL to optimize the airtime fraction for LTE-LAA without

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modelling and simulating the detailed LBT procedures. In [15], a duty-cycle free spectrum sharing framework has been designed, where the DRL algorithm is utilized to maximize the throughput via optimizing the LTE transmission time. In [16], the transmission time of frame-based LBT has been optimized via RL, where each device independently chooses the access technologies, including LTE, LTE-LAA, and WiFi. In [17], RL is combined with FL to optimize the contention window size of WiFi network for minimizing the collision probability. In [18], the authors have proposed to adjust the contention window size with a minimum delay, where the neural network is utilized to predict the number of Negative Acknowledges (NACKs). However, the above works simplified the access procedures with impractical assumption, which hinders its application in the practical scenario. More importantly, the generalization capability of these learning-based algorithms have never been verified, which may fail to guarantee the performance in dynamic practical scenario.

Recent works have focused on proposing new access schemes to improve the throughput. In [19], the short-term Channel Quality Indicator (CQI) has been identified as the potential tool to detect the presence of HN problem in multiple LTE-LAA scenario, which is expected to have an oscillating behavior. In [20], pilot and data transmission have been utilized to detect the HN problem in LTE-LAA, where the devices are required to periodically send control packets. In [21], a paired LBT solution has been proposed to improve the throughput while avoiding the HN problem in unlicensed millimeter-wave (mmWave) bands. In [22], the authors have proposed to adaptively change the ED threshold of LTE-LAA, where the ED threshold is decreased one by one when the transmission fails. However, the above solutions mainly optimized the conventional downlink system throughput, which failed to investigate the feasibility of satisfying the uplink high throughput requirements of UCBC services over the unlicensed spectrum. Furthermore, the existing works merely evaluated system throughput to indicate the network-centric performance, and ignored the user-centric Quality of Experience (QoE), which is more intuitive to reveal individual user experience in the UCBC [23].

In this article, we address the following fundamental questions: 1) how to optimize the uplink system throughput over unlicensed spectrum under the coexistence of heterogeneous networks; 2) how to guarantee the performance of WiFi network while improving the NR-U uplink throughput; and 3) how to evaluate the effectiveness of the proposed algorithm in improving the user-centric QoE performance. To do so, we develop a novel Cat4 LBT access scheme with adaptive Backoff procedure to dynamically optimize the uplink system throughput under the coexistence of NR-U and WiFi networks. Our contributions can be summarized as follows:

- We develop a novel Cat4 LBT access scheme to optimize the uplink system throughput by adaptively determining the Backoff speed under the coexistence of heterogeneous NR-U and WiFi networks. Under this framework, the uplink transmission procedure over the unlicensed spectrum is simulated by taking into account the traffic characteristic of the UCBC services, the process of LBT and CSMA/CA access schemes, the uplink transmission scheduling in NR-U network, and the collision among devices.
- We first propose an instantaneous interference level quantification mechanism, where multiple ED thresholds are applied to quantify the interference level both at gNB and UEs. We then design a periodical measurement report mechanism for UEs to share the quantified interference level with the associated gNB over the licensed spectrum. The gNB will then jointly consider its own interference level, and interference levels from associated UEs to determine the Backoff speed. It is noted that we introduce the user-centric QoE performance metric, user perceived throughput (UPT), to evaluate the file transmission throughput improvement.
- Finally, our proposed Cat4 LBT access scheme is evaluated to optimize the uplink system throughput in heterogeneous NR-U and WiFi networks. The results have shown that our proposed adaptive Cat4 LBT scheme achieves up to 70% performance gain, where the cell throughput of NR-U network increases by over 100%, and the cell throughput of WiFi network increases by 25%.

The remainder of this paper is organized as follows. Section II provides the system model. Section III presents the problem formulation and challenges analysis. Section IV elaborates our proposed novel Cat4 LBT with adaptive Backoff procedure for solving the problem. Section V illustrates the numerical results. Finally, Section VI concludes the paper.

II. System Model

As shown in Fig. 1, we consider the indoor scenario uplink transmission [24], where NR-U and WiFi networks deploy three small cells in a one-floor building, respectively. The set of WiFi stations (STAs) and NR-U UEs are denoted by $\mathcal{S}$ and $\mathcal{U}$, respectively. The set of access points (APs) and gNBs are denoted by $\mathcal{P}$ and $\mathcal{G}$, respectively. We assume that STAs and UEs are uniformly distributed in the scenario, where each STA or UE is connected to the closest AP or gNB. It is noted that the NR-U and WiFi networks share a single 20-MHz unlicensed channel for transmission.

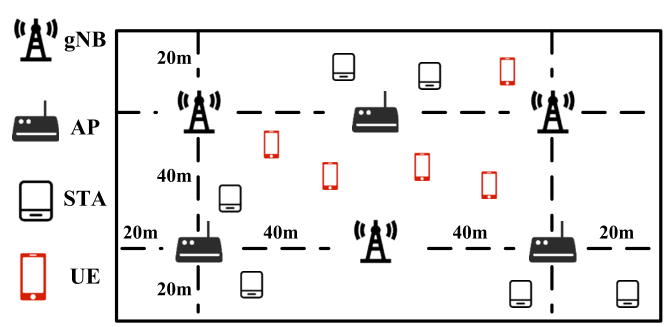


Fig. 1. Uplink transmission of NR-U and WiFi indoor coexistence scenario.

A. Network and Traffic Model

We consider a flat Rayleigh small-scale fading channel, where the channel power gains $\beta(x, y)$ between two generic locations $x, y \in \mathbb{R}^3$ is assumed to be exponentially distributed random variables with unit mean. All the channel gains are independent of each other, independent of the spatial locations, and identically distributed (i.i.d.).

The indoor mixed office path-loss model is adopted as [25]

$$\zeta_{\mathrm{L}}(x,y) = 32.4 + 17.3\log_{10}(d_{3\mathrm{D}}) + 20\log_{10}(f_{\mathrm{c}}), \quad (1)$$

$$\zeta_{\mathrm{N}}(x,y) = 32.4 + 31.9\log_{10}(d_{3\mathrm{D}}) + 20\log_{10}(f_{\mathrm{c}}), \quad (2)$$

where $\zeta_{\mathrm{L}}(x,y)$ and $\zeta_{\mathrm{N}}(x,y)$ represent the pathloss under line-of-sight (LoS) and non line-of-sight (NLoS), respectively, f_{c} is the carrier frequency, and $d_{3\mathrm{D}}$ is the distance between two locations x and y. The indoor mixed office LOS probability P_{LOS} is given as

$$P_{\mathrm{LoS}} = \begin{cases} 1 & , d_{2\mathrm{D}}<1.2\mathrm{m} \\ \exp(\frac{d_{2\mathrm{D}}-1.2}{4.7}) & , 1.2\mathrm{m} \le d_{2\mathrm{D}} \le 6.5\mathrm{m} \\ \exp(\frac{d_{2\mathrm{D}}-6.5}{32.6}) & , d_{2\mathrm{D}}>6.5\mathrm{m} \end{cases} \quad (3)$$

where $d_{2\mathrm{D}}$ is the projection of $d_{3\mathrm{D}}$ on the horizontal plane. Accordingly, NLoS probability P_{NLoS} is

$$P_{\mathrm{NLoS}} = 1 - P_{\mathrm{LoS}}. \quad (4)$$

Therefore, the mean channel power gains is derived as

$$h = (10^{-\zeta_{\mathrm{L}}/10}P_{\mathrm{LoS}} + 10^{-\zeta_{\mathrm{N}}/10}P_{\mathrm{NLoS}})\beta, \quad (5)$$

where the spatial indices (x, y) are dropped for the brevity of exposition.

We consider the FTP-3 traffic model for each STA and UE with fixed size $\mathrm{S}_{\mathrm{file}}$, where packets arrive according to a Poisson process with arrival rate λ [23], [26]. The packets of each device line in a queue to be transmitted, and are determined by the newly arrived and undelivered packets. First Come First Serve (FCFS) scheduling scheme is applied by placing the newly arrived packets at the end of the queue. Without loss of generality, we assume each packet has a time constraint $\mathrm{T}_{\mathrm{con}}$, where the packet is dropped if it is not successfully transmitted within this time constraint $\mathrm{T}_{\mathrm{con}}$.

B. Access Schemes over Unlicensed Spectrum

Both NR-U and WiFi networks are required to access the unlicensed spectrum via contention-based access schemes due to the lack of exclusive right, where NR-U and WiFi networks adopt Cat4 LBT and CSMA/CA access schemes over the unlicensed spectrum, respectively.

1) Carrier-Sense Multiple Access with Collision Avoidance Access Scheme: As shown in Fig. 2, the CSMA/CA scheme integrates the Backoff mechanism to randomize the transmission start time of STAs, which mitigates the collision due to the lack of coordination function. When the new packet arrives, the STA is required to perform CCA to check whether the channel is idle. If the channel has been idle over a distributed coordination function inter-frame space (DIFS) interval, the STA transmits the packet immediately. Otherwise, the STA defers its transmission until the channel becomes idle. Then if the channel is detected to be idle over a DIFS interval, the STA will initiate the Backoff procedure to further defer its transmission over a random time interval. Once the Backoff procedure completes, the STA sends its data within the transmission opportunity (TXOP). Upon receiving the packet correctly, the AP waits for a Short inter-frame space (SIFS) interval, and transmits an ACK back to the STA to confirm the correct reception.

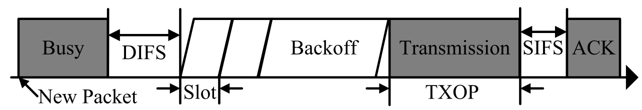


Fig. 2. Carrier-sense multiple access with collision avoidance procedure.

2) Listen-Before-Talk Access Scheme: To fairly share the unlicensed spectrum with WiFi network, 3GPP has agreed to adopt the Cat4 LBT scheme in NR-U network, which is developed based on the CSMA/CA scheme in WiFi network. Cat4 LBT scheme inherits the Backoff mechanism in the CSMA/CA scheme as shown in Fig. 3, which consists of the initial CCA (iCCA), and extended CCA (eCCA), respectively. When there is data to be transmitted, the UE is required to perform CCA to determine whether the channel is busy or idle. If the channel has been idle over a Defer interval, the UE transmits the packet immediately. Otherwise, the UE defers its transmission until the channel becomes idle. Then if the channel is detected to be idle over a Defer interval, the UE will initiate the Backoff procedure to further defer its transmission over a random time interval. The back-off procedure starts with the selection of an integer N, where N is a random number uniformly distributed in the range from 0 to the contention window CW. It is noted that the CW is initialized to be the minimum value $\mathrm{CW}_{\mathrm{min}}$. Next, the generated random number N decreases when the CCA identifies the channel as idle. Otherwise, the random number N freezes, and continues counting down when the CCA identifies the channel as idle again for a Defer interval. Once N reaches zero, the UE transmits its data within the maximum channel occupancy time (MCOT).

It is noted that the NR-U network adopts the Cat1 LBT scheme, known as "no LBT" to support fast ACK/NACK feedback transmission, where the feedback transmission does not need to perform any LBT if the gap between the end of data transmission and start of feedback transmission is less than or equal to $16us$. When the data transmission is successful, the contention window CW is reset to its minimum value $\mathrm{CW}_{\mathrm{min}}$. Otherwise, the device activates retransmission procedure for the lost packet, where the contention window size CW is doubled until it reaches a maximum value $\mathrm{CW}_{\mathrm{max}}$.

C. Difference Between NR-U and WiFi Networks

Although the Cat4 LBT scheme adopts similar procedures as CSMA/CA to guarantee the fairness, there are fundamental differences between the WiFi and NR-U networks in terms of the frame structure, uplink scheduling, and access parameters, which are presented in detail as follows

- **Frame structure:** In WiFi network, the STA can start the data transmission once the Backoff completes. However,

TABLE I
ACCESS PARAMETERS OF CSMA/CA AND LBT IN DIFFERENT PRIORITY CATEGORY

Access Category		Wait Time		CW_{min}		CW_{max}		MCOT/TXOP	
Wi-Fi	NR-U	Wi-Fi(DIFS)	NR-U(Defer)	Wi-Fi	NR-U	Wi-Fi	NR-U	Wi-Fi	NR-U
Voice(VO)	1	$25us$	$25us$	4	4	8	8	$2.080ms$	$2ms$
Video(VI)	2	$25us$	$25us$	8	8	16	16	$4.096ms$	$3ms$
Best Effort(BE)	3	$43us$	$43us$	16	16	1024	1024	$2.528ms$	$6ms$ or $10ms$
Background(BK)	4	$79us$	$79us$	16	16	1024	1024	$2.528ms$	$6ms$ or $10ms$

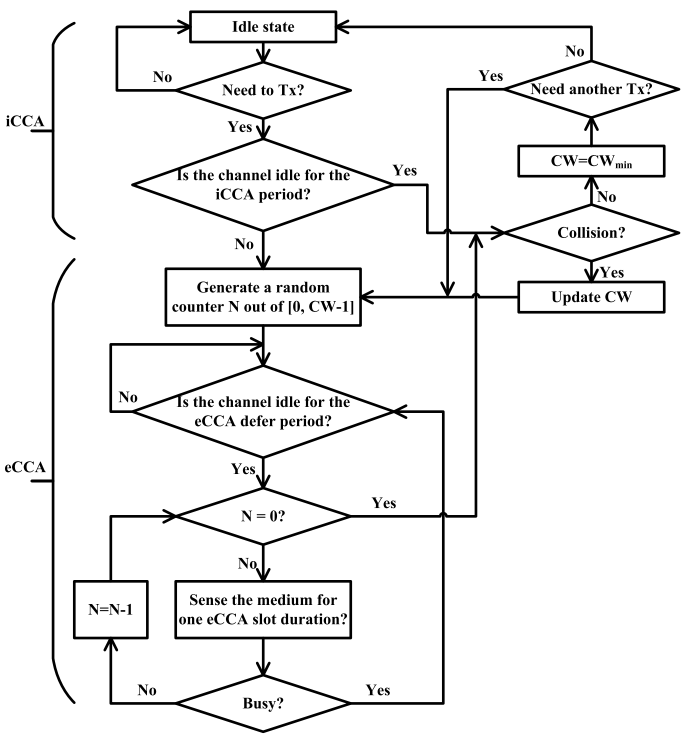


Fig. 3. Category-4 Listen-Before-Talk scheme flowchart.

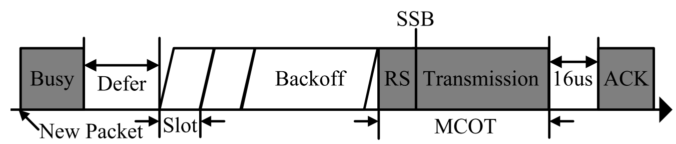


Fig. 4. Procedures of gNB scheduling and UE data transmission.

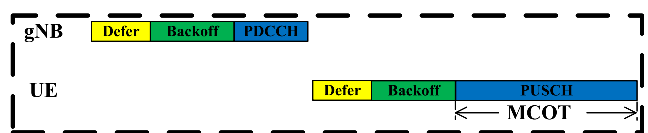


Fig. 5. Procedures of gNB scheduling and UE data transmission.

the NR-U UE can only start the data transmission at the exact Spectrum Slot Boundary (SSB), which can hardly be guaranteed due to the random nature of Backoff procedure [27]. Currently, 3GPP has not explicitly defined the behaviour between the end of Backoff and SSB. Considering that if the NR-U UE decides to wait for the SSB without transmission, WiFi STAs may identify the channel as idle and occupy the channel, which leads to poor NR-U network performance. Therefore, it is usually suggested to send an Reserved Signal (RS) to occupy the channel until the SSB [28]. However, the transmission of RS introduces the controlling overheads, especially with larger slot length (e.g., with a slot length $\theta = 500us$ in the LTE-LAA network). It is noted that the problem can be alleviated in NR-U network based on its flexible radio numerology, where the NR-U network adopts higher subcarrier spacing (SCS), and even mini-slot to reduce the slot length and RS overheads [29].

- **Uplink scheduling**: In the WiFi network, each STA performs the CSMA/CA to access the unlicensed channel once the new packets arrive, where the AP does not schedule the STA to transmit. Each WiFi STA accesses the channel independently, and transmits the uplink user data once it obtains the channel. However, the NR-U UEs need to be scheduled before transmitting the user data on the granted Physical Uplink Shared Channel (PUSCH) resource. The 3GPP standard has identified uplink transmission procedure as shown in the Fig. 5, where the gNB is required to perform the Cat4 LBT to schedule the UE via Physical Downlink Control Channel (PDCCH). Then, the UE performs Cat4 LBT to transmit the user data on the granted PUSCH resource [24].
- **Access Category**: The CSMA/CA scheme with fixed access parameters is also known as distributed coordination function (DCF). As the basic DCF with CSMA/CA scheme lacks capabilities to guarantee the QoS of different applications, the enhanced distribution coordination function (EDCF) has introduced the concept of access category (AC), where four priority levels are defined to differentiate the channel access probability for different traffic types as shown in the Table I [30]. Correspondingly, the LBT access schemes also define four priority levels with different parameters, where shorter wait time and contention window size correspond to higher priority service [31].

III. PROBLEM FORMULATION AND LIMITATIONS ANALYSIS

In this section, we first formulate the uplink system throughput optimization problem via capturing the characteristics of Backoff procedure and data transmission, and then analyse the challenges in the existing Cat4 LBT access scheme, which lays a foundation for our proposed scheme in Section IV.

A. Problem Formulation

To capture the characteristics of uplink transmission with CSMA/CA and LBT access schemes over unlicensed spectrum, we consider the Carrier Sensing (CS) & ED to model the Backoff procedure, and Signal to Interference Plus Noise Ratio (SINR) to model data transmission, respectively, which are then utilized to formulate the uplink system throughput optimization problem under the WiFi and NR-U networks coexistence scenario.

1) Carrier Sensing & Energy Detection: In WiFi network, each STA is required to perform CCA during the DIFS interval and Backoff procedure to determine whether the channel is busy or idle in each slot. The CCA in WiFi network consists of the CS & ED, where the CS detects the preamble transmission of WiFi network, and ED detects the total energy on the channel including both transmissions from NR-U and WiFi networks. We formulate the CS and ED of WiFi STA s $(s \in \mathcal{S})$ as

$$\mathrm{WiFi}_s^{\mathrm{CS}} = \sum_{s' \in \mathcal{S} \backslash s} \alpha_{s'} \mathrm{P_S} h_{s',s}, \tag{6}$$

$$\mathrm{WiFi}_s^{\mathrm{ED}} = \sum_{s' \in \mathcal{S} \backslash s} \alpha_{s'} \mathrm{P_S} h_{s',s} + \sum_{u \in \mathcal{U}} \alpha_u \mathrm{P_U} h_{u,s} + \sum_{g \in \mathcal{G}} \alpha_g \mathrm{P_G} h_{g,s}, \tag{7}$$

where $u \in \mathcal{U}$ denotes the UE, $g \in \mathcal{G}$ denotes the gNB. The $\alpha_{\{s',u,g\}}$ indicates whether STA/UE/gNB is transmitting or not, $h_{\{s',u,g\},s}$ is the channel gain, and $\mathrm{P}_{\{\mathrm{S,U,G}\}}$ represents the transmit power.

As shown in Eqs (6) and (7), the STA only senses the transmission of other STAs in the CS, but detects the transmission energy of both WiFi and NR-U networks in the ED. The STA will only identify the channel as idle when the values of CS and ED are under the pre-defined threshold $\lambda_{\mathrm{w}}^{\mathrm{CS}} = -82\mathrm{dBm}$ and $\lambda_{\mathrm{w}}^{\mathrm{ED}} = -62\mathrm{dBm}$, respectively.

In the NR-U network, the gNB $g \in \mathcal{G}$ and UE $u \in \mathcal{U}$ are required to perform CCA to transmit the uplink scheduling and uplink data, respectively. Different from WiFi network, the CCA of gNB and UE checks the ED as

$$\mathrm{NR}_g^{\mathrm{ED}} = \sum_{s \in \mathcal{S}} \alpha_s \mathrm{P_S} h_{s,g} + \sum_{u \in \mathcal{U}} \alpha_u \mathrm{P_U} h_{u,g} + \sum_{g' \in \mathcal{G} \backslash g} \alpha_{g'} \mathrm{P_G} h_{g',g}, \tag{8}$$

$$\mathrm{NR}_u^{\mathrm{ED}} = \sum_{s \in \mathcal{S}} \alpha_s \mathrm{P_S} h_{s,u} + \sum_{u' \in \mathcal{U} \backslash u} \alpha_{u'} \mathrm{P_U} h_{u',u} + \sum_{g \in \mathcal{G}} \alpha_g \mathrm{P_G} h_{g,u}. \tag{9}$$

When the ED is below the predefined threshold $\lambda_{\mathrm{n}}^{\mathrm{ED}} = -72\mathrm{dBm}$, the channel is identified as idle.

2) Signal to Interference Plus Noise Ratio: To capture the characteristic of transmission, we model the decoding process via SINR, where the SINR of STA data transmission, gNB scheduling transmission, and UE data transmission can be represented as

$$\mathrm{SINR}_s = \frac{\mathrm{P_S} h_{s,p}}{\mathcal{I}_s + \sigma_n^2}, \tag{10}$$

$$\mathrm{SINR}_g = \frac{\mathrm{P_G} h_{g,u}}{\mathcal{I}_g + \sigma_n^2}, \tag{11}$$

$$\mathrm{SINR}_u = \frac{\mathrm{P_U} h_{u,g}}{\mathcal{I}_u + \sigma_n^2}, \tag{12}$$

where

$$\mathcal{I}_s = \sum_{s' \in \mathcal{S} \backslash s} \alpha_{s'} \mathrm{P_S} h_{s',p} + \sum_{u \in \mathcal{U}} \alpha_u \mathrm{P_U} h_{u,p} + \sum_{g \in \mathcal{G}} \alpha_g \mathrm{P_G} h_{g,p}, \tag{13}$$

$$\mathcal{I}_g = \sum_{s \in \mathcal{S}} \alpha_s \mathrm{P_S} h_{s,u} + \sum_{u' \in \mathcal{U} \backslash u} \alpha_{u'} \mathrm{P_U} h_{u',u} + \sum_{g' \in \mathcal{G} \backslash g} \alpha_{g'} \mathrm{P_G} h_{g',u}, \tag{14}$$

$$\mathcal{I}_u = \sum_{s \in \mathcal{S}} \alpha_s \mathrm{P_S} h_{s,g} + \sum_{u' \in \mathcal{U} \backslash u} \alpha_{u'} \mathrm{P_U} h_{u',g} + \sum_{g' \in \mathcal{G} \backslash g} \alpha_{g'} \mathrm{P_G} h_{g',g}. \tag{15}$$

When the SINR_s is greater than the threshold η_{w}, the STA transmission can be successfully decoded. Similarly, when the SINR_g or SINR_u is greater than the threshold η_{n}, the gNB or UE transmission can be successfully decoded.

3) User Perceived Throughput: Since the system throughput can only demonstrate the network-level performance, we introduce a user-centric QoE performance metric called UPT to evaluate the file transmission throughput. The UPT is obtained by averaging all file throughputs [23], where each file throughput T_{file} is calculated as

$$T_{\text{file}} = \begin{cases} \dfrac{\mathrm{S}_{\text{file}}}{T_{\text{depature}} - T_{\text{arrival}}} & \text{, Transmitted File} \\ \dfrac{S_{\text{served}}}{T_{\text{end}} - T_{\text{arrival}}} & \text{, Unfinished File} \\ 0 & \text{, Dropped File} \end{cases} \tag{16}$$

where S_{file} is the file size, S_{served} is the transmitted file size by the end of simulation, T_{arrival} is the arrival time of the file, and T_{depature} represents the transmitted time of the file. It is noted that the file throughput is zero when the file is dropped due to time violation.

4) System Throughput Optimization: As discussed above, the WiFi STAs perform CSMA/CA individually to access the channel without scheduling, and all the STAs that accessed the channel would transmit in a grant-free way. The gNB is required to perform the Cat4 LBT scheme to access the channel, and transmits the scheduling information via the PDCCH. Then the scheduled UE is required to perform Cat4 LBT scheme to transmit the user data based on the scheduled resource.

The WiFi and NR-U networks aim at maximizing the uplink system throughput, which can be formulated as the optimization

$$\text{(P1)}: \quad \max_{\mathcal{T}} \ (N_{\mathrm{w}} + N_{\mathrm{n}}) \times \mathrm{S}_{\text{file}}, \tag{17}$$

where S_{file} is the file size, N_{w} and N_{n} represent the number of successfully transmitted packets in WiFi and NR-U networks, respectively. To maximize the system throughput, we need to find the optimal transmission vector $\mathcal{T}$, which can maximize the number of effective concurrent transmissions, while not resulting in performance losses caused by SINR degradation or collisions, especially for neighboring transmissions.

As explained above, WiFi network employs both CS and ED to detect transmissions over the unlicensed spectrum, and NR-U network only uses ED. When a WiFi STA s $(s \in \mathcal{S})$ has data to transmit to its associated AP with the CSMA/CA procedure, we have

$$\mathcal{T}(s)=\begin{cases}1, & \begin{array}{l}10\log_{10}\left(\mathrm{WiFi}_s^{\mathrm{CS}}\right)<\lambda_{\mathrm{w}}^{\mathrm{CS}} \text{ and}\\ 10\log_{10}\left(\mathrm{WiFi}_s^{\mathrm{ED}}\right)<\lambda_{\mathrm{w}}^{\mathrm{ED}} \text{ and}\\ N=0\end{array}\\ 0, & \text{otherwise}\end{cases} \tag{18}$$

where $\mathrm{WiFi}_s^{\mathrm{CS}}$ and $\mathrm{WiFi}_s^{\mathrm{ED}}$ represent the CS and ED value during CCA, respectively. The pre-defined thresholds for CS and ED are $\lambda_{\mathrm{w}}^{\mathrm{CS}}$ and $\lambda_{\mathrm{w}}^{\mathrm{ED}}$, and N is the residual random number. Eq (18) indicates that WiFi STA s can only transmit when satisfying the following conditions: 1) when the sensed energy from other WiFi transmission at STA s is lower than $\lambda_{\mathrm{w}}^{\mathrm{CS}}$; 2) when the aggregated sensed energy from the ongoing WiFi and NR-U networks transmissions is lower than $\lambda_{\mathrm{w}}^{\mathrm{ED}}$; and 3) the random number N counts down to zero, which depends on the Backoff speed s_{w}.

On the other hand, if transmitter is an NR-U gNB g or UE u, we have

$$\mathcal{T}(g)=\begin{cases}1, & \begin{array}{l}10\log_{10}\left(\mathrm{NR}_g^{\mathrm{ED}}\right)<\lambda_{\mathrm{n}}^{\mathrm{ED}} \text{ and}\\ N=0\end{array}\\ 0, & \text{otherwise}\end{cases} \tag{19}$$

$$\mathcal{T}(u)=\begin{cases}1, & \begin{array}{l}10\log_{10}\left(\mathrm{NR}_u^{\mathrm{ED}}\right)<\lambda_{\mathrm{n}}^{\mathrm{ED}} \text{ and}\\ N=0\end{array}\\ 0, & \text{otherwise}\end{cases} \tag{20}$$

where $\lambda_{\mathrm{n}}^{\mathrm{ED}}$ is the NR-U ED threshold, $\mathrm{NR}_g^{\mathrm{ED}}$ is the sensed energy from the transmissions over the unlicensed spectrum at gNB, and $\mathrm{NR}_u^{\mathrm{ED}}$ is the sensed energy from the transmissions over the unlicensed spectrum at UE. Eqs (19) and (20) indicate that gNB and UE can only transmit if it experiences a sensed energy lower than the ED threshold, and the random number N counts down to zero with Backoff speed s_{n}.

Given Eqs (18) (19) (20), because $\lambda_{\mathrm{w}}^{\mathrm{CS}}$, $\lambda_{\mathrm{w}}^{\mathrm{ED}}$, and Backoff speed s_{w} are fixed values defined by the IEEE 802.11 standard, the issue of finding the optimal transmission vector $\mathcal{T}$ becomes choosing a configuration of $\lambda_{\mathrm{n}}^{\mathrm{ED}}$ and Backoff speed s_{n} to maximize the system uplink throughput.

B. Limitations in Existing LBT Scheme

The existing Cat4 LBT scheme relies on the generated random number in Backoff procedure to mitigates the collision among devices by randomizing the transmission start time. However, the existing Cat4 LBT scheme suffers from single fixed ED threshold $\lambda_{\mathrm{n}}^{\mathrm{ED}}$, unreliable measurement report, and single fixed Backoff speed s_{n}, which prevent the NR-U network from fully utilizing the unlicensed spectrum to achieve the desired uplink throughput.

1) Single Fixed ED threshold: As we have mentioned, the existing Cat4 LBT scheme utilizes single fixed ED threshold $\lambda_{\mathrm{n}}^{\mathrm{ED}}$ in CCA, where the sensed energy is compared with the ED threshold to determine the channel as busy or idle. It is noted that the sensed energy represents the interference from transmissions of other devices. However, the single fixed ED threshold setting does not take into account the dynamic changing interference environment, and discards the interference information. Therefore, the existing Cat4 LBT scheme fails to adapt to the sophisticated interference environment, which leads to the typical HN problem and EN problem as shown in the Fig. 6.

The HN problem happens when both STA and UE identify the channel as idle (i.e., the sensed energy is lower than the ED threshold) due to pathloss and channel fading, and transmit simultaneously to the AP and gNB, respectively. However, the strong co-channel interference leads to decoding failure at the AP and gNB. The EN problem happens when the UE identifies the channel as busy (i.e., the sensed energy is higher than the ED threshold) due to the co-channel interference from the neighboring STA, and defers the transmission to gNB. However, gNB could still decode the transmission from UE with low interference because the gNB is far away from STA, which leads to low spectral efficiency. In a word, the high ED threshold setting enables multiple devices to transmit simultaneously, but may lead to stronger interference. On the contrary, the low ED threshold setting mitigates the probability of collision, but leads to low spectrum efficiency [32].

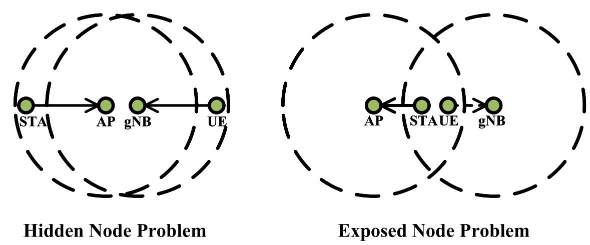
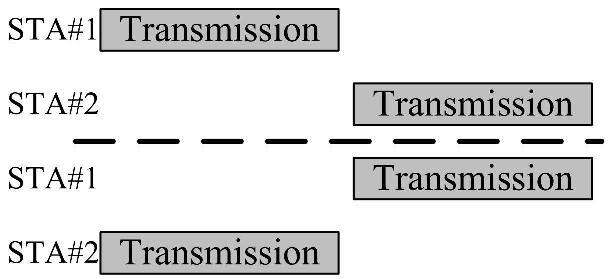


Fig. 6. Hidden node problem and exposed node problem under the coexistence of NR-U and WiFi networks.

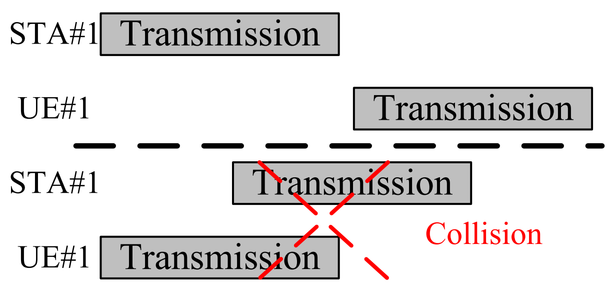
It is noted that asymmetry ED thresholds setting under the coexistence of NR-U and WiFi networks further deteriorates the HN and EN problem, where the ED threshold is $\lambda_{\mathrm{n}}^{\mathrm{ED}}=-72\mathrm{dBm}$ in NR-U network, and $\lambda_{\mathrm{w}}^{\mathrm{ED}}=-62\mathrm{dBm}$ in WiFi network [33]. As shown in Fig. 7 (a), STA2 may sense the transmission of STA1, and defer its transmission until the channel to be idle, and vice versa due to the symmetry ED setting. However, in Fig. 7 (b), although the UE1 may sense the transmission of STA1 with -72dBm ED threshold, the STA1 may not sense the transmission of UE1 with -62dBm ED threshold, which leads to a collision. Therefore, the setting of ED threshold is of vital importance to the system throughput under the coexistence of NR-U and WiFi networks.

2) Unreliable Measurement Report: In the NR-U network, the gNB is required to access the unlicensed spectrum to schedule the UE before data transmission. However, due to the lack of reliable measurement report mechanism, the gNB cannot obtain the instantaneous interference experienced by the UEs, where the UE that experienced strong interference may be scheduled and leads to transmission failure.

The 3GPP has introduced the UE measurement report mechanism over the unlicensed spectrum as shown in Fig. 8, where the average reference signal strength indicator (RSSI) and channel occupancy (CO) are reported to the gNB. The RSSI serves as the key performance indicator for load and



(a) Symmetry ED setting under the coexistence of WiFi networks.



(b) Asymmetry ED setting under the coexistence of NR-U and WiFi networks.

Fig. 7. Symmetry ED setting and asymmetry ED setting over the unlicensed spectrum.

interference on the given carrier, which measures the average total received power of the whole band, and CO is defined as the percentage of measured RSSI samples above a predefined threshold. However, the existing measurement is trigged by the transmission of discovery reference signal (DRS) from gNB over the unlicensed spectrum, which is subject to the LBT and suffers from low reliability. Moreover, the RSSI measurement time configuration (RMTC) determines the RSSI measurement periodicity to be [40, 80, 160, 320, or 640 ms], and measurement duration to be [1, 14, 28, 42, or 70 OFDM symbols]. Therefore, the measurement report represents the average experienced interference of the UE instead of instantaneous interference, which fails to reflect the characteristic of dynamic changing interference environment in a real-time manner. Furthermore, the measurement report is also transmitted over the unlicensed spectrum via LBT scheme, which suffers from low reliability and high latency.

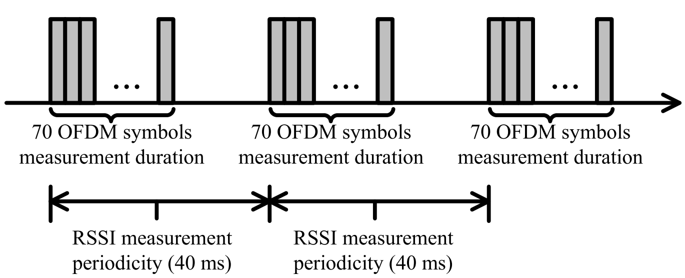


Fig. 8. Average RSSI and CO measurement report.

3) Single Fixed Backoff Speed: Due to the randomness of the generated number N in Backoff mechanism, the collision problem is alleviated under the coexistence scenario over the unlicensed spectrum. However, as the interference information is discarded, the existing Backoff mechanism utilizes fixed Backoff speed $s_{\mathrm{n}} = 1$, where the generated random number is decreased one by one in every idle slot. The fixed Backoff speed setting lacks flexibility and leads to unnecessary overheads in the exponential Backoff mechanism, where the devices that have failed in previous transmissions double the contention window size, and have higher probability of generating larger number N. When the device generates large random number N and counts down, the interference may already decrease from high level to low level. Hence, the channel may be occupied by the devices with small residual number. Even if the device successfully occupies the channel after long Backoff, the channel utilization is degraded due to high Backoff overheads.

IV. Novel LBT Access Scheme with Adaptive Backoff Procedure

We propose a novel Cat4 LBT scheme to solve the challenges discussed in the Section III, where the gNB or UE $m \in \mathcal{M} = \mathcal{G} \cup \mathcal{U}$ quantifies the instantaneous interference level $l_m \in \mathcal{L} | \mathcal{L} = \{0, 1, ..., L\}$ based on the sensed energy $\mathrm{NR}_m^{\mathrm{ED}}$ in Eqs (8) (9), and multiple ED thresholds $\Lambda_{\mathrm{n}}^{\mathrm{ED}} = \{\lambda_1, \lambda_2, ..., \lambda_L | \lambda_1 < \lambda_2 < ... < \lambda_L\}$. The Backoff speed s_m is then adaptively determined according to the instantaneous interference level l_m. Moreover, we propose a measurement report mechanism for UEs to upload the instantaneous interference level, which can be utilized by gNB to determine the Backoff speed and the UE scheduling.

A. Interference Level Quantification

As the single fixed ED threshold only identifies the channel as busy or idle, and discards the dynamic changing interference information, we propose to utilize multiple ED thresholds $\Lambda_{\mathrm{n}}^{\mathrm{ED}} = \{\lambda_1, \lambda_2, ..., \lambda_L | \lambda_1 < \lambda_2 < ... < \lambda_L\}$ to quantify the instantaneous interference level $l_m \in \mathcal{L} | \mathcal{L} = \{0, 1, ..., L\}$ experienced by the gNB or UE, where L is the pre-defined largest interference level.

Fig. 9 presents a general flowchart of instantaneous interference level quantification, where the sensed energy $\mathrm{NR}_m^{\mathrm{ED}}$ in Eqs (8) (9) is compared with multiple ED thresholds $\Lambda_{\mathrm{n}}^{\mathrm{ED}}$ to determine the interference level l_m. Specifically, if the sensed energy is lower than λ_1, the interference level is identified as the lowest with $l_m = 0$. Similarly, if the sensed energy is larger than λ_L, the interference level is identified as the highest with $l_m = L$.

Taking an example, we instantiate the multiple ED thresholds as $\Lambda_{\mathrm{n}}^{\mathrm{ED}} = \{-82\mathrm{dBm}, -77\mathrm{dBm}, -72\mathrm{dBm}\}$ in the paper. When the sensed energy is lower than -82dBm, the interference level is set to be lowest as $l_m = 0$. When the sensed energy is higher than -82dBm but lower than -77dBm, the interference level is set to be $l_m = 1$. When the sensed energy is higher than -77dBm but lower than -72dBm, the interference level is set to be $l_m = 2$. Otherwise, the interference level is

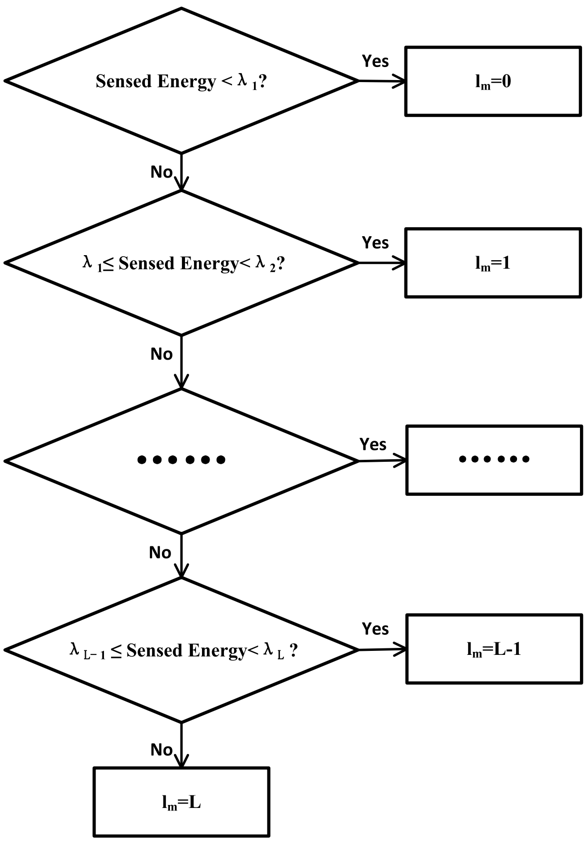


Fig. 9. General flowchart of instantaneous interference level quantification.

set to be the highest $l_m = 3$. This example can be formulated as

$$l_m = \begin{cases} 0 & , \mathrm{NR}_m^{\mathrm{ED}} < -82\mathrm{dBm} \\ 1 & , -82\mathrm{dBm} \leq \mathrm{NR}_m^{\mathrm{ED}} < -77\mathrm{dBm} \\ 2 & , -77\mathrm{dBm} \leq \mathrm{NR}_m^{\mathrm{ED}} < -72\mathrm{dBm} \\ 3 & , \mathrm{NR}_m^{\mathrm{ED}} > -82\mathrm{dBm} \end{cases} . \quad (21)$$

B. Interference Level Sharing

In the existing Cat4 LBT scheme, the gNB performs the Backoff procedure without considering the experienced interference at the associated UEs due to the lack of effective and reliable measurement report mechanism. Specifically, in the current report mechanism, the gNB is required to transmit the DRS over the unlicensed spectrum first, then the UE is required to access the unlicensed spectrum to report the average RSSI and CO measurement. Both the transmission of DRS and measurement report depend on the LBT procedures, which fail to guarantee the reliability of measurement report.

To enable the UEs to periodically report the instantaneous interference level, we propose to utilize the periodical resource allocated for scheduling request (SR) over the licensed spectrum, which is allocated for each connected UE to indicate its willingness for uplink transmission. The detailed SR resource allocation follows three different situations depending on the SR periodicity $\mathrm{SR}_{\mathrm{per}}$ as follow

- When the $\mathrm{SR}_{\mathrm{per}}$ is larger than one slot, the UE determines the SR transmission occasion to be a slot with index $n_{s,f}$, which follows

$$(n_f \times N_{\mathrm{slot}}^{\mathrm{frame}} + n_{s,f} - \mathrm{SR}_{\mathrm{off}}) \mod \mathrm{SR}_{\mathrm{per}} = 0, \quad (22)$$

  where n_f is the index of frame, $N_{\mathrm{slot}}^{\mathrm{frame}}$ is the number of slots in each frame, and $\mathrm{SR}_{\mathrm{off}}$ is the offset of SR resource allocation;
- When $\mathrm{SR}_{\mathrm{per}}$ is one slot, the UE expects that $\mathrm{SR}_{\mathrm{off}} = 0$, and every slot is a SR transmission occasion;
- When $\mathrm{SR}_{\mathrm{per}}$ is smaller than one slot, the UE determines a SR transmission occasion to be a symbol with index z, which follows

$$(z - z_0) \mod \mathrm{SR}_{\mathrm{per}} = 0, \quad (23)$$

  where z_0 is the value of starting symbol index.

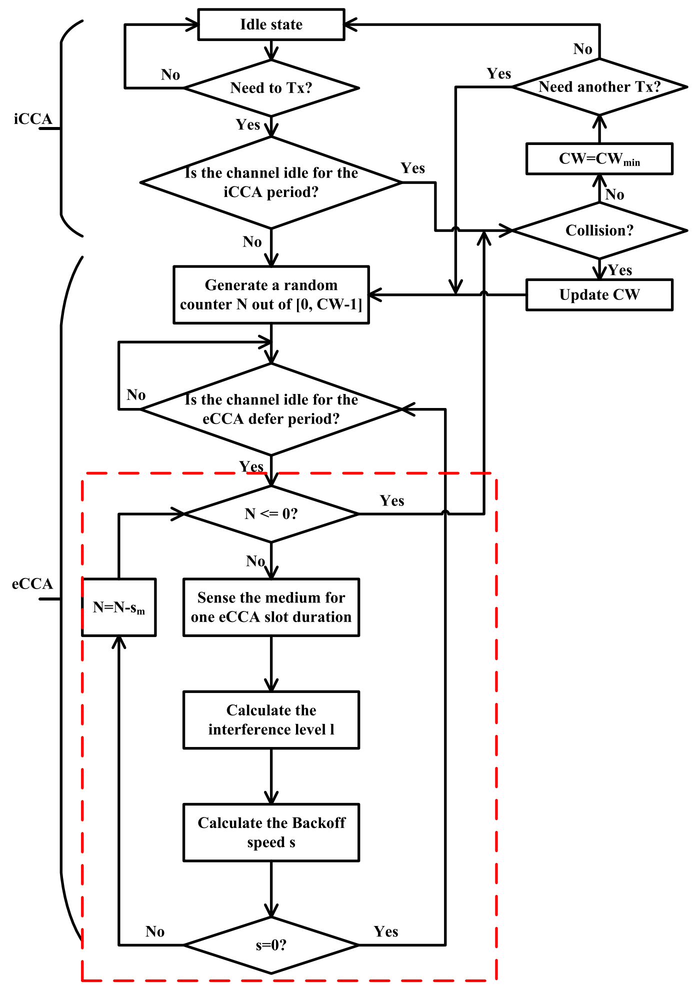


Fig. 10. Proposed Category-4 Listen-Before-Talk scheme flowchart with adaptive Backoff procedure.

C. Backoff Speed Determination

We present our proposed Cat4 LBT access scheme with adaptive Backoff procedure in Fig. 10. Based on the quantified interference level l_m, the gNB or UE calculates the corresponding Backoff speed s_m, and then deducts the s_m from the random number N. When $s_m = 0$, it means the gNB or UE suffers from strong interference, and the random number N freezes similar as existing Cat4 LBT scheme. It is noted that the gNB or UE accesses the unlicensed spectrum when the random number N counts down to zero in the existing Cat4 LBT scheme. However, in our proposed scheme, the gNB or UE accesses unlicensed spectrum when the random number N is small or equal to zero. This is because the Backoff speed s_m may be larger than the residual random number N, which leads to $N - s_m \leq 0$. In the following, we will present the examples of the gNB Backoff speed s_g determination and associated UE Backoff speed $s_{u'}|u' \in \mathcal{U}'$ determination, respectively.

Based on the measurement report mechanism over the licensed spectrum, the gNB can determine the Backoff speed s_g considering its own interference level and associated UEs' interference levels. Taking an example, we instantiate the Backoff speed determination of gNB $g \in \mathcal{G}$ in the paper as

$$s_{\rm g} = 3 - \max(l_{\rm g}, \min(l_0, ..., l_{u'}, ..., l_{U'-1})), u' \in \mathcal{U}', \quad (24)$$

where l_g is the instantaneous interference level of the gNB g, and $l_{u'}|u' \in \mathcal{U}'$ represents the interference level of the associated UEs. The reason to consider the UE with lowest interference level is that the gNB can schedule the UE with the lowest interference level. Then, by taking the maximum value between interference level of gNB l_g, and lowest interference level among associated UEs $l_{u'}$, the probability of collision can be alleviated. When the interference level at the gNB or UEs reaches the highest value with $l_g = 3$, or $l_{u'} = 3$, the Backoff speed is set to be the lowest value with $s_g = 0$, and the random number N freezes.

When the gNB has successfully accessed the channel and scheduled the UE u', the UE $u' \in \mathcal{U}'$ can decide the Backoff speed $s_{u'}$ based on its own interference level $l_{u'}$. Taking an example, we instantiate the Backoff speed determination of UE $u' \in \mathcal{U}'$ as

$$s_{u'} = 3 - l_{u'}, u' \in \mathcal{U}', \quad (25)$$

where the random number freezes when the UE reaches the highest interference level.

V. Simulation Results

In this section, we evaluate the performance of our proposed approaches in Sec. IV via numerical experiments. We adopt the standard network parameters listed in Table II following [23]–[26]. As shown in Table II, we simulate the FTP-3 traffic model for each UE and STA, where the packets arrival rate is $\lambda = 2$. The size of each file is 0.5 Mbytes, and the file will be dropped if it cannot be successfully transmitted within $8\mathrm{s}$. As we mentioned above, both NR-U and WiFi networks define four different priority access classes, and each class has different parameters including wait time, MCOT length, and contention window size. For the FTP3 traffic in the uplink transmission, we adopt the fourth priority class. We also assume the NR-U system adopts 60 KHz sub-carrier spacing (SCS), and mini-slot with two symbol.

Fig. 11 plots the throughputs of NR-U and WiFi networks of benchmark scheme with different NR-U ED thresholds. We can observe that the throughputs of both NR-U and WiFi network reach a stable region under all ED threshold settings. This is because the traffic follows Poisson arrival with a fixed average arrival rate, and the packet that violates the time constraint is dropped. With the increasing of NR-U ED threshold from -82dBm to -62dBm, we can observe that the throughput of NR-U network increases from 6Mbps to 34Mbps due to higher transmission opportunities. However, we can see that the throughput of WiFi network keep decreasing from 13Mbps to 8Mbps, which indicates that simply increasing the NR-U ED threshold to achieve higher throughput of NR-U network is unfair to the WiFi network. It is noted that the impact of NR-U ED threshold on the throughput of WiFi network is decreasing, which means it is possible to achieve higher NR-U throughput by reducing the Backoff overheads without sacrificing the throughput of WiFi network.

Fig. 12 plots the average system throughput and UPTs of

TABLE II
Simulation Parameters

Parameters	Value
Height of gNB and AP	3 m
Height of UE and STA	1 m
File Size	0.5 Mbytes
SIFS	16us
Defer	79us
Maximum Contention Window	1024
Packet Arrival Rate	2
Transmit Power of UE and STA	18dBm
Transmit Power of gNB and AP	23dBm
Noise Power	-104dBm
SCS	60KHz
Mini-slot	36us
Time Limitation	8s
WiFi SINR Threshold	9dB
NRU SINR Threshold	5.5dB
WiFi Rate	21.7Mbps
NRU Rate	25.2Mbps
WiFi COT	2.528ms
NRU COT	6ms
WiFi Preamble Detection Threshold	-82dBm
WiFi Energy Detection Threshold	-62dBm
NRU Energy Detection Threshold	-72dBm
Number of UEs associated with each gNB	5
Number of STAs associated with each AP	5
Simulation Length	250s

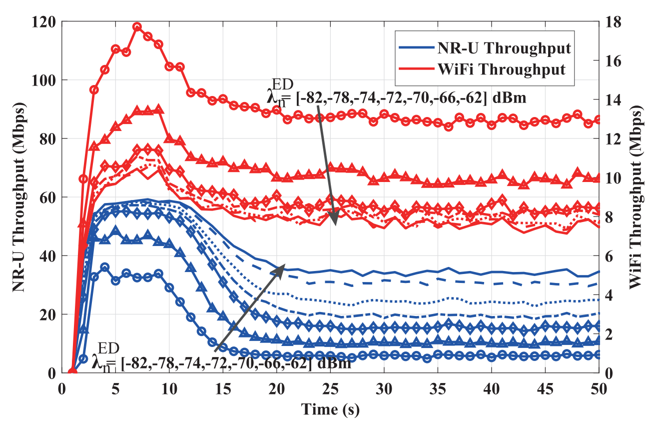


Fig. 11. Throughputs of NR-U and WiFi networks of benchmark scheme with different NR-U ED thresholds.

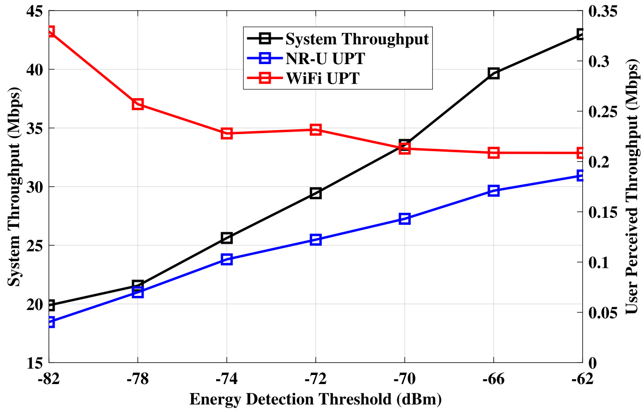


Fig. 12. Average system throughput and UPTs of NR-U and WiFi networks of benchmark scheme with different NR-U ED thresholds.

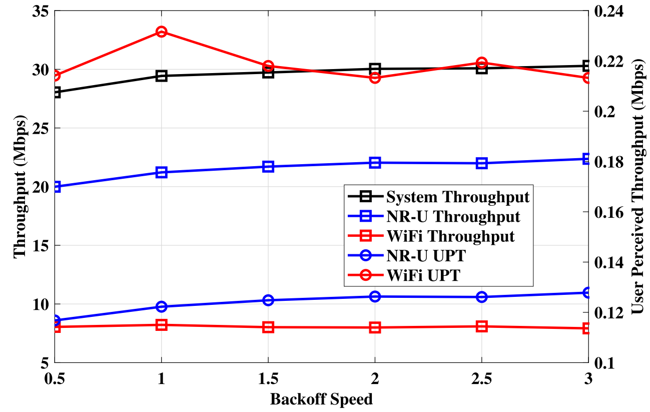


Fig. 13. Average throughputs and UPTs of NR-U and WiFi networks of benchmark scheme with different NR-U Backoff speed.

NR-U and WiFi networks of benchmark scheme with different NR-U ED thresholds, where the calculation of UPT follows Eq (16). We can observe that the system throughput keeps increasing with the increasing of NR-U ED threshold, which indicates that the advantages of NR-U network, including higher data rate and larger transmission time, contributes more to the gain of system throughput over the WiFi network. We can also see that the UPT of NR-U network is lower than that of WiFi network even with higher ED threshold. This is because the WiFi STA can access the channel without scheduling, which leads to less time consumption for each packet.

Fig. 13 plots the average throughputs and UPTs of NR-U and WiFi networks of benchmark scheme with different NR-U Backoff speed, where the calculation of UPT follows Eq (16). We can see that the system throughput increases from 28Mbps to 30Mbps, where the throughput of NR-U network increases from 20Mbps to 22Mbps, and the throughput of WiFi network almost remains 8Mbps. Compared to the ED threshold, directly increasing the Backoff speed of gNB has much lower impact on the throughput of NR-U and WiFi networks. This is because the higher ED threshold can accelerate the counting down process of random number N and leads to less defer time. We can also observe that the UPT of NR-U network increases slightly to 0.13Mbps, and the UPT of WiFi network almost remains the same around 0.22Mbps.

Fig. 14 plots the throughputs of NR-U and WiFi networks in proposed solution with different packet arrival rates. When the packet arrival rates $\lambda = 2$, we can see that the system throughput achieves around 50Mbps, where the throughput of NR-U network is 40Mbps, and the throughput of WiFi network reaches 10Mbps. Compared to the performance in Fig. 11, we can see that the NR-U throughput of our proposed scheme is even higher than that of benchmark scheme with -62dBm ED threshold setting. Moreover, the WiFi throughput of our proposed scheme reaches similar performance as -78dBm ED setting in Fig. 11. When increasing the packet arrival rate λ to 3, we can see that although the throughput of NR-U network decreases from 40Mbps to 36Mbps, the throughput of WiFi network remains around 10Mbps.

Fig. 15 plots the average throughputs and UPTs of NR-U

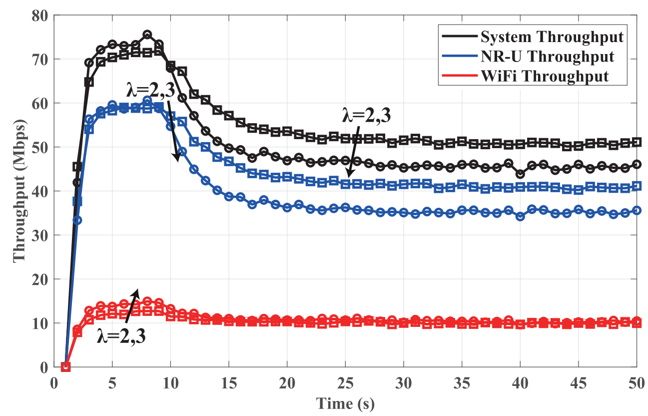


Fig. 14. Throughputs of NR-U and WiFi networks in proposed solution with different packet arrival rates.

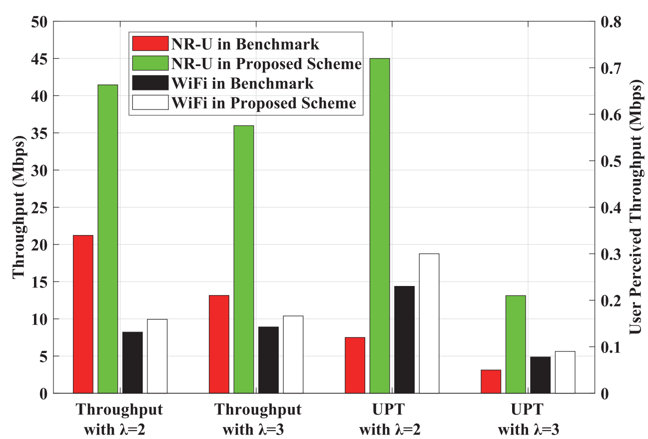


Fig. 15. Average throughputs and UPTs of NR-U and WiFi networks in proposed solution with different packet arrival rates.

and WiFi networks in proposed solution with different packet arrival rates, where the calculation of UPT follows Eq (16). We can observe that both throughputs and UPTs of NR-U and WiFi networks under different packet arrival rates increase in our proposed solution, which indicates that our proposed scheme increases the system throughput without sacrificing the performance of WiFi network. This is because our proposed scheme considers the instantaneous interference levels both at the gNB and UEs, which adaptively adjusts the Backoff speed for accessing the channel without causing serious interference to WiFi network. Specifically, for the packet arrival rate $\lambda = 2$, the throughput of NR-U network increases from 21Mbps to 41Mbps, where the performance gain is near 100%. The throughput of WiFi network increases from 8Mbps to 10Mbps, where the performance gain is around 25%. The UPT of NR-U network increases by 500%, and the UPT of WiFi network increases by 30%.

VI. Conclusion and Future Work

In this paper, we developed a novel Category-4 (Cat4) LBT access scheme, to optimize the Backoff speed for maximizing the uplink system throughput in Uplink Centric Broadband Communication (UCBC) under the coexistence of heterogeneous NR-U and WiFi networks. We first developed an instantaneous interference level quantification mechanism, where both the gNB and associated UEs quantify the interference level during CCA. We further proposed a reliable periodical report mechanism for UEs to share their quantified interference level with the associated gNB, where the UEs can utilize the allocated scheduling request (SR) resource over the licensed spectrum. Furthermore, we designed the adaptively Backoff speed determination method, where the gNB jointly considers its own interference level, and interference levels of associated UEs to obtain the Backoff speed. Finally, we introduced a user-centric QoE performance metric called user perceived throughput (UPT) to evaluate the file transmission throughput.

Our results demonstrated that our proposed adaptive LBT scheme significantly outperforms the benchmark scheme in terms of both uplink system throughput and UPT. Our numerical results shed light on that the NR-U network has inherent advantages over the WiFi network, including the data rate, maximum channel occupancy time length, scheduling policy, etc, which makes the fairness among heterogeneous networks to be an important problem to study.

References

[1] F. Hu, Y. Deng, H. Zhou, T. H. Jung, C.-B. Chae, and A. H. Aghvami, "A vision of an XR-aided teleoperation system toward 5G/B5G," *IEEE Commun. Mag.*, vol. 59, no. 1, pp. 34–40, Jan. 2021.

[2] H. Zhou, C. She, Y. Deng, M. Dohler, and A. Nallanathan, "Machine learning for massive industrial internet of things," *IEEE Wireless Commun.*, vol. 28, no. 4, pp. 81–87, Aug. 2021.

[3] K. B. Letaief, Y. Shi, J. Lu, and J. Lu, "Edge artificial intelligence for 6G: Vision, enabling technologies, and applications," *IEEE J. Sel. Areas Commun.*, vol. 40, no. 1, pp. 5–36, Jan. 2022.

[4] *Huawei 5.5G*. [Online]. Available: https://www.huawei.com/en/news/2020/11/mbbf-shanghai-huawei-david-wang-5dot5g

[5] A. Mukherjee, J.-F. Cheng, S. Falahati, H. Koorapaty, D. H. Kang, R. Karaki, L. Falconetti, and D. Larsson, "Licensed-Assisted Access LTE: coexistence with IEEE 802.11 and the evolution toward 5G," *IEEE Commun. Mag.*, vol. 54, no. 6, pp. 50–57, Jun. 2016.

[6] H.-J. Kwon, J. Jeon, A. Bhorkar, Q. Ye, H. Harada, Y. Jiang, L. Liu, S. Nagata, B. L. Ng, T. Novlan, J. Oh, and W. Yi, "Licensed-assisted access to unlicensed spectrum in LTE Release 13," *IEEE Commun. Mag.*, vol. 55, no. 2, pp. 201–207, Feb. 2017.

[7] Q. Chen, G. Yu, and Z. Ding, "Enhanced LAA for unlicensed LTE deployment based on TXOP contention," *IEEE Trans. Commun.*, vol. 67, no. 1, pp. 417–429, Jan. 2019.

[8] M. Hirzallah, M. Krunz, B. Kecicioglu, and B. Hamzeh, "5G new radio unlicensed: Challenges and evaluation," *IEEE Trans. on Cogn. Commun. Netw.*, vol. 7, no. 3, pp. 689–701, Sep. 2021.

[9] S. Lagen, L. Giupponi, S. Goyal, N. Patriciello, B. Bojović, A. Demir, and M. Beluri, "New radio beam-based access to unlicensed spectrum: Design challenges and solutions," *IEEE Commun. Surveys Tuts.*, vol. 22, no. 1, pp. 8–37, 1st Quart., 2020.

[10] 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. 153 027–153 056, 2020.

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

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

[13] L. Zhang, H. Yin, Z. Zhou, S. Roy, and Y. Sun, "Enhancing WiFi multiple access performance with federated deep reinforcement learning," in *2020 IEEE 92nd Vehicular Technology Conference (VTC2020-Fall)*. IEEE, Nov. 2020, pp. 1–6.

[14] U. Challita, L. Dong, and W. Saad, "Proactive resource management for LTE in unlicensed spectrum: A deep learning perspective," *IEEE Trans. Wireless Commun.*, vol. 17, no. 7, pp. 4674–4689, Jul. 2018.

[15] J. Tan, L. Zhang, Y.-C. Liang, and D. Niyato, "Intelligent sharing for LTE and WiFi systems in unlicensed bands: A deep reinforcement learning approach," *IEEE Trans. Commun.*, vol. 68, no. 5, pp. 2793–2808, May 2020.

[16] J. Tan, S. Xiao, S. Han, and Y.-C. Liang, "A learning-based coexistence mechanism for LAA-LTE based hetnets," in *2018 IEEE International Conference on Communications (ICC)*. IEEE, May 2018, pp. 1–6.

[17] R. Ali, Y. B. Zikria, S. Garg, A. K. Bashir, M. S. Obaidat, and H. S. Kim, "A federated reinforcement learning framework for incumbent technologies in beyond 5G networks," *IEEE Netw.*, vol. 35, no. 4, pp. 152–159, Jul. 2021.

[18] Z. Ali, L. Giupponi, J. Mangues-Bafalluy, and B. Bojovic, "Machine learning based scheme for contention window size adaptation in LTE-LAA," in *2017 IEEE 28th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*. IEEE, Oct. 2017, pp. 1–7.

[19] P. Campos, A. Hernández-Solana, and A. Valdovinos-Bardají, "Dealing with the hidden node problem in multioperator laa-lte scenarios," in *2018 IFIP/IEEE International Conference on Performance Evaluation and Modeling in Wired and Wireless Networks (PEMWN)*. IEEE, Sep. 2018, pp. 1–7.

[20] R. K Sheshadri, K. Sundaresan, E. Chai, S. Rangarajan, and D. Koutsonikolas, "Eli: Empowering LTE with interference awareness in unlicensed spectrum," in *2018 IEEE 26th International Conference on Network Protocols (ICNP)*. IEEE, Sep. 2018, pp. 280–290.

[21] S. Lagen, L. Giupponi, B. Bojovic, A. Demir, and M. Beluri, "Paired listen before talk for multi-rat coexistence in unlicensed mmwave bands," in *2018 IEEE International Conference on Communications Workshops (ICC Workshops)*. IEEE, May 2018, pp. 1–6.

[22] L. Li, J. P. Seymour, L. J. Cimini, and C.-C. Shen, "Coexistence of Wi-Fi and LAA networks with adaptive energy detection," *IEEE Trans. Veh. Technol.*, vol. 66, no. 11, pp. 10 384–10 393, Nov. 2017.

[23] *Further advancements for E-UTRA physical layer aspects*, document TR 36.814 V9.2.0, 3GPP, Sophia, Antipolis, France, 2017.

[24] *Study on NR-based access to unlicensed spectrum*, document TR 38.889 V16.0.0, 3GPP, Sophia, Antipolis, France, 2018.

[25] *Study on channel model for frequencies from 0.5 to 100 GHz*, document TR 38.901 V16.1.0, 3GPP, Sophia, Antipolis, France, 2019.

[26] *Study on Licensed-Assisted Access to Unlicensed Spectrum*, document TR 36.889 V13.0.0, 3GPP, Sophia, Antipolis, France, 2015.

[27] V. Loginov, E. Khorov, A. Lyakhov, and I. Akyildiz, "CR-LBT: Listen-before-talk with collision resolution for 5G NR-U networks," *IEEE Trans. Mobile Comput.*, Jan. 2021, [early access].

[28] J. Kim, J. Yi, and S. Bahk, "Uplink channel access enhancement for cellular communication in unlicensed spectrum," *IEEE Access*, vol. 8, pp. 216 386–216 397, Nov. 2020.

[29] K. Kosek-Szott, A. Lo Valvo, S. Szott, P. Gallo, and I. Tinnirello, "Downlink channel access performance of NR-U: Impact of numerology and mini-slots on coexistence with Wi-Fi in the 5 GHz band," *Comm Com Inf Sc*, vol. 195, p. 108188, Aug. 2021.

[30] J. Zheng, J. Xiao, Q. Ren, and Y. Zhang, "Performance modeling of an LTE LAA and WiFi coexistence system using the LAA Category-4 LBT procedure and 802.11e EDCA mechanism," *IEEE Trans. Veh. Technol.*, vol. 69, no. 6, pp. 6603–6618, Jun. 2020.

[31] Y. Ma, "Analysis of channel access priority classes in lte-laa spectrum sharing system," in *2018 27th International Conference on Computer Communication and Networks (ICCCN)*. IEEE, Jul. 2018, pp. 1–7.

[32] C. S. Yang, C. K. Kim, J.-M. Moon, S.-H. Park, and C. G. Kang, "Channel access scheme with alignment reference interval adaptation (aria) for frequency reuse in unlicensed band LTE: Fuzzy Q-Learning approach," *IEEE Access*, vol. 6, pp. 26 438–26 451, May 2018.

[33] M. Mehrnoush, V. Sathya, S. Roy, and M. Ghosh, "Analytical modeling of Wi-Fi and LTE-LAA coexistence: Throughput and impact of energy detection threshold," *IEEE/ACM Trans. Netw.*, vol. 26, no. 4, pp. 1990–2003, Aug. 2018.