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Enhanced Collision Resolution Methods With Mini-Slot Support for 5G NR-U

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ABSTRACT To improve the capacity of cellular systems without additional expenses on licensed frequency bands, the 3GPP consortium has designed cellular technologies that use the unlicensed spectrum. The important peculiarity of the usage models of these technologies, the latest of which is New Radio Unlicensed (NR-U), is the coexistence with Wi-Fi networks deployed in the same frequency band. That is why NR-U uses channel access methods similar to those of Wi-Fi. However, the performance of Wi-Fi networks notably deteriorates in coexistence scenarios. One of the reasons is the slotted structure of transmissions of cellular base stations in the unlicensed spectrum, which may imply the use of a reservation signal. The paper proposes two novel channel access methods for NR-U, in which an NR-U base station randomly stops sending the reservation signal to listen to the channel to detect and resolve collisions. Analytical models are developed to validate the proposed methods and evaluate their efficiency, taking into account important features of NR-U networks, such as flexible numerology and mini-slot transmissions. The obtained numerical results show that the proposed methods significantly improve the performance of the Wi-Fi or NR-U network without degradation of the throughput of the other technology in coexistence scenarios.

INDEX TERMS 5G, coexistence, collision resolution, mini-slots, NR-U, Wi-Fi.

I. INTRODUCTION

Rapid growth of the amount of mobile traffic makes cellular operators and network developers use more spectrum. One of the most perspective solutions to satisfy the growing throughput requirements without additional payments for the scarce licensed spectrum is the use of license-exempt bands.

That is why in 2015 the 3rd Generation Partnership Project (3GPP) consortium developed the License-Assisted Access (LTE-LAA) technology as a part of the 3GPP Release 13 specification. LTE-LAA enabled operation in the unlicensed spectrum in the 5 GHz band. However, this band was already occupied with consumer electronics using other wireless technologies, e.g., widely deployed Wi-Fi. Thus, the design of LTE-LAA raised a significant coexistence problem of the two technologies in the same frequency band [1]–[4]. Specifically, LTE-LAA and Wi-Fi use slightly different channel access. Modern Wi-Fi devices (STAs) use Enhanced Distributed Channel Access (EDCA), which is based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) [5]. LTE-LAA, in turn, uses the Listen Before Talk (LBT) method to operate in the unlicensed spectrum. As EDCA, LBT is based on carrier sensing with an exponential backoff procedure. But, in contrast to EDCA, LTE-LAA has to follow the same slotted structure of the transmissions as the legacy LTE, i.e., a base station can start data transmission only at the licensed spectrum slot boundaries. Although the backoff procedure may finish at any moment within the LTE slot, the 3GPP specification does not regulate the behavior of the base station until the next slot boundary. Simply waiting for the next slot boundary may result in losing channel access if Wi-Fi stations start transmission before the next slot boundary. Thereby it entails low LTE-LAA performance [6], [7]. For this reason, many research papers [6]–[11] imply that a base station sends a reservation signal until the next slot boundary. The reservation signal prevents the medium from being occupied by other devices. Therefore it improves the performance of cellular

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networks in coexistence scenarios. At the same time, it causes excessive overhead and dramatically reduces the performance of Wi-Fi networks [7], [10], [12].

Recently finished 3GPP Release 16 introduces the New Radio Unlicensed (NR-U) technology, which is an improvement of LTE-LAA for 5G [13]. NR-U base stations inherit the same channel access scheme and coexistence issues [14]–[16]. But in contrast to LTE-LAA, NR-U is more flexible, which is favorable for the operation in the unlicensed spectrum. Specifically, NR-U supports flexible numerology, i.e., the licensed spectrum slots may have configurable duration. In addition, NR-U introduces mini-slot transmissions, which are not restricted to the licensed spectrum slot boundaries and may begin at any OFDM symbol boundary.[1] NR-U features mitigate the drawbacks of the reservation signal by substantially shortening its duration [11].

Being based on CSMA, EDCA and LBT are still collision-prone methods, and some collision avoidance schemes are required in addition to the binary exponential backoff procedure. For example, Wi-Fi stations may perform an RTS/CTS handshake before the data transmission, avoiding long collisions of data frames. However, NR-U does not have such a mechanism to decrease the negative influence of collisions between NR-U and Wi-Fi stations in coexistence scenarios.

The industry considers several ways to provide fair and efficient coexistence of NR-U and Wi-Fi networks in both actively used 5 GHz and promising 6 GHz bands [16]. One of them is to apply a common energy detection threshold in both Wi-Fi and NR-U, which is used to detect transmissions of other technologies. This solution can be easily implemented in new devices, but it is irrelevant for already deployed stations. Another approach is to use a common preamble that may be especially beneficial if some other technologies utilize the mentioned frequency bands in the future. However, neither of the proposals has been standardized so far.

Thus, the coexistence of Wi-Fi and NR-U networks is still an open issue. In our previous paper [18], we proposed a method called LBT with Collision Resolution (CR-LBT) approach that allows NR-U base stations to detect and resolve collisions, thereby improving the overall performance. However, in [18], we tested the efficiency of CR-LBT, assuming that data transmissions can start only at the licensed spectrum slot boundaries. Also, we considered only an error-free channel, which simplifies analysis but is too unrealistic.

The contribution of the paper is as follows. First, we extend the ideas of CR-LBT and design two novel channel access methods for NR-U base stations called eCR-LBT and gCR-LBT, which notably increase the throughput of Wi-Fi or NR-U network without affecting the performance of the other network. Moreover, gCR-LBT can be applied fruitfully with mini-slot transmissions enabled in 5G. Second, we develop analytical models to evaluate the performance of the proposed methods taking into account possible channel errors. Finally, we conduct extensive numerical experiments to show the benefits of eCR-LBT and gCR-LBT in coexistence scenarios as well as pure NR-U deployments.

[1] A mini-slot contains at least two OFDM symbols because of the demodulation reference signal [17]

TABLE 1. Accepted abbreviations.

Abbreviation	Description
RS	reservation signal
STA	Wi-Fi station
gNB	NR-U base station
CR-LBT	LBT with collision resolution
eCR-LBT	enhanced CR-LBT
gCR-LBT	CR-LBT with a guaranteed number of CR slots
MCOT	maximum channel occupancy time
CR interval	collision resolution interval
CR slot	collision resolution slot

The rest of the paper is organized as follows. In Section II, we compare the channel access methods of Wi-Fi and NR-U operating in the 5 GHz band. The overview of the related research is presented in Section III. Section IV describes CR-LBT [18] and the proposed methods. In Section V, we design analytical models to evaluate the efficiency of our proposals. The results of our numerical experiments are presented in Section VI. The concluding remarks are summarized in Section VII. The list of the accepted abbreviations is in Table 1.

II. COMPARISON OF CHANNEL ACCESS METHODS IN UNLICENSED 5 GHz BAND

In this section, we discuss channel access methods for the unlicensed spectrum in Wi-Fi and NR-U.

A. WI-FI NETWORKS: ENHANCED DISTRIBUTED CHANNEL ACCESS

Modern Wi-Fi stations employ Enhanced Distributed Channel Access based on CSMA/CA [5]. Before frame transmission, each STA senses the channel. If the channel is idle, the STA starts the transmission. Otherwise, the STA waits until the channel becomes idle for Arbitration Inter-Frame Space (AIFS) and performs an exponential backoff procedure. In particular, the STA initializes a backoff counter with a random integer number uniformly distributed on $[0, W-1]$, where W is called the contention window. Then, the STA decrements the backoff counter each time the channel is sensed idle for the time $\sigma = 9$ μs. If the STA detects the channel busy, it suspends the backoff counter. The STA resumes the backoff counter when the channel is idle for an AIFS.

When the backoff counter reaches zero, the STA starts the transmission. The transmission may contain several MAC Protocol Data Units (MPDUs), but the duration of a frame exchange sequence does not exceed $\text{TXOP}_{\text{limit}}$ (transmit opportunity limit). To reduce overhead, modern Wi-Fi STAs support aggregation, i.e., concatenating several frames in the transmission in an aggregated MPDU (A-MPDU). Moreover, frames in A-MPDU may be decoded independently. Each of the aggregated frames contains a special bit responsible for soliciting a Block Acknowledgment (BA) frame. The BA frame indicates which data frames are delivered and which ones are lost. Thus, if the recipient successfully decodes the A-MPDU preamble and at least one aggregated frame, it replies with a BA frame.

Initially, the contention window is set to W_{min}. If the STA receives no acknowledgment, it repeats the backoff procedure and transmits undelivered frames again. Every retry, the STA doubles the contention window until it reaches the maximal value $W_{max} = 2^m W_{min}$, where $m \in \mathbb{N}$. The STA resets the contention window to W_{min} after a successful transmission attempt, i.e., after receiving an acknowledgment frame.

With EDCA, the STA has four queues mapped to four access categories (ACs) corresponding to different Quality-of-Service (QoS) traffic classes. Each AC has its own set of EDCA parameters (AIFS, $TXOP_{limit}$, etc.), providing differentiation in the channel contention and the amount of airtime.

STAs may use the Request To Send/Clear To Send (RTS/CTS) mechanism to protect long transmissions from collisions. Specifically, after the end of the backoff procedure, a STA may send a short RTS frame. Having decoded the RTS frame, the receiver replies with a short CTS frame after a Short Inter-Frame Space (SIFS). SIFS after receiving the CTS frame, the originating STA starts data transmission. Both RTS and CTS frames have a field that indicates the duration of the subsequent frame exchange. Therefore, all the STAs that receive RTS and/or CTS frames consider the channel busy during the indicated time and do not contend for the channel. If the collision does happen, it involves short RTS/CTS frames and is quickly detected.

B. LTE-LAA/NR-U NETWORKS: LISTEN BEFORE TALK

Both NR-U and LTE-LAA operate based on the carrier aggregation framework. It means that they need a licensed carrier. NR-U base stations (gNBs) reuse the same channel access mechanism for downlink transmissions as LTE-LAA that is Listen Before Talk (LBT) [17]. It has much in common with EDCA used in Wi-Fi networks. For example, LBT is also based on CSMA/CA with a binary exponential backoff procedure and supports four priority classes (PCs) that correspond to EDCA ACs, see Table 2. The maximum duration of a continuous transmission is limited and defined as the MCOT (Maximum Channel Occupancy Time), which corresponds to $TXOP_{limit}$ in Wi-Fi.

The adjustment of the contention window size relies on a Hybrid Automatic Repeat Request (HARQ) feedback. If the transmission lasts for several slots, each slot is acknowledged separately. The transmission may be unsuccessful because of collisions or noise in the channel. Note that only HARQ acknowledgments (Acks) related to the beginning of channel occupancy time are taken into account. It allows increasing the contention window only after collisions but not after a noise-induced transmission failure [13].

NR-U transmissions have the following periodical structure. The transmissions are organized into 1 ms subframes divided into slots of duration θ (licensed spectrum slots), each containing 14 OFDM symbols. Moreover, NR introduces flexible numerology, i.e., the licensed spectrum slot length can be configured as shown in Table 3. Specifically, NR-U gNBs can use subcarrier spacings of 15 kHz and 30 kHz in 5 GHz band. In contrast, LTE-LAA supports only 500 μs slots, each containing seven OFDM symbols.

TABLE 2. Channel access parameters for different LBT priority classes in downlink.

Priority class	W_{min}	W_{max}	MCOT, ms
1	4	8	2
2	8	16	3
3	16	64	8
4	16	1024	8

TABLE 3. Flexible numerology in NR.

Subcarrier spacing, kHz	OFDM symbol duration, μs	Slot duration, μs
15	71.4	1000
30	35.6	500
60	17.9	250
120	8.92	125
240	4.46	62.5

LTE-LAA base stations can start the transmission only at the licensed spectrum slot boundaries. However, the behavior of the base station in the gap between the end of the backoff procedure and the next licensed slot boundary is not specified. It is suggested [6]–[11] that a gNB sends a reservation signal (RS) to prevent the medium from occupying by other devices. The RS boosts the performance of cellular networks, but it also has considerable drawbacks thoroughly discussed in [6], [18].

Although NR-U inherits the same periodic structure of transmissions, it also supports mini-slot transmissions. Such a transmission may begin with a granularity of one OFDM symbol rather than a licensed spectrum slot, and the first slot in the transmission (mini-slot) may occupy from 2 to 13 OFDM symbols [13]. Consequently, it allows almost immediate data transmission after the end of the backoff procedure.

Mentioned NR-U features are highly beneficial for operation in the unlicensed spectrum. However, NR-U still does not have any mechanism, e.g., such as RTS/CTS in Wi-Fi, to handle collisions among gNBs only or among gNBs and STAs. It is crucial for NR-U performance because collisions of long NR-U transmissions waste much channel time.

III. RELATED PAPERS

The coexistence of Wi-Fi and LTE-LAA/NR-U technologies in the unlicensed bands is discussed in many papers [7], [10], [11], [15], [19]–[21].

The research in [7] illustrates that the usage of the reservation signal significantly improves the throughput and access delay in LTE-LAA networks. However, the performance of Wi-Fi networks degrades. In [15], the authors present a profound overview of NR-U operation supported with simulations of indoor and outdoor coexistence scenarios. They show that NR-U usually outperforms Wi-Fi in terms of throughput and latency. The authors in [11] study the influence of mini-slot transmissions on the performance of NR-U and Wi-Fi networks in coexistence scenarios. They consider channel access methods both with the RS and without it. It is demonstrated that utilizing small licensed spectrum slots without the RS may improve fairness in coexistence scenarios. In contrast to analytical modeling and simulations, in [21], the authors measure the performance of LTE-LAA and Wi-Fi networks deployed in Chicago. They show that LTE-LAA notably increases the throughput of cellular networks, but the average delay in Wi-Fi networks substantially increases in coexistence scenarios.

Many studies [10], [19], [20] conclude that the operation with default LBT channel access parameters (MCOT, W_{min}, etc.) is unfair to Wi-Fi networks. The authors in [20] show that adjusting some LBT parameters (AIFS and W_{min}) improves fairness. Moreover, in [19], the authors demonstrate that proportional fairness can be achieved by tuning the duration of LTE-LAA transmission.

Many solutions are proposed in the literature to improve the performance of Wi-Fi and LTE-LAA/NR-U networks in various coexistence scenarios. Studies [9], [22] focus on the impact of the energy detection threshold. The default energy detection threshold in LTE-LAA is lower than in Wi-Fi, leading to unfair coexistence. Therefore, in [22], the authors propose two algorithms to adaptively change the threshold for LTE-LAA, which are beneficial for the performance of the cellular network.

A set of papers [23]–[26] considers modifications of LBT in which the adjusting of the contention window is not exponential. In [23], machine learning is used to predict the optimal size of the contention window of LTE-LAA based on the number of negative acknowledgments. The authors of [24] calculate the collision probability based on the share of negative HARQ acknowledgments and the occupancy of the channel estimated during the backoff procedure. They use the calculated probability to scale the contention window of LTE-LAA stations optimally. According to the results, both approaches [23], [24] improve fairness in coexistence scenarios. Moreover, in [25], [26], the authors propose several schemes of adjusting contention window bounds for LTE-LAA based on the real-time estimation of Wi-Fi activity.

In [27], the authors suggest varying the ratio of $\text{TXOP}_{\text{limit}}$ and MCOT to equalize the throughputs of the networks. However, they do not consider the aggregate performance of the system, which may degrade because of shortening the transmission duration.

Some alternatives to the legacy LBT scheme are presented in [28]–[30]. In [28], the authors propose a *p*-persistent modification of LBT and design an adaptive algorithm to select the optimal value of *p*. The authors in [29] suggest LTE-LAA to utilize a CTS-to-self frame defined in the Wi-Fi standard to access the channel. In [30], the authors assign different transmission probabilities to LTE-LAA stations, allowing for fairness and channel conditions. The proposed scheme provides a high gain in LTE-LAA throughput and proportional fairness among cellular stations.

All the mentioned solutions are aimed at either improving LTE-LAA performance or achieving fairness. However, these approaches imply significant changes in corresponding specifications and standards, which limits backward compatibility.

In [31], the authors propose a collision resolution method called R-SplitC for NR-U networks. They show that R-SplitC improves the performance of cellular networks. However, they design an analytical model only for pure NR-U deployments. The coexistence scenario is studied only with simulation and for equal numbers of gNBs and STAs, ignoring scenarios with other shares of STAs. In addition, in contrast to CR-LBT, R-SplitC cannot resolve collisions among gNBs and STAs without corrupting a Wi-Fi frame. Moreover, in [31], non-default channel access parameters (CW_{max}, $\text{TXOP}_{\text{limit}}$) for Best Effort AC are used [11]. Combined with considering only ideal channel conditions, it may notably affect the accuracy of the performance evaluation.

In our previous study [18], we proposed a CR-LBT channel access method (CR-LBT) for 5G NR-U. CR-LBT significantly increases the throughput of Wi-Fi networks. Furthermore, the CR-LBT requires minor changes in the 3GPP specifications and may be implemented at the gNB side. However, as shown in [18], when the number of STAs is greater than the number of gNBs, the throughput of NR-U network degrades up to 50% relative to LBT with the RS. In addition, that paper does not consider mini-slot transmissions, and the model assumes an error-free channel.

In contrast, in this paper, we propose novel eCR-LBT and gCR-LBT channel access methods with a more configurable behavior of gNBs in collisions. The methods provide a throughput gain for NR-U or Wi-Fi network while keeping the performance of the other technology the same as in the case when gNBs use the legacy LBT method with the RS. Moreover, when we design analytical models to evaluate the performance of the proposed methods, we take into account mini-slots transmissions and imperfect channel conditions.

IV. COLLISION RESOLUTION METHODS

In this section, we discuss the original CR-LBT and its weaknesses. Then we describe the methods developed in this paper to eliminate the drawbacks of CR-LBT. For brevity, we introduce the term of a *gNB's starting point* that is a moment when the gNB can start data transmission. Let L be the period of the starting points. Then, $L = \theta/14$ if mini-slot transmissions are used, and $L = \theta$, otherwise, where θ is the duration of the licensed spectrum slot.

A. DESCRIPTION OF CR-LBT

Let us describe the key ideas of CR-LBT [18]. Using CR-LBT, the gNB divides the time interval t between the end of the backoff procedure and the next starting point into Collision Resolution slots (CR slots) of duration δ.

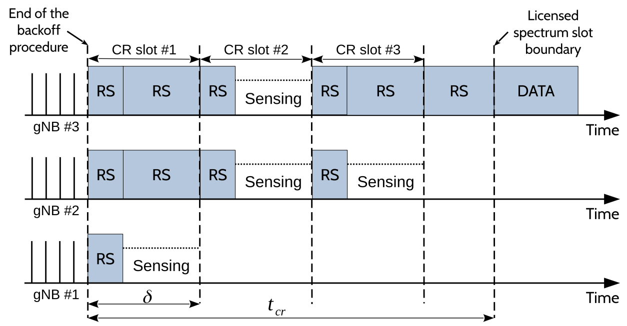

FIGURE 1. An example of channel access with eCR-LBT, $L = \theta$.

The number of available CR slots is calculated as follows:

$$k = \left\lfloor \frac{t}{\delta} \right\rfloor, \tag{1}$$

and since $0 \leq t < L$, the maximum number of CR slots K_L equals

$$K_L = \left\lfloor \frac{L}{\delta} \right\rfloor. \tag{2}$$

Each CR slot has the following structure. At the beginning of the CR slot, the gNB sends the RS of the duration T_{reserv}. In the second part of the CR slot of the duration $T_{sense} = \delta - T_{reserv}$, the gNB either keeps sending the RS or listens to the channel. If a gNB finds the channel busy while listening during the interval T_{sense}, it detects the collision, postpones the transmission, doubles the contention window, and repeats the backoff procedure. Otherwise, i.e., if the gNB either finds the channel idle or sends the RS for T_{sense}, it moves to the next CR slot (if any). If the gNB does not postpone its transmission after all CR slots or $k = 0$, it sends the RS until the next starting point and then transmits data. The time interval t_{cr} containing CR slots and the subsequent RS is called the Collision Resolution interval (CR interval). The particular values of $T_{reserve}$ and T_{sense} are discussed in [18].

In the first CR slot, the gNB always senses the channel to detect possible collisions with STAs. In each of the next CR slots, the gNB sends the RS during T_{sense} with probability ξ and listens to the channel with probability $(1 - \xi)$.

Let us discuss the disadvantages of CR-LBT [18]. First, if a collision involves gNBs and STAs, the gNBs always postpone their transmissions after the first CR slot. Such an approach gives Wi-Fi an unfair advantage over NR-U in scenarios with the predominant number of STAs. Second, the gNBs cannot resolve collisions among them unless the CR interval contains at least two CR slots. Moreover, as we show in Section VI, CR-LBT is ineffective if a gNB uses a configuration with short periods of starting points (e.g., mini-slot transmissions).

B. eCR-LBT AND gCR-LBT

In this paper, we design two novel methods, which work as follows. The first one is Enhanced CR-LBT (eCR-LBT),

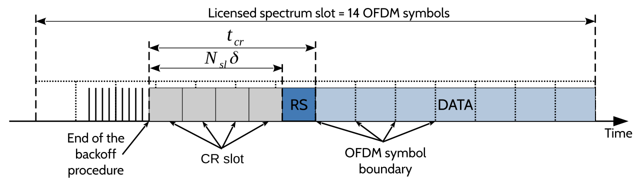

FIGURE 2. An example of channel access with gCR-LBT with $N_{sl} = 4$ and mini-slot transmissions ($L = \theta/14$).

which is a more flexible successor of CR-LBT. With eCR-LBT, a gNB sends the RS in the first CR slot during T_{sense} with probability ϕ and listens to the channel with probability $(1-\phi)$. The behavior of the gNB in the subsequent CR slots is the same as with CR-LBT and described above. Note that $\phi = 0$ in CR-LBT [18].

In contrast to the CR-LBT, which requires at least two CR slots for collision resolution, eCR-LBT can resolve collisions among gNBs even if only one CR slot is available. Moreover, the new parameter ϕ allows more flexible tuning of the method by regulating gNBs' behavior towards STAs in the first CR slot. As we show in Section VI, it is important in coexistence scenarios with a high percentage of STAs.

The second method called gCR-LBT is an extension of CR-LBT with a **g**uaranteed number of CR slots, which makes ideas of CR-LBT appropriate for mini-slot transmissions. With gCR-LBT, a gNB always allocates a predefined number $N_{sl} > 0$ of CR slots after the end of the backoff procedure even if $K_L < N_{sl}$, see Fig. 2. The structure of CR slots is the same as in eCR-LBT, i.e., a gNB sends the RS during T_{sense} in the first CR slot with probability ϕ and in the subsequent CR slots with probability ξ. Having processed N_{sl} CR slots, the gNB sends the RS till the next starting point, followed by data transmission. Thus, gCR-LBT is the most effective for the configurations with a short period L of starting points. Note that the duration of the gap between the end of the backoff procedure and the next starting point $t = t_{cr}$ with the CR-LBT and eCR-LBT methods and $t \leq t_{cr}$ with gCR-LBT.

In this paper, we propose to choose the number of CR slots N_{sl} so that it is enough to resolve possible collisions, but at the same time, it does not add excessive overhead. We study how to select the appropriate value of N_{sl} in Section VI. As a result, gCR-LBT combines the features of both eCR-LBT and mini-slots transmissions.

Another advantage of gCR-LBT is related to the case when gNBs count licensed spectrum slots asynchronously. With CR-LBT, asynchronous counting leads to unfair contention for the channel because each gNB processes different numbers of CR slots. In contrast, gCR-LBT provides equal probabilities of collision resolution for all gNBs involved in the collision because each of them handles exactly N_{sl} CR slots.

V. ANALYTICAL MODELS

In this section, we develop analytical models for eCR-LBT and gCR-LBT. In Section V-A, we describe the considered system. We formulate and prove two theorems that

TABLE 4. Accepted notations.

Notation	Description
θ	duration of a licensed spectrum slot
L	period of gNB's starting points
δ	duration of a CR slot
t	duration of the gap between the end of the backoff procedure and the next starting point
t_{cr}	duration of the CR interval
ϕ	probability that a gNB does not listen to the channel in CR slot #1
ξ	probability that a gNB does not listen to the channel in CR slot $\#i$, where $i > 1$
N_{sl}	number of guaranteed CR slots in gCR-LBT
K_L	maximal number of CR slots
$T_{w,s}$	duration of Wi-Fi successful transmission
$T_{w,c}$	duration of Wi-Fi unsuccessful transmission
T_l	duration of NR-U transmission
d_w (d_l)	Wi-Fi (NR-U) nominal data rate
N_w (N_l)	number of STAs (gNBs) in the network
q_w (q_l)	probability that a STA's subframe (gNB's slot) does not encounter channel errors
η	probability that a Wi-Fi receiver manages to decode the frame preamble thanks to the capture effect
$W_{min,w}$ ($W_{min,l}$)	minimal size of the contention window for STA (gNB)
$W_{max,w}$ ($W_{max,l}$)	maximal size of the contention window for STA (gNB)
τ_w (τ_l)	probability that a given STA (gNB) selects the current virtual slot for a transmission
ρ_w (ρ_l)	probability that a given STA (gNB) doubles the contention window after the transmission
$\pi_{w,s}, \pi_l, \pi_e$	probability that a virtual slot has a duration of $T_{w,s}, T_l, \sigma$ respectively
σ	duration of an empty virtual slot
T_{slot}	average duration of a virtual slot
S_w (S_l)	total throughput of Wi-Fi (NR-U) network

mathematically represent the behavior of gNBs in collisions according to the proposed methods in Section V-B. Then we use the theorems to design network models in Sections V-C and V-D. For convenience, major notations are listed in Table 4.

A. CONSIDERED SYSTEM

We consider a network with N_l gNBs and N_w STAs operating over the same frequency band in a single 20 MHz channel. The network is saturated, i.e., each node always has frames to transmit, and the number of retransmissions is unlimited. All STAs and gNBs are located in the transmission range of each other, and there are no hidden terminals. Also, we assume that the licensed spectrum slot boundaries of all gNBs are synchronized.

A gNB transmission lasts for T_l, including the CR interval of duration t_{cr}, and consists of several complete NR-U slots because MCOT is multiple of θ. We assume that the time interval t between the end of the backoff procedure and the next starting point is uniformly distributed on the interval $[0, L)$. d_l denotes NR-U data rate, i.e., each full licensed spectrum slot contains a payload of size $d_l\theta$.

A successful Wi-Fi transmission lasts for $T_{w,s} \leq T_l$ and contains n_w aggregated subframes. The duration of the Wi-Fi collision is $T_{w,c} \ll T_{w,s}$ if RTS/CTS mechanism is used and $T_{w,c} \approx T_{w,s}$ otherwise. Each Wi-Fi subframe contains the payload of size $d_w T_{w,s}/n_w$, where d_w is a Wi-Fi data rate.

Let q_w (q_l) be the probability that a particular Wi-Fi subframe (data in NR-U licensed spectrum slot) is not affected by channel errors, i.e., $q_w = q_l = 1$ corresponds to the ideal channel considered in [18]. Additionally, we assume that the probability q_l remains the same for incomplete NR-U slots (first and/or last slot in the channel occupancy time).

B. PROBABILITY OF gNB's TRANSMISSION AFTER THE CR INTERVAL

Theorem 1: Consider that n gNBs and, maybe, some STAs simultaneously finish the backoff procedure, and k CR slots are available ($n \geq 1$, $k \geq 0$). The STAs (if any) transmit in the channel in the first w CR slots, $0 \leq w \leq k$. Then the probability $C(n, k, w)$ that ***exactly one gNB*** *does not postpone its transmission after k CR slots equals*

$$C(n,k,w) = \begin{cases} 1, & n=1, \quad k \geq 0, \ w=0; \\ \phi\xi^{w-1}, & n=1, \quad k>0, \ w>0; \\ 0, & n>1, \quad k=0, \ w=0; \\ n\phi(1-\phi)^{n-1}, & n>1, \quad k=1, \ w \leq k; \\ (1-\phi)^n C^*(n,k-1,0) & \\ +\sum_{i=1}^{n}\binom{n}{i}\phi^i(1-\phi)^{n-i} & \\ \times C^*(i,k-1,0), & n>1, \quad k>1, \ w=0; \\ \sum_{i=1}^{n}\binom{n}{i}\phi^i(1-\phi)^{n-i} & \\ \times C^*(i,k-1,w-1), & n>1, \quad k>1, \ w>0, \end{cases} \tag{3}$$

where $C^*(n,k,w) = C(n,k,w)|_{\phi=\xi}$.

Proof: Note that $w = 0$ corresponds to the case when $k = 0$ or the collision involves only gNBs.

Suppose that exactly one gNB finishes the backoff procedure. If there are no available CR slots ($k = 0$), the gNB is unable to detect a collision with STAs, hence it does not postpone its transmission, i.e., $C(1, 0, 0) = 1$. If $k > 0$ and there are no STAs transmitting in the channel ($w = 0$), the collision does not occur, i.e., $C(1, k > 0, 0) = 1$. If there are $k > 0$ CR slots available, but STAs also transmit ($w > 0$), the gNB should not listen to the channel until it becomes idle, i.e., $C(1, k > 0, w > 0) = \phi\xi^{w-1}$.

Suppose that the collision involves $n > 1$ gNBs. $k = 0$ means that the gNBs are unable to detect any collisions and all of them start the transmissions, i.e., $C(n > 1, 0, 0) = 0$. If $k = 1$, to resolve the collision exactly one gNB should not listen to the channel in this CR slot, i.e., $C(n > 1, 1, w \geq 0) = n\phi(1-\phi)^{n-1}$.

For the other values of k, the probability $C(n, k, w)$ is calculated recursively for known $C^*(n, k-1, w-1)$ and $C^*(n-1, k-1, w-1)$, where $C^*(n, k, w) = C(n, k, w)$ provided that ϕ in (3) is replaced with ξ.

Let us consider the case $\{n > 1, k > 1, w = 0\}$ in detail. If all gNBs simultaneously listen to the idle channel (it happens with probability $(1-\phi)^n$), none of them postpone the transmission, and n gNBs remain participating in the collision resolution procedure. If $i < n$ gNBs do not listen to the channel (it happens with probability $\binom{n}{i}\phi^i(1-\phi)^{n-i}$), then $(n-i)$ gNBs postpone the transmission and i gNBs remain contending for the channel.

The difference between the last two cases in (3) reflects that if all gNBs simultaneously listen to the busy channel ($w > 0$), all of them postpone the transmission. □

Theorem 2: Let the conditions of Theorem 1 hold. Then the probability $B(n, k, w)$ that ***at least one gNB*** *does not postpone its transmission after k CR slots equals*

$$B(n,k,w) = \begin{cases} 1, & n>0, \quad k \geq 0, \quad w=0; \\ 1-(1-\phi)^n, & n>0, \quad k=1, \quad w=1; \\ \phi\xi^{w-1}, & n=1, \quad k>0, \quad w>0; \\ \sum_{i=1}^{n}\binom{n}{i}\phi^i(1-\phi)^{n-i} & \\ \times B^*(i,k-1,w-1), & n>1, \quad k>1, \quad w>0, \end{cases} \tag{4}$$

where $B^*(n,k,w) = B(n,k,w)|_{\phi=\xi}$.

Proof: If there are no available CR slots ($k = 0$), the gNBs do not listen to the channel, hence they do not postpone the transmission, i.e., $B(n > 0, 0, 0) = 1$. If the collision involved gNBs only, at least one of the gNBs starts its transmission after the CR interval, i.e., $B(n > 0, k \geq 0, 0) = 1$.

Suppose that one CR slot is available and at least one STA is involved in the collision ($k = w = 1$). Then all the gNBs postpone their transmission as long as all of them listen to the channel in that CR slot, i.e., $B(n > 0, 1, w > 0) = 1-(1-\phi)^n$.

Suppose that the collision involves one or several STAs ($w > 0$) and exactly one gNB provided that $k > 0$. Then the gNB should not listen to the channel until it becomes idle, i.e., $B(1, k > 0, w > 0) = \phi\xi^{w-1}$.

In other cases, the probability $B(n, k, w)$ is calculated recursively for known $B^*(n, k-1, w-1)$. In particular, if i gNBs do not listen to channel in the first CR slot (it happens with probability $\binom{n}{i}\phi^i(1-\phi)^{n-i}$), each of $(n-i)$ gNBs postpones its transmission and only i gNBs remain.

We can derive the expression for $B^*(n, k, w)$ by replacing ϕ in (4) with ξ. □

Both theorems remain correct if Wi-Fi transmission is longer than the CR interval, $w > k$. In this case, we take $w = k$, i.e., $C(n, k, w) = C(n, k, min(k, w))$ and $B(n, k, w) = B(n, k, min(k, w))$.

C. MODEL OF eCR-LBT

Similar to [18], [32], we assume that the backoff counters of all nodes work synchronously and that the probability that a STA(gNB) doubles the size of contention window after its transmission attempt does not depend on the backoff stage and the number of retransmissions in the past. Thus, we can apply a well-known approach based on the term of the virtual slot. A virtual slot is a time interval between the two consecutive countdowns of a backoff counter. For further analysis, we introduce the following probabilities:

- τ_w (τ_l) is the probability that a given STA (gNB) selects the current virtual slot for a transmission;
- ρ_w (ρ_l) is the probability that a given STA (gNB) doubles its contention window after the transmission attempt.

Similar to [32], to find τ_w (τ_l), we compute the average number of virtual slots counted by a STA (a gNB) before a transmission attempt:

$$\tau_w = \frac{2}{1 + W_{min,w} + \rho_w W_{min,w}\frac{1-(2\rho_w)^{m_w}}{1-2\rho_w}}; \tag{5}$$

$$\tau_l = \frac{2}{1 + W_{min,l} + \rho_l W_{min,l}\frac{1-(2\rho_l)^{m_l}}{1-2\rho_l}}, \tag{6}$$

where $m_w = \log_2(W_{max,w}/W_{min,w})$ and $m_l = \log_2(W_{max,l}/W_{min,l})$ are the number of STA's and gNB's backoff stages respectively.

To find ρ_w, we first consider the probability of the complementary event. We assume that the Wi-Fi preamble is virtually concatenated to the first subframe. Thus, a Wi-Fi transmission is unsuccessful if the first subframe is corrupted by channel errors or collisions. Moreover, suppose a collision involves several gNBs and one STA. Then if all gNBs detect the collision in the first CR slot and channel errors do not corrupt the first subframe, we assume that the Wi-Fi receiver manages to demodulate the preamble of the frame thanks to the capture effect [33] with probability η. If a Wi-Fi frame overlaps with another frame under other conditions, the transmission fails. As a result, a given STA has a successful transmission in the current virtual slot if the following conditions are met:

- none of the other STAs select the virtual slot for transmission (it happens with probability $(1-\tau_w)^{N_w-1}$);
- either none of gNBs select the virtual slot for transmission (it happens with probability $(1-\tau_l)^{N_l}$) or exactly $i = 1, 2, \ldots, N_l$ gNBs select it (it happens with probability $\binom{N_l}{i}\tau_l^i(1-\tau_l)^{N_l-i}$), but:
  - the number of available CR slots is greater than zero (it happens with probability $1-\delta/L$);
  - all gNBs involved into collision detect the STA's transmission in the first CR slot (it happens with probability $(1-\phi)^i$);
  - a Wi-Fi receiver manages to demodulate the preamble thanks to the capture effect (it happens with probability η);
- the first subframe does not encounter channel errors (it happens with probability q_w).

As a result, we calculate ρ_w as follows:

$$\rho_w = 1 - q_w(1-\tau_w)^{N_w-1} \times\left[(1-\tau_l)^{N_l} + \eta\left(1-\frac{\delta}{L}\right) \times \sum_{i=1}^{N_l}\binom{N_l}{i}\tau_l^i(1-\tau_l)^{N_l-i}(1-\phi)^i\right]. \quad (7)$$

The same method is used to find ρ_l. Let $\alpha(n, w)$ be the probability that after a collision of n gNBs and maybe some STAs, exactly one gNB does not postpone its transmission, and this transmission does not overlap with Wi-Fi data transmissions (if any). By averaging the probability $C(n, k, w)$ given by (3) over possible numbers k of CR slots, we can find $\alpha(n, w)$ as follows:

$$\alpha(n, w) = \sum_{k=0}^{K_L-1}\frac{\delta}{L}C(n, k, w)z(k, w) + \left(1 - K_L\frac{\delta}{L}\right)C(n, K_L, w)z(K_L, w), \quad (8)$$

where $z(k, w)$ denotes the probability that a gNB's data transmission does not overlap with a Wi-Fi frame (if any). In particular, the overlapping does not happen as long as the duration of the CR interval t_{cr} is less than $T_{w,c}$:

$$z(k, w) = \begin{cases} 1, & k \geq w; \\ \dfrac{(k+1)\delta - T_{w,c}}{\delta}, & k = w-1; \\ 0, & k < w-1. \end{cases} \quad (9)$$

Note that $z(k, w) \equiv 1$ provided that the collision involves gNBs only.

A given gNB does not increase the contention window after the transmission in the current virtual slot if the first slot in the transmission experiences no channel errors (it happens with probability q_l) and one of the following conditions is met:

- none of the STAs selects the virtual slot for transmission, and only the given gNB starts its transmission after the CR interval (it happens with probability $p_{l,1}$);
- at least one STA selects the virtual slot for transmission, and: (i) only the given gNB starts the transmission after the CR interval, and (ii) all the STAs finish their transmissions before the given gNB starts its transmission (it happens with probability $p_{l,2}$).

Using (8), we calculate the probabilities $p_{l,1}$ and $p_{l,2}$ as follows:

$$p_{l,1} = (1-\tau_w)^{N_w}\sum_{i=0}^{N_l-1}\binom{N_l-1}{i}\tau_l^i \times(1-\tau_l)^{N_l-1-i}\frac{\alpha(i+1, 0)}{i+1}; \quad (10)$$

$$p_{l,2} = (1-(1-\tau_w)^{N_w})\sum_{i=0}^{N_l-1}\binom{N_l-1}{i}\tau_l^i \times(1-\tau_l)^{N_l-1-i}\frac{\alpha\left(i+1, \lceil T_{w,c}/\delta\rceil\right)}{i+1}. \quad (11)$$

As a result, we use (10) and (11) to find the probability ρ_l as follows:

$$\rho_l = 1 - q_l(p_{l,1} + p_{l,2}). \quad (12)$$

Jointly solving the system of equations (5)–(7) and (12), we compute the probabilities τ_w, τ_l, ρ_w, ρ_l.

Let us find the throughput of the Wi-Fi network. Let $\pi_{w,s}$ be the probability that some STA has a successful transmission in a given virtual slot. Using (7), we can express $\pi_{w,s}$ as follows:

$$\pi_{w,s} = N_w\tau_w(1-\rho_w). \quad (13)$$

If the transmission is successful, the receiving STA always decodes the first subframe, which contains the payload of size $d_wT_{w,s}/n_w$, and, with probability q_w, decodes each of the rest $(n_w - 1)$ subframes which contain the payload of size $(n_w - 1)\, d_wT_{w,s}/n_w$. As a result, we obtain:

$$S_w = \frac{\pi_{w,s}}{T_{slot}}(1 + (n_w-1)\, q_w)d_w\frac{T_{w,s}}{n_w}, \quad (14)$$

where T_{slot} is the average duration of the virtual slot (to be derived in (24)).

Let us find the throughput of the NR-U network. We assume that if the part of the NR-U slot is corrupted, the whole slot is lost.

Suppose that one gNB and maybe some STAs simultaneously finish the backoff procedure. If the gNB does not postpone its transmission after the CR interval, which includes k CR slots, it successfully delivers $p(k, w)$ payload on average:

$$p(k, w) = X(k, w)\theta d_lq_l + (\theta - k\delta - \frac{\delta}{2})d_lq_l, \quad (15)$$

where $X(k, w)$ is the number of complete licensed spectrum slots not distorted by collision in the gNB's data transmission; $(k\delta + \delta/2)$ is the average duration of the CR interval, which includes k CR slots. The second component in (15) reflects the payload contained in the last NR-U slot. This payload is less than θd_l because the channel occupancy time T_l includes the CR interval. We find the number of slots $X(k, w)$ as follows:

$$X(k, w) = \begin{cases} \dfrac{T_l}{\theta} - 1, & w = 0; \\ \dfrac{T_l}{\theta} - 1 - \left\lceil\dfrac{\max(T_{w,c} - k\delta - \delta/2, 0)}{\theta}\right\rceil, & w > 0. \end{cases} \quad (16)$$

The first case in (16) reflects that gNB's transmission contains only one incomplete slot because of the CR interval if no STAs are involved. Additionally, the other case takes into account that a Wi-Fi frame may be longer than the CR interval and, therefore, collide with several NR-U slots.

Suppose a collision involves n gNBs and, maybe, some STAs. Let $D(n, w)$ be the average payload that can be delivered in the NR-U network if the collision is resolved. Averaging $C(n, k, w)$ obtained with (3) over the number k of CR slots and using (15), we can calculate $D(n, w)$ as follows:

$$D(n,w) = \sum_{k=0}^{K_L-1} \frac{\delta}{L} C(n,k,w)p(k,w) + \left(1 - K_L\frac{\delta}{L}\right) C(n,K_L,w)p(K_L,w). \quad (17)$$

Suppose that some gNBs select the current virtual slot for transmission and one of the following conditions is met:

- none of STAs select the virtual slot for transmission, and exactly one gNB does not postpone its transmission after the CR interval. In this case, on average, the payload of size $d_{l,1}$ is delivered in the NR-U network.
- several STAs select the virtual slot for transmission, but exactly one gNB does not postpone its transmission after the CR interval. In this case, on average, the payload of size $d_{l,2}$ is delivered in the NR-U network.

By averaging $D(i, 0)$ over i, we obtain:

$$d_{l,1} = (1-\tau_w)^{N_w} \sum_{i=1}^{N_l} \binom{N_l}{i} \tau_l^i (1-\tau_l)^{N_l-i} D(i,0). \quad (18)$$

Similarly to (18), we calculate $d_{l,2}$ as follows:

$$d_{l,2} = \left(1 - (1-\tau_w)^{N_w}\right) \times \sum_{i=1}^{N_l} \binom{N_l}{i} \tau_l^i (1-\tau_l)^{N_l-i} D(i, \lceil T_{w,c}/\delta \rceil). \quad (19)$$

As a result, on average, the gNBs deliver the payload of size $(d_{l,1} + d_{l,2})$ in one virtual slot, and we can calculate the throughput of the NR-U network as follows:

$$S_l = \frac{d_{l,1} + d_{l,2}}{T_{slot}}. \quad (20)$$

Let us find the average duration of a virtual slot T_{slot}. The probability $\pi_{w,s}$ that a virtual slot has a duration of $T_{w,s}$ is given by (13). Also, the probability π_e of an empty virtual slot of duration σ is expressed via (5)–(6) as follows:

$$\pi_e = (1-\tau_l)^{N_l}(1-\tau_w)^{N_w}. \quad (21)$$

Let us compute the probability π_l that the current virtual slot contains a gNB's transmission and, consequently, has a duration of T_l. To begin with, we introduce the probability $\beta(n, w)$ that at least one gNB does not postpone its transmission after the CR interval. To find $\beta(n, w)$, we average $B(n, k, w)$ given by (4) over the number k of CR slots:

$$\beta(n,w) = \sum_{k=0}^{K_L-1} \frac{\delta}{L} B(n,k,w) + \left(1 - K_L\frac{\delta}{L}\right) B(n,K_L,w). \quad (22)$$

The virtual slot has a duration of T_l if at least one gNB starts its transmission after the CR interval, i.e., one of the following conditions is met:

- at least one gNB and no STAs select the virtual slot for transmission (it happens with probability $\left(1-(1-\tau_l)^{N_l}\right)(1-\tau_w)^{N_w}$);
- $i = 1, 2, \ldots, N_l$ gNBs and at least one STA select the virtual slot for transmission (it happens with probability $(1-(1-\tau_w)^{N_w})\binom{N_l}{i}\tau_l^i(1-\tau_l)^{N_l-i}$), but at least one gNB does not postpone its transmission after the CR interval.

Using (22), we find π_l as follows:

$$\pi_l = (1-\tau_w)^{N_w}\left(1-(1-\tau_l)^{N_l}\right) + \left(1-(1-\tau_w)^{N_w}\right) \times \sum_{i=1}^{N_l} \binom{N_l}{i} \tau_l^i (1-\tau_l)^{N_l-i} \beta\left(i, \lceil T_{w,c}/\delta \rceil\right). \quad (23)$$

As a result, with (13), (21) and (23), we derive the expression for the average virtual slot duration as follows:

$$T_{slot} = \pi_{w,s}T_{w,s} + \pi_e\sigma + \pi_l T_l + (1 - \pi_e - \pi_{w,s} - \pi_l)T_{w,c}. \quad (24)$$

Thus, we obtain all the necessary values to calculate the throughputs of both Wi-Fi and NR-U networks with equations (14) and (20), respectively.

D. MODEL OF gCR-LBT

In the gCR-LBT model, we use the same definitions of values introduced in the eCR-LBT model. But some expressions from Section V-C need to be modified because the number of CR slots in the CR interval is fixed and equal to $N_{sl} > 0$.

The equations for probabilities τ_w and τ_l remain the same as in Section V-C: (5)–(6). As $N_{sl} > 0$, gNBs always have an opportunity to detect a collision with STAs in the first CR slot. Therefore, in the gCR-LBT model, we calculate the probability ρ_w as follows:

$$\rho_w = 1 - q_w(1-\tau_w)^{N_w-1}\left[(1-\tau_l)^{N_l} + \eta \sum_{i=1}^{N_l} \binom{N_l}{i} \tau_l^i (1-\tau_l)^{N_l-i} (1-\phi)^i\right]. \quad (25)$$

To find ρ_l, we modify the expression for the probability $\alpha(n, w)$ obtained in the eCR-LBT model. As the number of CR slot is fixed, we now find $\alpha(n, w)$ as follows:

$$\alpha(n,w) = \begin{cases} C(n, N_{sl}, 0), & w = 0; \\ C(n, N_{sl}, w) z(N_{sl}), & w > 0, \end{cases} \quad (26)$$

where $z(N_{sl})$ denotes the probability that gNB's data transmission does not overlap with a Wi-Fi frame:

$$z(N_{sl}) = \begin{cases} 1, & T_{w,c} < N_{sl}\delta; \\ 0, & T_{w,c} > N_{sl}\delta + L; \\ \dfrac{L - (T_{w,c} - N_{sl}\delta)}{L}, & N_{sl}\delta \le T_{w,c} \le N_{sl}\delta + L. \end{cases} \quad (27)$$

The CR interval contains N_{sl} CR slots and the RS, therefore $N_{sl}\delta \le t_{cr} \le N_{sl}\delta + L$. Consequently, a Wi-Fi frame never collides with a gNB's data transmission provided that $T_{w,c} < N_{sl}\delta$, but an overlapping always occurs if $T_{w,c} > N_{sl}\delta + L$.

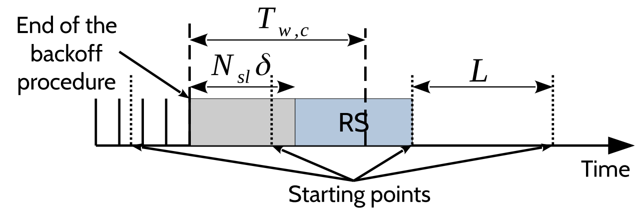

FIGURE 3. Clarification for (27), $N_{sl}\delta \le L \le T_{w,c} \le N_{sl}\delta + L$.

Let us consider the other case: $N_{sl}\delta \le T_{w,c} \le N_{sl}\delta + L$. The CR interval exceeds the duration of Wi-Fi frame $T_{w,c}$ if a gNB finishes the backoff procedure at such a moment that the intervals $N_{sl}\delta$ and $T_{w,c}$ end within the same period L. Thus, the overlapping happens as long as a gNB finishes the backoff procedure in the interval of duration $(T_{w,c} - N_{sl}\delta)$ within the period L. The relative location of this interval within the period L depends on the ratio between L, $N_{sl}\delta$ and $T_{w,c}$ (e.g., Fig. 3).

With (26)–(27), we can calculate ρ_l using expressions (10)–(11) and (12) from Section V-C. Solving together (5)–(6), (25) and (12), we can find probabilities τ_w, τ_l, ρ_w and ρ_l for the gCR-LBT model.

Similar to (26), we find $\beta(n, w)$ and $D(n, w)$ as follows:

$$\beta(n, w) = B(n, N_{sl}, w), \tag{28}$$
$$D(n, w) = C(n, N_{sl}, w)p(w), \tag{29}$$

where $p(w)$ is the average payload delivered by one gNB if it does not postpone its transmission after the CR interval.

As in Section V-C, $X(w)$ is the number of complete licensed spectrum slots in the data transmission which are not distorted by the collision. To simplify the calculation of $X(w)$, we assume that the CR interval ends at the licensed spectrum slot boundary. The CR interval contains N_{sl} CR slots and the RS, therefore its average duration is $(N_{sl}\delta + L/2)$. Thus, $p(w)$ is calculated as follows:

$$p(w) = X(w)\theta d_l q_l + \left(\theta - (N_{sl}\delta + \frac{L}{2}) \bmod \theta\right) d_l q_l, \tag{30}$$

where mod denotes the operation of computing a remainder; $X(w)$ can be found as follows:

$$X(w) = \begin{cases} \left\lfloor \dfrac{T_l - N_{sl}\delta - L/2}{\theta} \right\rfloor, & w = 0; \\ \left\lfloor \dfrac{T_l - \max(N_{sl}\delta + L/2, T_{w,c})}{\theta} \right\rfloor, & w > 0. \end{cases} \tag{31}$$

The second component in (30) reflects that the last NR-U slot in the transmission is incomplete because of the CR interval and contains less payload. The first case in (31) reflects that the CR interval may cover several licensed spectrum slots. Furthermore, the other case in (31) takes into account that the duration of a Wi-Fi frame may exceed the CR interval.

With new expressions (29)–(31), we can find the throughput of the NR-U network using (18)–(20). To calculate the throughput of the Wi-Fi network S_w, we can use (13) and (14) derived in Section V-C. The expressions for probabilities $\pi_{w,s}$, π_e and π_l remain the same as in Section V-C and are given by (13), (21) and (23), respectively. The average virtual slot duration T_{slot} is given by (24).

VI. NUMERICAL RESULTS

In this section, we study the efficiency of the proposed channel access methods in two scenarios. In Scenario 1, we consider an NR-U only network with N_l gNBs. Scenario 2 represents a coexistence scenario with a fixed total number of nodes and a variable share of STAs, $N_w + N_l = 10$ unless otherwise stated. In both scenarios, we focus on the numerology with $\theta = 500$ μs with allowed mini-slot transmissions ($L = \theta/14 \approx 36$ μs) or without them ($L = \theta = 500$ μs).

We use the following notations in the figures. "CR-LBT" denotes the collision resolution method from [18], which corresponds to eCR-LBT with $\phi = 0$. "Baseline" stands for the legacy LBT with the RS and is modeled by setting $\phi = \xi = 1$ the eCR-LBT model. Other configurations of eCR-LBT are shown as eCR-LBT with specified values of ξ and ϕ. gCR-LBT with N_{sl} CR slots is denoted as gCR-LBT with corresponding values ξ and ϕ.

Unless otherwise stated, we use values listed in Table 5 in our experiments. Wi-Fi (NR-U) channel access parameters correspond to the Best Effort Access Category (LBT Priority Class 3). Also, we use T_l and $T_{w,s}$ equal to MCOT and $\text{TXOP}_{\text{limit}}$, respectively. $T_{w,c}$ represents a duration of one RTS frame if RTS/CTS is used. Thus, the values of W_{min}, W_{max}, T_l, $T_{w,s}$, $T_{w,c}$, σ are taken from the corresponding specification/standard. Similar to [18], nominal data rates d_w and d_l of both network are the same and equal 75 Mbps. We estimate the number of subframes n_w in A-MPDU as the number of MPDUs of the length of 1500 bytes for the chosen data rate, i.e., $n_w = d_w T_{w,s}/1500 \approx 15$ subframes. Since the LTE specification requires the selected modulation and coding scheme to keep a block error rate lower than 10% [34], we take $q_l = q_w = 0.9$ in our experiments. The value of η depends on the deployment scenario, but we take it equal to 0.5 for simplicity. Default values of ξ and δ are the same as in [18] and, for determination, we take $\phi = \xi$ as default.

We validated our analytical models with simulation. The simulation does not use several simplifications applied in the network models. In particular, the simulation does not use the assumptions related to the duration of the CR interval. According to the obtained results, the difference between the models does not exceed 3% in all the considered scenarios, see Fig. 4. Therefore, the analytical models are accurate enough.

Let us start the performance analysis by selecting an appropriate value of N_{sl} for gCR-LBT. Fig. 5 and 6 represent the throughput of the NR-U network in Scenario 1 and the total throughput in Scenario 2, respectively, for $L = 36$ μs. In both scenarios, gCR-LBT does not work well with a small number of CR slots because of the low probability of collision resolution. On the other hand, a large number of CR slots leads to unnecessary overhead and decreases the throughput as well. Therefore, we select $N_{sl} = 5$ as a quasi-optimal value, which

TABLE 5. Default values of model parameters.

Parameter	Value
T_l	8000 μs
θ	500 μs
L	500 μs in eCR-LBT and CR-LBT, 36 μs in gCR-LBT
$T_{w,s}$	2500 μs
$T_{w,c}$	44 μs if RTS/CTS is used, 2500 μs otherwise
n_w	15
σ	9 μs
$W_{min,w}, W_{min,l}$	16
$W_{max,w}, W_{max,l}$	64
d_w, d_l	75 Mbps
η	0.5
δ	30 μs
ϕ, ξ	0.5
q_l, q_w	0.9

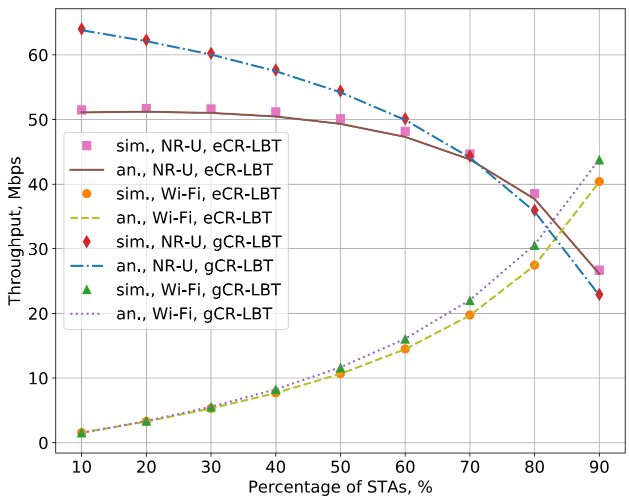

FIGURE 4. Comparison of the NR-U and Wi-Fi throughputs obtained in analytical models and simulation in Scenario 2 with $L = 36$ μs, RTS/CTS.

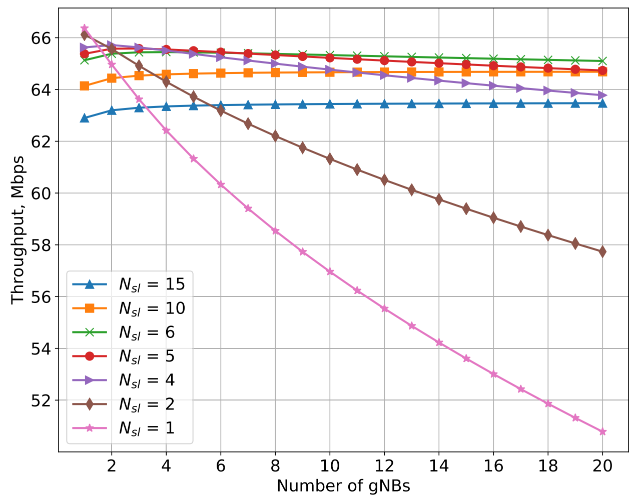

FIGURE 5. NR-U throughput in Scenario 1 with gCR-LBT, $L = 36$ μs and various N_{sl}.

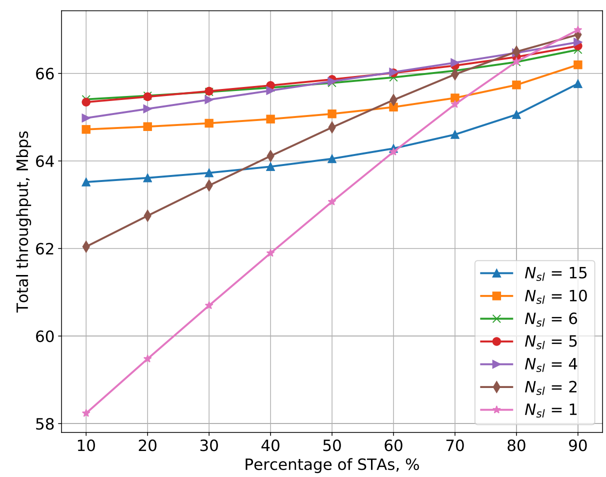

FIGURE 6. Total throughput in Scenario 2 with gCR-LBT, RTS/CTS, $L = 36$ μs and various N_{sl}.

improves the performance in both NR-U only and coexistence scenarios, and we use it in further experiments.

Let us compare different channel access methods in Scenario 1. Fig. 7 illustrates the throughput of the NR-U network operating with PC1–PC4 channel access parameters listed in Table 2. The results show that gCR-LBT outperforms the other methods, demonstrating high throughput, which is close to NR-U nominal data rate. Furthermore, in contrast to the Baseline, the throughput only slightly depends on the number of nodes. Thus, the proposed gCR-LBT resembles the RTS/CTS mechanism used in Wi-Fi. Moreover, the higher is the priority of the traffic (i.e., the smaller is the index of PC), the higher is the achieved throughput gain relative to the Baseline. It happens because lower PCs use smaller contention window bounds, resulting in more collisions that can be successfully resolved. However, for the network with one gNB, the Baseline with $L = 36$ μs is a better option because, in the absence of collisions, it has the lowest overhead associated with the RS.

Let us move to Scenario 2 with $N_l + N_w = 10$ nodes in total and compare the CR-LBT and the eCR-LBT methods for $L = 500$ μs, i.e., when gNBs do not use mini-slot transmissions. Fig. 8 depicts the NR-U and Wi-Fi throughputs in Scenario 2 with and without RTS/CTS. In both cases, we see the same trend as the percentage of STAs increases: the NR-U throughput decreases and the Wi-Fi throughput rises. In addition, Fig. 8 illustrates the impact of the difference between MCOT and $TXOP_{limit}$ (8 ms vs. 2.5 ms) on channel resource sharing between the technologies. For example, for equal number of nodes of each technology, gNBs achieve more than three times higher throughput than STAs for any ϕ. Thus, gNBs obtain more airtime than STAs after winning the contention for the channel. Moreover, the figures show that the NR-U throughput increases and the Wi-Fi throughput descends with increasing ϕ. It happens because the parameter ϕ mainly regulates the behavior of gNBs towards STAs in collisions.

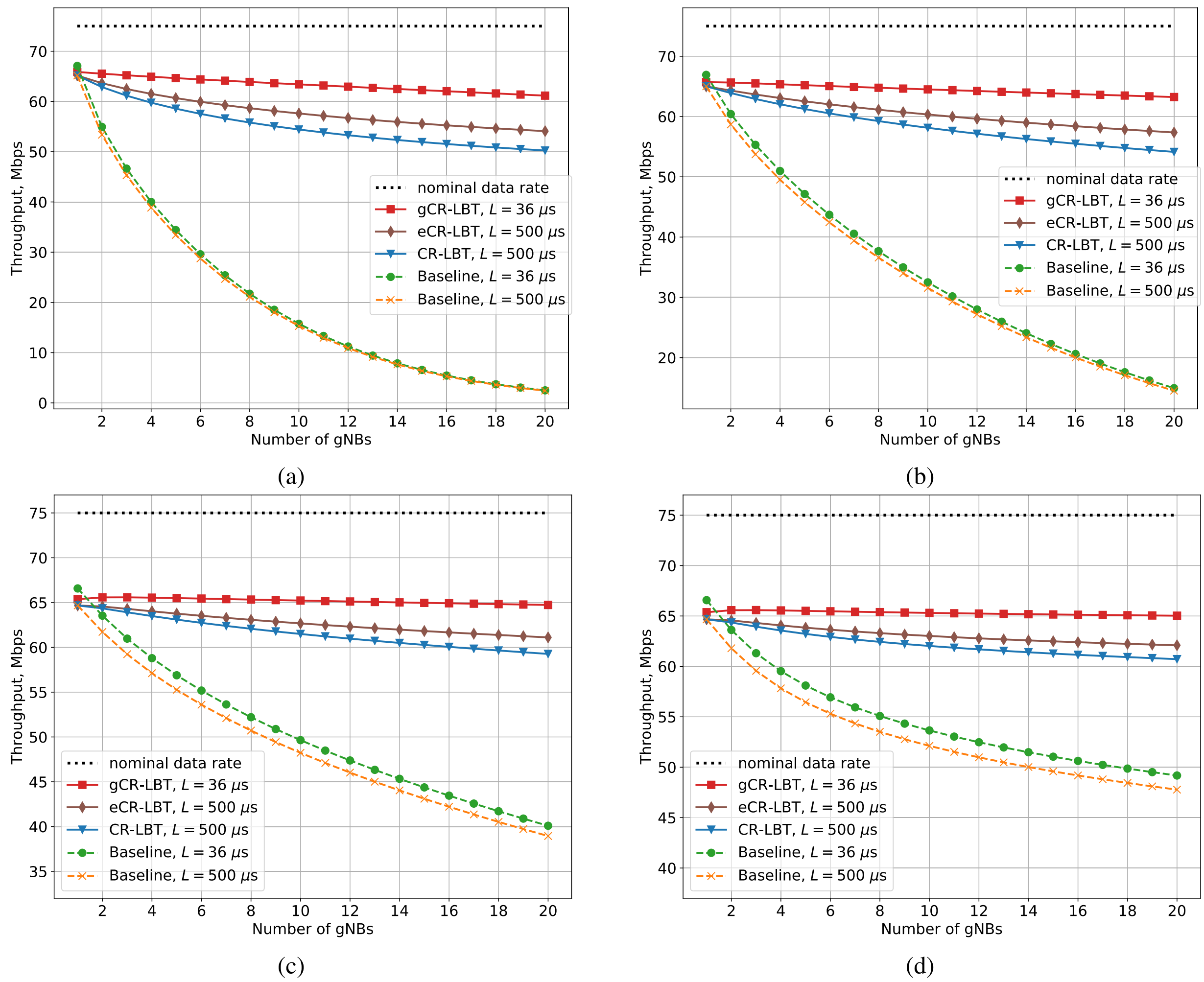

FIGURE 7. **Throughput of the NR-U network in Scenario 1 for: (a) LBT PC 1; (b) LBT PC 2; (c) LBT PC 3; (d) LBT PC 4.**

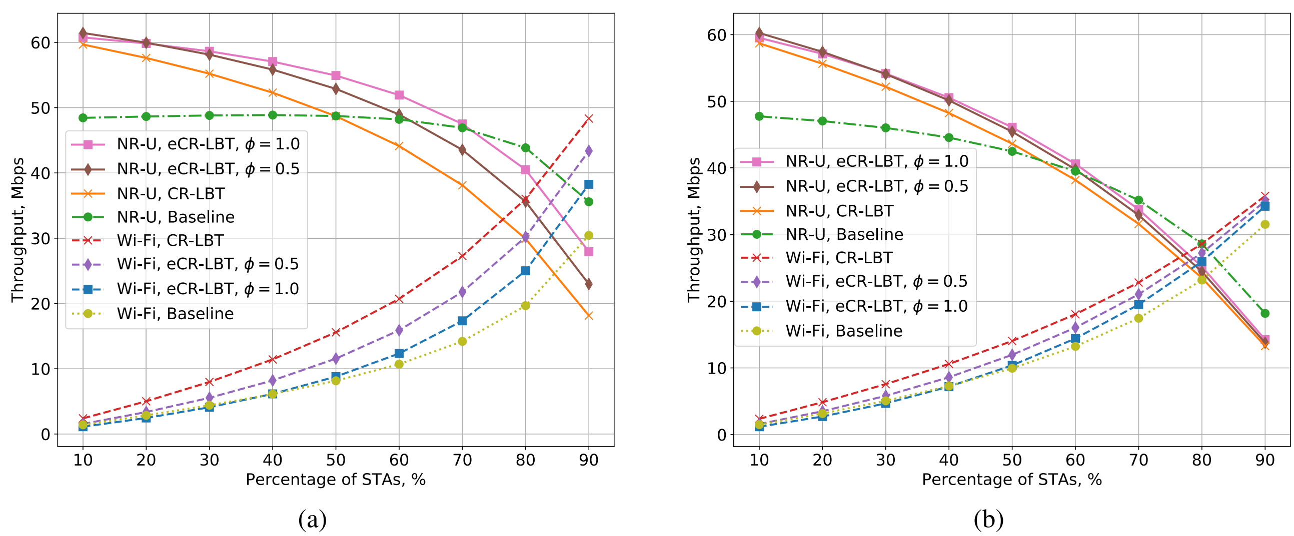

FIGURE 8. **NR-U and Wi-Fi throughputs in Scenario 2 for $L = 500$ μs: (a) with RTS/CTS; (b) without RTS/CTS.**

Fig. 9 illustrates the impact of the parameter ϕ on the total throughput in Scenario 2. As it is shown, both CR-LBT and eCR-LBT provide a positive gain in overall throughput relative to the Baseline, up to 70% of STAs if RTS/CTS is not used, since less channel time is wasted on collisions. However, both CR-LBT and eCR-LBT are more effective if

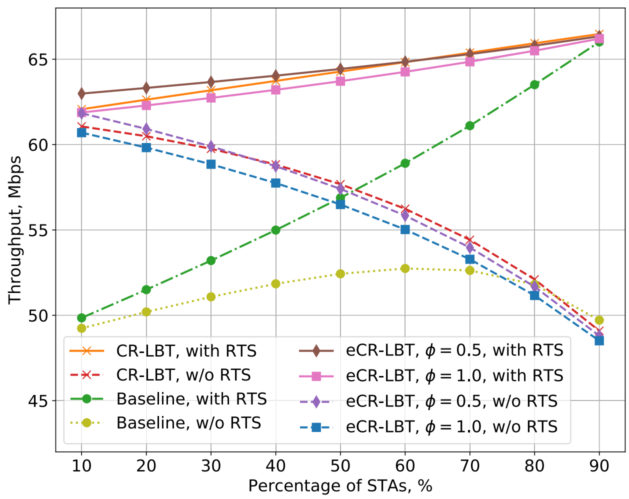

FIGURE 9. **Total throughput in Scenario 2 for $L = 500$ μs.**

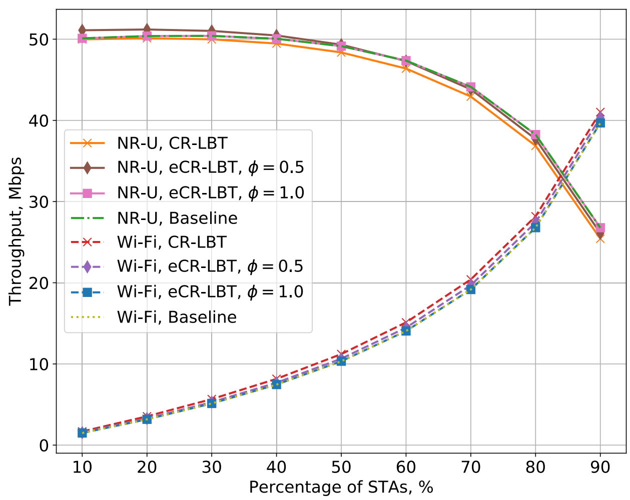

FIGURE 10. **NR-U and Wi-Fi throughputs in Scenario 2 for $L = 36$ μs, with RTS/CTS.**

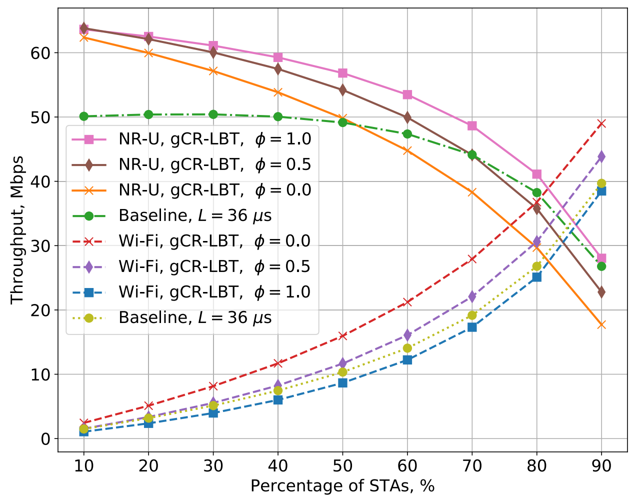

FIGURE 11. **NR-U and Wi-Fi throughputs in Scenario 2 with gCR-LBT compared to the baseline for $L = 36$ μs, with RTS/CTS.**

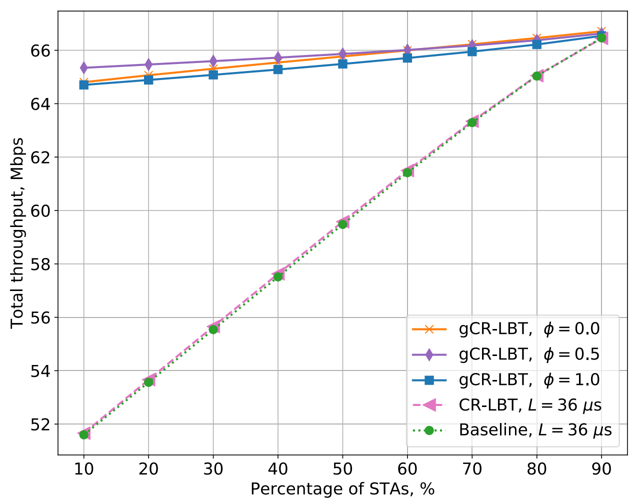

FIGURE 12. **Total throughput in Scenario 2 with gCR-LBT compared to the baseline for $L = 36$ μs, with RTS/CTS.**

Wi-Fi STAs use the RTS/CTS handshake because the duration of the CR interval often exceeds the duration of the RTS frame. Furthermore, the performance of the networks is similar to the one shown in [18]. It means that taking into account channel errors does not qualitatively affect the collision resolution methods. In addition, the total throughput only slightly changes with ϕ because adjusting ϕ causes only the redistribution of channel resources between NR-U and Wi-Fi networks. Since the cases with and without RTS/CTS are qualitatively similar, we mainly concentrate on Wi-Fi with RTS/CTS in further experiments.

Fig. 10 illustrates the throughputs of NR-U and Wi-Fi networks under the configuration with $L = \theta/14$. As expected, with a high frequency of gNB's starting points, CR-LBT and eCR-LBT do not provide any notable gain compared to the Baseline for any value of ϕ, since the CR interval contains no more than one CR slot that is not enough for successful collision resolution.

On the contrary, gCR-LBT is designed to be applied with mini-slot transmissions. Fig. 11 and 12 illustrate the throughputs of NR-U and Wi-Fi networks and a total throughput in Scenario 2, respectively. Comparing them and Fig. 8a and 9, it is seen that gCR-LBT with $L = \theta/14$ shows the performance similar to eCR-LBT with $L = \theta$.

For further analysis, let us introduce the following metrics. G_l (G_w) is the throughput gain of NR-U (Wi-Fi) network relative to the Baseline if the gCR-LBT/eCR-LBT/CR-LBT is used:

$$G_w = \frac{S_w - S_{w,base}}{S_{w,base}}; \tag{32}$$

$$G_l = \frac{S_l - S_{l,base}}{S_{l,base}}, \tag{33}$$

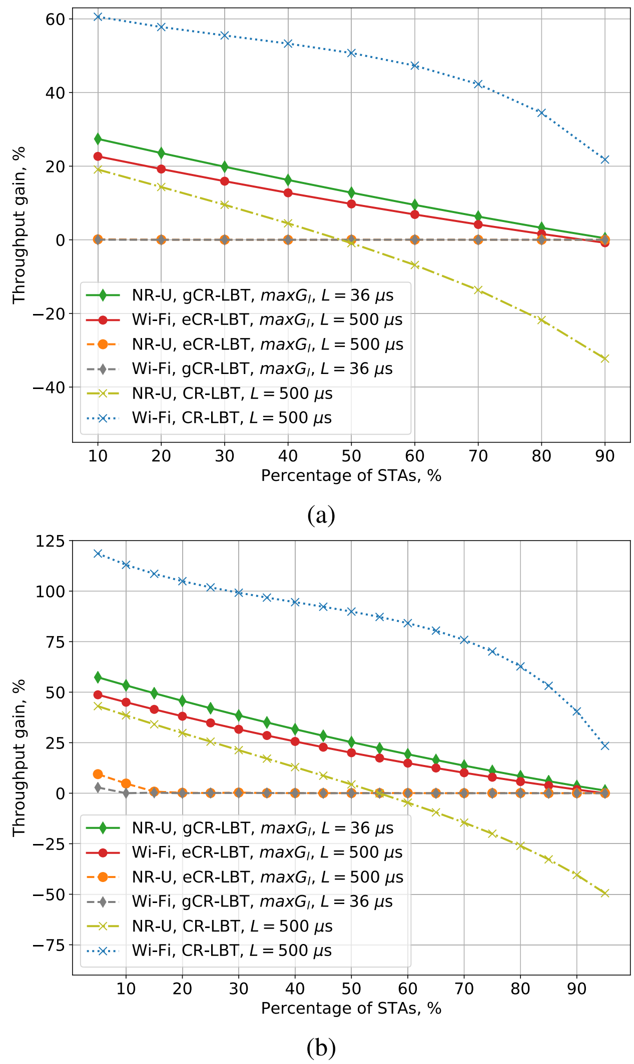

FIGURE 13. Maximum throughput gain of NR-U network that can be achieved while keeping the performance of Wi-Fi network no worse that it is in the baseline with $L = 36$ μs, with RTS/CTS: (a) 10 nodes in total; (b) 20 nodes in total.

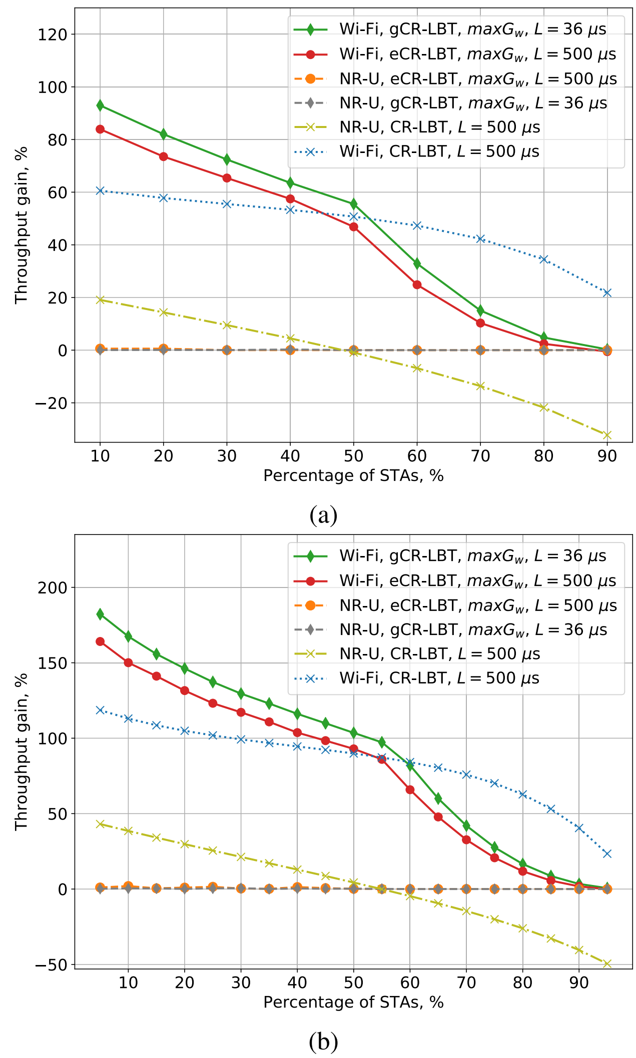

FIGURE 14. Maximum throughput gain of Wi-Fi network that can be achieved while keeping the performance of Wi-Fi network no worse that it is in the Baseline with $L = 36$ μs, with RTS/CTS: (a) 10 nodes in total; (b) 20 nodes in total.

where $S_{l,base}$ ($S_{w,base}$) is the throughput of NR-U (Wi-Fi) network in the Baseline. In particular, we take Baseline with $L = 36\ \mu$s in further experiments because it provides a higher NR-U throughput, see Fig.7c.

Let $maxG_l$ ($maxG_w$) denotes the method of selecting optimal values of parameters ϕ and ξ to achieve the maximum NR-U (Wi-Fi) provided that the constraint $G_w \geq 0$ ($G_l \geq 0$) is met. In the $maxG_l$ and $maxG_w$ methods, we use an exhaustive search with step $\Delta\phi = \Delta\xi = 5 \cdot 10^{-3}$ in range [0, 1] for each percentage of STAs.

Fig. 13a and 13b illustrate the maximum throughput gain of NR-U network that is achieved with $maxG_l$ in Scenario 2 with 10 and 20 nodes in total, respectively. The gains are calculated relative to the Baseline with $L = 36\ \mu$s. As expected, the maximum gain for the NR-U network is possible at the expense of the performance of the Wi-Fi network due to the redistribution of channel resources. Additionally, a higher total number of nodes results in a higher maximum gain, up to 57%. It happens because eCR-LBT and gCR-LBT are more effective when more collisions involving gNBs occur. Also, both methods notably extend the range relative to CR-LBT where positive NR-U gain can be achieved.

Fig. 14a and 14b illustrate the maximum throughput gain of Wi-Fi network that can be achieved with $maxG_w$ in Scenario 2 with 10 and 20 stations in total, respectively. The figures show that eCR-LBT and gCR-LBT provide the throughput gain, up to 182%, that exceeds the gain obtained with CR-LBT for some percentage of STAs. Specifically, in the range with more than 50% of gNBs, eCR-LBT and gCR-LBT may be configured to demonstrate higher throughput than CR-LBT for the NR-U or Wi-Fi network while keeping the performance of the other network the same as in the Baseline. At the same time, CR-LBT outperforms both methods in terms of Wi-Fi throughput if more than half of the nodes are Wi-Fi

STAs because CR-LBT does not limit the decrease in NR-U throughput. Note that gCR-LBT achieves a higher throughput than eCR-LBT for both $maxG_w$ and $maxG_l$ due to the shorter RS in numerology with $L = 36\ \mu$s.

Thus, both eCR-LBT and gCR-LBT may provide notable gains in proper numerologies in both NR-U only and coexistence scenarios. Moreover, the maximum throughput gain for the Wi-Fi network is nearly three times higher than it is for the NR-U network in the coexistence scenarios (182% vs. 57%). It happens because the gain is calculated relative to legacy LBT with the RS, which is an unfair method for coexisting with Wi-Fi as shown in Fig. 8. Also, note that gCR-LBT usually outperforms eCR-LBT thanks to reduced overhead.

VII. CONCLUSION

In this paper, we developed eCR-LBT and gCR-LBT channel access methods for 5G NR-U networks. The key idea of the methods is to detect and resolve collisions among gNBs and STAs, thereby improving the overall performance in coexistence scenarios. By adjusting the parameters of the methods, we can regulate the behavior of gNBs in collisions, hence redistribute the channel resources between NR-U and Wi-Fi networks. Such an opportunity is crucial for the performance of the networks in coexistence scenarios when one of the technologies has a predominant number of nodes. Moreover, the design of gCR-LBT makes it highly beneficial for mini-slot transmissions and numerologies with a short duration of a licensed spectrum slot. To study the efficiency of the proposed methods, we derived analytical models, taking into account imperfect channel conditions. The numerical results show that both methods may provide a notable throughput gain for NR-U or Wi-Fi network relative to the legacy LBT without degradation in the performance of the other technology. The gain is up to 182% for Wi-Fi or up to 57% for the NR-U network. Furthermore, it is shown that eCR-LBT and gCR-LBT can be successfully applied in dense pure NR-U networks because they resemble the RTS/CTS mechanism used in Wi-Fi.

As a part of future work, we plan to extend the proposed solutions to multichannel operation, i.e., when a gNB performs collision resolution methods simultaneously in several aggregated channels and Wi-Fi STAs use channel bonding. Specifically, we intend to consider the issue of the coexistence of Wi-Fi and NR-U in the same primary channel.

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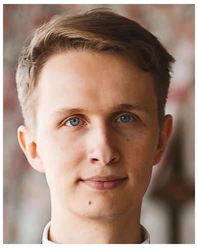

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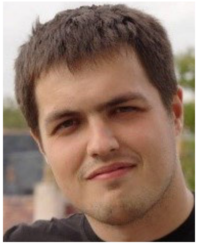

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