Resolving 5G NR-U Contention for Gap-Based Channel Access in Shared Sub-7 GHz Bands

MAREK ZAJĄC AND SZYMON SZOTT
Faculty of Computer Science, Electronics and Telecommunications, AGH University of Science and Technology, 30-059 Krakow, Poland
Corresponding author: Szymon Szott (szott@agh.edu.pl)

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ABSTRACT New Radio Unlicensed (NR-U) enables 5G networks to operate in unlicensed channels, including the sub-7 GHz bands where transmitters are required to adhere to a set of contention resolution rules known as listen before talk (LBT). NR-U derives from a scheduled radio access technology where transmissions are expected to begin at fixed slot boundaries. The end of an LBT procedure, however, may not coincide with such a boundary. One solution to this problem is to have the NR-U base station wait a gap period to align with the slot boundary. We design, implement, and validate a simulator of NR-U channel access and conduct a performance analysis to assess several important issues: slot boundary synchronization between NR-U base stations, gap placement methods, impact of transmission settings, and performance under dense deployments. We also propose a method for improving the fairness of contending NR-U base stations and conclude our research with guidelines for configuring NR-U networks operating under gap-based channel access.

INDEX TERMS Channel access, coexistence, MAC, NR-U, synchronization slot, wireless networks, unlicensed bands.

I. INTRODUCTION

Shared bands are an attractive resource for cellular radio access technologies to increase their capacity beyond licensed bands. Using shared bands was first considered in the form of periodic transmissions in LTE Unlicensed (LTE-U) [1] and then with improved coexistence through channel sensing in LTE Licensed-Assisted Access (LAA) [2]. The latest, fifth generation (5G) of cellular technology (New Radio, NR), comes with its variant for accessing shared bands: NR Unlicensed (NR-U) [3]. Similar in principle to LAA, NR-U adheres to ETSI’s listen before talk (LBT) channel access scheme for coexisting with Wi-Fi, the incumbent technology in shared bands. While LBT is based on Wi-Fi’s random channel access, it needs to be adapted to suit the scheduled access approach of technologies such as LAA and NR-U [4].

The scheduled approach of NR, as well as its predecessor, requires that transmissions are synchronized to slot boundaries, which correspond to subframe starting positions [5]. This is trivial in licensed channels, where the NR base station (the next generation Node B, gNB) supervises all transmissions. In shared channels, this becomes a problem due to other transmitting devices and the need for contention resolution. LBT provides a simple and effective method to resolve this contention, but the end of an LBT procedure may not coincide with NR-U’s slot boundary (Figure 1).

FIGURE 1. Channel access in NR-U follows the rules of LBT: access is granted after a defer period (to determine that the channel is idle) and a random number of backoff slots (to resolve contention). The problem is how to align LBT with the slot boundary. The two common solutions are to either block the channel by transmitting a reservation signal (RS) or to wait a gap period. In the latter case, the channel is idle for the gap period which enables other contending stations to begin their transmission.
to other problems, not only when coexisting with other Wi-Fi networks [3], but also when resolving contention among multiple gNBs. For example, the gap-based method, as we will show in Section V, is not as good at providing fair channel access as the RS-based method.

In this work, we focus on ensuring intra-technology fairness for NR-U. We consider the sub-7 GHz bands – in comparison to mmWave, they are more universally applicable (as a direct competitor to Wi-Fi) and suffer more from channel contention issues (no beamforming, longer range). We assume only downlink transmissions because a gNB with channel access can schedule uplink transmissions without further contention. We also consider environments free of Wi-Fi interference to better understand the interactions between gNB transmissions. As we report in Section II, the topic of channel access performance for contending gap-based gNBs has not yet been studied in the literature.

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evaluation methods suitable for studying fairness among gNBs under gap-based access:

- analytical models are an improper tool as they do not allow distinguishing gNBs,
- Monte Carlo simulations may hide underlying fairness issues,
- discrete-event simulators are applicable, but there has been a lack of support for both channel access methods (RS and gap).

Thus, we are motivated to study inter-gNB contention under gap-based access using a custom discrete-event simulator as described in Section IV.

III. CHANNEL ACCESS IN NR-U

To facilitate the understanding of the subsequent sections, in this section we describe how an NR-U base station (gNB) operates while accessing the channel. We first explain the principles of LBT and then characterize the specific features of NR-U channel access (gap period, scalable subcarrier spacing, and mini-slots) implemented in our model. In this description and in the ensuing analysis, we assume that (i) the load-based equipment (LBE) variant of LBT is used [12] and (ii) NR-U operates with a carrier in the licensed band [8].

A. LISTEN BEFORE TALK

A gNB has to precede each transmission in a shared band with an LBT procedure. First, the gNB has to check whether the channel is idle during a prioritization period, which consists of a fixed duration of 16 µs and a fixed number of \( m \) slots, each 9 µs long. The value of \( m \) depends on the channel access priority class (Table 1). The gNB performs clear channel assessment (CCA) after waiting for the initial 16 µs and after each of the \( m \) observation slots. If the channel is sensed idle during this prioritization period, the gNB is allowed to start a transmission. If the channel, however, is found to be occupied by another transmission, the gNB has to defer the transmission and additionally perform a backoff procedure at the next channel access (after a prioritization period). It draws a random value \( N \) between 0 and \( CW \) (the current contention window), which determines the number of observation slots for the backoff procedure. Then, the gNB has to wait for an additional \( N \) observation slots, each lasting 9 µs. Each time the channel is detected to be idle for a period of an observation slot, the backoff counter \( N \) is decremented. If the channel is sensed busy, the gNB freezes the backoff counter and continues to sense the channel. The backoff counter is resumed only after the channel has been again sensed idle for the initial prioritization period (16 µs + \( m \times 9 \) µs). Once the counter reaches zero, the gNB is allowed to start its transmission. Then, it has to release the channel after occupying it for no longer than a maximum channel occupancy time (MCOT), the value of which depends on the priority class.

If the transmission is successful, the gNB sends an immediate acknowledgment over the licensed carrier and sets its current contention window size \( CW \) to \( CW_{\text{min}} \). If the transmission results in a collision, \( CW \) is doubled, but cannot exceed \( CW_{\text{max}} \). Both \( CW_{\text{min}} \) and \( CW_{\text{max}} \) are defined by the channel access priority class, shown in Table 1. The flowchart of the entire LBT procedure is shown in Figure 2.

B. CHANNEL ACCESS

The transmissions made by a gNB follow a certain frame structure and the beginning of the transmission needs to be synchronized with the slot boundary. It is not guaranteed that the LBT procedure will end exactly at such a slot boundary, therefore the gNB has to wait an additional time, which depends on the synchronization slot duration and the time when the LBT procedure is finished.

This means that a gNB has one of two basic options:

- defer the transmission by inserting a gap period somewhere during the LBT procedure, e.g., before the backoff, as shown in Figure 3, or
- reserve the channel while waiting for the slot boundary using a jamming signal, called the RS, as shown in Figure 4.

Use of the latter option was considered normal practice in LAA deployments [2]. This approach, however, has been criticized by the IEEE [58] and the research community [5], [6], [59] as it causes a waste of radio resources. Additionally, the use of RS may be disallowed in the future [60]. Meanwhile, using the gap period has been considered as an RS alternative for NR-U. The gap can be inserted either before, after, or during the backoff procedure. This optimizes the performance of NR-U as it can spend more time actually transmitting data (because each channel access is limited by MCOT). On the other hand, it may pose a risk that another node will occupy the channel in the meantime.

C. SCALABLE SUBCARRIER SPACING AND MINI-SLOTS

The synchronization slot length also plays an important role in channel access. In the case of unlicensed spectrum, this length should be as short as possible to maximize channel utilization. LTE uses a fixed slot length of 1 ms and a subcarrier spacing of 15 kHz. NR introduces the concept of scalable subcarrier spacing, which can change from 15 kHz up to 480 kHz. This can reduce the OFDM symbol duration and therefore shorten the slot length. The slot length is equal to 1 ms divided by \( 2^\mu \) where \( \mu \) is an integer between 0 and 5.

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**TABLE 1.** Channel access parameter values for downlink transmissions of different priority classes [56].

| Priority class | \( m \) | \( CW_{\text{min}} \) | \( CW_{\text{max}} \) | MCOT [ms] |
|----------------|--------|------------------|------------------|-----------|
| 1              | 1      | 3                | 7                | 2         |
| 2              | 1      | 7                | 15               | 3         |
| 3              | 3      | 15               | 63               | 8 or 10   |
| 4              | 7      | 15               | 1023             | 8 or 10   |

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\(^2\)Technically, the general LBT requirements are formally defined in ETSI EN 301 893, while the specific NR-U channel access procedure for shared bands are defined in 3GPP TS 37.213 [56].
FIGURE 2. The LBT procedure flowchart of [57] using 3GPP nomenclature. The channel access engine (CAE) is a mechanism that determines when a transmission attempt is permitted. A gNB may have data to be transmitted in different priority classes and can use a different CAE (one for each implemented priority class).

FIGURE 3. Example of a successful LBT with the gap period before backoff, $m = 1, N = 5$.

FIGURE 4. Example of a successful LBT with an RS used to hold the channel until the synchronization slot boundary, $m = 1, N = 5$.

(0 and 3 for data transmissions). This means that using scalable subcarrier spacing, the slot length can be reduced to 125 $\mu$s.

Alternatively, non-slot based scheduling can be used. While the standard slot contains 14 OFDM symbols, NR supports mini-slots, which means that the transmission can start at any OFDM symbol and last 2, 4, or 7 OFDM symbols. In Rel-16, the slot can be as short as one OFDM symbol, further reducing slot duration down to approximately 9 $\mu$s (an OFDM symbol duration for the 120 kHz subcarrier spacing) [61]. Mini-slots are especially beneficial for NR-U as the transmission can start almost immediately after an LBT procedure, ensuring fair and efficient coexistence with other unlicensed technologies [62], though it is yet unclear if such precise scheduling can be successfully deployed in equipment.

D. PARTIAL SUBFRAMES

To increase the efficiency of LAA, the concept of partial subframes was introduced in Release 13 [63]. Partial subframes allow LAA to perform channel access not only at the start/end of a slot boundary, therefore increasing channel utilization.
A new frame structure, called Type 3 was introduced to allow such flexibility. Downlink burst transmissions utilizing partial subframes can start at the first or the second slot of a subframe. Because of the MCOT constraint, the transmission may not end at the slot boundary. According to the specification, a transmission burst may end at the slot boundary or at any one of the Downlink Pilot Timeslot ( DwPTS) durations. This means that the duration of the last subframe of a DL transmission burst can be equal to 3, 6, 9, 10, 11, 12 OFDM symbols or a whole subframe consisting of 14 OFDM symbols [64], resulting in a significant performance improvement [65]. NR-U also adopts this feature and Figure 5 shows an example of an NR-U transmission using partial subframes.

IV. SIMULATION MODEL

In this section, we describe the implementation of the simulation model, give an overview of several basic channel access examples, and demonstrate how the model was validated.

A. IMPLEMENTATION

The simulation model of NR-U channel access was implemented using SimPy – a Python framework supporting discrete-event simulations. Our implementation consists of objects belonging to three classes (Gnb, Channel, Transmission) as well as their internal operation logic.

Each base station is represented as an object of the Gnb class, which itself implements several methods (processes). The main process begins at \( t = 0 \) and, during the simulation, it spawns new processes (e.g., responsible for the backoff countdown or waiting the gap period) and schedules new events (e.g., transmitting a new subframe or waiting for the next synchronization slot boundary). Each base station also holds a reference to an object of the Channel class, which acts as a shared resource among the station processes. The Channel class contains a list of each station’s sensing processes and a list of ongoing transmissions to allow stations to determine whether the channel is idle or busy at any given moment. Finally, the Transmission class is used for data structures holding the basic transmission parameters (beginning, end, use of RS, as well as flags for collision detection).

In terms of internal operation, the Gnb class implements the LBT procedure in accordance with Figure 2. Additionally, it recognizes the requirement of NR-U base stations that they can only start a transmission at synchronization slot boundaries. First, the slot boundaries can be configured globally or on a per-gNB basis. Second, stations can be configured to either use RSs (transmitting an energy burst between the end of LBT and the beginning of the slot boundary) or perform self-deferral until the slot boundary occurs (the gap-based approach). Moreover, the simulator supports partial ending subframes (cf. Section III-D).

In terms of output metrics, the simulator collects the following statistics:

- collision probability – the ratio of failed transmissions to the total number of transmissions,
- normalized per-gNB airtime – the time that the channel was occupied for transmitting data by a single station, normalized to the total simulation time,
- channel efficiency – the ratio of the total per-gNB airtime to the total simulation time,
- Jain’s fairness index – calculated over the normalized per-gNB airtime, it describes how well the airtime is divided among all gNBs.

Each metric is collected for every station separately and later aggregated for network-wide statistics. The simulator also provides extended logging capabilities that allow for in-depth verification of the operation of individual procedures and processes.

B. EXAMPLES

To better understand NR-U operation, four simulation examples are given in Figure 6 for two contending base stations. The synchronization slot duration was set to 1 ms and all transmission parameters correspond to channel access class 3 (best effort).

Under gap-based access, if gNBs have randomly selected synchronization slot offsets, backoff does not play a role in contention resolution: the first gNB selects a larger backoff but is first to transmit (Figure 6a). With RS-based access (Figure 6b), contention resembles Wi-Fi: the station with the lowest backoff wins. Meanwhile, collisions occur if:

- under gap-based access – stations share a synchronization slot offset (Figure 6c),
- under RS-based access – stations select the same backoff value (Figure 6d).

We revisit these issues in detail in Section V.

C. VALIDATION

We validate our SimPy implementation of NR-U channel access by comparing the results with those from an alternative Monte Carlo simulator implemented in MATLAB [3]. This baseline was, in turn, validated using both an experimental testbed [3] as well as an analytical model [66]. Simulations were run for a varying number of contending gNBs, with each simulation lasting 100 seconds and with 10 independent runs for each data point. The transmission parameters for both simulators were set to identical values as follows:

- synchronization slot duration: 1 ms,
- transmission duration (MCOT): up to 8 ms,
- minimum contention window size: 15,
FIGURE 6. Examples of channel access contention between two gNBs based on simulator logs for gap and RS-based channel access. Times are given in µs since the last transmission ended. Dashed vertical lines represent 9 µs LBT slots. Red solid lines represent NR-U's synchronization slot boundaries.

- maximum contention window size: 63,
- gap-based access configuration: gap before backoff,
- slot boundaries: chosen randomly,
- partial ending subframes: enabled.

First, we measured the collision probability for RS-based access (Figure 7a). The probability of collision is proportional to the number of transmitting stations, as in Bianchi’s 802.11 model [24]. For gap-based access, the collision probabilities were close to or equal to zero in both simulators so they are not shown. Next, we measured channel efficiency for both RS and gap-based methods. The former behaves like 802.11, while the latter can better utilize the channel. We discuss these effects in more detail in the next section. Meanwhile, in all presented results, we observe a good match between our implementation and the baseline.

V. PERFORMANCE ANALYSIS OF NR-U

Using the simulation model of Section IV, we investigate the performance of contending full-buffer gNBs in various scenarios with full hearability and no physical layer errors.
As the evaluation metrics, we use Jain’s fairness index, channel efficiency, collision probability, and the empirical cumulative distribution function (CDF) of per-gNB airtime. We are looking for channel access methods in line with ETSI’s LBT specifications, which do not resort to using RSs and which exhibit high channel efficiency while maintaining per-gNB fairness. The CDF plots will demonstrate how both criteria are met.

A. BASE STATION SYNCHRONIZATION

NR-U base stations have to start their transmissions at the beginning of their respective synchronization slot boundaries (Section III). Stations with coinciding slot boundaries are considered synchronized. Figure 8 presents an example of two synchronized stations (gNB 1 and gNB 2) using gap-based access at the moment after their three first transmissions have consecutively collided. Both stations have now increased their contention window; gNB 2 has drawn a random backoff of 108 while gNB 1 – only 8. Therefore, gNB 1 starts transmitting at the next slot boundary (following an LBT procedure). Meanwhile, gNB 2 is unable to start its transmission as the total required wait time (i.e., $16 \mu s + 7 \times 9 \mu s + 8 \times 9 \mu s = 1100 \mu s$) exceeds the synchronization slot duration (1 ms). Since by this time gNB 1 has already started its transmission, gNB 2 is unable to proceed with its backoff countdown. In the next contention round, gNB 1 has reset its contention window to CWmin (15) and selected a new backoff value, smaller than 108, therefore gNB 2 remains unable to decrement its backoff.

The first obvious solution to this problem is to desynchronize gNBs, i.e., add a random offset to their synchronization slot boundaries to reduce the probability of collisions. While this approach is generally better, it can still fail under specific circumstances. Consider the example presented in Figure 9, where the slot boundaries of both gNBs are 137 $\mu$s apart. Now, gNB 2 is first to transmit while gNB 1 is unable to begin its backoff countdown. Once the channel is idle, gNB 1 is still unable to transmit as the time needed for LBT (i.e., $16 \mu s + 7 \times 9 \mu s + 8 \times 9 \mu s = 151 \mu s$) is longer than the time remaining before the next slot boundary (137 $\mu$s). This leads to a complete blocking of gNB 1 by gNB 2.

These two examples show that gap-based channel access may pose serious issues while striving for fairness. One gNB may limit or, in some cases, completely block another station from accessing the channel, regardless of the desynchronization of their slot boundaries. In further sections, we focus on finding a solution to this problem.

B. GAP PLACEMENT

The placement of the gap period is not defined in 3GPP specifications. Therefore, we proceed to evaluate several gap placement methods. Each plot was calculated based on the results of 10 runs, each with 10 simultaneously transmitting, randomly desynchronized gNBs. The transmission durations were set to 8 ms. Figure 10a shows the CDF for RS-based access: it is an almost vertical line. Such results are desirable – the base station that achieved the highest airtime was not too far off from the station with the lowest airtime. Despite these excellent results in terms of fairness, RS-based channel access did not fully utilize the resources due to MCOT limitations and a substantial number of collisions. In an ideal scenario, we expect a straight step from 0 to 1 for a normalized airtime of $1/n$, where $n$ is the number of stations. In our case, this would mean that every gNB successfully sends data for 10 s with ideal fairness and 100% channel efficiency (as the number of stations is 10 and the simulation time is set to 100 s). In this and subsequent figures, the grey dashed vertical line represents ideal channel sharing.

We consider several gap placement strategies: two straightforward approaches (gap before or after backoff) as well as two interleaved approaches (gap within backoff or backoff within gap). These strategies are defined in the following
sections and we will be referencing the combined results presented in Table 2 and Figure 10b.

1) GAP BEFORE BACKOFF
Inserting the gap period before the backoff ensures that each NR-U transmission is immediately preceded by a backoff countdown. Despite decent results for channel efficiency and collision probability, the fairness index is low (Table 2). Indeed, a large number of stations achieve zero or minimal airtime, while several stations can transmit for over 30% of the simulation time (Figure 10b). This confirms the issues with the gap period that were described in Section V-A.

2) GAP AFTER BACKOFF
The main problem described in the previous section that prevented stations from transmitting was that they were unable to decrement their backoff as they were obligated to first wait the gap period. When waiting for the backoff first and inserting the gap only after the backoff countdown finishes, stations achieve better metrics than for the gap before backoff case (Table 2). The main factor which determined which station won the contention was not the backoff (stations often managed to count their backoff down to zero) but rather the randomized synchronization slot offset. Usually, the station with the smallest offset wins access to the channel. It then finishes the transmission exactly at its synchronization slot boundary and cannot transmit again because it has to wait for the entire slot (1 ms) for its next transmission opportunity. Meanwhile, other stations have already decremented their backoff to zero and the station with the second smallest offset begins transmitting. Almost all stations transmit alternately in a pattern, which results in equal airtime values. A few stations have an airtime of zero – these were stations whose synchronization slot offsets were too close to other transmitting stations, causing them to always skip their synchronization slot boundary as they had to wait the obligatory prioritization period (i.e., 16 µs plus three 9 µs slots) after the previous transmission.

3) GAP DURING BACKOFF
The next evaluated idea was interleaving the gap within the backoff countdown. In this approach, LBT starts with a backoff countdown, but it does not decrement the counter to zero: it leaves a selected number of slots for a second backoff procedure right before the transmission. Thus, a gap period separates both backoff periods. This way, the chance of a station being blocked due to not decrementing its backoff should be minimized. Moreover, as there is still some part of the backoff left before the transmission, the randomized synchronization slot offset should be a less determining factor of which station wins the contention. There is still, however, the problem of optimally splitting the random backoff into two parts. In this particular case, two methods were tested:
leaving a fixed number of slots for backoff countdown before transmission (set to half of CWmin, i.e., 7, in our tests),

leaving a variable number of slots for backoff countdown before transmission (set to 50% of the randomly chosen backoff in our tests).

The obtained results were similar to each other but in both cases far from desirable. The CDF charts (Figure 10b) show that this approach is worse than the gap before or after backoff as the steps on the chart are clearly visible, indicating high instability. The alternative with variable slots performs better than with a fixed number of slots as no nodes achieve a normalized airtime higher than 0.2 and the fairness index is higher. Nonetheless, the results once again show the important disadvantages of the gap period over RS.

4) BACKOFF DURING GAP
We also evaluated a reverse approach: inserting the backoff in the middle of the gap period. Stations calculate how much time is needed for both backoff and gap. Then, they wait the first half of the gap, start the backoff procedure, and then continue to wait for the remaining half of the gap, performing an additional CCA before beginning a transmission. This approach should increase the chance of a station to decrement its backoff without completely blocking it like seen in the previous examples. Unfortunately, the results shown in Table 2 and Figure 10b are similar to those achieved for gap after backoff. The main differences are that there were fewer stations with high (over 0.2) values of normalized airtime which is good. On the other hand, there were also more blocked stations (with zero airtime). Overall, there was a significant dispersion in the achieved airtime for individual stations.

5) BACKOFF DISABLED
Having noticed that the contention between gNBs was mainly resolved by the randomized offsets (used for desynchronizing slot boundaries), we also evaluated disabling backoff altogether. The achieved output metrics were high (Table 2), but the CDF (Figure 10b) shows that a small group of gNBs was denied channel access. These were stations whose synchronization slot offsets were too close to those of other gNBs, as in the gap after backoff case.

6) GAP PLACEMENT SUMMARY
We conclude that none of the tested methods completely resolved the station blocking issues and the results were far from those achieved for RS-based channel access in terms of fairness. Stations were blocked because of synchronization effects caused by transmission durations equal to an integer number of subframes. We repeated the experiments with partial subframes enabled (Figure 11) to remove...
the synchronization effects. We conclude that all gap-based methods exhibit similar performance. Thus, for long synchronization slot lengths, if the transmission durations are a multiple of the subframe length, then gap after backoff is recommended. Otherwise, backoff may be disabled altogether.

C. SYNCHRONIZATION SLOT OFFSETS

The main issue of airtime being unequally distributed among gNBs was caused by their unfortunate selection of a random synchronization slot offset as described in Section V-A. In this section, we examine the impact of this synchronization slot offset selection and how it affects fairness.

1) MINIMAL OFFSET SPACING

In all previously shown results, the synchronization slot offsets were selected randomly. Now, we assume that all gNBs have full knowledge of other selected offsets\(^3\) and choose theirs to maintain a minimum distance from the offsets of other transmitting stations. Thus, each station, after the end of the previous transmission, has an increased chance of waiting the gap period without being blocked by other stations in the meantime. In the considered example of 10 transmitting gNBs, we set the synchronization slot to 1 ms. The behavior of the network was tested in scenarios where the minimum offset spacing varied between 0 and 100 µs. The former is the case where each station chooses its offset randomly. The latter is the case where stations are evenly spaced throughout a single synchronization slot. The backoff mechanism was disabled (having little impact as previously shown), the partial subframe mechanism was enabled, and the simulation time was set to 100 s. The results were consolidated from a total of 10 simulation runs per scenario.

As expected, fairness increases in proportion to the distance between the offsets, reaching 0.99 for a spacing of 100 µs (Figure 12). Additionally, the 95% confidence interval decreases, which indicates that the airtime received by each station is more stable. This can be better seen in Figure 13: the larger the spacing, the more vertical the line becomes, meaning the difference between the distribution of airtime between individual stations is fairer. Indeed, for 100 µs spacing, gap-based access achieves the same fairness as RS, but with improved channel efficiency (Table 3). We conclude that with a proper offset configuration, gap-based access outperforms the RS approach.

2) PARTIAL SUBFRAMES

We have previously shown that optimal synchronization slot selection is crucial for achieving satisfactory fairness. It is, however, rather puzzling that fairness increases gradually rather than abruptly. Considering that backoff was disabled, a station is obligated to wait only for a prioritization period of 43 µs (16 µs + 3 × 9 µs). Therefore, it would be expected that 43 µs is the threshold beyond which we should receive high fairness values. This is, however, not the case, as in the presented scenarios partial ending subframes were enabled. We will now consider in detail how partial ending subframes...
TABLE 3. Results (with 95% confidence intervals) for different minimum offsets between gNB slot boundaries under gap-based access in comparison with RS channel access.

| Minimum offset spacing | Jain’s fairness index | Channel efficiency |
|------------------------|-----------------------|--------------------|
| 0 µs                   | 0.545 ± 0.170         | 0.982 ± 0.003      |
| 20 µs                  | 0.634 ± 0.123         | 0.984 ± 0.001      |
| 40 µs                  | 0.811 ± 0.096         | 0.986 ± 0.0        |
| 60 µs                  | 0.869 ± 0.077         | 0.989 ± 0.002      |
| 80 µs                  | 0.962 ± 0.015         | 0.987 ± 0.0        |
| 100 µs                 | 0.999 ± 0.002         | 0.988 ± 0.0        |
| RS                     | 0.999 ± 0.0           | 0.683 ± 0.002      |

FIGURE 14. Airtime CDF showing the impact of partial subframes under ideal offset selection. The unfairness from partial ending subframes is caused by the issues illustrated in Figures 16 and 17. The dashed vertical line represents ideal channel sharing with perfect utilization.

FIGURE 15. Example of fair channel sharing when a transmission ends at a synchronization slot.

FIGURE 16. Example of unfair channel sharing when a transmission ends before a synchronization slot.

affect the minimal synchronization slot offset and how it can be dealt with.

Figure 14 shows a comparison of the simulation results with and without the partial subframe mechanism enabled for a minimum offset spacing of 60 µs (slightly higher than the minimum of 43 µs). This should be enough to give all stations an equal chance for accessing the channel. The line representing transmission with a constant duration proves this as it is vertical, meaning every station was able to transmit for an equal amount of channel airtime. Unfortunately, utilizing partial ending subframes drastically worsens the results.

To understand why this happens, consider the example of fair channel sharing in Figure 15. It shows two transmitting gNBs with their synchronization slot offsets set to 80 µs apart (for illustration). The first gNB sends finishes its transmission right on its synchronization slot boundary. The second gNB waits for a gap period following a prioritization period and starts a new transmission as its slot begins earlier. Fairness in channel access between these two gNBs is achieved.

Now, consider two examples of unfair channel sharing in Figures 16 and 17, when partial ending subframes play a key role. In the first example, the transmission ends before the slot boundary (one OFDM slot earlier in this case). As a result, gNB 1 starts its transmission again and gNB 2 is blocked as it has to wait longer for its synchronization slot. In the second example, the transmission ends one OFDM slot after the synchronization slot boundary. Because of this, gNB 2 does not have enough time to wait for the required prioritization period and skips its slot while gNB 1 starts its transmission again.

To prevent this unwanted behavior, several techniques can be deployed. One of the simplest solutions would be to force the station which has just finished its transmission to skip transmitting in the next synchronization slot boundary, allowing other gNBs to access the channel. We refer to this as next slot skipping and evaluate it under the previously described simulation settings. As can be seen in Figure 18 and Table 4, this resulted in only marginally better fairness (efficiency remained at a constant, high level). The issue with such an approach is that it might work well for a small number of stations (say, two or three), but in denser networks, it is rare for a gNB to transmit in two consecutive slots. Therefore, another strategy was evaluated, next TX skipping, in which every base station is obligated to skip its next opportunity to transmit. To mean that after every transmission it has to skip the next viable slot in which it could attempt a transmission. The obtained results were much better, increasing the fairness to 0.95 – almost as good as with RS but with better efficiency.
The length of the gap period depends on when the channel becomes idle, the length of the LBT procedure (e.g., how many backoff slots were chosen), and when the slot boundary starts. Therefore, the gap cannot be selected directly. On average, however, the gap is approximately half of the synchronization slot duration (i.e., the time between slot boundaries). This scheduling granularity can be improved by scalable subcarrier spacing and mini-slots introduced in Release-16 (cf. Section III-C). This may help in mitigating the issues mentioned in previous sections since all so far presented results were obtained using slot-based scheduling with 1 ms-long synchronization slots. In this section, we vary the synchronization slot length among the available options (1000, 500, 250, 125, 63, 36, 18, 9 µs) [3] and study its influence on fairness when partial ending subframes remain enabled.

Figure 19 shows a comparison of fairness for different synchronization slot durations and a varying number of stations. The obtained results show that as the synchronization slot duration decreases, fairness increases rapidly, achieving values above 0.95 for a slot duration of 125 µs regardless of the number of transmitting gNBs. This is because shorter synchronization slots allow transmissions to start almost immediately after LBT, as the gap between the end of LBT and the start of the data transmission is minimized (recall that gap before backoff was used). This brings the NR-U channel access mechanism more in line with the channel access method of Wi-Fi and allows gNBs to better adapt to the random access nature of unlicensed channels. Moreover, the previously proposed next TX skipping mechanism helps optimize the performance even further as shown in Figure 20. In conclusion, the flexible numerology introduced by NR might turn out to be a crucial feature for 5G deployments in unlicensed spectrum to maintain a satisfactory level of fairness.

### E. DENSE NETWORKS

NR-U can operate in standalone mode, which means that it does not have to rely on a licensed primary carrier. Therefore, NR-U gNBs can potentially be deployed not only by network operators but by any party, similar to Wi-Fi APs. The more such deployments in the same unlicensed channels, the more challenging it is to maintain an efficient service for many clients simultaneously. This section will focus on evaluating NR-U performance in such dense networks.

Figure 21 shows how fairness changes in dense topologies, with up to 128 gNBs operating on the same channel and selecting random synchronization slot offsets. The simulations were run using three different channel access methods: RS-based, gap-based, and gap-based with next TX skipping. The use of partial subframes was enabled and the synchronization slot length was set to 250 µs, which is the
The results for channel efficiency (shown in Figure 22) are more favorable for the two gap-based solutions. While with RS-based access the overall airtime deteriorates proportionally to the number of stations due to collisions, the use of the gap method allows maintaining a satisfactory channel efficiency for up to 128 simultaneously transmitting gNBs. This was mainly due to the high level of collisions for RS reaching over 96% compared to only 29% at the maximum under gap-based access, even though the results for gap were much less stable as can be seen from the 95% confidence intervals.

The reason for the low collision probability of gap-based access is that the data transmission is performed immediately after a successful backoff. Considering that all gNBs are desynchronized and gap before backoff is used, the transmission is always preceded with a CCA slot, meaning it is unlikely for a collision to occur. Meanwhile, in the RS-based method, stations are synchronized in their backoff countdowns, so the data transfer starts immediately after sending the reservation signal. Therefore, and it is probable for two gNBs to start transmitting the RS at the same time. In a real-world scenario, there would be a short switching delay of the transceiver between sensing the channel and transmitting. During this delay, the channel may become busy (especially in dense networks), but the gNB is unable to detect this, leading to a collision. The simulator was extended with a carrier sensing delay of 2 $\mu$s and the simulations were repeated. This had an impact on the results for gap-based channel access (Figure 23), but the channel efficiency results were still significantly better than those achieved for RS.

We have shown that the gap-based approach has high channel efficiency even in dense deployments and under realistic device parameter assumptions. What remains is the problem of airtime fairness among contending gap-based gNBs.
We evaluate whether the next TX skipping approach can be extended to solve this issue. The results in Figure 24 confirm that by increasing the number of omitted transmission opportunities, fairness can be improved. Satisfactory values of fairness can easily be achieved for a moderate number of gNBs, while for dense deployments gNBs need to postpone their transmissions for a much longer time. With appropriate settings, levels similar to those of RS-based access can be reached. Further work would be required to dynamically tune this configuration parameter, perhaps using reinforcement learning, which has been shown to be able to optimize channel access parameters in unlicensed bands [70].

### F. SUMMARY OF SIMULATION ANALYSIS

To summarize the findings of our paper, we evaluate several configurations of gap-based access (Table 5) for 10 contending gNBs configured with gap after backoff. Setting 1000 μs synchronization slots provides the most challenging configuration because slot duration is much larger than backoff and is a divisor of MCOT. We use RS-based access as our baseline and present the results in Figure 25.

First, we observe that basic gap-based access (configuration A) exhibits low fairness on account of gNBs being able to preempt other contending stations when their transmissions end before a slot boundary (Figure 16). Disabling partial ending subframes (configuration B) only slightly improves fairness, while a better approach is to retain partial ending subframes but have a central controller optimally configure slot offset spacing (configuration C). If deploying such a controller is practically infeasible, then a properly configured modification of channel access such as the proposed next TX skipping (configuration D) can further improve fairness, achieving performance similar to RS-based access. Meanwhile, the channel efficiency of the gap-based configurations is variable, but always better than for RS. To better compare both metrics, we calculate a weighted average that emphasizes fairness over efficiency, i.e., we used weights of 0.6 and 0.4 for fairness and efficiency, respectively. We observe that having either centrally configured gNBs or using next TX skipping provides high performance without resorting to using RSs.

### VI. CONCLUSION

In this paper, we addressed the problem of contending NR-U base stations (gNBs) in sub-7 GHz bands, where gNBs are required to conform to LBT and initiate transmissions at slot boundaries. We implemented and validated a discrete-event simulator, which allowed us to conduct an extensive performance analysis. From this analysis, our general conclusion is that choosing either gap or RS-based access is a trade-off between fairness and channel efficiency. Gap-based channel access allows base stations to better utilize radio resources and to obtain higher channel efficiency due to a significantly lower probability of collision. In contrast, RS-based access, while wasting more energy and more radio resources because of a reduced transmission time and a higher collision rate, allows maintaining a fair share of radio resources between all gNBs. Furthermore, we have arrived at the following specific lessons learned regarding gap-based access:

1) NR-U base stations (gNBs) cannot have their slot boundaries synchronized as this leads to low channel utilization and unfairness. If possible, contending gNBs should be configured to have a minimum offset
between their slot boundaries. The exact offset value depends on the numerology (e.g., we found 60 μs to be sufficient for 1 ms subframe slots). Otherwise, random offsets should be selected.

2) NR-U performance improves when synchronization slots are shorter, but there are limits to consider. In terms of numerology, 250 μs is the smallest value allowed in sub-7 GHz bands. Shorter durations can be achieved with mini-slots, but it is not known if such precise scheduling can be successfully deployed in equipment.

3) The main drawbacks of using gap-based access (in comparison to using RSs) are the arising fairness issues, which need to be solved. However, we observed that gap placement (either before or after the backoff period) does not play a critical role.

4) Fairness is particularly affected by partial-ending subframes: ending a transmission even 1 OFDM symbol earlier allows the gNB to preempt other contending stations, which negatively impacts overall fairness. Disabling this feature improves fairness, but may not always be desirable.

5) Our proposed solution to improve fairness for gap-based access under partial ending subframes is next TX skipping, i.e., intentionally refraining from transmitting at the next viable opportunity. This approach is helpful regardless of the synchronization slot duration.

6) Dense deployments of gNBs require more advanced solutions regardless of the channel access method: RS provides high fairness but low channel efficiency (due to high collisions) whereas the gap-based approach has better efficiency but low fairness. We have shown that the shortcomings of gap-based access can be neutralized by extending the concept of next TX skipping.

As future work, we foresee addressing the problem of further improving fairness among gap-based gNBs, especially in dense deployments by selecting an appropriate number of transmission opportunities to skip. Additionally, the methods proposed in this paper should be evaluated in coexistence scenarios with Wi-Fi networks as well as in “Wi-Fi free” deployments (e.g., factory environments), where NR-U could operate in the frame-based equipment (FBE) variant of LBT [9], possibly in a fully unlicensed mode (i.e., without a carrier in the licensed band). Finally, we remark that the goal of all mechanisms proposed to improve contention resolution should exhibit self-configuration and self-optimization, i.e., support network autonomy [71].

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MAREK Z AJA C received the M.Sc. degree in ICT from AGH University of Science and Technology, in 2021. He is currently working at Nokia Solutions and Networks as a Software Engineer developing tools for 4G base station testing. His research interest includes wireless networks.

SZYMON SZOTT received the M.Sc. and Ph.D. degrees (Hons.) in telecommunications from the AGH University of Science and Technology, Krakow, Poland, in 2006 and 2011, respectively. He is currently working as an Associate Professor with the Institute of Telecommunications, AGH University. In 2013, he was a Visiting Researcher with the University of Palermo, Italy, and Stanford University, USA. He is the author or coauthor of over 70 research papers. His research interests include wireless local area networks (channel access, quality of service, security, and inter-technology coexistence). In the past, he has been a member of ETSI’s Network Technology Working Group Evolution of Management towards Autonomic Future Internet (AFI), an IEEE 802.11 Working Group Member, and on the management board of the Association of Top 500 Innovators. He is a Reviewer of international journals and conferences. He has been involved in several European projects (DAIDALOS II, CONTENT, CARMEN, MEDUSA, FLAVIA, PROACTIVE, and RESCUE) and grants supported by the Ministry of Science and Higher Education and the National Science Centre.