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NR-U and IEEE 802.11 Technologies Coexistence in Unlicensed mmWave Spectrum: Models and Evaluation

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ABSTRACT New Radio-based access to Unlicensed spectrum (NR-U) intends to expand the applicability of 5G NR access technology to support operation in unlicensed bands by adhering to Listen-Before-Talk (LBT) requirement for accessing the channel. As the NR-U specification is being developed, simulations to assess the performance of NR-U and IEEE 802.11 technologies coexistence in unlicensed spectrum bands are crucial. In this paper, we report on extensions to a popular and open source network simulator, ns-3, to build an NR-U system-level simulator and to model the NR-U and IEEE 802.11 technologies coexistence in the currently available unlicensed spectrum bands. The proposed NR-U model capitalizes on an NR Release-15 based model that has been extended to operate in unlicensed bands, while meeting its regulatory requirements. For the coexistence analysis, we pay particular attention to the millimeter-wave bands and provide a complete set of simulation campaigns evaluating the coexistence of NR-U and IEEE 802.11ad Wireless Gigabit (WiGig) in the 60 GHz bands. In particular, we focus on determining whether NR-U fulfills its coexistence objective in terms of a fairness criterion by testing different NR-U parameters, such as the numerology, the bandwidth, the channel access scheme, the energy detection threshold, and the beamforming method.

INDEX TERMS NR-U, Wi-Fi, unlicensed spectrum, coexistence, mmWave, 60 GHz band.

I. INTRODUCTION

The 3rd Generation Partnership Project (3GPP) is about to complete the standardization of New Radio (NR), the Radio Access Technology (RAT) for 5th Generation (5G) systems [1], [2]. The first phase of the NR specification was released in 2018 (in Release-15), and the full specification is to be finalized with Release-16. One of the main new features of NR, compared to previous generations of mobile communication systems, is the inherent support for operation at the millimeter-wave (mmWave) spectrum region with wide-bandwidth [3] and the related beam management procedures [4]. Notably, significant amounts of unlicensed/shared bandwidth have been recently released in the mmWave spectrum region. In the unlicensed 60 GHz bands, there has been a release of 9 GHz of spectrum in Europe and of 14 GHz in the USA [5]. Also, in the USA, there has been a recent allocation of spectrum in the 37 GHz bands for shared access and above 90 GHz for unlicensed access. Since Long Term Evolution (LTE) Release-13, cellular communications have expanded their paradigm of operation to the unlicensed spectrum bands [6], [7]. For LTE, the main focus has been on the unlicensed 5 GHz bands, for which multiple LTE variants are currently available, namely Licensed-Assisted Access (LAA) (in 3GPP Release-13, 14 and 15) [8]–[12], LTE Unlicensed (LTE-U) (developed by the LTE-U Forum based on LTE Release-12) [6], [13] and MulteFire (developed by the MulteFire Alliance based on LTE Release-14) [14], [15]. Differently from LTE, which was designed for uninterrupted operation in licensed spectrum and then was modified to operate in the unlicensed 5 GHz bands, NR is being designed with the native feature to operate in the unlicensed spectrum, through the so-called New Radio-based access to Unlicensed spectrum (NR-U) extension [16]–[18].

The design of NR-U started in a Study Item of NR Release-16 in 2018 [16] and then continued in an NR

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Release-16 Work Item. Such Work Item focuses on the unlicensed/shared spectrum at sub 7 GHz bands (including the 2.4, 3.5, 5, and 6 GHz bands) and currently is still under development. In Release-17, a Study Item has already been approved in December 2019 to extend NR operation up to 71 GHz, and so also to unlicensed 60 GHz bands [19], [20]. Differently from LAA and LTE-U that have been standardized based on carrier aggregation using the 5 GHz bands, NR-U design considers multiple bands and also other deployment scenarios, such as dual connectivity and standalone operation in the unlicensed spectrum. The later represents an unprecedented milestone for cellular systems.

One of the key issues to allow cellular networks to operate in the unlicensed spectrum is to ensure a fair coexistence with other unlicensed systems, such as Wi-Fi in the 5 GHz bands (IEEE 802.11a/n/ac/ax) and directional multi-Gigabit Wi-Fi in the 60 GHz bands (IEEE 802.11ad/ay, also known as Wireless Gigabit (WiGig)) [21]–[23]. For a fair coexistence, any RAT that operates in the unlicensed spectrum has to be designed in accordance with the regional regulatory requirements of the corresponding bands [17]. In the case of the 5 GHz and 60 GHz bands, regulations in Europe and Japan mandate the use of Listen-Before-Talk (LBT) [24], among others. LBT is a spectrum sharing mechanism by which a device senses the channel using a Clear Channel Assessment (CCA) check before accessing to it, and which is already adopted by LAA, MulteFire, Wi-Fi, and WiGig.

Coexistence in the 5 GHz bands has been well studied in the literature, to let LTE gracefully coexist with Wi-Fi [25]–[27]. In these bands, it is commonly accepted that LAA is fairer to Wi-Fi than LTE-U because it uses the LBT mechanism, and so it behaves similarly to Wi-Fi. Recently, authors in [28] have presented a detailed coexistence study and comparison of LAA and LTE-U technologies through network simulations and evaluated how the channel access procedures, besides other important aspects like the traffic patterns, simulation setup, and proprietary implementation choices, impact the coexistence performance. However, similar studies for NR-U and Wi-Fi/WiGig coexistence, are not yet available for either below 7 GHz or mmWave bands.

3GPP TR 38.889 [16] presents NR-U and Wi-Fi coexistence results in the 5 GHz bands that are obtained by multiple companies, but the simulators are not publicly available, and the models are not described with much insight. Also, authors in [29] present results of a 5G system that integrates the 28 GHz licensed bands and the 60 GHz unlicensed bands, while coexisting with WiGig therein, but few details are revealed about the proprietary simulator that is used. As such, the obtained results in [16], [29] are not easily reproducible, and system performance metrics are presented without much detail revealed about the underlying models and assumptions. We believe that reproducibility and model openness are crucial to perform research in the area of coexistence of multi-RAT technologies in unlicensed spectrum. In this regard, the popular and open source ns-3 simulator provides the perfect framework for reproducible research and collaborative development, as it was already demonstrated in [28], and disposes of multi-RAT models. Notably, the ns-3 simulator has recently released novel models for NR Release-15 [30], [31] and IEEE 802.11ad [32], [33].

In this paper, we present a multi-RAT ns-3-based simulator for an end-to-end evaluation of the coexistence of 3GPP NR-U and IEEE 802.11-based technologies in unlicensed spectrum. The work is focused on the unlicensed mmWave bands by taking into account the directional (beam-based) transmissions, and so offers novel and unprecedented coexistence evaluation results between NR-U and WiGig (IEEE 802.11ad). The objective of the present work is extremely timely and relevant since 3GPP has not started yet the related Work Item, which is scheduled for Release-17 [19], [20]. To develop NR-U, we have extended the NR Release-15 model in [30] by incorporating new functionalities to allow operation in unlicensed bands, while fulfilling its regulatory requirements, in terms of LBT, maximum Channel Occupancy Time (COT), minimum Occupied Channel Bandwidth (OCB), and maximum power limits. The code is freely available from [34] under the GPLv2 license. The model supports multiple frequency bands and NR-U deployment scenarios, including carrier aggregation and standalone operation for NR-U. While a preliminary set of results were presented in [35], where we tested different LBT categories, in this paper we provide a detailed introduction of the simulator and an in-depth analysis of coexistence performance in the 60 GHz bands, through what we believe is the first open source tool for coexistence evaluations of NR-U with IEEE 802.11 technologies in mmWave bands. In particular, we evaluate coexistence performance in an indoor 3GPP-oriented scenario, where a standalone deployment of NR-U coexists with one of WiGig. We focus on discovering general behaviors as a function of a wide variety of NR-U parameters, such as the channel access scheme, numerology, bandwidth, Energy detection (ED) threshold, beamforming scheme. Thanks to the directionality of the transmissions, the propagation conditions of the mmWave bands, and the flexibility inherited from NR, our results appoint to NR-U as a friendly technology to WiGig in unlicensed mmWave bands.

The rest of the paper is organized as follows. Section II reviews current status about the NR-U and WiGig standardization processes. Section III describes the developed NR-U model with its implementation details, the adopted WiGig model and its improvements, and the coexistence simulator setup. Section IV presents an extensive set of ns-3 based simulation campaigns that we have performed, as well as the obtained end-to-end results for NR-U and WiGig coexistence in the 60 GHz bands. Finally, Section V concludes the paper. Throughout this paper, in line with 3GPP terminology, we refer to an NR terminal as User Equipment (UE) and an NR base station as next-Generation Node B (gNB). Similarly, according to IEEE 802.11 standards, Wi-Fi/WiGig terminal and base station are referred to as Station (STA) and Access Point (AP), respectively.

II. TECHNOLOGIES REVIEW

This section reviews the standardization process of NR-U technology in 3GPP and of 802.11ad/ay (WiGig) technology in IEEE. Key design features and functionalities, coexistence scenarios and fairness objective, are also highlighted.

A. 3GPP NR-U HIGHLIGHTS

Based on 3GPP timeline, NR-U for sub 7 GHz is currently being standardized in Release-16 [16], while NR-U for mmWave bands is scheduled for Release-17 and beyond. The primary objective of NR-U is to extend the applicability of 5G NR to unlicensed spectrum as a general purpose technology that allows fair coexistence across different RATs.

To assess the coexistence, the NR-U Work Item focuses mainly on three modes of operation:

- Carrier aggregation NR-U, which is based on LTE-LAA introduced in Release-13. Carrier aggregation NR-U uses aggregation of NR-U in unlicensed spectrum and either NR or LTE in licensed spectrum.
- Dual connectivity NR-U, which is based on LTE-eLAA introduced in Release-14. Dual connectivity NR-U assumes simultaneous connectivity with NR-U in unlicensed spectrum and either NR or LTE in the licensed spectrum.
- Standalone NR-U, which is a novel approach in 3GPP Release-16. Standalone NR-U works in unlicensed spectrum without being anchored to any licensed carrier, similarly to what was proposed by MulteFire for LTE.

The NR-U design is further complicated in the standalone deployment scenario because all the signals must use the unlicensed band, thus requiring a redesign of initial access and scheduling procedures.

The objective of 3GPP is to define the necessary enhancements to NR to determine a single global solution for NR-U. The key basis for all the enhancements is to be compliant with the regulatory requirements [17], which include LBT, maximum COT, OCB, power limits (in terms of maximum equivalent isotropically radiated power and maximum power spectral density) and specific functionalities (such as dynamic frequency selection and frequency reuse), in case of 5 GHz and 60 GHz bands. Such requirements impose certain redesign of the standard procedures, channels and signals, as well as challenges at the implementation level. For example, the LBT requirement creates uncertainty for the channel availability, which is fundamentally different from the licensed-based access, where all the transmissions occur at prescheduled and fixed times.

Based on that, modifications to several NR Release-15 features are being considered, including:

- Initial access procedures and signals. For example, changes to the Synchronization Signal/Physical Broadcast Channel (SS/PBCH) transmissions and the random access procedure to account for LBT, as well as changes to the Physical Random Access Channel (PRACH) preamble transmissions to meet the OCB requirement.
- DownLink (DL) channels and signals. This includes dynamic Physical Downlink Control Channel (PDCCH) monitoring, Physical Downlink Shared Channel (PDSCH) transmissions to support flexible starting point due to LBT, mechanisms to detect COT start for UE power saving purposes, COT structure indication.
- UpLink (UL) channels and signals. For example, block interlaced based Physical Uplink Control Channel (PUCCH) and Physical Uplink Shared Channel (PUSCH) design to account for the OCB requirement, flexible starting points for PUSCH transmissions due to LBT, and sounding reference signal enhancements.
- Paging procedures. This includes flexibility in monitoring paging signals, which may not be transmitted as prescheduled due to LBT.
- Hybrid Automatic Repeat Request (HARQ) procedures. For example, additional ACK/NACK transmission opportunities, to avoid declaring a NACK in case of prevented ACK transmission, and multi grant transmissions.
- Configured grant mechanisms. For that, flexibility in time-domain resource allocation is considered to overcome the LBT impact.
- Wideband operations. For example, to support transmissions of a bandwidth larger than that of a Wi-Fi channel bandwidth.
- Measurement framework. This envisions changes to the radio link monitoring procedures due to the LBT requirement.

Recent agreements of the NR-U Work Item for sub 7 GHz bands include two SS/PBCHs transmissions per slot, PRACH transmission with repetition of sequence in frequency domain, increase of the random access response window from 10 ms to 20 ms, Physical Resource Block (PRB)-based interlace design for PUSCH and PUCCH, and additional PDCCH monitoring paging occasions within a single paging occasion.

Additionally, channel access procedures are discussed, such as the selection of the LBT category and the corresponding parameters for each of the downlink and uplink channels under different conditions. The LBT protocol for NR-U follows the LBT procedure defined in LTE-LAA, which was indeed inspired by the Wi-Fi CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) mechanism. A state machine for the LBT CCA process is presented in [28]. In particular, for NR-U, four LBT categories have been defined [16]:

- Category 1 (Cat1 LBT): Immediate transmission after a short switching gap of 16 μs.
- Category 2 (Cat2 LBT): LBT without random back-off, in which the CCA period is deterministic (e.g., fixed to 25 μs).
- Category 3 (Cat3 LBT): LBT with random back-off with a contention window of fixed size, in which the extended CCA period is drawn by a random number within a fixed contention window.

- Category 4 (Cat4 LBT): LBT with random back-off with a contention window of variable size, in which the extended CCA period is drawn by a random number within a contention window, whose size can vary (e.g., exponentially) based on channel dynamics.

For different transmissions in a COT and various channels/signals to be transmitted, different categories can be used. In brief, as in LAA, Cat4 LBT is used for gNB or UE to initiate a COT for data transmissions, while gNB can use Cat2 LBT for specific signaling like discovery reference signals (see details in [16]).

The rules for shared COT have also been defined for NR-U in [16]. For a gNB initiated COT, the responding devices are allowed to transmit without performing a CCA check (i.e., Cat1 LBT) if there is a gap between DL and UL transmissions of less than 16 us. For a gap of more than 16 us, but less than 25 us, within the COT, only short sensing (i.e., Cat2 LBT) is needed at the responding devices. Otherwise, if the gap is longer than 25 us, regular LBT (i.e., Cat4 LBT for data) has to be done at responding devices. Besides, differently from LAA, which supported a single DL/UL switching point within the COT, NR-U supports multiple DL/UL switching points within the COT.

In December 2019, 3GPP plenary planned to extend NR operation up to 71 GHz, and so also to unlicensed 60 GHz [19], [20]. The key design aspects related to the coexistence of NR-U at 60 GHz unlicensed bands, such as directional LBT and the corresponding beam management impacts [17], are expected to be considered in Release-17 as part of the newly approved study items.

B. IEEE 802.11AD/AY HIGHLIGHTS

IEEE 802.11 Wireless Local Area Networks (WLANs) standards have started technology development to use the unlicensed spectrum at 60 GHz bands with multi-Gigabit/s data rates, through 802.11ad amendment, in 2013 [22], and its recent enhancement through 802.11ay amendment in 2019 [23], [36]. As compared to legacy IEEE 802.11 systems, IEEE 802.11ad/ay (or WiGig) includes several fundamental changes and additions. For example, a hybrid Medium Access Control (MAC) layer, specific beam training processes for directional transmissions, more aggressive frame aggregation, fast session transfer to 802.11ac/n, relay support, and the definition of a Personal Basic Service Set.

Differently from Wi-Fi in 5 GHz bands, WiGig uses a hybrid MAC approach that has three different mechanisms: contention-based access, scheduled channel time allocation, and dynamic channel time allocation or polling. However, in all the access modes, CSMA/CA is used with a CCA that considers an omnidirectional sensing and a random back-off with a contention window of variable size. In WiGig, differently than NR-U, there is no notion of shared COT, and every device has to apply a CCA before accessing the channel. However, different durations of the sensing stages are defined for different control/data frames.

The beam steering process has been carefully designed in WiGig to precisely align transmit and receive beams. Mainly, the beamforming training is composed of two phases: sector level sweep and an optional beam refinement phase. Both are based on beam sweeping processes, thus incurring overheads and additional frames that are defined and devoted exclusively for the beam training.

As previously mentioned, IEEE 802.11ad/ay is particularly designed to operate standalone in the 60 GHz bands. While IEEE 802.11ad considers operation in a single channel of 2.16 GHz bandwidth, IEEE 802.11ay enables aggregation of up to 4 channels, thus leading to a total aggregated bandwidth of 8.64 GHz. However, both also support fast session transfers to IEEE 802.11ac/n operating in the 5 GHz bands in case of channel blockage and relay support.

Differently from NR-U, IEEE 802.11ad/ay amendments have already been completed and published. So, for more details about IEEE 802.11ad/ay specifications, we refer interested readers to [21]–[23], [36].

C. COEXISTENCE SCENARIOS AND OBJECTIVE

The 3GPP NR-U Work Item has defined the scenarios to assess the NR-U and Wi-Fi coexistence performance in sub 7 GHz bands. Two main layout scenarios are defined based on the deployment and propagation environment conditions: indoor and outdoor sub 7 GHz. The coexistence evaluation procedure considers two operators, operator A and operator B, deploying two different RATs (and thus address, e.g., Wi-Fi and NR-U coexistence) or two operators of the same RAT, e.g., to evaluate either Wi-Fi and Wi-Fi coexistence, or NR-U and NR-U coexistence. The coexistence objective for NR-U is measured in terms of a fairness, which is defined as it was for LAA in Release-13: NR-U devices should not impact deployed Wi-Fi services (data, video, and voice services) more than an additional Wi-Fi network would do on the same carrier [37]. Therefore, the standard way to evaluate the fairness is first to consider a Wi-Fi/Wi-Fi deployment (operator A/operator B) and then replace one Wi-Fi network by an NR-U network, to assess the performance of the Wi-Fi and NR-U coexistence and determine the impact of NR-U on the Wi-Fi system as compared to the Wi-Fi/Wi-Fi deployment. More details on the simulation methodology and parameters for indoor and outdoor sub 7 GHz scenarios can be found in TR 38.889 [16]. In the rest of the paper, we replicate the same procedure in the 60 GHz band for coexistence between NR-U and WiGig. We extend the indoor and outdoor sub 7 GHz scenarios to indoor mmWave and outdoor mmWave [17], to evaluate 60 GHz coexistence scenarios.

III. NR-U AND WiGig COEXISTENCE SIMULATION MODELS

This section describes the ns-3 based coexistence simulator that we have built, the NR-U model that we have developed, including the design choices and implementation details, and the adopted WiGig model and its improvements.

A. COEXISTENCE SIMULATOR

The NR-U and WiGig coexistence simulator has been built starting from previous works done in ns-3 community in the area of NR [30] and WiGig [32], [33]. The status of the two simulators was very different at the beginning of the work. WiGig was not able to model interferences from other technologies and account with those and was relying on a channel model that was not aligned with 3GPP [38]. To simulate 3GPP scenarios, we decided to make the two simulators compatible with the 3GPP channel model in [38]. We improved the capabilities of WiGig also to receive interference from signals of other technologies. Besides, we made the antenna models (including modeling of the uniform planar arrays and antenna element radiation patterns) of the two technologies compatible, to foster results comparability.

B. NR-U MODELS

On the NR side, we started from the models described in [30], and we extended NR with the distinguishing features of NR-U. As the standardization works for NR/NR-U above 52.6 GHz have not yet started, we have used the NR Release-15 design specification and extended it to incorporate the 60 GHz regulatory requirements in terms of maximum COT, LBT, OCB and power limits, as well as the corresponding impacts they impose on the design. The same regulatory requirements also apply to the 5 GHz bands, as well as the 2.4 GHz bands, although the specific values may vary. Therefore, the developed model can operate in all the currently available unlicensed spectrum bands while meeting the regulatory requirements.

Notice that, since the study items and work items for NR and NR-U operation above 52.6 GHz in Release-17 still have to start, changes may appear in the specification. However, we do not expect significant changes for the models that we currently propose in the simulator and this paper. The reason is that, from the authors' point of view, in the 60 GHz band, the waveform (i.e., OFDM) is not expected to change because the improvements that are offered by alternative waveforms in high-frequency ranges are small, when considering that the radiated power in the unlicensed bands is constrained and the directional antenna gains already provide much of it. So, the model that we present here may need small refinements in the future, based on the agreements resulting from NR and NR-U standardization for above 52.6 GHz bands in 3GPP Release-17, but a significant refactoring is not expected.

Fig. 1 presents the architecture of our NR-U device implementation design. A Component Carrier Manager (CCM) manages the traffic distribution among different carriers. For each carrier, a Channel Access Manager (CAM) defines the way the NR node accesses the channel. Among different options, the CAM models also allow LBT-based access through any of the potential categories considered by the standard. The sensing capability is incorporated into the NR-U model through the ED block at the Physical (PHY), which performs CCA based on indication from the LBT block in the CAM with the ultimate goal of checking channel availability before transmitting on it. In this work, we have implemented omnidirectional sensing, i.e., omniLBT, at the gNBs, since for the time being it is the only kind of sensing considered for NR-U in 3GPP [39]–[42]. More studies on omnidirectional versus directional sensing may be scheduled in the context of a future work item in Release-17 [43]. Previous studies in omnidirectional versus directional sensing tradeoffs, are discussed here [44], [45]. At the UE side, instead, we focused on directional sensing, i.e., dirLBT, since differently from the gNB, the UE only has to communicate with its gNB. An important note is that the two options are static. The sensing phase is always performed directionally at the UE and omnidirectionally at the gNB. For the UE, directional sensing is implemented by using the beam used for transmission/reception towards/from the serving gNB.

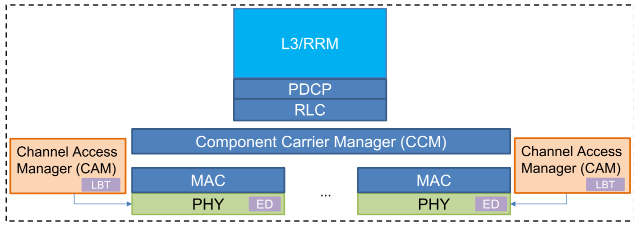

FIGURE 1. NR-U device architecture with multiple component carriers and LBT after MAC processing implementation.

We have implemented the 3GPP LBT procedure, which is also used for LTE-LAA [28]. All four LBT categories are supported in the DL (i.e., at gNB side) (see Section II-A): Cat1 LBT, Cat2 LBT, Cat3 LBT, and Cat4 LBT. In UL, we support Cat1 LBT and Cat2 LBT. This is compliant with DL data and DL control transmissions, as well as UL control transmissions in NR. That is, it is perfectly suited for packet transmissions going from gNBs to UEs, which, without loss of generality, is the main focus of this work. In case UL data transmissions needed to be simulated, simple extensions would allow the support of Cat3 LBT and Cat4 LBT in the UE as well.

Every time LBT is successful, the channel is granted for the duration of the maximum COT. All the LBT categories have different attributes to configure: the ED threshold, the CCA slot duration, the defer interval during CCA, and the maximum COT duration. In addition, the simulator allows configuration of the minimum and maximum values of Contention Window Size (CWS) for Cat4 LBT, the CWS for Cat3 LBT, and the deferral period for Cat2 LBT. The values that we use for simulations are reported in Table 2 in the next section.

During the COT, we currently focus on a single DL-UL switching point. So, in the current implementation, the channel is released at the gNB after the UL control, whenever there is a DL to UL switch, or when between two DL transmissions there is a gap that is larger than 25 us, as per NR-U specification. Multiple DL-UL switching points can also be configured.

Another important design aspect is the decision of the moment when LBT has to be performed at the gNB with respect to the MAC processing. There are two options:

1) LBT before MAC processing: Start the LBT procedure before the MAC starts the scheduling decisions (hence, passing the data to the MAC scheduler only after the channel has been declared clear);
2) LBT after MAC processing: Start the LBT procedure after the MAC has processed and scheduled the data (therefore, sensing the channel already knowing the data packets that the PHY must send).

In general, in LTE/NR, the MAC works ahead with respect to the slot in which the data occupies the channel. For example, LTE works two subframes ahead with respect to when the data is over the air. Therefore, the two options are not equivalent. Option (1) may generate an inefficiency in spectrum usage because there is a gap between when the channel is granted and when it gets occupied. On the other hand, in option (2), there is a risk that the channel is not granted when the scheduler has decided to occupy it. In our implementation, we opted to reduce the inefficiencies in channel occupancy, against a more complex implementation, and we selected the LBT after MAC option. Such option (2) is already integrated into the NR-U device architecture that we illustrated in Fig. 1. In addition, option (2) guarantees that the implementation is also adequate for NR-U operation in sub 7 GHz bands, for which the duration of a slot is larger than the one employed for mmWave bands and, consequently, the inefficiency of the option (1) would be significant and would affect the coexistence performance.

Also, there is to consider that NR transmissions follow a certain frame structure and the beginning of the transmissions need to be synchronized with the slot boundary. LBT introduces randomness in the instant in which the channel is granted. If it happens in the middle of the slot, we wait for the slot boundary, and we do not reserve for the channel, as it was a normal practice in LTE-LAA. We make this choice because the slot duration in mmWave bands is much lower than it was for LTE, so we consider that the impact is limited. This may generate inter-RAT collisions as WiGig may start transmission in this gap, but also reduces channel occupancy of NR-U.

To meet the OCB requirement, for DL data transmission, we use a Time-Division Multiple Access (TDMA) beam-based access, in which OFDM symbols are allocated among beams and different UEs associated to the same beam can be allocated in different PRBs. Fig. 2 shows the current implementation at the gNB side, including the omniLBT sensing and the TDMA beam-based access, considering three beams (B_1, B_2, B_3) and two UEs scheduled within the third beam (UE_c, UE_d). For control channels to meet the OCB requirement, we spread such signals through the whole bandwidth. Finally, we constraint the maximum radiated power according to the regulatory requirements and distribute the

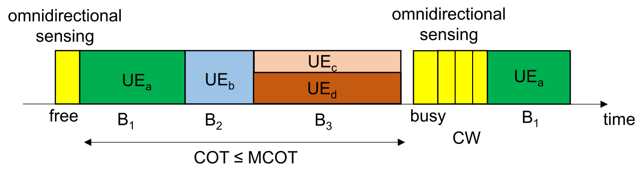

FIGURE 2. **Omnidirectional LBT implementation at gNB side and related scheduling operations to meet the OCB requirement.**

available power uniformly among the PRBs to meet the power spectral density constraint.

Let us remark that the proposed NR-U device model supports different NR-U deployment scenarios, including Carrier Aggregation of NR in licensed carrier and NR-U in unlicensed carrier, as well as Standalone NR-U, described in Section II-A. The developed NR-U model does not include the enhancements related to RACH, SS/PBCH, PDCCH, PDSCH, PUSCH, PUCCH transmissions that are being considered in the 3GPP for sub 7 GHz bands (as discussed in Section II-A), but we just simulate these channels while satisfying the requirements of LBT, maximum COT, OCB, and power limits. The developed NR-U model provides the basis for NR to operate in unlicensed mmWave spectrum while meeting the worldwide regulatory requirements, and new features can easily be incorporated in the future as the specification work moves forward.

Notice that, as the operational frequency increases, there may be less and less need to consider additional mechanisms, like LBT, to make NR operate in a friendly manner with other technologies. The reason is that the directionality of transmissions in mmWave bands makes interference situations negligible in certain deployments.

To evaluate the real need for LBT and to generalize the models, we have implemented various CAMs in the NR-U system-level simulator:

- AlwaysOn: It implements an NR-like behavior, in which channel access is always granted and NR-U operates in an uninterrupted fashion. Please note that the gNB transmits only if there is some data to transmit, following the indication of the MAC scheduler.
- OnOff: It implements a duty-cycled behavior, which alternates ON and OFF periods, without performing LBT to access the channel. Our design considers gNB-UE synchronization, meaning that the UEs follow the same duty cycle pattern of the gNB.
- LBT: It implements the 3GPP LBT procedure for channel access, as previously described.

In Table 1 (second column), we summarize the features and functionalities that are used and are available in the NR-U system-level simulator, including also the features that are imported from NR.

C. WiGig MODELS

For WiGig, we have used, as a basis, the models described in [32], [33]. We made some improvements to the WiGig

TABLE 1. NR-U and WiGig models.

	NR-U	WiGig
Frame structure	TDD NR-compliant frame structure with slots and OFDM symbols of numerology-dependent length [1], [30]: - frame: 10 ms, subframe: 1 ms - each subframe has 2^{μ} slots (associated to $15\times2^{\mu}$ kHz SCS) - numerologies μ=0,1,2,3,4 are supported - each slot is composed of 14 OFDM symbols - 1st symbol: DL control, 14th symbol: UL control, 2nd to 13th symbols flexibly allocated to DL and UL data	TDD WiGig-compliant [22], [32]: - Beacon interval of 102.4 ms, including BTI, A-BFT, ATI and DTI phases - Beacon Transmission Interval (BTI) of 1.2 ms - Association Beamforming Training (A-BFT), composed of 8 slots and 16 frames per slot - Announcement Transmission Interval (ATI): currently deactivated - Data Transmission Interval (DTI) of 98 ms: currently based on contention, but also supports contention-free and poling [32]
Antenna models	3GPP-compliant [46]: - Antenna arrays: 1 uniform planar array per AP/STA, $M\times N$ antenna elements, no polarization - Antenna elements: isotropical radiation and directional radiation are supported	3GPP-compliant [46]: - Antenna arrays: 1 uniform planar array per AP/STA, $M\times N$ antenna elements, no polarization - Antenna elements: isotropical radiation and directional radiation are supported
Beamforming methods	Two methods are available: beam-search method and singular value decomposition (SVD)-based method [31]. Both are ideal in the sense that no resources are used for beam training.	Beam-search method, implemented with a real training through BTI phase (to train AP beam) and A-BFT phase (to train STA beam) [32]
DL/UL data/control channels	- DL/UL data: transmitted and received directionally - DL control: sent quasi-omnidirectionally from gNBs and received directionally at UEs - UL control: sent directionally from UEs and received quasi-omnidirectionally at gNBs	- DL/UL data: transmitted and received directionally - DL control: sent directionally from APs and received quasi-omnidirectionally at STAs - UL control: sent directionally from STAs and received quasi-omnidirectionally at APs
Error models	- NR PHY abstraction for DL and UL data channels [48] including support for MCS Table1 and MCS Table2 [48], LDPC coding and block segmentation [49] - No error model for DL/UL control	- 60 GHz sensitivity error model for DL/UL data and control frames
Modulation	OFDM	Both single carrier and OFDM
Channel Coding	LDPC	LDPC
MCS	QPSK, 16-QAM, 64-QAM, 256-QAM	BPSK, QPSK, 16-QAM, 64-QAM
HARQ	- NR PHY abstraction for HARQ including support for HARQ-IR and HARQ-CC	Not supported by the standard
Retransmissions	Up to 4 with retransmission combining	Up to 7 without retransmission combining
MAC	Scheduled-based access: - In DL, OFDMA and TDMA accesses are supported with round-robin, proportional-fair and maximum rate rules for the MAC scheduler - In UL, TDMA access is supported	Contention-based access for DL and UL
Link adaptation	Two adaptive modulation and coding schemes are supported: Error model and Shannon bound	Link adaptation based on the Shannon bound
Operational modes	Standalone NR-U and Carrier Aggregation NR-U	Standalone WiGig
Channel access	LBT, OnOff, AlwaysOn	CSMA/CA

model in order to enable a coexistence evaluation and ensure a fair coexistence comparison. In particular, we improved models in [32], [33] so that:

1) the interference from different RATs can be modeled and taken into account,
2) channel models are compliant with the 3GPP recommendations for above 6 GHz [38] and
3) antenna models for uniform planar arrays and element radiation patterns are compliant with the 3GPP [46].

We have fixed these aspects to be able to simulate the 3GPP scenarios, and also unified the beamforming representation (through antenna weights, a.k.a., beamforming vectors, rather than spatial radiation patterns that were used in the WiGig model) to be compatible with the 3GPP channel model that is based on channel matrices. This allows the interaction of the NR-U and WiGig models.

In addition, the WiGig model was not considering any link adaptation algorithm and was working only with a fixed and preconfigured Modulation Coding Scheme (MCS) during the whole simulation. From the standardization point of view, WiFi/WiGig do not specify any particular strategy to select the MCS. However, adaptive modulation and coding is a critical feature not only for evaluation of WiGig operation itself, but also for coexistence setups, in which it is important to adapt the transmission strategy to the channel observations. In this regard, we have extended the WiGig rate manager, beyond the constant rate manager approach, and we have created a new rate manager that selects and updates the MCS based on the perceived SINR.

Finally, we made other small improvements to the WiGig model, always keeping in mind the coexistence evaluation. These include random initialization of the beacon intervals

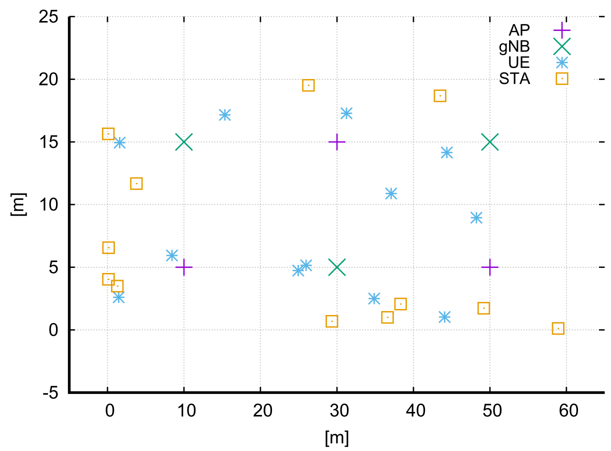

FIGURE 3. Indoor scenario with 3 gNBs, 3 APs, 12 UEs, and 12 STAs.

(or frame structures) of different APs, and inclusion of a beam reciprocity assumption (as it is assumed in the NR model, and by extension in our NR-U). In the case of WiGig, this removes the need to train e.g., the beam of the AP used for transmission and for reception towards a specific STA. Instead, the same beam is used for each AP/STA and so a single training of the transmit/receive beam of such node is required.

In Table 1 (third column), we summarize the features and functionalities that are used and available in the WiGig system-level simulator, as imported from the basic WiGig model and improved through the enhancements mentioned above.

IV. NR-U AND WiGig EVALUATION CAMPAIGNS

This section presents the simulation scenario that we have used to assess NR-U and WiGig coexistence in the 60 GHz band. Then, we present multiple simulation campaigns and discuss the obtained end-to-end results.

A. SCENARIO

For simulations, we consider a dense indoor hotspot deployment, as shown in Fig. 3. We consider a smaller version of the deployment evaluated by 3GPP in [16] for coexistence between NR-U and Wi-Fi in the 5 GHz band, which used a 120 m $\times$ 80 m area and a distance among two nodes of 40 m. In our scenario, as IEEE 802.11ad normally operates with short-range communications (between 1 m and 10 m), we set a minimum distance among two neighbors gNB/AP nodes of 10 m in the vertical plane and 20 m in the horizontal plane, and we limit the UE/STA deployment area to 60 m $\times$ 20 m. In summary, two operators deploy three base stations each in a single floor building. Each operator serves 12 users randomly distributed in a 60 m $\times$ 20 m area around the base stations. We simulate different scenarios, in which each operator can deploy either WiGig or NR-U technology. The paper focuses on the standalone operation of NR-U since it is more challenging from the coexistence perspective.

Table 2 reports the simulation parameters and functionalities, for NR-U and WiGig technologies. Through the simulation campaigns, we study the impact of some NR-U parameters, which are listed in Table 2 as variations of the baseline configuration.

B. SIMULATION CAMPAIGNS

For the scope of the paper, we are interested in modeling the system in a situation in which the system is not saturated. The reason is that, in case of congestion, data packets would be stuck in the queue of each device, invalidating any latency measurement (due to bufferbload effect) and making it difficult to reach any coexistence conclusion. Theoretically speaking, with 2.16 GHz of bandwidth at the maximum MCS, a single NR device using all the bandwidth for all the time can transmit up to 8.81 Gbps. Assuming that a WiGig device can transmit at the same rate (or at least, in the same order of magnitude), with 24 different nodes, we have a theoretical rate per-node of 376 Mbps. Therefore, we have selected one particular load value through preliminary simulations, to achieve a system state in which the load is high, but still does not congest the network. The selected value is 50 Mbps application load per node, in the downlink direction, so from the gNB/AP to the UE/STA, using constant bit rate traffic, and we test different configurations for NR-U when coexisting with WiGig.

The technologies influence each other in various aspects, including the perceived SINR, and consequently, the selected transmission rate (MCS). Hence, depending on the deployment, each device can either transmit at a full rate or enqueue some data in case the selected MCS is not able to support the traffic rate or there are not enough resources to transmit. Each simulation parameter influences this interaction, and therefore, extensive simulation campaigns are needed. Specifically, the simulation campaigns that we have performed focus on assessing the impact of:

- NR-U channel access manager,
- NR-U numerology,
- NR-U bandwidth,
- NR-U ED threshold,
- NR-U beamforming method.

For each simulation campaign, 20 random deployments (within the deployment scenario already described) are performed, to get statistical significance. Approximately 120 seconds are needed to run a single simulation of 1.5 simulated seconds, but we have used a parallel cluster to increase the number of simulations running per hour. As our objective is to investigate the system close to the saturation point, the constant bit rate applications start randomly within an interval of 10 ms, and run without interruption for 1 second. Considering the node positioning effects on the interference, as well as the MCS, instead of simulating longer time samples in a fixed position, we opted for increasing the statistical significance as we discussed earlier. As output statistics, we focus on four key indicators: channel occupancy

TABLE 2. Main scenario simulation parameters.

Parameter	Value (baseline)	Value (tested variations)
Deployment and propagation parameters:		
Channel model	3GPP Indoor Hotspot Mixed Office	
Deployment	2 operators, 3 base stations and 12 users per operator	
gNB/AP/UE/STA height	1.5 m	
Channel bandwidth	2.16 GHz	
Central frequency	58 GHz	
Noise power spectral density	-174 dBm/Hz	
Traffic parameters:		
Direction	downlink	
Application packet size	1000 Bytes	
Application load	50 Mbps	
Device parameters:		
gNB/AP antennas	8x8	
UE/STA antennas	4x4	
gNB/UE transmit power	17 dBm	9.67 dBm, 12.68 dBm
AP/STA transmit power	17 dBm	
gNB/AP/UE/STA noise figure	7 dB	
NR-U parameters and functionalities:		
Frame structure	SCS=120 kHz	SCS=60 kHz, SCS=240 kHz
Channel bandwidth	2.16 GHz	400 MHz, 800 MHz
Beamforming method	beam search	SVD-based
Beam reciprocity	yes	
Link adaptation	adaptive MCS (Shannon-based adaptation)	
Error model	NR PHY abstraction based on EESM [47]	
MCS table	MCS Table1	
HARQ method	HARQ-IR	
MAC	scheduled-based	
gNB CAM	Cat4 LBT	AlwaysOn, OnOff
UE CAM	Cat2 LBT	AlwaysOn, OnOff
RLC mode	RLC-UM	
RLC buffer size	999999999 Bytes	
LBT CAM:		
gNB ED threshold	-79 dBm (omniLBT)	-69 dBm, -59 dBm
UE ED threshold	-69 dBm (dirLBT)	
CCA slot duration	5 us	
defer interval during CCA	8 us	
Maximum COT	9 ms	
Cat 4 LBT minimum CWS	15	
Cat 4 LBT maximum CWS	1023	
Cat 3 LBT CWS	15	
Cat 2 LBT defer period	25 us	
DL-UL switching points	one within COT	
OnOff CAM:		
duty cycle	50%: ON and OFF periods of 9 ms	
WiGig parameters and functionalities:		
Frame structure	BI length =102.4ms, BTI length=1.2ms, 8 SS slots and 16 SSW frames per slot, no ATI	
Channel bandwidth	2.16 GHz	
Beamforming method	beam search	
Beam reciprocity	yes	
Link adaptation	adaptive MCS (Shannon-based adaptation)	
Error model	60 GHz sensitivity model	
MAC	contention-based	
RTS/CTS	disabled	
PDU and SDU aggregation	enabled	
CSMA/CA:		
AP/STA ED threshold	-79 dBm (omniLBT)	
CCA slot duration	5 us	
defer interval during CCA	8 us	
CSMA/CA minimum CWS	15	
CSMA/CA maximum CWS	1023	

(measured as the percentage of time that a gNB/AP node occupies the channel, through an indicator that each node logs every time it accesses the channel), packet delay at Internet Protocol (IP) level (measured per packet), per-user throughput at IP level (for those devices that receive at least one packet, measured per device), and system throughput (i.e., the total throughput of the system, measured per operator). For each of the output statistics, the maximum value and the minimum value are plotted with whiskers, the 95% percentile and the 5% percentile are displayed with

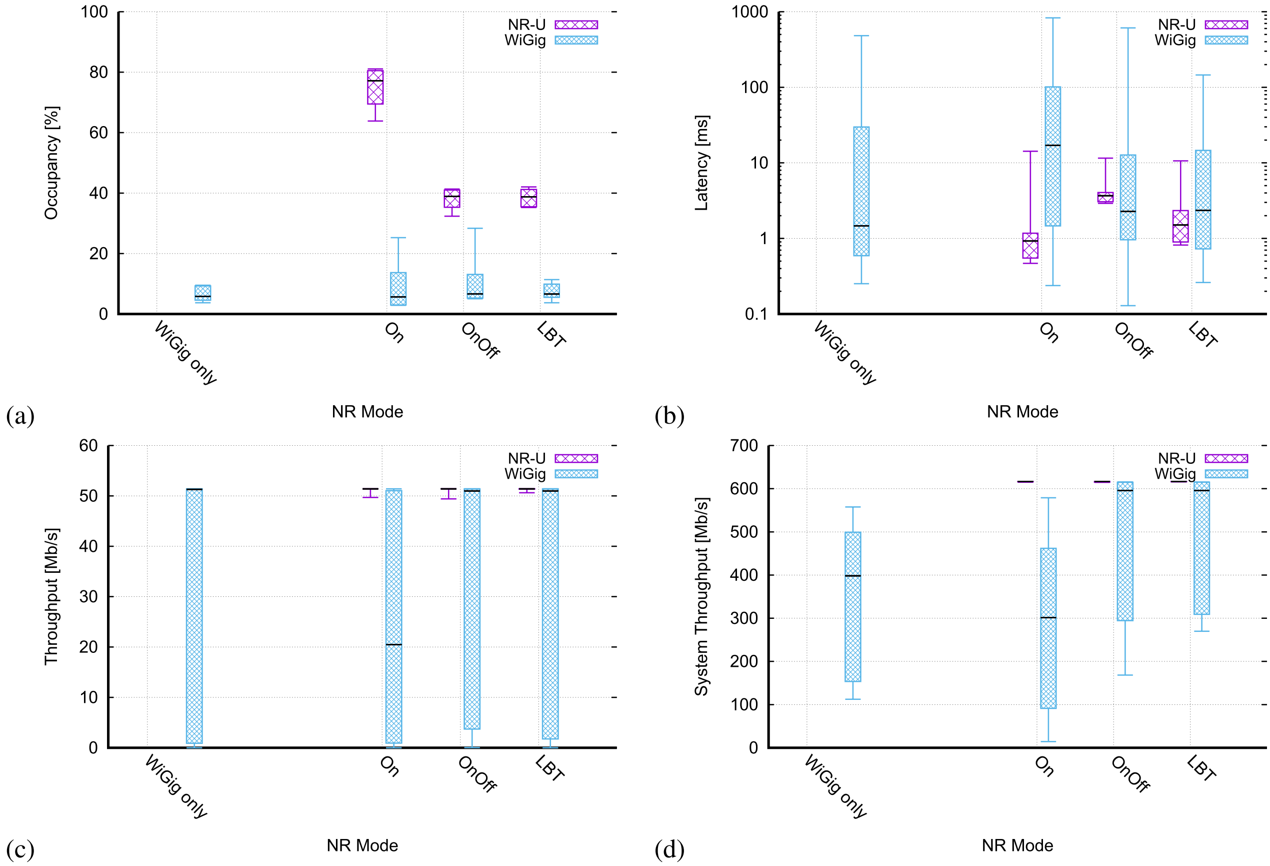

FIGURE 4. **Impact of NR-U CAM type. (a) Occupancy, (b) latency, (c) per-user throughput, (d) system throughput.**

boxes. Within each box, a horizontal solid line represents the 50% percentile.

For each simulation campaign, we show four groups of figures, one for each of the output statistics, i.e., (i) channel occupancy, (ii) packet delay at IP level, (iii) per-user throughput at IP level, and (iv) system throughput. The results are shown for different scenarios, i.e., when both the operators deploy WiGig (denoted by *WiGig only*) and when one operator deploys WiGig and the other deploys NR-U. In the WiGig only case, all the 24 users are IEEE 802.11ad-based. For other cases, 12 devices are IEEE 802.11ad-based and 12 devices are using NR-U, with the NR-U parameters indicated at the x-axis label. The results of WiGig coexistence with WiGig, i.e., WiGig only, provide the baseline to compare with, for all the WiGig coexistence with NR-U scenarios. Based on the 3GPP fairness definition, NR-U is expected to operate in a *fair* and *friendly* manner to WiGig, by not impacting WiGig's performance more than another WiGig device would do [17].

C. IMPACT OF NR-U CHANNEL ACCESS MANAGER

In the first simulation campaign, we evaluate the impact of different CAM types. The gNB and the UE access mechanisms that we compare are:

- On: NR-U with AlwaysOn CAM at both the gNBs and the UEs (i.e., NR-U noLBT);
- OnOff: NR-U with OnOff CAM (9ms ON and 9ms OFF), at both the gNBs and the UEs;
- LBT: NR-U with Cat4 LBT at gNBs and Cat2 LBT at UEs.

Results in terms of occupancy, latency, per-user throughput, and system throughput are shown in Fig. 4. Note that, in [35] we have presented a preliminary study about various LBT categories combinations for the case of 50 Mbps load per node, which concludes that the concrete LBT categories are not so crucial to the fairness, as it was for LTE-LAA, but also exhibits that the more conservative the implementation is, the more inter-RAT and intra-RAT collisions can be reduced. Among the LBT implementations that we have simulated in [35], Cat4/Cat2 is the most conservative, while Cat3/On is the most aggressive. Accordingly, in this paper, we focus on the following LBT categories combination: Cat4 LBT at gNBs and Cat2 LBT at UEs, as it is the fairest and more conservative option between all the different LBT combinations, besides the one also selected for LTE-LAA.

We observe in Fig. 4.(a) that the channel occupancy of NR-U devices is significantly higher than that of the WiGig devices. The reason is that the minimum resource allocation granularity of NR-U is an entire OFDM symbol, while IEEE 802.11ad has no such restriction (i.e., its access is not slotted).

The channel occupancy in WiGig strictly depends on the time needed to transmit the IEEE 802.11ad frames and varies for every IEEE 802.11ad frame. More precisely, the duration of WiGig's transmissions depends on the amount of data to be transmitted and the selected MCS, but they always span through the whole bandwidth. In NR-U, instead, for small packet sizes, the OFDM symbol can remain partially empty in the frequency domain, but the channel still occupies the whole OFDM symbol length (e.g., 8.92 us for SubCarrier Spacing (SCS) of 120 kHz), which may lead to inefficient channel usage. From the simulator, we have observed that the average length of a WiGig transmission is around 3.5 us. This means that for the same data, an NR-U device is occupying the channel almost three times more than a WiGig device. A similar behavior was found in the case of Wi-Fi coexistence with LTE-LAA [28], where the difference was even higher because the minimum allocation granularity in LTE is one subframe of 1 ms.

On the other hand, if we compare the different channel access schemes simulated for NR-U, the channel occupancy of OnOff and LBT based techniques are lower than that of the AlwaysOn (see Fig. 4.(a)). For the OnOff scheme, the reason is that during the OFF period (which in our configuration lasts for 9 ms), an NR-U device has time to accumulate data in Radio Link Control (RLC) buffers. This allows filling more efficiently the OFDM symbols during the transmission opportunities. Similarly, LBT backoff allows more time to accumulate data during sensing and backoff times.

From a delay perspective, it can be observed in Fig. 4.(b) that NR-U performs considerably better than IEEE 802.11ad. This result is due to two main reasons: 1) the slot-based access and appropriate scheduling used in NR-U and 2) the HARQ retransmission combining used in NR-U. On the one hand, WiGig uses contention-based access, which makes WiGig more prone to intra-RAT collisions. Instead, NR-U considers slot-based access through a fixed frame structure and includes appropriate scheduling schemes to schedule the UEs, thus reducing the intra-RAT collision probabilities. On the other hand, if transmissions collide or channel blocking arises, HARQ in NR-U may still provide successful decoding of the data after combining the retransmissions; WiGig, instead, does not include HARQ mechanisms and keeps retransmitting without combining, thus eventually increasing the latency. It can also be observed that, for these reasons, WiGig traffic is affected by higher standard deviation as compared to NR-U.

The latency performance of WiGig devices is affected when coexisting with NR-U AlwaysOn (see Fig. 4.(b)), and this results in worse performance than for the WiGig-WiGig coexistence scenario. Results show that the inclusion of either LBT or OnOff mechanisms makes NR-U a fairer technology for coexistence. In particular, the OnOff and LBT implementations increase the end-to-end latency at NR-U devices (as compared to the AlwaysOn case). Still, they do not have an adverse impact on the latency of WiGig's devices (as compared to the baseline WiGig-WiGig scenario).

From throughput results in Fig. 4.(c)-(d), we observe that in all the scenarios, WiGig throughput presents a higher standard deviation than NR-U. This is because, in the proposed deployment, few STAs/UEs are located at the cell edge, and WiGig experiences more difficulties in serving this kind of users, as compared to NR-U. NR technology is shown to be more robust than WiGig to serve cell edge users, and this is due to key features like scheduling and HARQ retransmission combining, as we explained above. In fact, in NR-U cases, all the data can be delivered with an extremely reduced standard deviation (see Fig. 4.(c)-(d)). The appropriate scheduling and retransmission combining in NR-U allow serving all the devices adequately.

If we observe the median values, WiGig per-user throughput is not affected by coexisting with NR-U, except for the case in which coexists with NR-U AlwaysOn, for which WiGig cannot find the channel free to transmit. Indeed, the system throughput of WiGig is significantly improved, compared to the WiGig only case, when coexisting with NR-U with the OnOff and LBT channel access schemes (see Fig. 4.(d)). This is because STAs/APs try to decode all WiGig signals, so the higher the number of WiGig nodes in the scenario, the higher the time wasted trying to decode signals that go towards other nodes. This effect is reduced instead when WiGig coexists with NR-U. All in all, except for the case of NR-U AlwaysOn, NR-U does not have any adverse negative impact on the throughput performance of the WiGig devices. So, in terms of throughput, NR-U with either duty cycle or an LBT based channel mechanism fulfills its coexistence design objective.

Summary 1. Even if NR-U occupies the channel for more time than WiGig, the latency of the WiGig nodes is maintained when they have to coexist with NR-U nodes. Latency and throughput results, which show that the traffic can be delivered successfully, appoint to NR-U with LBT and NR-U OnOff as friendly technologies to WiGig. The only exception is NR-U with AlwaysOn access (i.e., NR without any spectrum sharing technique), because it is compromising the fairness (reducing WiGig throughput and increasing WiGig latency). We conclude that, a channel access scheme considering the existence of other technologies should be considered.

Summary 2. From the above results, we observe that the channel access coexistence options for NR-U based on LBT or duty cycle (OnOff) are similarly friendly to WiGig. Thanks to the directionality of the transmissions and the propagation characteristics of the mmWave bands, both schemes can successfully meet the fairness criterion.

D. IMPACT OF NR-U NUMEROLOGY

In the second simulation campaign, we assess the impact of changing the operative numerology of NR-U devices. In these tests, we consider three different SCSs: 60 kHz, 120 kHz,

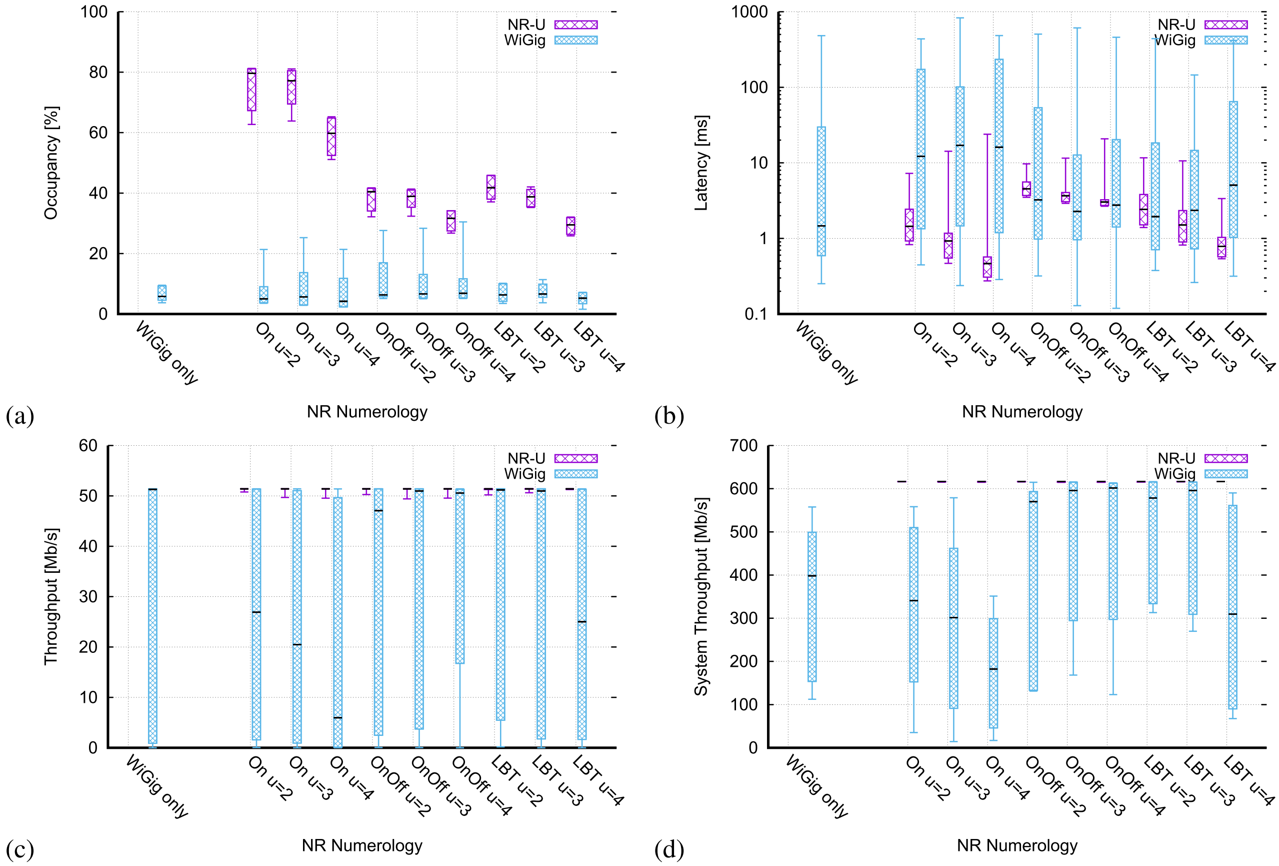

FIGURE 5. **Impact of NR-U numerology. (a) Occupancy, (b) latency, (c) per-user throughput, (d) system throughput.**

and 240 kHz.[1] They are displayed in the horizontal axis of the figures as u=2, u=3, and u=4, respectively. Results in terms of occupancy, latency, per-user throughput, and system throughput are shown in Fig. 5. Let us remark that the general observations discussed in the previous section regarding the WiGig/WiGig scenario as compared to the WiGig/NR-U scenario, either with OnOff, LBT, or AlwaysOn based techniques, still hold for fixed numerology. Thus, in this section, we focus on assessing the numerology effect on the coexistence performance.

In Fig. 5.(a), we can observe that increasing the numerology we reduce the channel occupancy of NR-U for all channel access mechanisms. That is because, with a reduced OFDM symbol length (which is inversely proportional to the SCS), we get a more efficient spectrum usage, reflected in the lower occupancy value. From our results, it stands that the improved efficiency also depends on the channel access type. OnOff and the LBT options are not similarly decreasing the occupancy, when reducing the SCS, for lower numerologies. In general, OnOff access provides a more efficient channel occupancy, due to the fact that it allows accumulating more packets in RLC buffers during the OFF periods, which can then better occupy the transmission opportunity during the ON period, as compared to LBT-based access.

Regardless of the channel access managers, increasing the numerology reduces the latency of the NR-U system. This result is because NR processing times and the transmission duration are inversely proportional to the SCS (i.e., higher SCS, lower times). On the other hand, such a numerology increase, and reduced occupancy in NR-U, does not reduce the WiGig latency and promotes different trends on the WiGig throughput. In particular, for the cases of AlwaysOn and LBT CAMs, the median of the WiGig latency increases (see Fig. 5.(b)) with the numerology, and the WiGig median throughput is significantly reduced when changing from numerology 3 to 4 (see Fig. 5.(c)-(d)). The reasons depend on two opposite effects: 1) the reduced length of the slots with higher numerologies, reduces the processing and transmission times of NR-U, 2) the reduced slot length allows for reduced aggregation of packets, which increases the number of ON to OFF transitions.

When WiGig coexists with NR-U AlwaysOn, we observe that low numerologies are better for coexistence with WiGig. This is because, when reducing the numerology, the slot length increases (i.e., the scheduling interval), and as such, NR-U can aggregate more data and use a lower number of

[1]Currently, in the NR standard, only 60 and 120 kHz SCSs can be used for data transmission within the mmWave region that goes up to 52.6 GHz. However, we expect that in the future, higher numerologies such as that of SCS=240 kHz will be included in the standard.

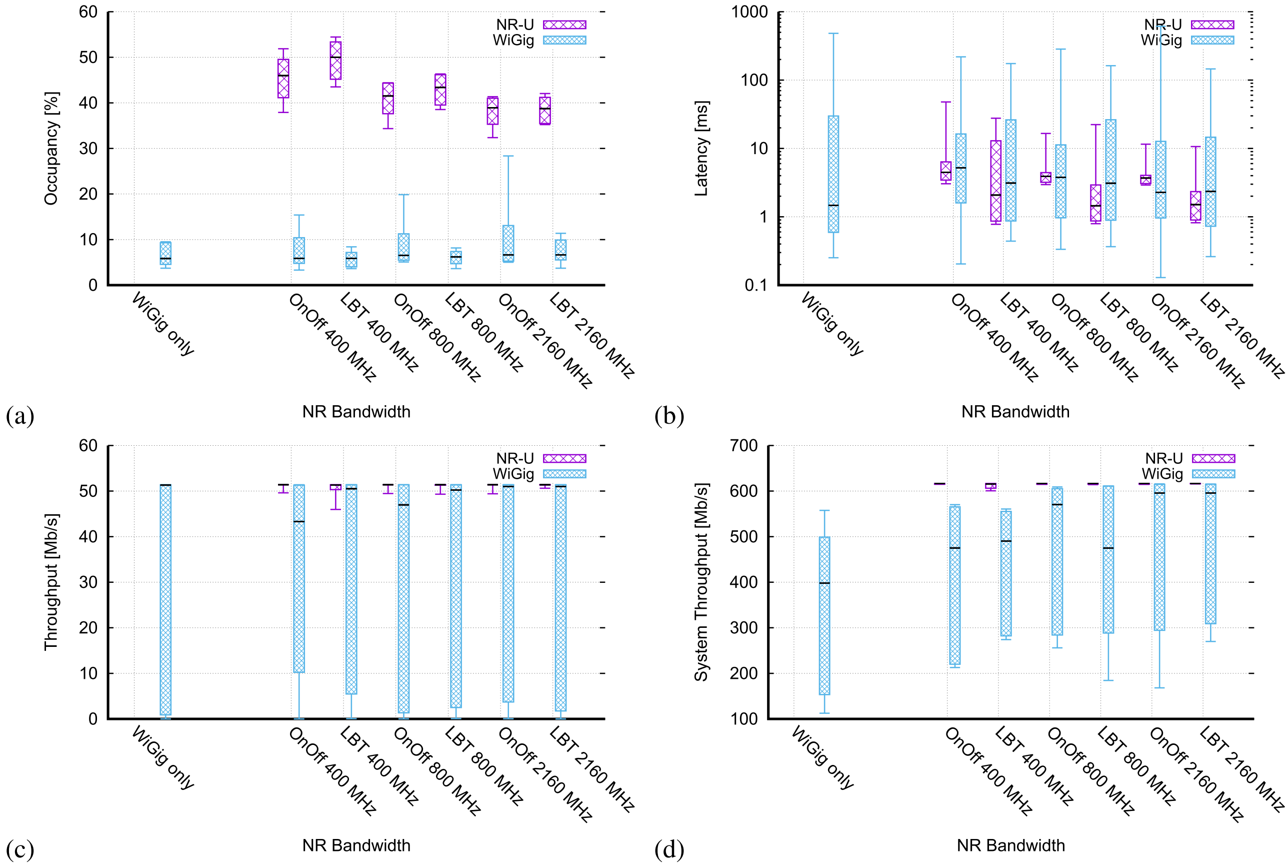

FIGURE 6. Impact of NR-U bandwidth. (a) Occupancy, (b) latency, (c) per-user throughput, (d) system throughput.

ON to OFF transitions. This results in better latency and throughput for WiGig nodes. Effect number 2 dominates the results.

When WiGig coexists with NR-U OnOff, the opposite result is observed, and higher numerology is better for WiGig. This is because the OnOff CAM at NR-U nodes already naturally allows for packet aggregation during OFF periods and, therefore, higher numerology is beneficial for WiGig, due to the reduced transmission times of NR-U, i.e., effect number 1 is dominating the results.

Similarly, also when WiGig coexists with NR-U LBT, we observe an interplay of effects depending on 1) the aggregation facilitated by the backoffs (LBT), and 2) the aggregation due to the scheduling interval (slot). The inter-packet arrival time (IPAT) defined in the traffic model, also comes into play. With the considered packet size and load, the resulting IPAT is 160 us. The slot lengths for the considered numerologies are 250 us (u=2), 125 us (u=3), and 62.5 us (u=4). In the case of LBT Cat4, the minimum sensing period after the defer interval is 75 us (5 us times the minimum CWS of 15). If we add to the scheduling interval (slot length) the minimum sensing period after the defer interval (75 us), we get an aggregation period of 325 us (u=2), 200 us (u=3), and 137.5 us (u=4). For u=2 and u=3, the IPAT is lower than the aggregation period. As such, there is aggregation in NR-U, so that increasing the numerology is beneficial for WiGig, due to the reduced NR-U transmission times. Instead, for u=4, the IPAT is higher than the aggregation period. Therefore, in this case, a higher number of ON to OFF transitions is observed in NR-U, which affects WiGig's performance.

Summary 3. Increasing the numerology has a beneficial effect for NR-U, both in terms of channel occupancy and latency. Instead, unexpectedly, such a numerology increase is not always beneficial for WiGig and, whether it is beneficial or not depends on the channel access scheme that is used at NR-U, for the considered traffic type. From a coexistence perspective, with NR-U AlwaysOn, lower numerology is desirable for WiGig; with NR-U OnOff, higher numerology is preferred; while, with NR-U LBT, the optimal numerology depends on the IPAT. Note that this conclusion is tied to the constant bit rate traffic application with small packet sizes, which creates more discontinuous channel accesses. Instead, if a bursty traffic model was considered (e.g., FTP model), for which bigger packet sizes are transmitted with large inter-packet arrival times, then we expect that higher numerology would be beneficial in all the cases since the accesses to the channel will be continuous once the channel is granted. Notice that in this study, we have focused on constant bit rate traffic with small packets, because it is more

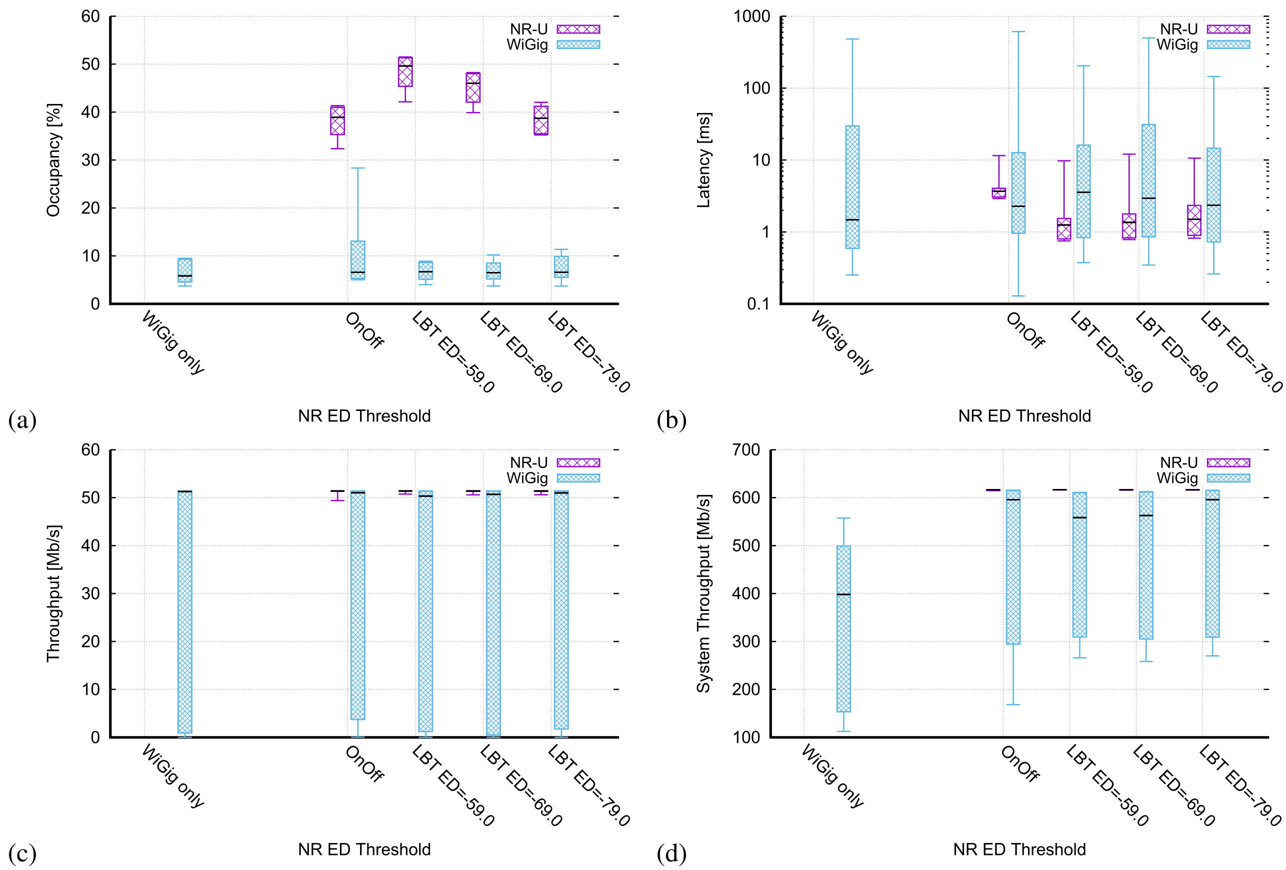

FIGURE 7. Impact of NR-U ED threshold. (a) Occupancy, (b) latency, (c) per-user throughput, (d) system throughput.

challenging traffic to handle from coexistence point of view, as we already demonstrated in [28].

E. IMPACT OF NR-U BANDWIDTH

In the third simulation campaign, we fix the NR numerology to u=3 (i.e., 120 kHz SCS), and vary the NR channel bandwidth within values of 400 MHz, 800 MHz, and 2160 MHz, displayed on the horizontal axis of the figures.[2] Note that when changing the NR channel bandwidth, we also change the total transmit power (as shown in Table 2), since we assume that the transmit power spectral density (dBm/Hz) is kept fixed. This is done for comparison purposes and also to meet the power spectral density limits in the unlicensed context.

As we have shown in the previous sections, the AlwaysOn CAM demonstrated an unfair coexistence behavior with WiGig. Therefore, we do not include it in the comparisons, but we focus only on OnOff or LBT (Cat4/Cat2). We discuss results in terms of occupancy, latency, per-user throughput, and system throughput that are depicted in Fig. 6.

[2]According to NR specification up to 52.6 GHz frequency ranges, the maximum allowed channel bandwidth is 400 MHz. However, it is expected that in future releases, and especially for frequencies above 52.6 GHz, larger channel bandwidths will be supported.

The selected bandwidth affects the performance. By increasing it, we are able to reduce the NR-U channel occupancy, when using either an OnOff or LBT (see Fig. 6.(a)). Also, when NR-U uses a duty-cycle based access, increasing the bandwidth enables the reduction of the end-to-end latency for both NR-U and WiGig technologies (see Fig. 6.(b)), and the WiGig throughput is also improved (see Fig. 6.(c) and Fig. 6.(d)). The reason lies again in the improved spectral efficiency. More bandwidth means that more data can be transmitted in one symbol. Hence, the channel can be released faster, to leave space for other nodes to transmit, even during the ON period of the NR-U with OnOff. From a coexistence perspective, using the same bandwidth at both RATs improves the end-to-end latencies for both technologies. Using NR-U OnOff with a bandwidth lower than WiGig, with 400 MHz or 800 MHz, does not allow to meet the coexistence objective in terms of median latency and median per-user throughput, even if this is met in terms of system throughput.

Nevertheless, in case that WiGig coexists with NR-U based on LBT, the WiGig traffic is less influenced by the bandwidth used by NR-U (see Fig. 6.(b) and Fig. 6.(c)). Here, a trade-off appears: increasing the bandwidth reduces the transmission times, as previously mentioned, but at the same time increases the power received by neighboring nodes (as the transmit power spectral density is fixed), thus impacting the number

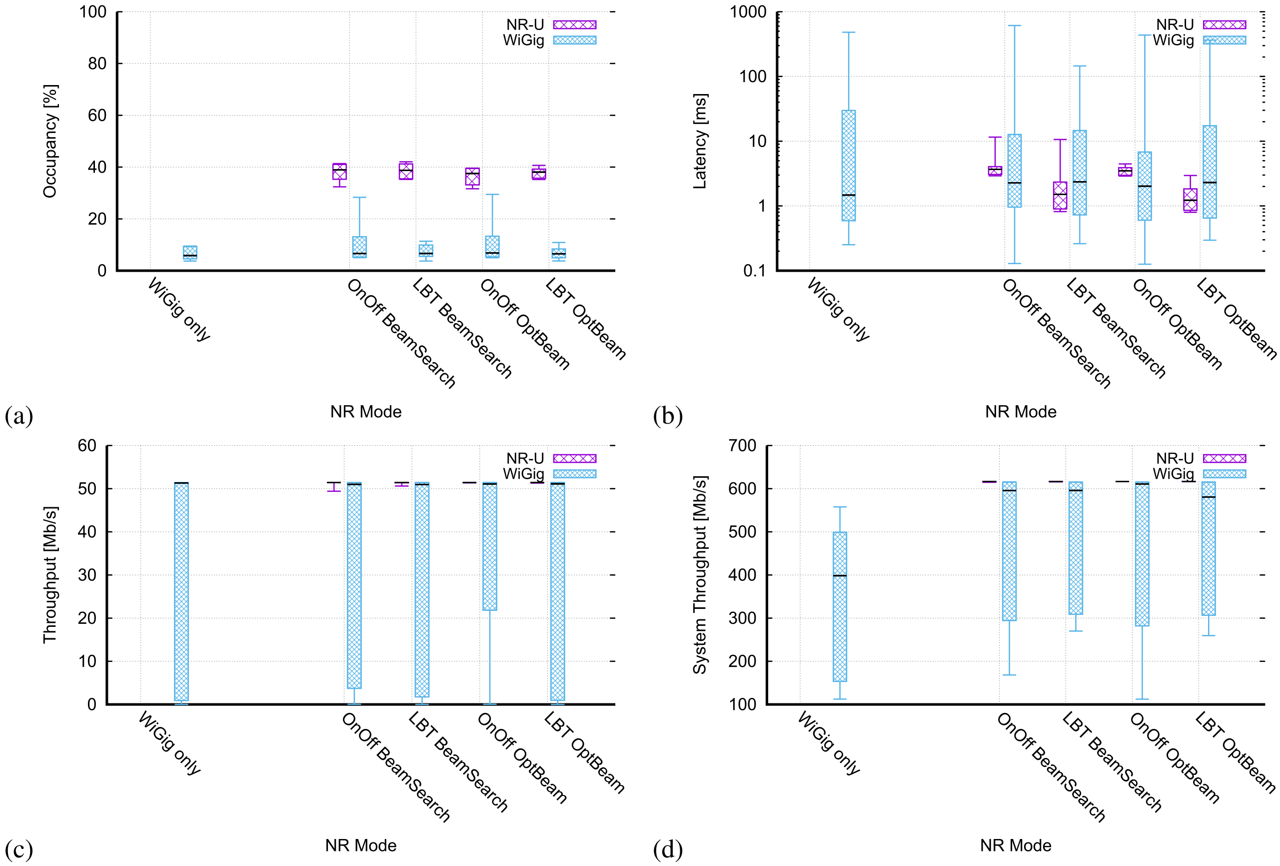

FIGURE 8. **Impact of NR-U beamforming method. (a) Occupancy, (b) latency, (c) per-user throughput, (d) system throughput.**

of WiGig's backoffs, for different NR-U signals spread over 400, 800, or 2160 MHz channel bandwidths. At system performance level, the two effects compensate each other, so that we do not observe a strong dependence on the NR bandwidth in case of NR-U LBT, and the fairness criterion is met in all cases. This is an important conclusion, since, for example, in terms of energy consumption, it is beneficial to reduce the operational bandwidth. In other words, under an LBT based access, we can enhance the NR-U energy consumption by reducing the channel bandwidth, while still meeting the coexistence objective and not degrading WiGig performance more than another WiGig network does.

Summary 4. Results show that NR-U with OnOff, using the same bandwidth as WiGig is beneficial for their coexistence. Instead, NR-U with LBT can use different bandwidths while meeting the coexistence objective.

F. IMPACT OF NR-U ENERGY DETECTION

In the fourth simulation campaign, we fix the numerology (to u=3, i.e., 120 kHz SCS) and the NR channel bandwidth (to 2160 MHz), and focus on varying the ED threshold used at gNB devices. We use three different ED thresholds: −79 dBm, −69 dBm, and −59 dBm, while the WiGig APs ED threshold is fixed to −79 dBm. Notice that we cannot further lower the ED threshold since the noise floor for 2,16 GHz bandwidth is 80,65 dBm. Results in terms of occupancy, latency, per-user throughput, and system throughput are shown in Fig. 7.

It can be observed that a higher ED threshold at the gNBs (e.g., −59 and −69 dBm) negatively impacts WiGig performance; gNBs access to the channel in a more aggressive manner (thus, occupying more time the channel and generating inter-RAT collisions), so that WiGig's latency is increased and WiGig's throughput is reduced as compared to the case of using a lower ED threshold at gNBs. In particular, −79 dBm, i.e., the ED threshold used by WiGig, provides slightly better results.

Summary 5. In the considered 3GPP scenario, characterized by a dense indoor deployment stressed by interference, results show that the ED threshold should be set in a conservative manner, i.e., NR-U using the same energy detection threshold as WiGig (-79 dBm) is beneficial for coexistence, although the observed impact is not crucial. Note, however, that such conclusion is tied to the considered spatial deployment as well as transmit power and antenna/beamforming models.

G. IMPACT OF NR-U BEAMFORMING METHOD

In the last simulation campaign, we fix the NR numerology, the NR channel bandwidth and the ED threshold to the ones of the baseline configuration (i.e., 120 kHz SCS, a bandwidth of 2160 MHz, and −79 dBm ED threshold), and focus on varying beamforming method used at NR-U devices to select the transmit/receive beams for each gNB-UE pair. We compare two NR-U beamforming methods:

- BeamSearch: beam search based method, in which the best pair of transmit/receive beams among a set of predefined beams is selected.
- OptBeam: SVD (Singular Value Decomposition)-based method, in which the left/right eigenvectors of the long-term channel covariance matrix are selected as transmit/receive beams.

The results for the different beamforming methods are shown in Fig. 8, in terms of occupancy, latency, throughput, and system throughput.

Regarding the beamforming methods, it can be observed that both the optimal beamforming method (OptBeam) and the beam sweeping option (BeamSearch) provide similar performances for both NR-U and WiGig. Theoretically, OptBeam achieves a larger Signal-to-Interference-plus-Noise Ratio (SINR) at NR-U nodes. This makes that NR-U transmissions last for slightly less time, compared to the BeamSearch (as shown in terms of occupancy and latency in Fig. 8.(a)-(b)), thus leaving more opportunities to WiGig to transmit, which ends up with a slightly larger served throughput and reduced latency at WiGig (see Fig. 8.(b)-(d)).

Summary 6. The impact of the beamforming method is not significant, and we can conclude that NR-U is already performing pretty well in terms of coexistence with the beam sweep method.

V. CONCLUSION

In this paper, we have presented an open-source extension to the ns-3 simulator that allows researchers, academia, and industry to perform system-level simulation studies of the coexistence between 3GPP NR and IEEE 802.11 technologies in unlicensed spectrum bands, from an end-to-end perspective. The simulator and this study are made available in a timely manner, when the work and study items in 3GPP, targeting NR-U operation in 60 GHz band, have not started yet. In particular, we have focused on the NR-U and IEEE 802.11ad (WiGig) coexistence in the 60 GHz bands. For that, we have developed an NR-U model, which is based on an extension of the NR Release-15 model to account for the regulatory requirements, such as maximum COT, LBT, OCB, and power limits. Then, with such models, we have performed an exhaustive set of simulation campaigns. We have investigated an indoor scenario with multiple users and a deployment of WiGig along with NR-U nodes in a single floor building.

First, we have examined the impact of different NR-U channel access schemes on WiGig nodes from various performance indicators. We have observed that with the proposed traffic model, NR-U occupies more the channel, due to the frame structure and slotted access. This occupancy is reduced when packets are accumulated in RLC queues due to waiting periods enforced by channel access methods based on LBT or duty cycle. In terms of latency and throughput, we have observed that WiGig is negatively affected when coexisting with uninterrupted NR-U, while LBT and duty cycle access better favor the coexistence behavior. We have also analyzed the impact of changing the ED threshold at NR-U devices, showing that a lower ED threshold and a more conservative approach are beneficial for WiGig nodes.

Second, we have analyzed the impact of the selected NR numerology, showing that different effects interplay, depending on the traffic model, the length of slots, and the ability to accumulate packets in the queues. Depending on the selected access procedure and the considered traffic model, the optimal numerology for coexistence may vary. With an uninterrupted operation, WiGig prefers the use of lower numerology; with a duty cycle approach, higher numerology is instead better; while with LBT, the traffic model and the backoff parameters determine the optimal numerology.

Third, as for the bandwidth to use, results show that in general fair coexistence is achieved when NR-U uses the same bandwidth as WiGig. However, NR-U with LBT is able to meet the coexistence objective, even when transmitting in a reduced bandwidth part. This is an encouraging conclusion for multiple bandwidth part configurations and reduced energy consumption options. Finally, we have also studied the impact of different beamforming methods at NR-U. We have observed that this aspect does not show a significant impact on the coexistence performance. This is because directionality per se already reduces interference occasions.

As future work, we plan to extend the present analysis to different spatial deployments and traffic models, since we have observed that traffic patterns have an impact on coexistence behaviors, to extrapolate the generality of our conclusions for other scenarios. Other aspects, like the impact of bandwidth part configurations and implementation of preambles at NR-U, as suggested by the IEEE community, will be studied. Regarding the development, future plans include the evaluation of directional LBT at the gNB side, as well as more sophisticated sensing strategies that may use information from the receiver, as initially investigated in [50].

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