

Cellular and Wi-Fi in Unlicensed Spectrum: Competition leading to Convergence

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Abstract—In order to look into the future, it is essential to review the history. Traditionally, the unlicensed spectrum has been widely dominated by Wi-Fi (IEEE 802.11-based) technologies. However, in current deployments, due to the recent cellular (3GPP LTE and NR-based) technologies operation expansion to the unlicensed spectrum, IEEE and 3GPP technologies compete for the access. In this paper, we review the history of IEEE and 3GPP technologies operation in the unlicensed spectrum and highlight future trends. We will show that, as a result of the competition, both technologies are converging to use similar features in the radio access, such as large bandwidth operations and efficient designs. Then, we will expose options for their future convergence, including cellular and Wi-Fi interworking, as well as the combination of cellular and Wi-Fi connections in unlicensed bands. Finally, based on current competition-based deployments, we present a system-level evaluation of NR-U and Wi-Fi coexistence in the 60 GHz unlicensed spectrum bands.

Index Terms—5G, 6G, Wi-Fi, unlicensed spectrum.

I. INTRODUCTION

The unlicensed spectrum is unrestricted and available for all wireless communications devices to use, as long as they meet the regulatory requirements of the corresponding bands. Typically, the bands for “free usage” (license-free access) are those with worst propagation conditions, e.g., those that are affected by water attenuation or oxygen absorption. However, due to its relative ease of access, the unlicensed spectrum is nowadays one of society’s most valuable resources [1], [2].

Traditionally, the unlicensed spectrum has been widely dominated by Wi-Fi (IEEE 802.11-based) technologies, which have been designed to access the unlicensed spectrum since 1997 and operate exclusively therein. Most of the widely deployed Wi-Fi versions, such as 802.11a/n/ac/ax [3], [4], operate in the 5 GHz bands. In addition, Wi-Fi technologies were pioneers in the use of the 60 GHz bands within the millimeter-wave (mmWave) spectrum region for short-range communications, through 802.11ad/ay specifications [5], [6].

Recently, cellular (3rd Generation Partnership Project (3GPP)-based) technologies have expanded their operation to the unlicensed spectrum as well. Such extension started in 2015 with Long Term Evolution (LTE)-based 4G systems in 3GPP Release-13 [7]. At that time, the main focus of LTE in the unlicensed spectrum was on the 5 GHz bands and multiple LTE variants arose, namely Licensed-Assisted Access (LAA) [8], [9], LTE Unlicensed (LTE-U) [10] and MulteFire [11]. Also, 3GPP in Release-13 studied the case of aggregating LTE and Wi-Fi radio links through LTE-WLAN Aggregation (LWA) and LTE-WLAN Radio Level Integration with IPsec Tunnel (LWIP) [12], but in this case, the Wi-Fi

technology is the one using the unlicensed spectrum. The cellular operation expansion to the unlicensed spectrum is also considered in New Radio (NR)-based 5G systems. In fact, NR is being designed with a native feature to operate in unlicensed spectrum, through the so-called NR-based access to Unlicensed spectrum (NR-U) extension in Release-16 [13], [14]. Notably, NR-U will support, among others, standalone operation in the mmWave spectrum region, including the 60 GHz band, as agreed for Release-17.

In current deployments, both Radio Access Technologies (RATs) (Wi-Fi and cellular) compete to access the unlicensed spectrum. IEEE 802.11-based technologies operate exclusively in unlicensed spectrum bands with large bandwidth and a simple design based on the principle of interference avoidance. Instead, 3GPP-based technologies in unlicensed spectrum inherit all the virtues of the design originated for the limited and expensive licensed spectrum, driven by the principle of interference management and coordination. Nevertheless, as we will analyze later, both RATs are converging to use large bandwidth in a very efficient manner. Indeed, Wi-Fi was originally intended for indoor laptops connectivity and cellular for outdoor mobile terminals coverage. However, cellular has already entered years ago the indoor market with small cells, and is further expanding through new revolutionary trends, like the one foreseeing inclusion of cellular connectivity in laptops, as promised by Microsoft [15]. This new trend is expected to promote the competition even further. The questions about the evolution of these two families of technologies that as of today are open are: What will happen in the future as a result of the standards and spectrum sharing competition? Will IEEE and 3GPP technologies use the same unlicensed spectrum but in non-overlapping coverage deployment areas? And/or will the technologies be deployed with overlapping coverage areas and share the spectrum fairly? And/or will they converge in the Radio Access Network (RAN)?

In this paper, we review the history of IEEE and 3GPP technologies’ operation in the unlicensed spectrum, including different enhancements and versions that have been or are in the process of being standardized. Then, we highlight future operational options. Finally, we present a system-level simulation-based study of NR-U and Wi-Fi coexistence in the 60 GHz unlicensed mmWave spectrum bands through the popular and open-source ns-3 simulator, considering the case in which both RATs are collocated and compete to access the spectrum. For that, we use the 802.11ad model in [16] coexisting with an NR Release-15 model [17] that we have extended to meet the 60 GHz regulatory requirements.

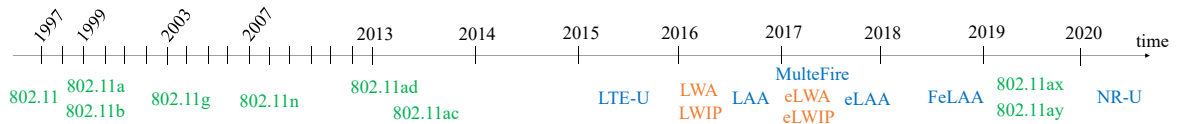


Fig. 1: Standardization timeline of technologies that use unlicensed spectrum.

II. UNLICENSED SPECTRUM: HISTORY UP TO DATE

The unlicensed spectrum that has global worldwide availability includes the 2.4 GHz, 5 GHz, and 60 GHz bands. Currently, there is a process to add the 6 GHz bands to this set, as well. The only constraint for any device to operate in such bands is to meet the regulatory requirements, which vary among regions and bands but in general include: the use of Listen-Before-Talk (LBT) as a spectrum sharing mechanism (also known as Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) in the Wi-Fi context), a maximum Channel Occupancy Time (COT), a minimum occupied channel bandwidth (OCB) requirement, power limits (in terms of maximum radiated power and maximum power spectral density), and the use of specific functionalities such as dynamic frequency selection and frequency reuse [14].

IEEE 802.11-based technologies have been designed to access the unlicensed spectrum since 1997, focusing initially on the 2.4 GHz bands (802.11b/g) and 5 GHz bands (802.11a/n). Due to the more significant amount of bandwidth available in the 5 GHz bands, most of the widely deployed Wi-Fi versions operate therein. Also, huge development efforts are being invested in the 5 GHz bands. For example, the 802.11ac amendment (also known as Wi-Fi 5) introduced the use of Multi-User Multiple-Input Multiple-Output (MU-MIMO) [3]. Its recent enhancement in 802.11ax (also known as Wi-Fi 6) further extended MU-MIMO and adopted Hybrid Automatic Repeat and reQuest (HARQ) and Orthogonal Frequency-Division Multiple Access (OFDMA) through a scheduled-based access, for the first time in Wi-Fi systems [4]. Remarkably, a few years ago, IEEE 802.11 standards started technology development to use the 60 GHz bands through 802.11ad amendment [5], and its recent enhancement in 802.11ay [6].

On the other hand, 3GPP-based technologies have started to exploit the unlicensed spectrum a few years ago. In 3GPP, two main groups have been created depending on the RAT that is used to access the unlicensed spectrum:

- 1) technologies that are based on the integration of LTE and Wi-Fi radio links and that use Wi-Fi to access the unlicensed spectrum (i.e., LWA and enhanced LWA (eLWA), LWIP and enhanced LWIP (eLWIP)), and
- 2) technologies that use modified versions of LTE or NR to access and operate in the unlicensed spectrum (i.e., LTE-U, LAA and its various enhancements (eLAA and feLAA), MulteFire, and NR-U).

The LTE extensions to operate in the unlicensed spectrum started in 2015, focusing on the 5 GHz bands, through different variants. LAA in 3GPP considered a carrier aggregation-based deployment mode (anchored to a licensed carrier) and an LBT-based channel access scheme for the unlicensed band [8], [9]. LTE-U was developed by the industrial consortium LTE-U Forum for those regions in which LBT is not a requirement,

as in the USA, and was based on a carrier aggregation-based deployment mode as well, but with a duty cycle-based channel access scheme [10]. Finally, MulteFire was developed by the MulteFire Alliance and considered standalone operation in unlicensed bands while being tight to LBT [11].

Differently from LTE, which was designed for uninterrupted operation in licensed spectrum since Release-8 and then was modified to operate in the unlicensed 5 GHz bands, NR in 3GPP is being designed with a native feature to operate in the unlicensed spectrum, through the NR-U extension in Release-16 [13], [14]. NR, and NR-U by extension, are the first cellular-based technologies that include support for operation in mmWave bands. In contrast to LAA, which has been standardized by 3GPP based on carrier aggregation using the 5 GHz band, NR-U design considers multiple bands (sub 7 GHz bands and mmWave bands) and also other deployment scenarios, such as dual connectivity and standalone operation in the unlicensed spectrum. The later represents an unprecedented milestone for 3GPP-based cellular systems.

In Fig. 1, we illustrate the timeline of the different RATs that have been standardized for use in the unlicensed spectrum (or are in the process of being standardized) so far. The timeline includes widely deployed IEEE 802.11 standards with their different amendments, and the 3GPP-based standards that follow different releases of LTE and NR.

Table I presents a taxonomy of the different RATs that use the unlicensed spectrum. For each RAT, we detail the standardization body, the underline technology, the operational unlicensed spectrum (sub 7 GHz and/or above 7 GHz), the supported deployment capabilities, and the RAT that is used to access the unlicensed spectrum. Also, we highlight their key supported features in terms of operational frequency bands, maximum supported bandwidth (including aggregation), MIMO support, MU-MIMO support, maximum supported modulation, HARQ support for combining transmissions, channel access scheme, and multiple access scheme.

III. CELLULAR AND WI-FI CONVERGENCE

From Fig. 1 and Table I, it can be observed that IEEE 802.11-based technologies have been designed to access the unlicensed spectrum from a long time ago with the support of large bandwidth. On the other hand, 3GPP-based technologies in the unlicensed spectrum are more recent and are characterized by a more sophisticated and efficient design, including HARQ, OFDMA, and MU-MIMO since the beginning. Nevertheless, with the latest amendments and versions (i.e., IEEE 802.11ax and NR-U), it can be observed that **both RATs are converging to use large bandwidth in a very efficient manner** through the support of key features such as HARQ, OFDMA, high-order modulations, and high-order MIMO (see Table I). So, both RATs are converging in terms of features used in the radio access, by adopting the best of both worlds.

TABLE I: Taxonomy of technologies that use unlicensed spectrum.

	Standardization body	Underline Technology	Operational spectrum	Deployment capabilities	RAT in unlicensed	Key features
802.11n	IEEE	802.11a/g	sub 7 GHz	standalone (unlicensed)	Wi-Fi	Unlicensed bands: 2.4, 5 GHz, Aggr. bandwidth: 40 MHz MIMO: up to 4 streams, MU-MIMO: no Modulation: up to 64-QAM, HARQ support: no channel access and multiple access scheme: CSMA/CA
802.11ad	IEEE	802.11	above 7 GHz	standalone (unlicensed)	Wi-Fi	Unlicensed bands: 60 GHz, Aggr. bandwidth: 2.16 GHz MIMO: up to 8 streams, MU-MIMO: no Modulation: up to 64-QAM, HARQ support: no channel access and multiple access scheme: CSMA/CA
802.11ac	IEEE	802.11n	sub 7 GHz	standalone (unlicensed)	Wi-Fi	Unlicensed bands: 5 GHz, Aggr. bandwidth: 160 MHz MIMO: up to 8 streams, MU-MIMO: up to 4 Modulation: up to 256-QAM, HARQ support: no channel access and multiple access scheme: CSMA/CA
LTE-U	LTE-U Forum	LTE Rel-12	sub 7 GHz	carrier aggregation (licensed + unlicensed)	LTE	Unlicensed bands: 5 GHz, Aggr. bandwidth: 60 MHz MIMO: up to 8 streams, MU-MIMO: up to 4 Modulation: up to 256-QAM, HARQ support: yes channel access scheme: duty-cycle, multiple access scheme: OFDMA
LWA	3GPP	LTE Rel-13	sub 7 GHz	LTE + Wi-Fi integration at PDCP	Wi-Fi	LTE Rel-13 + Wi-Fi
LWIP	3GPP	LTE Rel-13	sub 7 GHz	LTE + Wi-Fi integration at IP	Wi-Fi	LTE Rel-13 + Wi-Fi
LAA	3GPP	LTE Rel-13	sub 7 GHz	carrier aggregation (licensed + unlicensed)	LTE	Unlicensed bands: 5 GHz, Aggr. bandwidth: 80 MHz MIMO: up to 8 streams, MU-MIMO: up to 8 Modulation: up to 256-QAM, HARQ support: yes channel access scheme: LBT, multiple access scheme: OFDMA
MulteFire	MulteFire Alliance	LTE Rel-14	sub 7 GHz	standalone (unlicensed)	LTE	Unlicensed bands: 1.9, 2.4, 5 GHz, Aggr. bandwidth: 80 MHz MIMO: up to 8 streams, MU-MIMO: up to 8 Modulation: up to 256-QAM, HARQ support: yes channel access scheme: LBT, multiple access scheme: OFDMA
eLWA	3GPP	LTE Rel-14	sub 7 GHz, above 7 GHz	LTE + Wi-Fi integration at PDCP	Wi-Fi	LTE Rel-14 + Wi-Fi
eLWIP	3GPP	LTE Rel-14	sub 7 GHz, above 7 GHz	LTE + Wi-Fi integration at IP	Wi-Fi	LTE Rel-14 + Wi-Fi
eLAA	3GPP	LTE Rel-14	sub 7 GHz	carrier aggregation (licensed + unlicensed), dual connectivity (licensed + unlicensed)	LTE	Unlicensed bands: 5 GHz, Aggr. bandwidth: 80 MHz MIMO: up to 8 streams, MU-MIMO: up to 8 Modulation: up to 256-QAM, HARQ support: yes channel access scheme: LBT, multiple access scheme: OFDMA
FeLAA	3GPP	LTE Rel-15	sub 7 GHz	carrier aggregation (licensed + unlicensed), dual connectivity (licensed + unlicensed)	LTE	Unlicensed bands: 5 GHz, Aggr. bandwidth: 100 MHz MIMO: up to 8 streams, MU-MIMO: up to 8 Modulation: up to 256-QAM, HARQ support: yes channel access scheme: LBT, multiple access scheme: OFDMA
802.11ax	IEEE	802.11ac	sub 7 GHz	standalone (unlicensed)	Wi-Fi	Unlicensed bands: 1 to 6 GHz, Aggr. bandwidth: 160 MHz MIMO: up to 8 streams, MU-MIMO: up to 8 Modulation: up to 1024-QAM, HARQ support: yes channel access scheme: CSMA/CA, multiple access scheme: OFDMA
802.11ay	IEEE	802.11ad	above 7 GHz	standalone (unlicensed)	Wi-Fi	Unlicensed bands: 60 GHz, Aggr. bandwidth: 8.64 GHz MIMO: up to 8 streams, MU-MIMO: up to 8 Modulation: up to 64-QAM, HARQ support: no channel access and multiple access scheme: CSMA/CA
NR-U	3GPP	NR Rel-16	sub 7 GHz, above 7 GHz	carrier aggregation (licensed + unlicensed), dual connectivity (licensed + unlicensed), standalone (unlicensed)	NR	Unlicensed bands: 2.4, 3.5, 5, 6, 37, 60 GHz, Aggr. bandwidth: 6.4 GHz MIMO: up to 8 streams, MU-MIMO: up to 12 Modulation: up to 1024-QAM, HARQ support: yes channel access scheme: LBT, multiple access scheme: OFDMA

We associate such convergence to the competition-based access. On the one hand, typical cellular features like HARQ and OFDMA have been introduced in Wi-Fi just after the appearance of cellular RATs in unlicensed (see Fig. 1). On the other hand, NR-U supports a short-length frame structure and flexible access, as well as simplified protocols typical of Wi-Fi, to account for the characteristics of the unlicensed bands, such as the unavailability of the channel due to LBT. Examples of that are the grant-less uplink transmission to reduce scheduling delays, the asynchronous HARQ operation, and the additional occasions for monitoring and transmission repetitions, considered in NR-U. However, there is still a notable difference: Wi-Fi, due to the lack of a core network, does not support coordination among different access points.

Note that it is not only a technical competition in terms of spectrum sharing but also of two big standardization bodies (IEEE and 3GPP). However, we envision that, differently from the cellular-based standardization bodies wars that lead to a single winner for 4G, 5G, and 6G (i.e., 3GPP), in the

unlicensed context both RATs may coexist fairly without killing the other. Three *non-exclusive* options (1-3) and one exclusive with all the previous (4), may appear in the future:

- 1) Wi-Fi and cellular deployments provide non-overlapping coverage areas so that they use the same unlicensed spectrum but in different geographical areas (e.g., Wi-Fi in indoors and cellular in outdoors),
- 2) Wi-Fi and cellular deployments have overlapping coverage areas and share the spectrum fairly (i.e., the objective of current 3GPP/IEEE designs),
- 3) Wi-Fi and cellular deployments converge in the RAN (as we will discuss next), for both non-overlapping and overlapping coverage deployment areas,
- 4) IEEE and 3GPP build a single standard (6G or 7G) (in which politics come into play).

Recently, the wireless industry is pushing Wi-Fi and cellular convergence in the RAN by means of **cellular and Wi-Fi interworking**. The Wireless Broadband Alliance (WBA) and the Next Generation Mobile Networks (NGMN) Alliance

have recently published a joint white paper outlining the opportunities afforded by service and network convergence of Wi-Fi 6 (IEEE 802.11ax) and 5G (3GPP NR) [18] to extend the access capabilities in multiple dimensions simultaneously (coverage, throughput, latency, availability, and reliability) in different key use cases, such as enterprise, manufacturing, connected city, public spaces, and residential connectivity. The 3GPP has been working on cellular and Wi-Fi interworking over the last decade. Two types of integration are considered:

- core network integration, which enables access of untrusted and trusted non-3GPP access networks such as Wi-Fi to the 4G/5G core network [19]. So, both RANs connect to the same 4G/5G core.
- RAN level integration, in which the Wi-Fi access point is directly connected to an anchor cellular base station, as it was initially proposed in LWA and LWIP [12].

In cellular and Wi-Fi interworking, it is considered that 3GPP-based RATs operate in licensed bands, and are complemented and extended by Wi-Fi working in unlicensed bands.

However, given the latest extensions of LTE and NR operation in the unlicensed spectrum, a larger degree of RAN convergence in the unlicensed spectrum may be achieved to improve further the access capabilities experienced by the users in the future. Such RAN convergence may be realized by **combining the cellular and Wi-Fi connections** in unlicensed bands. For example, by extending the existing concepts of RAN/core level integration (such as dual connectivity and seamless session mobility among the different radio access networks) to the case in which both the cellular base stations and Wi-Fi access points operate exclusively in unlicensed bands (e.g., standalone NR-U and IEEE 802.11ax/ay), or even by extending such concepts to a higher level by means of multi-point transmission/reception and carrier aggregation through the different RATs. For that, a new logical interface would be needed in order to provide network manageability, policy control and coordination among access points of different RATs (i.e., gNBs in 3GPP NR/NR-U and APs in IEEE).

IV. CASE STUDY: NR-U AND WIGIG COMPETITION

In this section, we present a system-level simulation-based study on the coexistence of 3GPP NR-U and IEEE 802.11ad (a.k.a., WiGig) in the unlicensed 60 GHz bands. For that, we use the open-source and well-known ns-3 simulator that has recently release models for NR [17] and WiGig [16]. For NR-U, the NR Release-15 model in [17] is extended such that the 60 GHz regulatory requirements, such as maximum COT, LBT, OCB and power limits, are satisfied.

As a coexistence simulation scenario, we consider a dense indoor hotspot deployment that consists of two operators deploying 3 base stations each in a single floor building of 60m×20m area. Each operator can deploy WiGig or NR-U technology and serves 12 users randomly distributed in the building. The 3GPP Indoor Hotspot channel model is used [20]. Devices operate at 58 GHz central frequency with 2.16 GHz channel bandwidth, using 8×8 and 4×4 uniform planar arrays at gNBs/APs and UEs/STAs, respectively, with 17 dBm transmit power. Noise power spectral density is -174

dBm/Hz and noise figure is set to 7 dB. We run a simulation campaign with 50 Mbps application load per user in the downlink direction, using constant bit rate traffic.

The results are shown for different scenarios: when both the operators deploy WiGig (denoted by *WiGig only*) and when one operator deploys WiGig and the other deploys NR-U, with different NR-U parameters. Based on the 3GPP fairness definition, NR-U is expected to operate in a *fair* manner to WiGig by not impacting WiGig's performance more than another WiGig device would do [14]. Therefore, the results of the WiGig only scenario provide the baseline to compare for all the WiGig coexistence with NR-U scenarios.

We compare various channel access schemes for NR-U *i) OnOff*: NR-U with a 50% duty cycle of 9 ms, i.e., 9 ms ON and 9 ms OFF, *ii) LBT*: NR-U with Cat4 LBT at the gNBs and Cat2 LBT at the UEs, *iii) On*: NR-U with uninterrupted operation. For each case, we evaluate two different numerologies that are considered for NR operation in mmWave bands, i.e., subcarrier spacings of 60 kHz ($u=2$) and 120 kHz ($u=3$).

In terms of output statistics, channel occupancy (measured as the percentage of time that each node occupies the channel), packet delay at Internet Protocol (IP) level, and throughput at IP level are recorded, and shown in Fig. 2, Fig. 3, Fig. 4, respectively. For each of the output statistics, the maximum value and the minimum value plotted with whiskers, and the 95% percentile and the 5% percentile are plotted with boxes. In each box, a horizontal solid line represents the 50% percentile.

As shown in Fig. 2, the channel occupancy of NR-U devices is significantly higher than that of WiGig devices. The reason is that the minimum resource allocation granularity of NR-U is an OFDM symbol, while IEEE 802.11ad has no such slot-based access. In terms of delay and throughput (see Fig. 3 and Fig. 4), NR-U performs considerably better than IEEE 802.11ad. This is due to two main reasons: 1) the slot-based access and appropriate scheduling used in NR-U versus the contention-based access used in WiGig (which makes WiGig more prone to intra-RAT collisions) and 2) the HARQ retransmission combining used in NR-U (which makes NR-U more robust to channel impairments and interferences). Also, due to these reasons, WiGig traffic is affected by a higher standard deviation, as compared to NR-U. Finally, regardless of the channel access scheme, increasing the numerology reduces the latency of the NR-U system because NR processing times and the transmission duration are inversely proportional to the subcarrier spacing. However, unexpectedly, such a numerology increase in NR-U does not reduce the WiGig median latency and affects its deviation.

For what regards the coexistence, it can be observed that the latency performance of WiGig devices is affected when coexisting with NR-U On (see Fig. 3), and this results in worse performance than for the WiGig only scenario. Similarly, in terms of throughput (see Fig. 4), WiGig cannot serve all the traffic when coexisting with NR-U On, because it cannot find the channel free to transmit. However, thanks to the directionality of the transmissions and to the propagation conditions of the mmWave bands, we observe that the channel access coexistence options for NR-U based on LBT or duty cycle (OnOff) are similarly friendly to WiGig. All in all, NR-

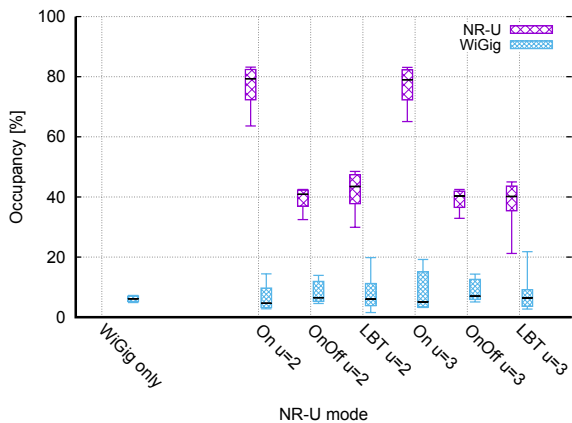


Fig. 2: Channel occupancy.

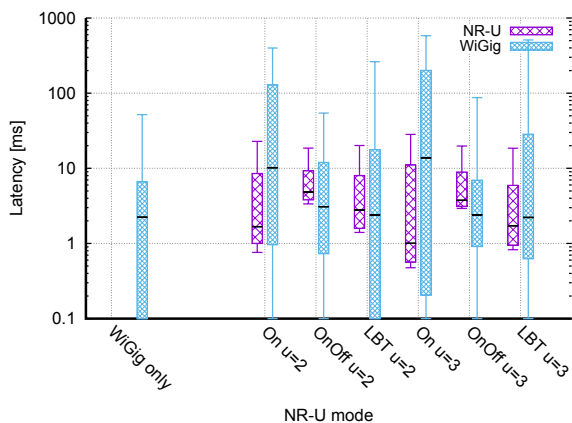


Fig. 3: Latency.

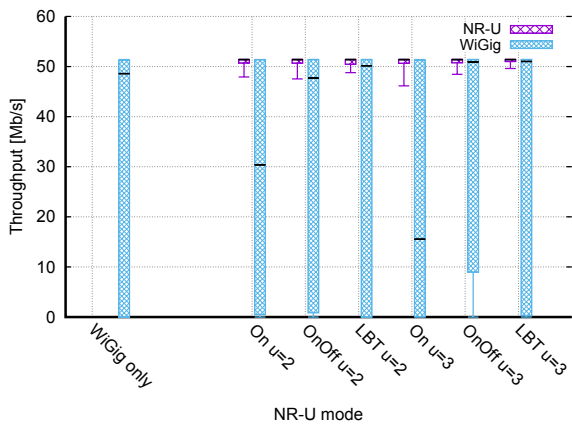


Fig. 4: Throughput.

U is a fair technology to coexist with WiGig as long as a channel access considering the existence of other technologies (i.e., LBT or duty cycling) is considered, because an NR-U On with uninterrupted implementation provides instead decreased performance for WiGig in terms of latency and throughput.

From the above results, it can be concluded that a competition-based access (NR-U and WiGig) is beneficial for the users, as compared to a case in which all the indoor connections are WiGig-based. Accordingly, these results provide the baseline, but larger benefits could be achieved by using RAN convergence, e.g., by enabling the devices to connect to NR-U and/or WiGig access points.

V. CONCLUSIONS

IEEE and 3GPP-based technologies that use unlicensed spectrum follow a competition-based access in current deployments. As a result of the competition, in the latest releases and amendments, cellular and Wi-Fi technologies have converged to use and develop similar features in the radio access, reaching a more efficient design and supporting operation in large bandwidth. However, maybe in the future, they also converge in the RAN. Such convergence can be realized either by using cellular and Wi-Fi interworking or even by combining the cellular and Wi-Fi connections in unlicensed bands.

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