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KQI Performance Evaluation of 3GPP LBT Priorities for Indoor Unlicensed Coexistence Scenarios

Eduardo Baena *, Sergio Fortes and Raquel Barco

Departamento de Ingeniería de Comunicaciones, Campus de Teatinos, Universidad de Málaga, Andalucía Tech, 29071 Málaga, Spain; sfr@ic.uma.es (S.F.); rbm@ic.uma.es (R.B.)

* Correspondence: ebm@ic.uma.es

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Abstract: The rapid proliferation of user devices with access to mobile broadband has been a challenge from both the operation and deployment points of view. With the incorporation of new services with high demand for bandwidth such as video in 4K, it has been deemed necessary to expand the existing capacity by including new bands, among which the unlicensed 5-GHz band is a very promising candidate. The operation of future 3GPP (Third Generation Partnership Project) mobile network standards deployments in this band implies the coexistence with other technologies such as WiFi, which is widespread. In this context, the provision of Quality of Service (QoS) or Quality of Experience (QoE) becomes an essential asset and is a challenge that has yet to be overcome. In this sense, 3GPP has proposed a traffic prioritization method based on the Listen Before Talk access parameters, defining a series of priorities. However, it does not specify how to make use of them, and even less so in potentially conflicting situations. This paper assesses the end-to-end performance of downlink unlicensed channel priorities in dense scenarios via implementing a novel simulation setup in terms of both multi-service performance and coexistence.

Keywords: unlicensed band; Coexistence; NR-U; LAA; eLAA; WiFi; simulation; signalling

1. Introduction

The fourth generation of mobile telephony Long-Term Evolution (LTE) seems to have reached its maturity in commercial deployments. However, the sharp increase in the forecasted capacity demand for mobile networks [1] combined with the upgrade of devices and services with higher requirements make the expansion of spectral resources inevitable. Following this trend, cellular network operators see in the unlicensed bands the ideal solution to support the capacity gain necessary to compensate the new demands.

While a further extension of the operational spectrum is foreseen, the free bands currently available in Europe for this purpose are 2.4 and 5 GHz. Within this framework, 3GPP (Third Generation Partnership Project) created the Licensed Assisted Access (LAA) standard [2] so that LTE could operate in the downlink in unlicensed bands. To adapt the LTE (and later standards) synchronous operation to a contention-based access channel, the use of Listen Before Talk (LBT) protocol has been established with the added purpose of maintaining equitable access with respect to the WiFi devices [3]. This protocol, as shown in Figure 1, has evolved being included as part of 3GPP developments to adapt mobile technologies to their operation in the unlicensed band.

From this proposal, later versions deepen the capabilities for 3GPP unlicensed spectrum support: LAA included a series of preconfigured values of the access parameters to the unlicensed channel called priority classes that would fulfill the function of providing a certain degree of Quality of Service (QoS) without going into details of its operation. Subsequently, in enhanced LAA (eLAA), the uplink channel is further added and the priorities are defined in the same way for this channel. Afterwards, FeLaa (Further enhanced LAA) becomes the first 5G standard that adapted LAA and eLAA adding new functionalities. In addition, non-3GPP technologies, such as the one proposed by the MulteFire Alliance [4], have been derived from 3GPP to operate exclusively in the unlicensed band.

Finally, the recently completed Release 16 NR-U [5] offers two different flavors for deployment: on the one hand the option of licensed assisted and on the other hand a completely standalone operation as proposed by MulteFire. For all these standards, the use of the LBT priorities initially proposed for LAA is common, however none of these specify which types of traffic or under which conditions their use is appropriate.

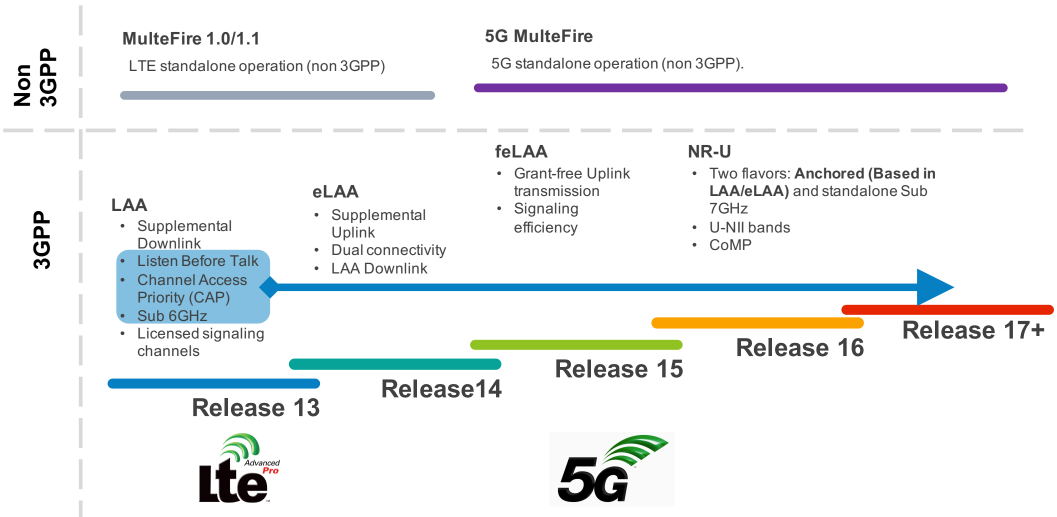


Figure 1. 3GPP unlicensed standards evolution.

Even though 3GPP-based unlicensed standards and WiFi use the same techniques in their physical layer [5], namely Orthogonal Frequency Division Multiplexing (OFDM) and Multiple Input Multiple Output spatial multiplexing (MIMO), they differ in other aspects such as the transmission power, bandwidth, Modulation and Coding Schemes (MCS) or error correction codes, to name a few. Regarding the packet loss recovery mechanisms, although they present similarities, the differences are substantial. While WiFi uses automatic retransmission (ARQ), 3GPP incorporates the Radio Link Control layer (RLC) with hybrid ARQ [6]. Besides, in terms of scheduling, 3GPP acts as a synchronous system, via a centralized scheme. At the same time, WiFi operates half-duplex random access where the receiver must confirm all frame transmissions. Although both approaches can achieve similar performance in terms of data rate, the random access used by WiFi produces persistent collisions when there are several devices connected to the network [7].

At present, although several articles evaluate the coexistence of both mechanisms [8], there is still a need to investigate in this area with end-to-end performance assessment purposes especially in dense environments [9], avoiding, as far as possible, the degradation of pre-existing technologies. Most of the collected works mentioned in [8] choose a certain configuration of the access channel parameters to show the benefits of their proposal or to demonstrate the harmful or beneficial effect on WiFi. Many of these chosen parameters are not sufficiently justified or do not fully comply with the standard. In neither case do they cover the entire range of cases proposed by the 3GPP priorities.

It is important to highlight that, due to the operational differences mentioned above for both standards at the protocol level, a detailed study of all aspects that impact on the quality perceived by the users is necessary. Since an implementation of a coordination mechanism it is not foreseeable, possible ways to improve coexistence become a priority.

Therefore, it is not only a question of comparing the access methods being mutually respectful (LBT in 3GPP standards and CSMA/CA in WiFi) but also to determine how the channel sharing affects the operation of the upper layers (e.g., the MAC) and describe the interaction with themselves and each other as well as the impact on the application layer. In this regard, some works can be found in the literature specially focused on mathematical modeling.

In [10,11], the impact of priorities is assessed with a standardized throughput indicator and assuming ideal propagation conditions. However, the problem of heterogeneity of coexisting systems is identified, while the proposed scenario is far from dense. On the other hand, with respect to simulation works, several outstanding papers have appeared lately, among which it is worth mentioning the one by De Santana et al. [12] where, despite the use of ns3 tool, a simplified scenario that does not reflect any of the problems posed by coexistence in the foreseeable dense indoor environments is proposed. It also focus on a single priority configuration with a fixed traffic load. Lastly, the exhaustive study made by the ns3-based LAA model creators in [13] presents a setting where only FTP traffic is simulated, and the impact of each relevant random access parameter is studied. However, neither video traffic nor the priorities proposed by the 3GPP are included.

In this field, the contribution of the present work is on the end-to-end assessment of the LBT channel access priorities configurations in order to provide QoS and Quality of Experience (QoE). To this end, two types of services were simulated in an indoor dense environment, one of them being real-time (video streaming) and the other non-real-time (FTP) for different levels of traffic intensity. Thus, this is the first time that a multi-service end-to-end performance is assessed in the LBT-based 3GPP standards—WiFi coexistence literature leading to key conclusions on the performance of each priority and recommendations for future QoE-based use of LBT channel access configurations. From these results, a definition is derived and the framework about traffic prioritization for 3GPP standards in unlicensed band is implemented.

The structure of this work can be summarized as follows. In Section 2, the access characteristics to the unlicensed channel in WiFi and 3GPP LBT are described. Section 3 presents the evaluation framework designed for user end-to-end multi-service performance evaluation. Thereafter, a description of the relevant indicators being evaluated is presented in Section 4, followed by Section 5 presenting an exhaustive description of the scenario and parameters of the simulation leading to the performance assessment analysis. Finally, Section 6 summarizes the conclusions of this work

2. Unlicensed Medium Access Mechanisms

This section summarizes the functioning of the medium access mechanisms implemented in each of the coexisting technologies in the 5-GHz band, describing the parameters that regulate each of them.

2.1. 3GPP Standards

As described in the description of the shared channel download of the 3GPP standards [5] in 5-GHz unlicensed bands (including eLAA, FeLAA and NR-U) the use of Listen Before Talk is mandatory, although it is allowed to include or not the use of the licensed band for signaling in the uplink. To this end, several variants of LBT mechanism have been considered for DSCH unlicensed channel access.

LBT in this context is a contention mechanism where the transmitter has to check the channel state before using it. It relies mainly on two basic processes: the clear channel assessment procedure (CCA) with energy detection (ED) threshold to sense the channel state for a defer period whether any signal (regardless of its kind) is present above a certain power value. As shown in Figure 2, when the channel is detected free, then the LAA station is allowed to transmit for a Maximum Channel Occupancy Time (MCOT). Otherwise enhanced CCA (eCCA) is activated and has to wait for a backoff period of time determined by a Contention Window (CW) measured as a number of time slots.

Before standardization by 3GPP, several variants or categories (CAT) of LBT were considered [14] for its implementation:

- Category 1: No LBT procedure is performed

- Category 2: LBT without random backoff with deterministic waiting time when the channel is found free
- Category 3: LBT with random backoff and fixed contention window size
- Category 4: LBT with random backoff and variable contention window size

In the above mentioned study of coexistence [15] made by 3GPP, it is concluded that the LBT category allowing a better coexistence with respect to WiFi due to the configuration flexibility of its parameters is Category 4 (CAT4). Under this category, which has finally been standardized, different priorities are defined. Each priority represents a predetermined set of values for the parameters implicated in the LBT process. As shown in Table 1, within this category, four priority classes [5] have been established according to MCOT and C_w size values combinations.

Table 1. 3GPP LBT CAT4 priority classes.

Priority Class (p)	CW_{min}	CW_{max}	MCOT
1	3	7	2 ms
2	7	15	3 ms
3	15	63	8 ms
4	15	1023	8 ms

As observed, each of the priorities defines a combination of backoff time (given by C_w) and transmission time. Taking into account this principle, Priority 1, having a lower backoff time, will have a higher probability of transmitting, although each transmission will have less time available. Thus, according to theoretical models proposed [16], Priority 1 should offer a higher performance than Priority 3 or 4.

2.2. WiFi

According to the 802.11 WiFi standards (including its latest versions ad and ax), the primary channel access mechanism used for unlicensed band is the Distributed Coordination Function or DCF [17] based on CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance). WiFi DCF uses aCCA sensing based mechanism similar to LBT (Figure 2) with two related functions: Carrier Sense (CCA-CS) to detect and decode a WiFi preambles and Energy Detect (CCA-ED) for non-WiFi energy in the operating channel and back off data transmission. Although they operate simultaneously, different thresholds are set for each function.

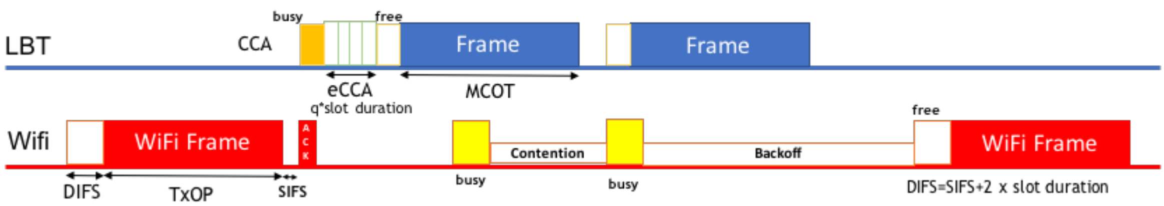


Figure 2. Comparison of WiFi and LBT access mechanisms for the unlicensed band.

When the channel is empty for a DIFS (DCF Inter Frame Space) period duration, the WiFi station sends the whole frame. In the case of finding the channel busy, a random timer (with backoff count) starts. Such timer only decreases its value when free channel has been sensed during the slot period. Once it expires, the WiFi stations must transmit. Every time a frame is correctly decoded at the receiver, an ACK is sent after SIFS (Short Inter Frame Space). Thus, when such confirmation (ACK) is not received, the backoff period is increased in an exponential way.

In summary, although the mechanism of access to the LBT and CSMA/CA contention channel are very similar. In WiFi, the detection of a collision is done by means of a confirmation frame (ACK).

Conversely, in 3GPP standards, there is no such frame, so collision detection is based on the feedback from the hybrid automatic repeat request (HARQ). Thus, according to the standard, if 80% of the HARQ feedbacks from the most recent MCOT are NACKs, a retransmission is required [5].

3. Evaluation Framework

To model both technologies as realistically as possible, the well-known simulator ns3 [18] was chosen. For the evaluation, a simulated setup was developed based on ns3, implementing on top a framework for the simultaneous execution of Real Time Video Streaming (RTVS) and FTP services and the multi-layer monitoring of their performance. This tool has an important acceptance within the wireless research field [19] given the fact that relevant entities in the industry have developed its WiFi and LTE modules.

The scope of ns3 simulations is to include multi-layer interactions of commercial standard deployments. The ns3 Evalvid module [20] was used for the simulation of RTVS service. This module contains a set of tools to generate video traffic based on sender/receiver traces. In this way, it allows the encoding and comparison of the original video versus the received one, from which the differences due to its transit through the network are obtained.

In the proposed evaluation, a 4K AVC MPEG-4 encoded file (3840 × 2160 resolution, 120 fps with 28.3 MB size) containing 20 s of video is sent. To emulate real-time behavior, all frames with an end-to-end delay of more than 150 ms are discarded.

Additionally, for the modeling of the 3GPP downlink unlicensed channel, the LAA ns3-module was used [21]. This includes the indoor scenarios and FTP Model I type of traffic as proposed by 3GPP [22] to evaluate the performance of both systems. The architecture of the proposed simulation is shown in Figure 3.

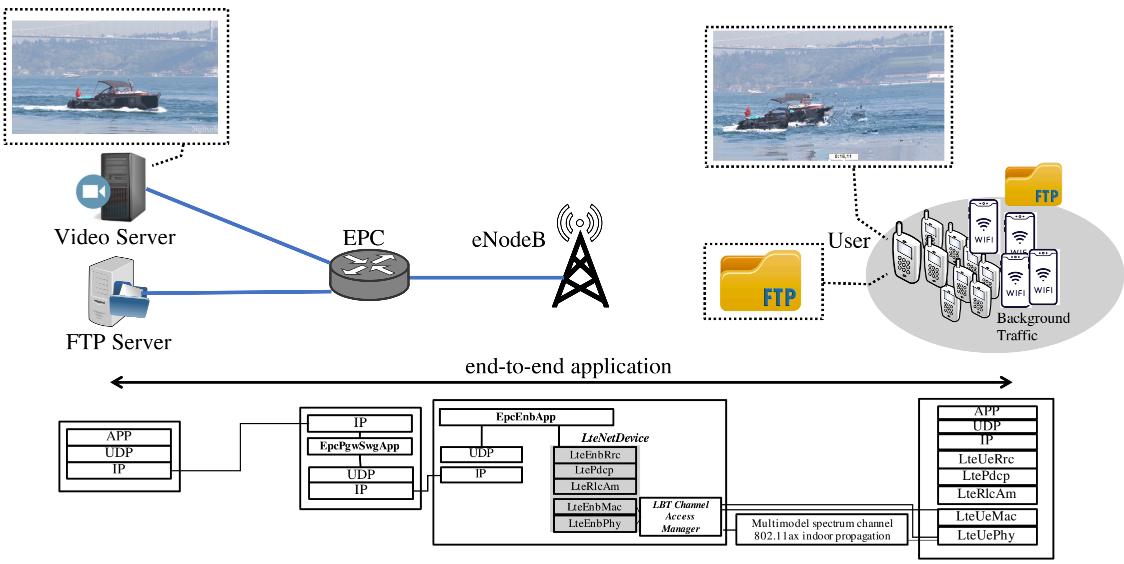


Figure 3. Multiservice end-to-end simulation architecture.

For link performance computation, the ns3 LAA module uses the [23] model to extract the Mutual Information Effective SINR Metric (MIESM) as a Link-to-System Mapping (LSM) function, as done in [24]. Finally, MIMO was modeled as a gain of SINR over SISO, as specified in [25] where the statistical gain of several MIMO solutions with respect to SISO is argued.

The development of the framework adapted the evalvid module code to work through the LBT protocol in the version that supports it. In addition, the LAA module was modified to support the priorities as well as the performance indicators in the following section. This setup allows a novel multi-service end-to-end simulation of a coexistence environment between 3GPP LBT downlink technology and WiFi.

4. Performance Indicators

The indicators identified for the proper performance analysis of the unlicensed coexistence scenarios are divided into three categories in terms of the quality of experience provided to the users, the background traffic user perceived quality and the level of fairness between WiFi and 3GPP LBT downlink service provision. About this last aspect, it has to be noted that, following the general deployment considerations established by 3GPP [26], coexisting deployments are expected to be provided by different operators and without any coordination between them besides the general collision avoidance mechanisms defined in the previous section.

4.1. Key Quality Indicators

The metrics that determine user-perceived QoE were based on the KQIs defined by ETSI and 3GPP [26] as an objective measure of end-to-end quality perception, distinguishing between the different services. These are classified in several service categories, among which Integrity is the most representative in our assessment. This category measures the degree to which the service is offered with an acceptable quality without major drawbacks once obtained. Thus, the corresponding KQIs relative to the FTP service and RTVS are presented in Table 2.

Table 2. Service KQIs measured.

Service	Category	Parameter	Unit	Reference
Real Time Video Streaming	KQI-Integrity	Frame Loss Ratio	(%)	[27]
		Cumulative Jitter	(ms)	[28]
		Frame end-to-end delay	(ms)	[28]
		Peak signal-to-noise ratio (PSNR)	0–5	[29]
File Transfer Protocol (FTP)	KQI-Integrity	File Transfer average throughput	(Mbps)	[26]
		File Transfer Delay	(s)	[26]

- Peak Signal Noise Ratio (PSNR) is a measure that compares the video signal pixel by pixel and frame by frame. It is totally blind to the spatial and temporal relationships between pixels and, as a result, very diverse distortions that clearly produce very different quality perceptions get similar values of PSNR.
- Frame Loss Ratio (FLR) represents the ratio between the number of frames that have errors and the total number of frames sent.
- Delay is the time (ms) required to transmit a frame along its entire end-to-end network path.
- Jitter refers to the variation in delay time in milliseconds between video frames when transmitted over a network.

The delay and jitter (understood as the time differential between video frames) measurements are formally specified in the article that exposes the evalvid module [20].

4.2. Background Traffic User Performance Indicators

In contrast to these, the User Performance Indicators (UPI) are outlined. Such metrics are measured to quantify its performance of the background traffic generated by the users. These are measured in this context from the background FTP traffic: mean throughput, mean delay and mean jitter measured at IP level. Since the MAC to PHY delay is fixed to a value of 2 ms, the resulting delay is computed as the time between the first IP packet of the file was sent until its arrival in the receiver. Finally, the throughput is calculated as the IP packet size divided by its delay [30].

4.3. Fairness

Another crucial aspect highlighted by 3GPP is the concept of *fairness* with respect to other wireless technologies operating in the same band. In this way, the standard defines it as the *capacity of a 3GPP* *network to not affect the active WiFi networks in one operator rather than an additional WiFi network operating in the same operator, in terms of throughput and latency* [2]. In this respect, beyond the aforementioned 3GPP definition, there is no defined unanimity for its objective assessment. In the following, we can find in the literature a survey of different approaches [31] depending on their application in the context of wireless networks (energy consumption, resource allocation, power control, etc.). All these methods have in common the definition of a precise goal (for example, equal video quality) that, in our case, by the definition of 3GPP is not clear. More specifically in the field of WiFi-LBT, Mehrnoush et al. [32] proposed using the average throughput per user with a simple division between the scenario with two WiFi operators and the one of WiFi-3GPP coexistence.

However, this approach only considers one metric and does not give a complete idea of how the behavior is modified when both technologies are used. In this sense, Ali et al. [33] proposed the mapping between fairness and first-order stochastic dominance. Under this premise, the precept of fairness is fulfilled much more faithfully under the authors' criteria and can thus be extended to various parameters. It is because of this lack of flexibility that the Jain Fair Index, which is quite widespread for scheduling protocols for example, has proven not to be a good candidate in this case [34].

Taking this into account, the performance indicators chosen for the coexistence evaluation of WiFi and LBT scenario (denoted as W+L) [15] are based on UDP file transfer service model following a Poisson arrival process with a fixed file size (FTP Model I), as explained in [22], to generate background traffic.

Therefore, based on comparison given by a scenario with two WiFi operators coexisting (called WiFi-WiFi, W+W), an assessment of fairness based on Experimental CDF comparison using Kolmogorov–Smirnov two-sided tests used as described in [33] follows the procedure in Algorithm 1.

Thus, the distribution of WiFi UPI-based performance (i.e., mean latency and throughput) when coexisting with LBT are considered to be similar to the baseline performance distribution given by W+W scenario when P value (probability of a null hypothesis) being true with a certain significance level α reaches a certain value (i.e., 0.05). Equivalently, its obtained Dmax is at least D_α.

Algorithm 1: Fairness evaluation

Input: Performance UPI values (throughput and latency) measured at IP level
Output: Null hypothesis, P-value, Dmax

1. Compute UPI ECDF of the different flows of background traffic through the WiFi network of the operator B, when it coexists with the WiFi network of the operator A, and use it as a baseline (W+L scenario)
2. Perform step 1 for the case when the WiFi network of the Operator B coexists with the LBT network of the Operator A (L+W)
3. Run a two-sided sample Kolgomorov–Smirnov test
4. Calculate P and Dmax values
5. Accept or reject the null hypothesis (both distributions are similar or fair) based on P-value
6. In case of null hypothesis rejection compare Dmax wih D_α value

It is important to highlight in this context that, even if this condition is not met, the value of Dmax can be used to assess the degree of fairness as long as its value approaches D_α [33]. In this context, a nearby Dmax value will therefore be considered fairer than one whose difference with D_α is greater

5. Performance Assessment

This section evaluates the impact of 3GPP LBT priorities on service performance in coexistence for indoor dense scenarios. The environment defined by 3GPP for this kind of analysis [22] is used. Thus, among all the deployment scenarios for 5G (rural, dense, urban and urban macro outdoor), the one chosen is proposed in TR38.889 [15] as a baseline on coexistence as indoor Hotspot scenario and specified as the most suitable to evaluate the coexistence with 802.11ac WiFi networks whose power and technical characteristics defined by ETSI do not allow exceeding 23 dBm.This criterion is followed by some of the key articles on coexistence of 3GPP-WiFi technologies in unlicensed band [13,16,35,36]. Both LBT and WiFi nodes share the same 20-MHz channel (number 36 within 5-GHz band).

5.1. Scenario

As shown in Figure 4, an indoor layout of 120 m × 50 m where two Operators A and B with four base stations and a total of 20 static users per operator randomly placed all over the layout are coexisting.With this setting established, a hotspot use case where the users have very low or quasi-static mobility is considered. The base station/access points are aligned with 30 m separation between them and at 5 m distance between operators. The results are evaluated by averaging 50 different random user distribution scenarios with 500 s runs each.

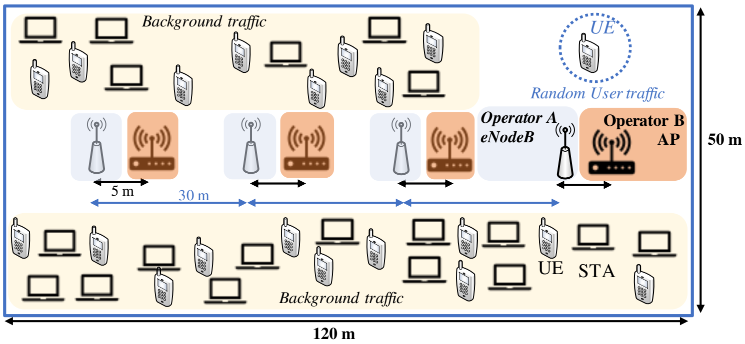


Figure 4. Simulated office indoor coexistence scenario.

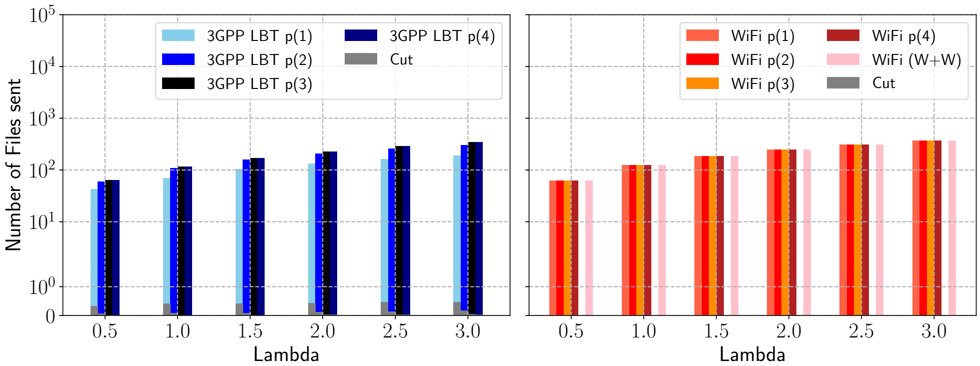
Thus, in each run, a randomly selected user who makes use of the FTP/Real Time Video Streaming (RTVS) services is evaluated ("Random User traffic" in Figure 4) while the rest of the user devices ("Background traffic" in Figure 4) generate a download FTP Model I traffic with intensity that varies according to the lambda parameter (from 0.5 to 3 files/s). In this manner, the QoE performance (i.e., KQI) of the user is evaluated in the presence of a background traffic load from low to high.

The interference between WiFi access points and base stations is managed by contention mechanisms (CSMA/CA in WiFi and 3GPP LBT); no further Distributed Control Function is enabled. Unlike the synchronized and collision-free access in which 3GPP technologies operate, the necessary medium access layer given by the CSMA and LBT protocols has some drawbacks associated with it, such as the hidden node or the exposed node. When a terminal has started transmitting for the limited time (in the form of TxOP or MCOT), it is possible that interference may occur in nodes that are not able to detect such transmission (because it is below its energy detection threshold). Thus, in short transmissions, there is more chance of collisions by nodes that cannot detect it. Therefore, when an interference is produced during the transmission of a WiFi Access Point and, given the half-duplex nature of the protocol, the retransmission mechanism is activated trying to resend the interfered frame and causing greater congestion of the air environment and making further collisions of part of the hidden nodes of the co-existing technology more likely.

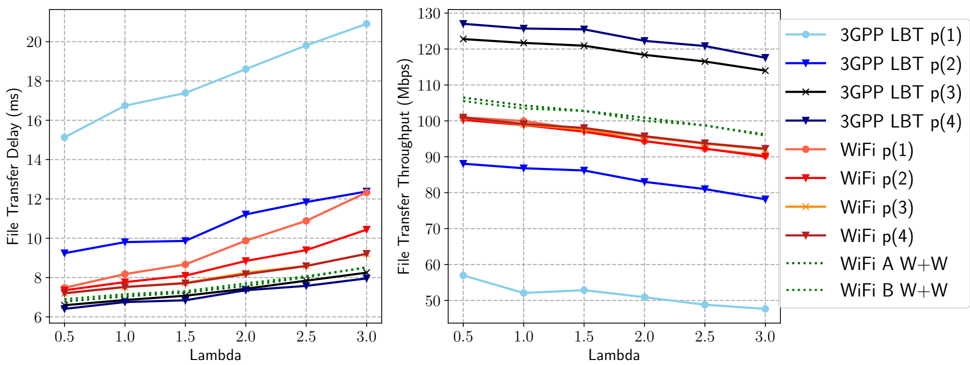
All the aforementioned performance indicators in Section 4 are analyzed following a top-down approach in order to correctly analyze the interaction phenomena produced in coexistence. The background FTP Model I (UDP) traffic from the application layer is analyzed first, including the total number of files sent and which of these have arrived complete. The average performance figures among all background users are also shown. Then, the KQI obtained by the user taking into account these conditions are shown and compared with the KPI obtained by the network. Next, to explain the results, details of some lower layer parameters are shown to support the explanations. Finally, the fairness of both coexisting mechanisms is evaluated as described in the previous section.

5.2. Background Traffic (Load)

As shown in Figure 5a, WiFi sends a fixed number of files depending on the intensity while 3GPP LBT varies depending on the priority used. More specifically, the use of Priorities 1 and 2 reduces the total number of files sent and losses occur (cut bar). If we look at the metrics of the FTP Background traffic (Figure 5), i.e. File Transfer Mean Throughput and the File Transfer Mean Delay, it can be seen that in Priorities 1 and 2 there is a significant drop in quality. This means that not only are fewer files sent, but also the quality of service offered to the user is of a lower quality than in the case of Priorities 3 and 4 (in principle intended for Best Effort traffic [5]).



(**a**) Total Files Downloaded

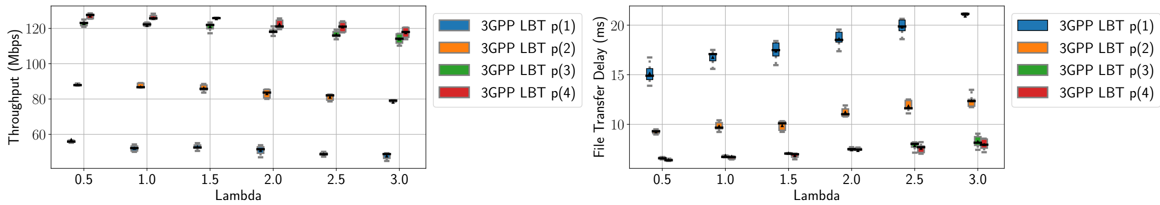


(**b**) Averaged FTP KQIs

Figure 5. Background traffic results.

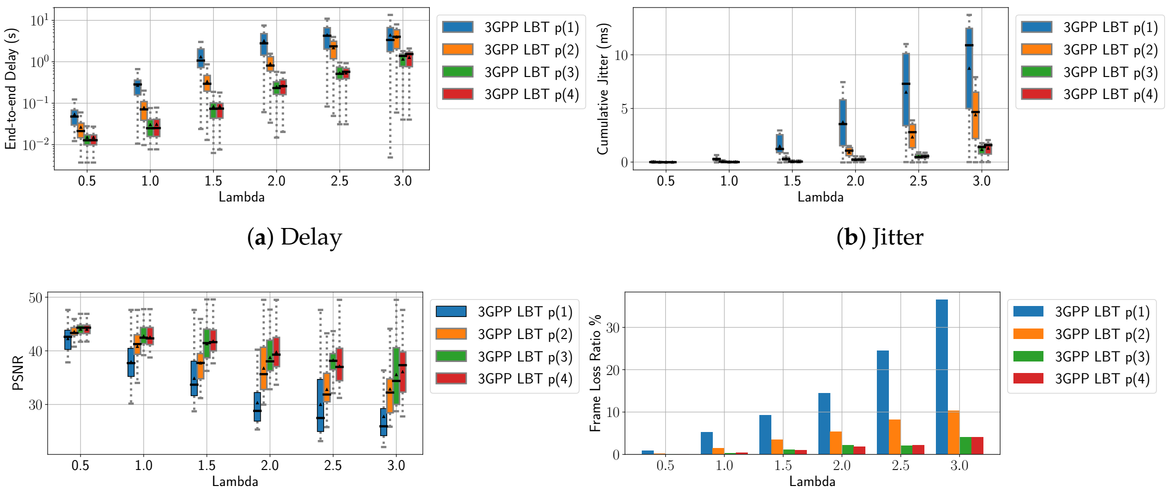
5.3. User Traffic

Subsequently, Figures 6 and 7 display the results obtained at the level of KQI indicators for the user of FTP and RTVS services. They are shown in boxplot form taking into account the results of all the iterations and all frames in video streaming (which is why more samples have been captured). The first aspect that can be observed is that the behavior of the priorities is very similar to the one followed by the Background traffic, that is Priorities 1 and 2 present a longer delay (Figures 6b and 7a) and jitter values (Figure 7b) and lower throughput (Figure 6a) and PSNR (Figure 7d) than Priorities 3 and 4.



(**a**) Throughput (**b**) Delay

Figure 6. User FTP KQI results obtained.



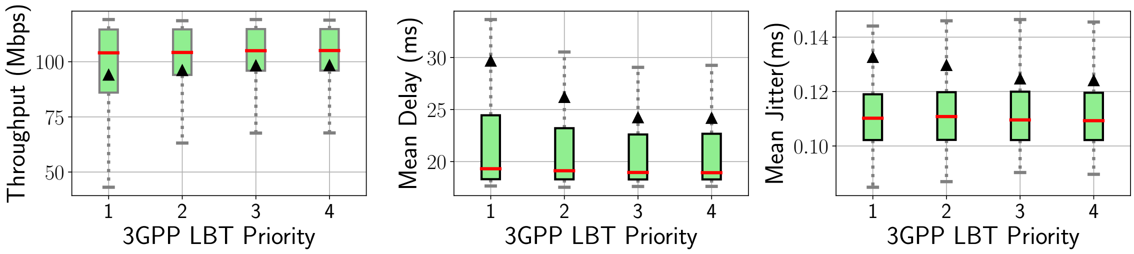
(**a**) Delay (**b**) Jitter

(**c**) PSNR (**d**) Loss

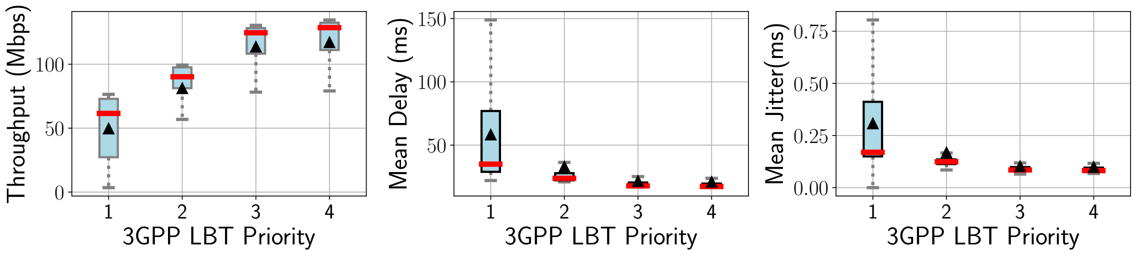
Figure 7. User Real Time Video Streaming KQI results obtained.

To deepen in these results, in Figure 8, a boxplot of the UPIs for both technologies is presented, measured in terms of the IP packages with prefixed MAC to channel delays so that only the delay introduced by the access to the channel varies. We see that in LBT as the priority is increased the performance improves and the dispersion decreases; this is not so for WiFi, where, although the average follows a linear progression, the dispersion is maintained. This fact means that priorities' selection influence LBT performance more than WiFi traffic due mainly to two factors: (1) a lower use of the channel as fewer MCOTs are needed; and (2) a higher probability of collision when the contention window and the MCOT are reduced, especially between distant LBT stations as they are synchronized at subframe level [13]. Such phenomenon is proved in Figure 9 which shows how changes in LBT contention window (indicating a collision) imply a very similar lost packets pattern. Unlike what happens in WiFi where collisions are measured based on the number of retransmissions made, it can be seen that a similar behavior is practically maintained (accentuated for Priorities 1 and 2). Hence, in LBT, lost packets do not depend on the configuration but on the traffic load.

The fact 3GPP LBT has the channel for a more considerable amount of time means that, although waiting times are longer in the case of a collision, the transmissions have greater efficiency by having more resources. It is also appreciated in Figure 8a that an LBT performance drop (UPT decrease and higher latency values) is produced with Priorities 1 and 2. This adverse effect (especially in Priority 1) is due to a shorter duration of MCOT and short backoff times C_W, which, in turn, cause an increased number of channel access attempts by WiFi retransmissions. Since WiFi ED-CCA threshold is higher than the one set by LBT (Table 3), such repeated attempts result in a significant increase in the number of collisions produced by the WiFi retransmitted frames causing higher delays in LBT [37]. Nevertheless, in Priority 1, the UPT is constant regardless of the traffic intensity due to a higher probability of accessing the medium but shorter transmission times compared to other priorities.



(**a**) WiFi IP UPIs



(**b**) 3GPP LBT IP UPIs

Figure 8. FTP UPI results obtained.

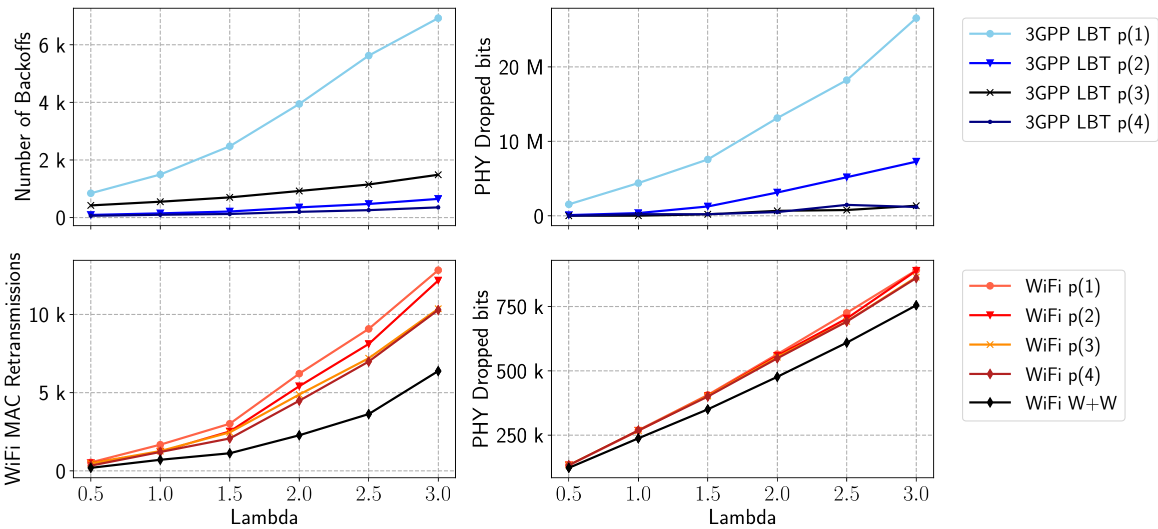


Figure 9. MAC/PHY Layer analysis.

Table 3. Simulation parameters.

Parameter	3GPP LBT	WiFi
Standard version	Rel.13	802.11ac
MCS selection Scheme	Adaptive based on SINR (AMC) with BER= 1×10^{-5}	
Frequency	5180 MHz	5180 MHz
Bandwidth	20 MHz	20 MHz
Max power TX (dBm)	18 dBm	18 dBm
Antenna gain (dBi)	5 dBi base stations	
Antenna type	Omnidirectional	Omnidirectional
Thresholds CCA (dBm)	ED (−72 dBm)	(PD, ED) = (−82, −72) dBm
Antenna configuration	MIMO 2 × 2	MIMO 2 × 2
Minimum duration of sensing period	34 us	43 us
Channel model	ITU InH IEEE	
User distribution	Uniform random distribution	
Noise figure in UE	9 dB (−104 dBm noise floor)	
DRS, Packet Scheduler	80 ms, Proportional Fair	N/A
CW Updating Rule	"any NACK" (to detect collisions)	N/A

5.4. Fairness

On the subject of fairness, the results of the K-S test shown in Table 4 confirm that in none of the priority settings does the parameter p reach the proposed alpha (0.05). This means that 3GPP LBT is not a fair method in any of these cases, although by means of the parameter Dmax it can be stated that Priority 4 is the closer to fairness than the rest of options.

Table 4. Fairness assessment based on K-S test

	3GPP LBT p(1)		3GPP LBT p(2)		3GPP LBT p(3)		3GPP LBT p(4)		$D\alpha = 0.05$
	D-max	*p*-Value	D-max	*p*-Value	D-max	*p*-Value	D-max	*p*-Value	
Throughput	0.32860	5.73×10^{-98}	0.31439	1.03×10^{-98}	0.292340	1.25×10^{-78}	0.294113	1.44×10^{-77}	0.02371
Latency	0.28093	1.01×10^{-71}	0.25849	8.68×10^{-61}	0.24505	1.13×10^{-54}	0.24682	1.85×10^{-55}	0.02371

Therefore, it can be concluded that the phenomenon that has the most impact, and therefore must be avoided, is the collisions between both technologies. In this manner, the more transmissions there are, the more likely they are to collide, thus it is advisable to make the number of such transmissions as efficient as possible, particularly in the dense scenario that is the subject of this research.

Although in principle the use of a shorter backoff time is more likely to use the channel, as the standard and the literature suggest [16], it is also more likely in this context to interfere with other transmissions that are going unnoticed. Thus, these results raise the need to adopt specific mechanisms for especially dense environments that allow improving the coexistence between both technologies while maximizing 3GPP LBT performance.

6. Conclusions

This article presents an end-to-end multi-service performance evaluation by simulating an indoor dense coexistence environment. In such scenario, two non-cooperative deployments in the unlicensed sub-6-GHz bands coexist. The first is an operator using 3GPP Listen Before Talk access technology and the other is an operator with the WiFi 802.11ac. In this context, the performance and fairness of each priority established by 3GPP for LBT CAT4 proposed for LAA, eLAA and FeLAA and applicable for 5G NR-U were evaluated for a real-time service (FTP) and a non-realtime (Video Streaming) service.

According to the results obtained, and in contrast to the predicted from abstract models, Priorities 3 and 4 show very similar behavior, offering higher levels of user satisfaction measured in KQI for both real-time and non-real-time service compared to Priorities 1 and 2 and greater fairness towards WiFi. Therefore, it is proved that, in indoor dense coexistence scenarios, the 3GPP LBT parameter with the most significant impact is the Maximum Channel Occupation Time (MCOT). As a rule, configurations with longer MCOT provide higher user throughput and lower latencies. Nevertheless, it is essential to note that fairness is always compromised for all priorities, indicating that WiFi is still degraded.

Based on the evaluation made, it is necessary to find ways to optimize user's performance and fairness in dense scenarios for future 5G NR-U developments in the unlicensed band. In addition, it can be inferred that the use of lower priority values (3 and 4) is recommended to get the best user experience, even if their waiting times are longer. A method to manage the synchronization between 3GPP Listen Before Talk base stations in order to avoid self-collisions when shorter duration signals are sent (1–2 ms) is therefore needed. In this way, an algorithm to dynamically assign priority classes and further elaboration on network metrics (e.g., cell throughput, resource blocks utilization, network power consumption, etc.) are envisioned as future work.

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Abbreviations

The following abbreviations are used in this manuscript:

3GPP	Third Generation Partnership Project
AM	Acknowledged Mode (RLC)
AP	Access Point
ARQ	Automatic Repeat Request
BER	Bit Error Rate
BLER	Block Error Rate
BS	Base Station
CCA	Clear Channel Assessment
CDF	Cumulative probability Distribution Function
CQI	Channel Quality Indicator
CS	Carrier Sense
CSI	Channel State Information
CSI-RS	Channel State Information Reference Signal
CSMA	Carrier Sense Multiple Access
CW	Contention Window
DCI	Downlink Control Information
DRS	Discovery Reference Signal
DSCH	Downlink Shared Data Channel
ED	Energy Detection
eLAA	Enhanced Licensed Assisted Access
FeLAA	Further Enhanced Licensed Assisted Access

FTP	File Transfer Protocol
KQI	Key Quality Indicator
K-S	Kolmogorov-Smirnov
LAA	Licensed Assisted Access
LBT	Listen Before Talk
LSM	Link-to-System-Mapping
LTE	Long-Term Evolution
MCOT	Maximum Channel Occupancy Time
MCS	Modulation and Coding Scheme
MIESM	Mutual Information Effective SINR Metric
MIMO	Multiple Input Multiple Output
NR-U	New Radio Unlicensed
PF	Proportional Fair
PDSCH	Physical Downlink Shared Channel
QoE	Quality of Experience
QoS	Quality of Service
RLC	Radio Link Control
RRM	Radio Resource Management
RTVS	Real Time Video Streaming
SINR	Signal to Interference Noise Ratio
SISO	Single Input Single Output
SRS	Sounding Reference Signal
STA	WiFi Station
TxOP	Transmission Opportunity
UE	User Equipment
UPI	User Performance Indicator
W+L	WiFi and LBT coexistence scenario
W+W	WiFi and WiFi coexistence scenario

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