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Evaluating Unlicensed LTE Technologies: LAA vs LTE-U

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ABSTRACT Recently, there has been much interest by the cellular network industry in utilizing unlicensed spectrum to expand potential capacity. In particular, two LTE unlicensed technologies gained much attention: licensed-assisted access (LAA) and LTE unlicensed (LTE-U). While these are rapidly entering the market, there are not many studies in the literature that are providing a complete evaluation and comparison of their performance. Available work usually focuses on single technology standalone evaluations. Also, despite the vast body of simulation results by industry and academia, the simulators are not publicly available, and the analytical models proposed in the literature do not offer complex enough frameworks for thorough performance evaluations. To carry out an evaluation study, we have built a comprehensive simulation platform, strictly complying with the standards and specifications of each technology. The models are built upon popular ns-3 simulator, have been designed in close consultation with industry experts, and have been validated through calibration processes and against analytical proposals and experimental platforms. In this paper, we provide a detailed overview, performance evaluation, and comparison of LAA and LTE-U in a wide variety of scenarios, following 3GPP and Wi-Fi Alliance (WFA) guidelines. We show that despite the market is confirming LAA as the leading unlicensed LTE technology, in certain setups, efficient implementations of LTE-U may prove unexpectedly better in coexisting with Wi-Fi. Similarly, the expected behaviors of the LAA LBT procedure can reveal untrue, depending on the traffic or interference patterns and specific implementation details, even in Wi-Fi. This paper also includes scenarios involving TCP, which is a rarely treated topic in the literature in the context of LTE and Wi-Fi coexistence. The end-to-end and full protocol stack simulation platform is openly available to foster results' reproducibility and collaborative development.

INDEX TERMS LTE unlicensed (LTE-U), licensed-assisted access (LAA), CSAT, Wi-Fi, coexistence, ns-3, simulation, performance evaluation, validation.

I. INTRODUCTION

According to a recent study commissioned by the Wi-Fi Alliance (WFA) [1], between 2020 and 2025 users worldwide are likely to experience a spectrum shortfall. As a result of the increasing demand for traffic and bandwidth, mobile operators are increasingly interested in deploying a complementary access utilizing unlicensed spectrum. There has been a special interest lately for accessing the 5 GHz band, traditionally mainly used by Wi-Fi technologies, with Long Term Evolution (LTE). This has generated the definition of novel LTE-based access technologies capable of operating in unlicensed spectrum, while coexisting with other technologies [2], [3], [4]. Moreover, recently, the use of unlicensed spectrum above 6 GHz has attracted a lot of attention by industry, regulation and standardization bodies. 3rd Generation Partnership Project (3GPP), in Release 16, has focused on a study item on New Radio (NR) in unlicensed band, below and above 6 GHz [5], which resulted in TR 38.889. A new Work Item on this subject is ongoing.

With emphasis on the 5 GHz band, depending on the radio access technology used to access the unlicensed spectrum, these technologies can be divided into two main groups: 1) technologies based on integration of LTE and Wi-Fi radio links and using Wi-Fi to access the unlicensed spectrum, and 2) technologies using LTE Radio Access Network (RAN) in unlicensed spectrum. The integration of LTE and Wi-Fi radio links has been proposed since 3GPP Release 13 [6]. Examples of these technologies are: LTE-WLAN Aggregation (LWA) and LTE-WLAN Radio Level Integration with

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IPsec Tunnel (LWIP). As for unlicensed LTE technologies, using LTE RAN to access the unlicensed spectrum, their main challenge is the fair coexistence with other wireless technologies operating in the same band. While LTE is designed to have an exclusive access to channel and perform in uninterrupted and synchronous fashion, the existing unlicensed technologies operate in a decentralized, asynchronous manner employing protocols typically based on carrier sensing in order to achieve a fair usage of the spectrum. Some of the challenges of such coexistence scenario are explained in [7], [8].

Therefore, a critical requirement for the design of unlicensed LTE is that it has to coexist with other technologies, like Wi-Fi, on a "fair" and "friendly" basis [2], [9], by extending its synchronous design. In some markets, like Europe and Japan, a Listen-Before-Talk (LBT) feature for Clear Channel Assessment (CCA) before accessing the 5 GHz unlicensed channel is required, while in others, such as the USA, China, India and Korea, there is no such requirement. For markets that do not require LBT, the industrial consortium LTE Unlicensed (LTE-U) Forum specified a proprietary solution for unlicensed LTE based on Release 12, which is referred to as LTE-U [10]. On the other hand, to meet LBT requirement, 3GPP has produced in Release 13 [2] Licensed-Assisted Access (LAA) specification, for Supplemental DownLink (SDL) in unlicensed band. In Release 14, the uplink operation was also defined, in the context of Enhanced LAA (eLAA) [11] and new features are under definition in the Further Enhanced LAA (feLAA) Study Item [12]. Several products have already been presented at Mobile World Congress 2017 and 2018 by companies such as Qualcomm, to reach the 1 and 2 Gigabit LTE, respectively, with and without aggregation of unlicensed bands. In particular, in many commercial deployments around the world, currently LAA is used as supplemental downlink to deliver Gigabit LTE, paving the way to 5G. On the other hand, recently, the Multefire alliance [4] proposed a solution for unlicensed LTE that operates in a completely stand-alone manner in unlicensed spectrum by capitalizing on 3GPP Release 13 and 14 LAA.

In this work, we focus on LAA and LTE-U since they represent the most promising and widespread LTE-based unlicensed technologies. This is because these two technologies use the same RAN in both licensed and unlicensed spectrum, which allows a unified mobility, authentication, security and management. Additionally, since they leverage Carrier Aggregation (CA) with the licensed carrier, they also guarantee wide-area coverage and the Quality of Service (QoS) typical of the licensed carrier. We carry out a detailed evaluation study of these technologies, and compare their performance towards their users and in terms of coexistence.

There is a common belief that LAA, thanks to the LBT feature, is in general superior to LTE-U when it comes to coexistence performance with Wi-Fi. We show in this paper that the reality is not so straightforward and we try to deeply understand the limits and strengths of each of the two technologies. A key challenge to evaluate and compare these technologies is that despite the large body of simulation results by industry [2], [3] and in the literature [13]–[15], the simulators are not publicly available, the two technologies have been evaluated in a standalone fashion, and they have not been compared yet over the same scenarios and the same simulation or test platforms. As a consequence, the obtained results are nor reproducible, neither comparable, and system performance metrics are presented without much details revealed about the underlying models and assumptions. Few analytical models have been proposed in the literature to study channel access of both technologies [16], [17], and [18]. However, these models employ different assumptions, which limit their capability to evaluate the impact of some of the key coexistence parameters.

In order to perform a coexistence study and comparison of LAA and LTE-U technologies we have built a detailed simulation platform, strictly complying with LTE-U Forum and LAA 3GPP specifications, extending the popular open source network simulator ns-3 [19]. This allows access to the full configuration of the system (i.e., from the application to the network interface) and the reproducibility of results. The simulator that we have built based on ns-3, allows to reproduce both 3GPP and WFA evaluation approaches, and differently from any other simulator used in literature or in 3GPP studies, allows a full protocol stack simulation and an end-to-end performance evaluation. The proposed models have been validated through calibration campaigns, following 3GPP approaches, and against analytical solutions and experimental platforms available in literature. Based on this simulation platform, we have carried out an extremely detailed simulation campaign, analyzing many aspects affecting coexistence, and comparing LAA and LTE-U coexistence performance. This has allowed us to reach meaningful conclusions, which are discussed throughout the paper. The work on this simulator has been supported by the WFA and by a small cell vendor, SpiderCloud Wireless, intensively working in unlicensed spectrum, and so it has been designed in close consultation with industry. The implementations of LAA and LTE-U models along with the documentation, and the simulation scenarios presented in this paper are publicly available at [20] to facilitate results reproducibility and further collaborative developments.

The outline of the paper is organized as follows. We provide a detailed description of state-of-the-art contributions in the area of performance evaluation of LAA and LTE-U technologies in Section II, and a comprehensive overview of the two technologies in Section III. In Section IV, we discuss the main differences with respect to the Wi-Fi access technology. In Section V, we provide descriptions of the LAA and LTE-U models that we implemented in the simulator; introduce the evaluation methodology, derive the simulation scenarios and metrics; and validate coexistence simulation model. In Section VI, we describe the performance evaluation, and we provide a summary of our findings and suggestions for future work. Section VII concludes the paper.

II. RELATED WORK ON PERFORMANCE EVALUATION STUDIES OF LAA AND LTE-U

Due to the increasing interest in unlicensed LTE, academia, industry, and standardization bodies, have dedicated lately a lot of work to investigate different spectrum sharing mechanisms for unlicensed LTE and 5G technologies [21], [22] and [23]. However, not much work is devoted to compare the two predominant unlicensed LTE technologies, LAA and LTE-U. As we mentioned earlier, it is generally considered that LAA is fairer to Wi-Fi since it uses an LBT mechanism, but nothing can be found in literature to confirm or deny this theoretic assumption. In this section, we describe available work in the literature, specifically focusing on the performance evaluation of the LAA and LTE-U.

Some of the very first performance evaluations in the literature were mainly focused on evaluating the effects of LTE on Wi-Fi without using any coexistence mechanisms by LTE, e.g., [24]. This study is mostly focused on the interference effects, and the impact of Physical Layer (PHY) parameters such as LTE bandwidth, carrier frequency, the impact of Wi-Fi CCA threshold and Multiple Input Multiple Output (MIMO) onto coexistence. In [25] the authors propose an analytical model and perform an experimental evaluation, where the LTE device does not implement any coexistence mechanism, but it instead implements a centralized mechanism for coordination of Wi-Fi and LTE. Some other studies evaluate only a single spectrum sharing mechanism, i.e., either the LBT [13], [26] or the LTE-U duty cycle [27].

The performance evaluations carried out by the industry also consider only a single technology, since they were carried out as a part of either LTE-U or LAA study. The results for LTE-U performance evaluation are shown in [3], and for LAA in [2]. In both cases, the performance evaluations were carried out with either proprietary simulators or testbeds that are not publicly available. Also, each of these studies established different methodologies, scenarios, traffic models and performance evaluation metrics. Because of this, it is very hard to draw conclusions on which technology performs better. As a result, we consider that, in order to compare the two technologies in an unbiased manner, it is crucial to establish a unified framework under which they can be evaluated with the same conditions.

To the best of our knowledge, only the authors in [14], [16]–[18] consider both unlicensed LTE technologies. However, in [14], [17], [18], [28] the authors evaluate LTE-U leveraging a fixed duty cycle scheme, which we do not consider as an appropriate benchmark, or state-of-the-art Carrier Sense Adaptive Transmission (CSAT) scheme for LTE-U, since the duty cycle has to be adaptive based on the activity observed on the channel. An example of highly performing CSAT, has been proposed by Qualcomm [10], [29]. In addition, contributions in [14], [17] and [18] do not consider an exponential backoff in LAA LBT, which though is what it is agreed in 3GPP [6]. Only the work in [16] models both spectrum sharing mechanisms and captures the main characteristics of each mechanism. In particular, the authors propose a novel throughput and interference model for heterogeneous technology coexistence in the same spectrum. While the latter proposal represents an effective analytical tool for the evaluation of different channel access mechanisms, its focus is limited to the Medium Access Control (MAC) and to some coexistence parameters. As a result, the insights cannot be used to evaluate the impact of higher layers and end-to-end effects of coexistence.

Taking into account the limitations of the available literature, in this work we carry out a performance evaluation of both technologies in a unified, full-protocol stack and open source simulation framework. In the proposed simulation model, the spectrum sharing mechanisms are defined according to LTE-U Forum and 3GPP specifications, respectively. As we will explain further in the paper, we consider a variety of scenarios for evaluation, directly inspired by both, 3GPP LAA evaluation study and WFA test plan methodologies, in order to be as complete as possible. We show a summary of related work in Table 1.

III. UNLICENSED LTE TECHNOLOGY BACKGROUND

In this paper, we focus on unlicensed LTE implemented as a technology anchored to licensed spectrum, and in particular on LAA and LTE-U technologies. In this section, for the reader's convenience, we provide a general overview of these technologies, focusing on the main features, which will be useful to better understand the simulation models presented in the rest of the paper, the nomenclature and the evaluation results. For further and more specific surveys on coexistence issues, for 4G and 5G, the reader is also referred to [22] and [23].

A. LAA TECHNOLOGY BACKGROUND

In the following, we discuss the main features of the LAA technology, in particular:

- LBT procedure
- Energy detection method
- Contention Window (CW) adjustment procedure
- Discovery Reference Signal (DRS)
- LAA reservation signal
- LAA partial subframe

1) LBT PROCEDURE

The main feature of LAA, which distinguishes it from LTE-U, is the support of LBT. Figure 1 depicts the LBT procedure defined in 3GPP. LBT is a mechanism with which an equipment applies a CCA to check the availability of the channel before transmitting on it. During the study item on LAA [2], different channel access mechanisms were evaluated, with and without random backoff and with and without variable CW. Category 4 mechanism, considering both random backoff and variable CW was selected for Physical Downlink Shared Channel (PDSCH) transmission. The Evolved Node B (eNB) is allowed to transmit after sensing the channel to be IDLE during the initial CCA defer period

TABLE 1. Related work on performance evaluation studies of LAA and LTE-U.

Reference work	Spectrum sharing technology	Evaluation methodology	Modeling assumptions
[2]	LAA only	- 3GPP contributions by a large number of small cell vendors. - Follows 3GPP evaluation methodology. - Coexistence scenarios: a) DL-only LAA and DL-only Wi-Fi (Annex B1) b) DL-only LAA and DL+UL Wi-Fi (Annex B2) c) DL+UL LAA and DL+UL Wi-Fi (Annex B3)	Proprietary simulators and testbeds.
[3]	LTE-U only	- Contributions by different vendors. - Various real-world scenarios: indoor/outdoor, high/low density configurations.	Proprietary simulators and testbeds.
[26]	LAA only (LBT with a fixed CW size)	- Stochastic model based on Markov chain. - Scenario with 1 LAA and 1 AP, and LAA coexisting with another LAA. - Simulations for different traffic rates.	- No exponential backoff in LAA; fixed CW size. - LAA and AP can always sense each other. channel knowledge. - Wi-Fi like model for LAA collision detection and error recovery.
[13]	LAA only	Simulations based on a 3GPP evaluation methodology.	Proprietary simulator.
[27]	LTE-U only (ALOHA-like CSAT)	- A stochastic geometry based model. - Only persistent downlink traffic.	- LTE-U employs ALOHA-like random access scheme. - Interference limited regime. - Perfect energy-detection. - Error model assumption: The transmission is successful if SINR is above a predefined threshold.
[16]	LAA and LTE-U	- A throughput and interference model for inter-technology coexistence. - Indoor/outdoor combinations of scenarios with/without internal walls. - Only downlink saturated traffic.	- Adaptive duty cycle modeled as ideal TDMA MAC. - Simulation limitation: 1 UE per AP.
[17]	LAA (no exponential backoff) and LTE-U (fixed duty cycle)	A throughput model for LTE and Wi-Fi coexistence.	- LTE-U duty cycle fixed. - No exponential backoff in LAA and Wi-Fi access. - Wi-Fi senses the channel busy when LTE transmits. - Fixed coding, 64 QAM for both, LTE and Wi-Fi. - Fixed duration of LTE transmissions.
[18]	LAA (LBT with a fixed CW size) and LTE-U (fixed duty cycle)	- A stochastic geometry based model. - Downlink saturated traffic only.	- Free space path loss model. - LBT fixed CW size. - LTE-U with a static muting pattern, synchronous and asynchronous eNBs patterns. - Channel access priority model options: 1) Wi-Fi and LAA equal priority; 2) LAA has lower priority than Wi-Fi by by setting a larger backoff timer for LAA.
[14]	LAA (LBT with a fixed CW size) and LTE-U (fixed duty cycle)	- Various indoor and outdoor setups. - CSAT muting subframes simulated with almost blank subframes.	- Proprietary simulator. - LBT fixed CW size. - Fixed duty cycle.
[28]	LAA and LTE-U	- 3GPP indoor scenario. - Standard LTE-U implementation without CSAT.	- ns-3 simulator. - LBT dynamic CW size. - LTE-U fixed duty cycle.

T_{d_cca} or after performing the Extended CCA (eCCA). The defer duration T_{d_cca} is composed of duration $T_f = 16\ \mu$s and m_p CCA slots, where each CCA slot duration is $T_{sl_cca} = 9\ \mu$s, as explained in Section 15.1.1 in [30]. The value of m_p depends on the channel access priority class, which is used to categorize the type of traffic scheduled in the unlicensed band, as specified in Table 2. For example, for the priority class 3, T_{d_cca} is 43 μs. If the channel is idle during T_{d_cca}, the eNB transmits the packet burst. Otherwise, the eNB shall perform the eCCA, during which it first draws a random value of a backoff counter N in the range of [0, CW_p] and starts sensing the channel for an eCCA defer duration, T_{d_ecca}.

TABLE 2. LAA channel access priority classes.

Channel access priority class	m_p	CW_{min}	CW_{max}	MCOT	Allowed CW sizes
1	1	3	7	2 ms	3, 7
2	1	7	15	3 ms	7, 15
3	3	15	63	8 or 10 ms	15, 31, 63
4	7	15	1023	8 or 10 ms	15, 31, 63, 127, 255, 511, 1023

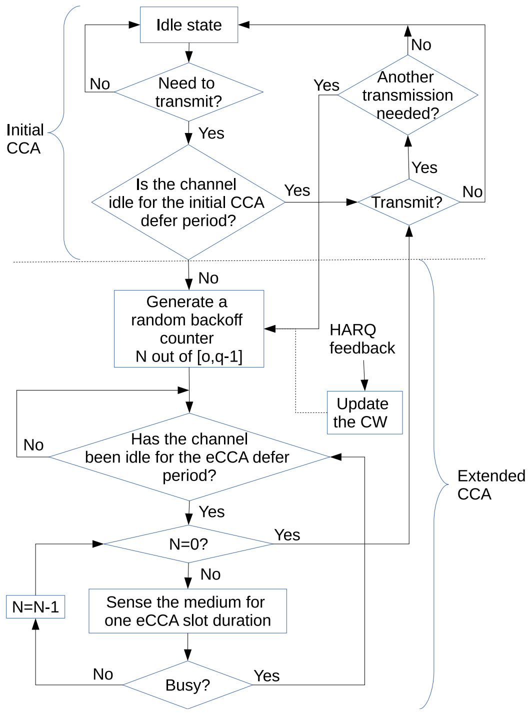


FIGURE 1. 3GPP LBT procedure.

The CW_p is the current CW size, which ranges between CW_{min} and CW_{max}, also specified by the priority class, as shown in Table 2. Once the channel is free for T_{d_ecca}, the eNB senses the channel to be idle for the duration of additional N eCCA slots, and each time that the channel is detected to be idle for a period of one eCCA slot, $T_{sl\_ecca} = 9\ \mu s$ (equal to T_{sl_cca}), the backoff counter is decreased by one. The channel is considered to be idle during T_{sl_ecca} if the detected power is lower than the energy detection threshold ED_{th} for at least 4 μs [30]. Otherwise, the slot is considered to be busy. If during the backoff process, the eNB detects that the channel is occupied, the backoff counter is frozen, and the eNB continues to sense the channel until it finds it to be idle for T_{d_ecca}. Once the backoff counter reaches zero, the eNB occupies the channel for a Transmission Opportunity (TxOP), no longer than the Maximum Channel Occupancy Time (MCOT), which depends on the priority class. An LAA eNB can occupy the channel up to 10 ms in case of Best Effort (BE) and Background (BK) traffic, i.e., priority classes 3 and 4, respectively. For other types of traffic, which require a higher quality of service, the length of the MCOT is shorter [30].

2) ENERGY DETECTION (ED) METHOD

The LBT procedure is based on the ED method to determine whether the channel is free to use. The ED method is a CCA mechanism which attempts to determine if the medium is busy by measuring the total energy a device receives. If the received energy is above a certain *ED threshold* the medium is considered busy. Because of this, the ED threshold is one of the most critical parameters to be set for fair coexistence. The maximum configurable ED threshold is defined by the regulations for each region. According to 3GPP agreements the established ED threshold for LAA should be −72 dBm for 20 MHz channel. The ED threshold should be adaptive, based on the mechanism defined in Section 15.1.4. in [30].

3) CW ADJUSTMENT PROCEDURE

3GPP provides a description of CW adjustment procedure in [30]. The initial value for CW window is defined by the priority class, as shown in Table 2. The CW size is increased upon collisions, which in LAA are detected by means of Hybrid Automatic Repeat Request (HARQ) feedbacks from a receiving node. In particular, the CW size at the eNB is increased if more than Z percentage of HARQ feedbacks corresponding to the PDSCH transmission in reference subframe k are determined as Negative Acknowledgement (NACK)s [30]. The default value of the Z parameter is 80%. Otherwise, the CW size is reset to the minimum value (CW_{min}). The reference subframe k is typically the first subframe of the most recent transmission burst for which some HARQ feedback is available.

4) DRS

The DRS is introduced in Release 12 to allow functionalities such as discovery of the LTE cell, synchronization to the LTE cell, and to perform Radio Resource Management (RRM) measurements. The DRS includes several signals like Primary Synchronization Signal (PSS), Secondary Synchronization Signal (SSS) and Cell-Specific Reference Signal (CRS), and if configured may have Channel State Information - Reference Signal (CSI-RS). The DRS is transmitted for both cells in ON-state and cells in OFF-state. A cell in OFF-state transmits a DRS so that the UE can detect, measure and report it to the network for efficient RRM functionalities. Release 12 DRS is transmitted with a fixed periodicity of 40, 80 or 160 ms within the Discovery signals Measurement Timing Configuration (DMTC) occasion. The fixed periodicity is relaxed for LAA, to make it compatible with the LBT requirement.

5) LAA RESERVATION SIGNAL

Legacy LTE transmissions are synchronous and start at a subframe boundary. However, the introduction of LBT introduces aleatority in the instant in which the channel is acquired by the transmitted node. Because of this, other neighboring systems with no such restriction, like Wi-Fi, can take a transmission opportunity while the LAA eNB is waiting until the following subframe boundary to start transmitting. To solve this, LAA reserves the channel by transmitting reservation signals after LBT is successful and the access is granted, and until the subframe or slot boundary, see section III-A.6). Note that the reservation signal spares channel occupancy time since its duration counts against the MCOT, and so decreases the spectral efficiency and increases unfairness towards Wi-Fi. To reduce inefficiencies caused by the LAA channel reservation, the partial subframe is proposed for LAA SCell. In Fig. 2 we illustrate how the reservation signal (RS) can be sent between when the LBT awards the channel and the subsequent subframe (SF) or slot boundary, for the case of MCOT equal to 4 ms. Depending on if the partial subframe is supported, the part of the MCOT between the end of the last full subframe in MCOT (SF3) until the end of the MCOT is not used for transmission.

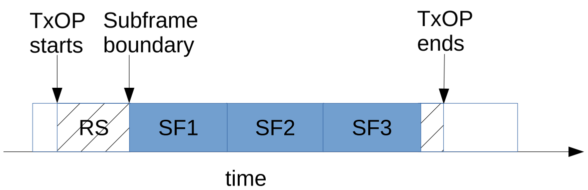


FIGURE 2. Example of MCOT of 4 ms and use of reservation signal sent upon a successful LBT until a subframe boundary.

6) LAA PARTIAL SUBFRAME

The partial subframe is a subframe with a shorter duration than 1 ms. In particular, in case LBT is successful in the middle of the subframe, the data transmission can start at the slot boundary (1 subframe has 2 slots of 0.5 ms each). Also, depending on the starting time of the transmission and due to the MCOT limitation, the grant may not end at the subframe boundary. To support such partial subframe transmissions for LAA, a new frame structure, Type 3, was introduced in Release 13 [31]. According to this frame structure, the transmissions can start at the slot boundary (symbol 0 or 7), and can end either with the full subframe or with a partial subframe following one of Downlink Pilot Time Slot (DwPTS) durations. The DwPTS is the downlink portion of the subframe of Type 2 for TDD. By using existing DwPTS, the duration of the transmission burst can be 3, 6, 9, 10, 11, or 12 OFDM symbols. The ending partial subframe can be utilized by reusing the DwPTS structure with almost no changes to the existing LTE. The partial subframe increases the complexity of the scheduling. To reduce the complexity, it is possible to limit the symbols at which the transmission can start/end. However, limiting the number of possible options reduces the efficiency. More information can be found in [32], [33].

B. LTE-U TECHNOLOGY BACKGROUND

LTE-U refers to the unlicensed LTE technology that was proposed and specified by the LTE-U Forum in [29], [34]. The LTE-U Forum was formed in 2014 by Verizon in cooperation with Alcatel-Lucent, Ericsson, Qualcomm Technologies, Inc., and Samsung, with the objective of collaborating together and generating technical specifications for LTE-U technology. These specifications support LTE operation in the 5 GHz UNII-1 and UNII-3 bands as SDL carriers, in conjunction with an LTE deployment in licensed bands, based on already published 3GPP Release 10 and later specifications. What characterizes LTE-U is the duty-cycling nature of the channel access procedure and the fact that it lacks LBT mechanism. When it comes to transmission according to the duty cycle pattern (i.e., it has an ON-OFF time pattern), LTE-U accesses the channel, regardless of the presence of Wi-Fi transmissions. This kind of the channel access may generate collisions with co-deployed Wi-Fi networks when the duty cycle pattern switches from OFF to ON, and this is the primary concern raised against the LTE-U technology. When the SCell is in ON-state, it transmits as a legacy LTE based on Release 10, 11 or 12. LTE-U SCell differs from the legacy LTE, active in the Primary Cell (PCell), in supporting the following aspects: 1) CSAT to access the channel, 2) Transmission of LTE-U Discovery Signal (LDS), 3) Ability to skip the transmission of Master Information Block (MIB)/System Information Block Type 1 (SIB1), and 4) Opportunistic SCell OFF.

1) CSAT

CSAT is the medium access procedure defined by the LTE-U forum in [29]. Based on CSAT, the Secondary Cell (SCell) first senses the medium to evaluate its occupancy, and then, depending on this measure, it establishes a duty cycle pattern, i.e., the percentage of time the SCell is to be ON. The duty cycle pattern is periodically adjusted so that the SCell only occupies the channel for a fair share. The LTE-U Forum specification does not define the algorithm according to which the duty cycle is adjusted, and it is left to the vendor to establish its adaptation algorithm. However, the LTE-U Forum defines the following constraints for the CSAT pattern:

- $4ms \leq T_{ON} \leq 20\ ms$
- $1ms \leq T_{OFF} \leq T_{LDS}$,

where T_{ON} is the ON-state duration and T_{OFF} is the OFF-state duration. T_{LDS} is the periodicity of LDS, which will be described in more details in the following subsection. The minimum of 4 ms for T_{ON} is required as long as there is data in buffers and is chosen to avoid frequent OFF/ON state transitions, which are likely to generate collisions. The maximum duration of 20 ms is allowed for uninterrupted transmission of the LTE-U SCell and is chosen to favor coexistence with other technologies. After reaching the maximum uninterrupted transmission duration, the LTE-U has to switch OFF during a period of 1 or 2 ms, which is normally referred to as *puncturing* period. The puncturing subframes are subframes during which the SCell is not permitted to transmit, in order to allow low-latency Wi-Fi traffic to go through. The duty cycle pattern, consisting of alternating T_{ON} and T_{OFF}

periods, is adaptive based on the activity sensed during the T_{OFF} times. Additionally, some CSAT implementations, like, e.g., Qualcomm's CSAT [10], define periods during which the sensing is performed specifically to detect the number of active Wi-Fi Access Point (AP)s that are present on the same channel. This part of the Qualcomm's CSAT method is called *AP scan* [10]. In this paper, in the implementation and in the results that are discussed in the following sections, we refer to the CSAT algorithm proposed by Qualcomm. We focus on this algorithm because it is very sophisticated, and it includes several features that favor the coexistence with Wi-Fi.

According to this algorithm, the adjustment of the CSAT duty cycle is performed in the following way. The averaged medium utilization (MU), $\overline{MU}$, is a weighted moving average of Wi-Fi activity over a monitoring window. The MU is obtained by summing up the durations of all Wi-Fi transmissions that were detected by the monitoring Wi-Fi device at the LTE-U node during the corresponding monitoring window. The $\overline{MU}$ is calculated as the weighted moving average in the following way:

$$\overline{MU}(t) = \alpha_{MU} \times MU(t) + (1 - \alpha_{MU}) \times \overline{MU}(t-1), \quad (1)$$

where α_{MU} is the weight. According to [10] there are two $\overline{MU}$ thresholds, a lower and a higher, MU_{low} and MU_{high}. If $\overline{MU}$ is greater than MU_{high}, then the T_{ON} is decreased by δ_{down}. On the another hand, if $\overline{MU}$ is lower than MU_{low} then the T_{ON} is increased by δ_{up}. δ_{down} and δ_{up} are CSAT parameters used to adjust the duty cycle, and they directly determine the speed of the convergence of the duty cycle. If $\overline{MU}$ is in between the two thresholds, the CSAT duty cycle remains unchanged. T_{ON} is bounded by the minimum and the maximum value. The minimum T_{ON} value, $T_{ON,min}$, is introduced to guarantee that LTE-U grants a fair share of the spectrum, and the maximum, $T_{ON,max}$ to guarantee that the OFF period is long enough to achieve a proper sensing of Wi-Fi activity. $T_{ON,max}$ is directly determined by the time during each cycle that LTE-U has to be in OFF state to monitor the Wi-Fi activity, $T_{OFF,min}$. Thus, $T_{ON,max}$ is calculated in the following way:

$$T_{ON,max} = T_{CSAT} - T_{OFF,min} \quad (2)$$

On the other hand, $T_{ON,min}$ threshold is adaptable and is determined in the following way:

$$T_{ON,min} = min\left\{C_{min}, \frac{(N_{LTE}+1) \times T_{CSAT}}{M_{LTE} + N_{Wi-Fi} + 1}\right\}, \quad (3)$$

where C_{min} is a parameter that is controlling the minimum duty cycle when no Wi-Fi activity is being sensed by the monitoring Wi-Fi device at LTE-U node. N_{LTE} is the number of LTE nodes with the same Public Land Mobile Network (PLMN) ID, and M_{LTE} is the number of all LTE nodes, regardless their PLMN ID. Since in this work we do not consider different PLMN IDs, N_{LTE} is equal to M_{LTE}. N_{Wi-Fi} represents the number of Wi-Fi nodes. N_{Wi-Fi} is obtained while performing the AP scan monitoring, by listening to the beacon signals. AP scan monitoring is independent of MU monitoring. While MU monitoring can last around 20 ms, the *AP* scan monitoring needs to last for more than 102.4 ms to allow a beacon detection belonging to all neighboring APs. This is because beacons are typically sent with 102.4 ms interval. Fig. 3 illustrates an example of CSAT pattern.

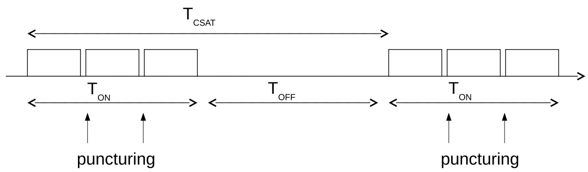


FIGURE 3. An example of CSAT pattern.

2) TRANSMISSION OF LDS

The LDS allows User Equipment (UE)s to obtain and keep SCell time and frequency alignment as well as performing SCell tracking and measurements [29]. LDS is a similar message to the DRS, introduced in previous section. LDS is broadcasted by the LTE-U eNB, only at subframe 5 occasions, with a fixed time periodicity and with a fixed offset according to the DMTC. The LDS does not contain CSI-RSs. It comprises CRS/PSS/SSS and Physical Downlink Control Channel (PDCCH)/PDSCH for SIB1 transmission. LDS configuration allows periodicities of 40, 80 or 160 ms.

3) ABILITY TO SKIP THE TRANSMISSION OF MIB/SIB1

The MIB and SIB1 signaling on the SCell allow the detection of eNBs belonging to other PLMNs. MIB and SIB1 shall be transmitted on SCell only when the MIB/SIB1 transmission period overlaps with a SCell transmission (SCell ON-state). However, the MIB has a minimum allowed periodicity, which is typically 160 ms. So, if it is not transmitted during this period, the LTE-U cell has to access the channel and send the MIB, without waiting for the ON-state. The duration of the MIB transmission (usually 1 ms) is counted towards the ON time.

4) OPPORTUNISTIC SCell OFF

SCells in an unlicensed spectrum have to be active only when traffic and coverage conditions really require it, and there is a clear benefit in offloading traffic in these bands. As a result, the SCell has to be turned OFF when there are no UEs in the SCell coverage area, or when the eNB does not have any data in its buffers for the UEs in the SCell coverage. The SCell configuration and activation procedures follow 3GPP Release 10 specifications. When the SCell is activated, the UE monitors the Downlink (DL) subframes at least from the 8th subframe after the subframe including the activation MAC control element command, as in case of the legacy LTE SCell. On the other hand, when the SCell is deactivated, the UE is only required to monitor LDS signals. UEs are not required to be activated for an LTE-U SCell in order to demodulate and perform measurements based on the LDS.

IV. DIFFERENCES BETWEEN WI-FI AND UNLICENSED LTE TECHNOLOGIES

Even if LAA adds to LTE the fundamental LBT functionality, perfectly imitating the Wi-Fi behavior, some intrinsic differences between LTE and Wi-Fi, make that the technologies occupy the channel differently. In this section, we discuss the main technological differences between Wi-Fi and unlicensed LTE technologies, which may impact coexistence performance. This section will facilitate the reader to understand the different coexistence behaviors that will be discussed in the evaluation sections. Differently from other works [22], we focus here on both LAA and LTE-U.

A. CHANNEL ACCESS

Even if Wi-Fi and LAA have similar LBT/CSMA approaches, the way they access the channel is different, due to their intrinsic technological differences. First of all, Wi-Fi can start its transmission at any time, whereas LTE is limited by its frame structure, requiring the use of reservation signals (as introduced in Section III-A.5). The inefficiency in LAA channel occupancy caused by the reservation signals can be reduced by leveraging the partial subframe feature. However, this further complicates the logic of the MAC and PHY protocols. In case of LTE-U, since there is no LBT, there is no need to transmit any reservation signal or to use partial subframes. The LTE-U transmission always starts at the subframe boundary, so it does not introduce inefficiencies. However, if a Wi-Fi node is transmitting, the probability of collision between LTE-U and Wi-Fi is higher than between LAA and Wi-Fi.

B. DETECTION PROCEDURES

As we mentioned earlier, LAA uses ED to determine whether the channel is free to use. On the other hand, Wi-Fi uses both ED and preamble detection (PD). In particular, LAA energy detects Wi-Fi at −72 dBm, while Wi-Fi energy detects LAA at −62 dBm and preamble detects other Wi-Fi devices at −82 dBm. As a result, in situations where LAA and Wi-Fi sense each other in the range of −62 dBm and −72 dBm, LAA will defer its access, while Wi-Fi will access the channel considering it to be idle. These setups are not only problematic for LAA, but also for Wi-Fi, since they can result in a variety of hidden node scenarios. To solve this issue, one of the proposals from 3GPP RAN1 was to consider adopting a lower ED threshold (−72 dBm) for new Wi-Fi systems, like 802.11ax. IEEE 802 declined this proposal considering that this would put in disadvantage 802.11a/n/ac systems which are using an ED threshold of −62 dBm, and also taking into account that LAA is not detecting 802.11 preambles at −82 dBm. Additionally, it is under consideration whether LAA shall transmit CTS-to-Self control frames to reserve the medium. This would allow Wi-Fi systems to detect and defer to LAA systems at −82 dBm. However, if Wi-Fi can preamble detect LAA, then it would be fair that also LAA can detect Wi-Fi preambles. The use of CTS-to-Self has been evaluated in Release 14, but its introduction was rejected since it may require installing a Wi-Fi card inside the LAA device.

C. COEXISTENCE AMONG UNLICENSED LTE TECHNOLOGIES

The addition of LBT has implications on the performance of LAA, when coexisting with another LAA. It can easily happen that one LAA defers its access to the channel when it detects that another LAA is transmitting. However, this may be undesirable since LTE successfully manages the interference with frequency-reuse 1. Thus, if LBT prevents multiple LAA nodes from transmitting simultaneously, this may degrade the spectral efficiency of the LTE network. On the other hand, in case of LTE-U, there are two options. LTE-U nodes of the same operator can be synchronous, which means that they transmit and are in OFF-state simultaneously, or they can be asynchronous. The first option requires a central network entity that synchronizes the duty cycles. So, it requires more implementation effort, but it may increase the spectral efficiency. On the other hand, if the nodes are asynchronous, it is to expect that the spectral efficiency will drop, but no implementation effort is required.

D. *CW* UPDATE

The CW size in both LAA and Wi-Fi is increased, if a receiving node is unable to decode the packet due to errors caused by poor channel conditions or collisions. The main difference between the CW update procedures of these two technologies lies in how a transmitter identifies a collision, and how a receiving node recovers the erroneous packet. As we mentioned earlier, in LAA, the CW is increased if the percentage of NACKs for a single reference subframe (usually the first subframe) of a transmission burst, is bigger than a predefined threshold. The standard suggests to set the threshold to 80% [30]. Setting such a high threshold value may cause LAA to be unable to detect collisions. For example, it may happen that only a small portion of scheduled users experience collisions, but they are not reported, because under 80%. In this case, the LAA eNB ignores these collisions, and does not increase its CW, so that potentially needed corrective actions are not taken. On the other hand, Wi-Fi increases its CW size when an Acknowledgment (ACK) or a Block Acknowledgment (BA) for the packet/s transmitted to a single user is not received. The Wi-Fi CW update scheme is then considering equally the feedback coming from different Wi-Fi Station (STA)s. This difference can cause that under specific conditions LAA updates the CW significantly less often than Wi-Fi [35].

E. COLLISION DETECTION MECHANISM

In LAA, HARQ feedback is chosen to detect and declare collisions. However, HARQ does not necessarily reflect collisions. LTE HARQ procedure is based on soft combining techniques, i.e., Incremental Redundancy (IR) and Chase Combining (CC), according to which the failed transmissions are not wasted, but combined with the retransmissions. As a result, it may happen that an unsuccessful retransmission, due to a collision, does not result in a NACK, because the combined information with previous transmissions is enough for the UE to decode the data successfully. In contrast, the Automatic Repeat reQuest (ARQ) mechanism that is used in Wi-Fi leverages acknowledgments and timeouts to detect the error. Thus, it always discards the data with errors and asks for a new transmission. For example, if the sender does not receive an ACK before the timeout expires, it will usually retransmit the frame/packet until the sender receives an ACK or exceeds a predefined number of retransmissions. Therefore, due to the efficiency of a soft combining technique used in the LTE HARQ procedure, it may happen that, Wi-Fi detects more collisions than LAA, and consequently it increases the CW more often [35].

F. COLLISION DETECTION DELAY

LAA uses the HARQ feedback corresponding to the starting subframe of the most recent transmission burst. One of the reasons to select the starting subframe as a reference subframe was to minimize the delay between the collision detection and the update of the CW size. Still, the difference in collision detection delay between Wi-Fi and LAA is significant. The time between the transmission and the corresponding feedback in Wi-Fi is in the order of μs, while in LAA is in the order of ms. Wi-Fi detects a failed transmission SIFS time after the transmission is finished, which is typically 16 μs. In Fig. 4, we illustrate the delay between the data transmission by the eNB in subframe n and the acknowledgment by the UE in subframe $n+4$, i.e., the delay is 4 ms [36]. Therefore, an update of CW in LAA is significantly delayed compared to Wi-Fi. The difference in this delay may generate very different reactions of these two technologies to the same channel conditions. For example, in the cases when Wi-Fi packets are small, Wi-Fi may detect various collisions with the same LAA node and update the CW accordingly, while the LAA node would be still waiting to receive the HARQ feedbacks of the starting subframe of the corresponding transmission. Fig. 4 illustrates the delays experienced by the HARQ feedback.

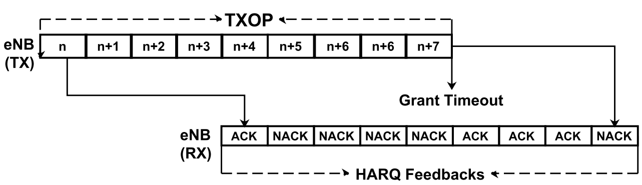


FIGURE 4. LTE eNB transmission and HARQ feedback delay.

V. ns-3 MODELS, EVALUATION FRAMEWORK, SCENARIOS AND CONFIGURATION

To support LAA and LTE-U evaluations we have developed extensions to ns-3 [19], an open-source system simulator popular in research and academia. As mentioned earlier, the implementation of LAA and LTE-U extensions to ns-3 is publicly available at [20]. Most of the existing coexistence simulators can be classified as link layer simulators with high fidelity models of the channel, PHY and MAC layers, but high levels of abstraction at higher layers. In contrast, ns-3 is a full stack system simulator, with more abstracted PHY layer models with respect to link layer simulators, but with higher fidelity models at higher layers. ns-3 LTE models [37] have been developed according to Femto Application Platform Interfaces (FAPI), defined by the Small Cell Forum and following small cell vendor recommendations. FAPI are defined to encourage competition and innovation between suppliers of hardware and software platforms, by providing a common Application Plaftorm Interface (API). The ns-3 Wi-Fi models have been developed following the IEEE standards, starting with initial 802.11a models and later extending to many aspects of the 802.11b/g/p/e/n/ac standards. In the following, we discuss the LAA and LTE-U models that we have developed, based on the widely used ns-3 LTE model, and that we will use in the evaluation. Then we go through the evaluation framework, the considered simulation scenarios and validation of coexistence model.

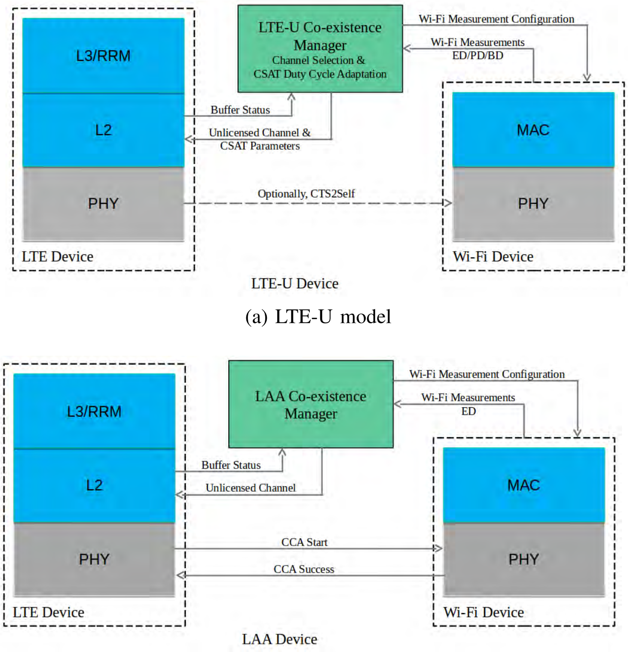
A. LAA AND LTE-U ns-3 MODELS

1) ns-3 LAA MODEL

Fig. 5b highlights the architecture of our LAA implementation design. The logic of the channel access operation is placed in a newly introduced entity, referred to as LAA Coexistence manager, which is added to the LTE device, and implements the LBT algorithm following 3GPP specifications as explained in Section III-A.1. As many actual products in the market, the LAA device in our model contains a Wi-Fi device which is used to perform the CCA based on the ED method. As shown in Fig. 5b, the LAA device is composed of a modified LTE device, and of a Wi-Fi device operating in a monitoring mode. LAA coexistence manager is hooked to the MAC and PHY layers of the LTE eNB device to allow the coordination between the MAC scheduler, and the PHY. Every time the LAA entity needs to transmit, it first requests the grant to access the channel from the LBT coexistence manager. The LBT coexistence manager performs the LBT procedure, relying on measurements from the Wi-Fi device. Once the LBT has determined that the channel is free to use, it provides a transmission grant to the LAA PHY.

Table 3 summarizes the default LAA parameters. The model supports exponential backoff according to the Category 4 design. Initial and extended CCA defer at 43 μs, and the LAA CCA slot time is 9 μs [38]. LAA ED threshold is tunable, separately from the Wi-Fi's threshold, and its value is set to -72 dBm. The maximum length of the TxOP is configurable, and it defaults to 8 ms. The update of the CW is implemented following a HARQ feedback based approach, as agreed in [38], [39].

Data transfer starts at the subframe boundary. We implement reservation signals to occupy the channel and force



(a) LTE-U model

(b) LAA model

FIGURE 5. Block diagrams of LTE-U and LAA models for ns-3.

TABLE 3. LAA default simulation parameters.

LAA parameter	Default value
CCA-ED threshold	-72 dBm
DRS interval	160 ms
MCOT	8 ms
Z threshold	80%
Min CW size	15 slots
Max CW size	63 slots
CCA Slot duration	9 μs
Initial and extended CCA	43 μs

other nodes to defer, while we are not occupying the channel with data. The reservation time is discounted from the transmission opportunity grant time. The DRS is modeled according to 3GPP specifications as discussed in Section III-A.4. DRS may have a variable position inside the DTMC window, and it should be subject to a priority LBT, with a fixed defer period of only 25 μs, but we consider a normal LBT, as for data. If data is scheduled during the DTMC window, DRS is embedded with data, otherwise, it is sent alone without data, and modeled as a transmission occupying 14 symbols (1 ms). DRS periodicity is configurable. Possible values are 40, 80 and 160 ms, and the default in our tests is 80 ms. Notice that DRS is only modeled to account for its channel occupancy. We assume that DRS impact on synchronization is not evaluated in the model, and UEs do synchronize through the licensed carrier. The system information (MIB/SIB1) is channeled through the PCell. Between the time when the MAC schedules a PDU, and when it actually reaches the air, there are 2 subframes (2 ms) of delay, due to PHY/MAC processing.

2) ns-3 LTE-U MODEL

Fig. 5a shows the architecture of our implementation design of the LTE-U device. The LTE-U device is composed of the modified LTE device where the algorithm handling the access is in the newly introduced entity referred to as LTE-U coexistence manager. Similarly to the LAA model, we introduce a Wi-Fi device in a monitoring mode to LTE-U device in order to support basic Wi-Fi PHY and MAC functionalities. The LTE-U coexistence manager has a central role in the LTE-U model since it performs the CSAT algorithm and it decides the LTE-U ON/OFF patterns. The LTE-U coexistence manager is attached to the Wi-Fi device, which is used for the channel monitoring, i.e., for ED, PD and beacon detection (BD). These measurements are used to adjust the duty cycle parameters. Differently from the LAA model, here the full control over the transmission is in the LTE-U coexistence manager, i.e., the LTE device never requests the grant, but waits for the grants that are generated and notified by the LTE-U coexistence manager. Once the grant is received, the LTE-U device starts transmitting.

The CSAT algorithm that we implemented is inspired by Qualcomm's CSAT, as explained in Section III. Table 4 summarizes the CSAT configuration parameters and provides the default values selected in our implementation. We set the default value of duration of AP scan monitoring, T_{apsc}, to 160 ms. During this period the transmission of LTE-U cell is OFF, except for the minimum MIB and LDS required signaling. I_{apsc} represents the frequency of performing the AP scan. This interval is expressed in number of CSAT cycles. E.g., every 8 or 16 CSAT cycles LTE-U cell performs the AP scan. A single CSAT period, T_{csat}, is composed of ON and OFF periods. Standard values of T_{csat} in the industry are 80 ms, and 160 ms, but higher values are also considered. As explained previously, the puncturing is necessary to protect latency sensitive Wi-Fi applications. There are two puncturing parameters, T_{punct} and I_{punct}, the puncturing duration and the puncturing interval, respectively. The duration of puncturing is typically 1-2 ms, and the interval is usually set to 20 ms. The CSAT adaptation is performed per CSAT cycle and MAC is notified in advance to account for PHY processing delay. The adaptation of CSAT cycle is performed at the end of the current CSAT cycle and is applied to the following one.

We model in ns-3 three control signals in LTE-U transmission patterns: MIB, SIB1 and LDS. We model them for channel occupancy purposes. The modeling of the control signals is based on the latest LTE-U requirements defined in [29]:

- MIB/SIB1: As explained in III-B.3, according to LTE-U specs (section 5.2 in [29]) MIB/SIB1 is transmitted on LTE-U SCell when its transmission period overlaps with a SCell ON-state and at least once every 160 ms. This implies a regular 10 ms transmission for MIB and 20 ms transmission for SIB1 during the ON-state. As a result, whenever the SCell ON period covers the subframe (SF) 0, the MIB is transmitted; whenever the SCell ON period

TABLE 4. LTE-U CSAT parameters.

CSAT parameter	Description	Default value
d	Duty cycle. Adaptable, but an initial value shall be set.	0.5
T_{csat}	ON + OFF interval. It takes values between 40 and 1280 ms	160 ms
$T_{OFF,min}$	Minimum time to monitor Wi-Fi activity during single T_{CSAT} period	20 ms
$T_{ONminPerTxOP}$	Based on LTE-U Forum specification is the minimum time the LTE-U cell is required to be in ON-state as long as there is data in users' buffer	$4ms$
I_{punct}	The puncturing interval	20 ms
T_{punct}	The puncturing length	1 ms
I_{apsc}	The AP scan periodicity	$16 \times T_{CSAT}$
T_{apsc}	The length of the AP scan period	160 ms
C_{min}	Controls the minimum duty cycle bellow ED threshold	120 ms
MU_{high}	Upper MU threshold	0.6
MU_{low}	Lower MU threshold	0.4
δ_{down}	The delta value used when MU is to be decreased	0.05
δ_{up}	The delta value used when MU is to be increased	0.05
α_{MU}	The weight used for $\overline{MU}$ calculation	0.8

covers SF 5, the SIB1 is transmitted, if it is scheduled in that frame. If MIB transmission is not scheduled during approximately 150 ms, its transmission is scheduled during the following frame, in SF 0, regardless of the SCell to be in ON period. This assures that MIB is transmitted at least every 160 ms.

- LDS: The LDS is defined as an instance of SF5 with CRS/PSS/SSS and PDCCH/PDSCH. As explained in III-B.2, the UE may assume that the LDS is transmitted at a fixed time periodicity with a fixed offset signaled in the configured DMTC as per 3GPP Release 12 DRS RRC configuration (section 5.3 in [29]). LDS uses the RRC signaling defined for 3GPP Release 12 DRS. Release 12 DRS RRC configuration allows periodicities, T_{DRS}, of 40, 80 and 160 ms. This means in practice that the LDS is transmitted every $T_{DRS} = T_{LDS}$, and the duration is 1 ms. The transmission time is counted against the overall SCell ON time.

3) ns-3 LTE CARRIER AGGREGATION

Both, the LAA and LTE-U, models rely on a CA implementation [40] because both technologies are anchored to a licensed PCell. The focus of our design is on the downlink traffic, while the uplink traffic (Physical Uplink Shared Channel (PUSCH), Physical Uplink Control Channel (PUCCH), Sounding Reference Signal (SRS)) is channeled through the primary carrier. The criteria for the CA downlink traffic splitting between PCell and SCell are the following:

- Signaling bearers (SRB0, SRB1) are transmitted over the primary carrier
- Guaranteed bit rate traffic is transmitted only over the primary carrier
- LTE Radio Link Control (RLC) retransmissions are transmitted through the primary carrier
- Secondary carrier is used opportunistically, i.e., only when the PCell is fully occupied

Additionally, the secondary carrier of a UE is activated only when the signal quality of the PCell is better than the activation threshold and after data is available to be transmitted at the secondary carrier. On the other hand, if the signal quality becomes lower than a predefined threshold the secondary carriers are deactivated. If the secondary carriers of all UEs are deactivated, then the transmission over the secondary carrier is disabled, except for the minimum obligatory signaling messages that are configured, e.g., for LTE-U these are MIB and LDS, for LAA the DRS.

In order to receive the data, the UE first needs to decode the Downlink Control Information (DCI), which is sent over PDCCH of the corresponding carrier. We have confirmed that this design is aligned with implementation in real-devices by many vendors. The PDCCH is modeled in the first symbols of the subframe. The number of symbols occupied by the PDCCH is configurable and can take values 1, 2 or 3 symbols. In our implementation it defaults to 1 ms.

In Table 5, we show the details of the ns-3 simulator implementation, in comparison to 3GPP [2] and WFA guidelines [9].

B. EVALUATION METHODOLOGY AND SIMULATION SCENARIOS

The central aspect of the performance evaluation methodology is the definition of fairness. The WFA and 3GPP have in parallel proposed two different evaluation methodologies, which we discuss in this section. The definition of fairness proposed by the WFA in [9] is aligned with the one defined by 3GPP in [2]. In particular, both definitions consider that a deployed system transmitting in an unlicensed channel operates fairly to Wi-Fi if its impact on the Wi-Fi users performance is no worse than the impact that would result from an additional Wi-Fi network introduced into the channel supporting the same traffic load as the deployed system. This definition also determines the evaluation methodology, which typically consists of two steps to be compared:

1) The baseline "Wi-Fi over Wi-Fi" scenario where performance are evaluated in a scenario in which Wi-Fi coexists with another Wi-Fi network.
2) The "Wi-Fi over LAA/LTE-U" scenario where one of the Wi-Fi networks is replaced by an unlicensed LTE network.

TABLE 5. Coexistence scenario configuration according to 3GPP, WFA and ns-3 model.

Unlicensed channel model	3GPP TR 36.899	Wi-Fi alliance guideline	ns-3 implementation
Network layout	Indoor/outdoor scenario	Various simple scenarios	Indoor, outdoor, and simple scenarios
System bandwidth	20 MHz	20/40 MHz	20/40 MHz
Number of carriers	1, 4 (to be shared between two operators), 1 unlicensed for evaluation of DL+UL Wi-Fi coexisting with DL-only LAA	-	1 licensed carrier for LAA DL/UL operation, 1-4 unlicensed for evaluation of DL+UL Wi-Fi coexisting with DL-only LAA
Total Base Station transmission power	18/24 dBm	20 dBm	18 dBm by default
STA transmission power	-	18 dBm	18 dBm by default
Data preamble type	11 n/ac	11 ac	11 n
Distance based path loss shadowing and fading	ITU InH	Computed on the basis of 3-D distance	802.11 ax indoor model
Antenna pattern	2D Omni-directional	2D Omni-directional	2D Omni-directional
BS antenna gain	5 dBi	0 dBi	5 dBi
UE antenna gain	0 dBi	-2 dBi	0 dBi
Number of UEs	Various scenarios	Various scenarios	Supports all 3GPP 36.889 and all WFA guidelines configurations
UE dropping	Randomly dropped within the coverage	Scenario specific	Supports both: random and scenario specific
Traffic model	a) FTP Model 1 and 3 based on TR 36.814 with size of 0.512 MBytes b) optionally: VoIP traffic model	a) FTP traffic model with an exponential reading time and with a model according to which some files are transfered with MTU of 1500 and some of 512 bytes. b) Full buffer traffic with MSDU size of 1500 bytes	a) FTP: FTP Model 1 based on TR 36.814, over UDP and TCP, with file size of 0.512 MBytes b) UDP full buffer traffic of MSDU of 1000 bytes c) VoIP traffic model
UE noise figure	7 dB	9 dB	Supported, 9 dB by default.
LAA cell selection	Based on RSRP (Reference signal received power)	Based on RSRP (Reference signal received power)	Based on RSRP (Reference signal received power)
Wi-Fi AP selection	Based on RSS (Received signal power strength)	Based on RSS (Received signal power strength)	Based on RSS (Received signal power strength)

In our simulation study, we consider that Unlicensed LTE (ULTE) is deployed as an SDL system, anchored to a licensed PCell. The SCell is deployed in the 5 GHz band, in channel 36, with 5180 MHz central carrier frequency, and 20 MHz of bandwidth. The simulator allows for aggregation of up to 4 secondary carriers, either licensed or unlicensed. As for the unlicensed band, we extended the simulator to support additional 5 GHz channels: 32, 40, 44, 48, 149, 153, 157, 161 and 165.

In this study, we focus on two main simulation topologies, Simple and 3GPP indoor. We also simulate two more scenarios, HN simple and BS corners as a variation of the main simulation topologies.

- Simple: the simple scenario is composed of two BSs that can be either eNBs or APs, and two users which can be either UEs or STAs. We use this scenario to model WFA's simple model with single clients in which the networks are co-located. To model this scenario we have implemented the simple topology shown in Fig. 8a. The distances between the BS and the user, $d1$, and between the two BSs, $d2$, can be configured to model different interference configuration.
- HN simple: The HN (hidden nodes) simple scenario is a variant of the simple scenario and we use it to create more specific cases with hidden nodes. To model this scenario we have implemented the modified simple scenario topology shown in Fig. 8b.
- 3GPP indoor: 3GPP TR36.889 proposes two simulation scenarios, indoor and outdoor. Although the simulator supports both, in this simulation study, due to space constraints, we focus only on the indoor scenario. The indoor scenario is more challenging than the outdoor for achieving fair coexistence due to close proximity between LTE eNB and Wi-Fi APs and STAs. The indoor scenario consists of two operators deploying 4 small cells in a single floor building. The small cells of each operator are centered along the shorter dimension of the building and they are equally spaced. Fig. 6 shows the layout and the dimensions of this scenario. Operators are using the licensed PCell, which can be at 3.5 GHz with a bandwidth of 10 MHz and total transmit power per carrier 24 dBm. The unlicensed SCell operates in the 5 GHz carrier with a bandwidth of 20 MHz and a total transmit power of 18 dBm. There are 20 UEs per unlicensed band per operator, and they are randomly distributed in the rectangular region. All UEs are within the coverage of the small cell in the unlicensed band. In LAA network, the cell selection decision is based

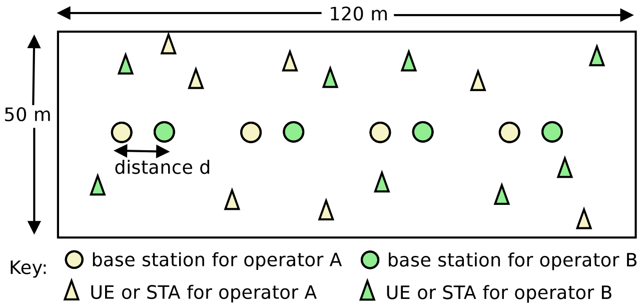


FIGURE 6. 3GPP Indoor scenario layout.

on RSRP in the unlicensed carrier, whereas in Wi-Fi, on Received Signal Strength Indicator (RSSI) of Wi-Fi APs.

- BS corners indoor: We define a variant of the indoor scenario in which the Base Station (BS)s are placed in the corners. The scenario is illustrated in Fig. 7. The objective here is to increase the number of hidden nodes and to study the behavior of ULTE technologies under these conditions.

The recommended traffic models by 3GPP are File Transfer Protocol (FTP) Model 1 or FTP Model 3. In this paper, we carry out the performance evaluation with FTP Model 1. FTP Model 1 is a non-full buffer traffic model, according to which users arrive with a Poisson process with arrival rate λ. One user downloads a single file which can be 2 Mbytes or 0.5 Mbytes. Parameter λ recommended values are 0.5, 1, 2, 2.5 for file size of 0.5 Mbytes. With this traffic model, the default value of base simulation duration in our simulation campaigns is 480 seconds, which translates into approximately 480 FTP flows per operator for any λ. In addition to the FTP traffic model, we also support a Constant Bit Rate (CBR) traffic up to saturation. In simulations with User Datagram Protocol (UDP) CBR traffic, since there is a single UDP flow per user, the simulation duration is shorter and by default is set to 20 seconds.

Table 6 summarizes common simulation parameters that we use for both LAA and LTE-U evaluations.

C. PERFORMANCE EVALUATION METRICS

The key considered performance metrics in this study are "user-perceived throughput" and "latency". In ns-3, we calculate them by using the built-in `FlowMonitor` tool that

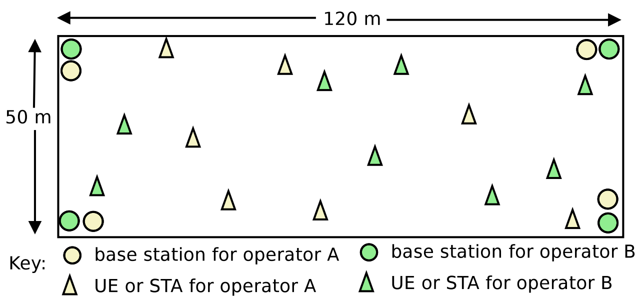


FIGURE 7. A modified version of 3GPP indoor scenario layout in which eNBs are placed in the corners.

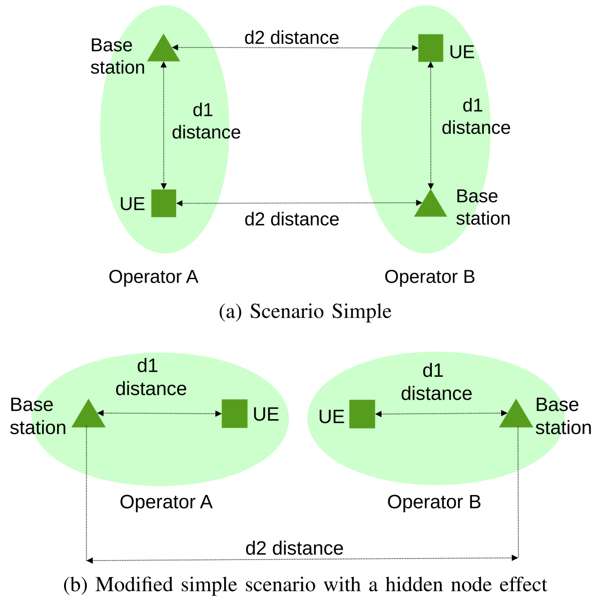


FIGURE 8. Simple scenario variants.

TABLE 6. Default common simulation parameters.

Parameter	Value
Base simulation duration (FTP Model 1)	480 seconds
Simulation duration (UDP CBR)	20 seconds
Default eNB configuration	1 PCC + 1 SCC
FTP Model 1 file size	0.512 Mbytes
FTP Model 1 lambda for LAA/LTE-U operator	5
FTP Model 1 lambda for Wi-Fi operator	2.5
UDP CBR rate for UE/eNb in scenario simple	150 or 300 Mbps
UDP CBR rate per STA/AP in scenario simple	75 or 150 Mbps
UDP CBR rate per UE in scenario indoor	2 or 4 Mbps
UDP CBR rate per STA in scenario indoor	1 or 2 Mbps
UDP packet size	1000 bytes
TCP initial congestion window	10
TCP segment size	536
TCP RLC mode	RLC-AM
Wi-Fi default CCA-ED threshold	-62 dBm
PDCCH duration	1 symbol (71 μs)

tracks statistics per flow including throughput and latency, and we then post-process these results to obtain CDFs. To correctly interpret the performance of each UE and flow in various scenario conditions, we also have instrumented the simulator to monitor additional metrics and measurements, such as channel occupancy time by each operator, total number of collisions among different technologies, retransmission rate per Wi-Fi device, percentage of LAA NACK HARQ feedback (i.e., $Z\%$), packet lost, backoff values per each LAA and Wi-Fi device, CW for LAA and Wi-Fi devices, LTE-U duty cycle, medium utilization as detected per every LTE-U device, number of AP detected by each LTE-U device and interference levels among all devices in unlicensed carrier, beacons lost and inter-beacon interval time.

We evaluate performance of different traffic models over both UDP and Transmission Control Protocol (TCP) transport protocols. TCP model in ns-3 integrates advancements

TABLE 7. Validation results.

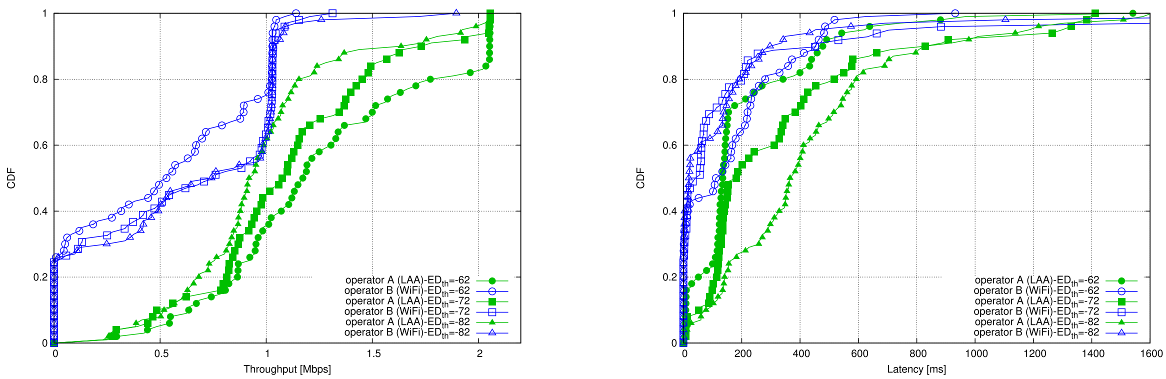
System	NI experiment	Theoretical modeling	Coexistence simulation
$R_W = 9\ Mbps, R_L = 7.8\ Mbps$			
2 Wi-Fi	8.0	7.77	8.03
1 Wi-Fi/ 1 LAA	1.80 and 5.22	1.49 and 5.26	1.58 and 5.20
4 Wi-Fi	7.89	7.24	7.69
2 Wi-Fi/ 2 LAA	1.31 and 3.82	1.34 and 4.72	1.48 and 5.52
6 Wi-Fi	7.16	6.90	7.34
4 Wi-Fi/ 2 LAA	1.86 and 3.10	2.01 and 3.56	1.98 and 5.26
$R_W = 18\ Mbps, R_L = 15.6\ Mbps$			
2 Wi-Fi	15.0	14.62	14.87
1 Wi-Fi/ 1 LAA	1.69 and 11.09	1.63 and 11.51	1.74 and 11.15
4 Wi-Fi	13.90	13.73	14.27
2 Wi-Fi/ 2 LAA	1.62 and 9.98	1.46 and 10.24	1.54 and 11.54
6 Wi-Fi	13.17	13.12	13.57
4 Wi-Fi/ 2 LAA	2.66 and 7.76	2.31 and 8.19	2.26 and 11.48
$R_w = 54\ Mbps, R_L = 70.2\ Mbps$			
2 Wi-Fi	35.40	34.38	35.28
1 Wi-Fi/ 1 LAA	1.40 and 57.80	1.73 and 55.18	1.91 and 54.83
4 Wi-Fi	34.78	34.07	34.53
2 Wi-Fi/ 2 LAA	1.98 and 51.20	1.54 and 48.98	1.94 and 52.94
6 Wi-Fi	33.19	32.85	32.58
4 Wi-Fi/ 2 LAA	2.98 and 43.11	2.57 and 40.99	3.31 and 39.66

made in the real world implementations, having as the main reference the Linux implementation [41]. TCP protocol defaults to TCP NewReno. As for the LAA/LTE-U link layer, we consider UDP over RLC Unacknowledged Mode (RLC-UM) and TCP over both RLC-UM and RLC Acknowledged Mode (RLC-AM).

D. VALIDATION OF THE PROPOSED MODELS

In this section, we discuss the validation of the proposed models. In particular, the coexistence simulator was built based on the ns-3 LTE and Wi-Fi modules. These two modules have been previously validated through extensive calibration campaigns and against experimental testbed cross-validation. The LTE module was built at CTTC by the authors of this paper in close collaboration with Ubiquisys (now Cisco) [37]. The LTE module is validated with an extensive set of tests that covers all the main modules/functionalities using the official ns-3 test framework. Calibration campaigns have been performed also in 3GPP reference scenarios [42]. Results show that the ns-3 LTE module achieves similar performance to those obtained by the 3GPP industrial simulators in the evaluated cases, both in terms of SINR distributions and users' throughput. LTE has been also validated against a real world testbed demonstrating that it can deliver voice quality and latency as good as an experimental testbed using actual LTE equipment over a range of signal-to-noise ratios [43]. As for the Wi-Fi module, it was validated against a real testbed in [44].

To further validate the models in the coexistence scenarios, we have also referred to the work in [45]. In this work, the authors propose a new analytical model for throughput of LTE-LAA and Wi-Fi systems in coexistence scenarios, and they validate it against an experimental results using the National Instruments (NI) platform. To perform validation in ns-3, we have implemented a coexistence validation script `lte-wifi-coexistence.cc` that is strictly following the system configuration considered in [45], along with different validation cases and topologies. The mentioned script is publicly available with the simulator that we propose in this paper, in the repository available in [20]. Following the validation strategy presented in [45], we consider two types of scenarios: Wi-Fi only, which is the baseline for comparison, and Wi-Fi coexisting with LAA. We carry out validation in 3 different scenario topologies considering respectively 2, 4, and 6 nodes. Note that in 4 and 6 nodes scenarios, when Wi-Fi is coexisting with LAA, the number of LAA nodes is 2. As in [45], we further evaluate throughput of Wi-Fi and LAA by configuring 3 different data rates for both, Wi-Fi and LAA, respectively, R_W and R_L. Wi-Fi uses the 802.11a standard with 20 MHz bandwidth, and LAA is configured to use the same 20 MHz channel. LAA PDCCH is modeled with 1 symbol. Data traffic is a full buffer and packet length is 2048 bytes. A maximum transmission unit of devices in ns-3 is configured to 2500 bytes to allow the transmission of 2048 bytes without fragmentation that would lead to degradation in throughput performance, which is not considered in the analytical model and NI experiment. LAA is configured with channel access priority 3 class (MCOT=8 ms, Min CW = 15 and Max CW = 63), which is also the priority class that is configured in the LAA simulations of this paper. In Wi-Fi only scenario Wi-Fi is configured to have Min CW = 15 and Max CW = 1023, while when coexisting with LAA the Max CW of Wi-Fi is set to 63 as in LAA. In Table 7, we show the comparison of the results obtained by the simulator versus the theoretical model and experimental platform. We can observe that there is the same trend of Wi-Fi throughput in the simulation and theoretical model, when changing the date rate and the number of nodes. There is a difference in the trend of LAA performance for lower data rates. Note that according to the analytical model in [45],



(a) Throughput of LAA and Wi-Fi flows

(b) Latency of LAA and Wi-Fi flows

FIGURE 9. Impact of LAA ED threshold, $ED_{th} \in \{-62, -72, -82\}$ dBm, evaluated in 3GPP indoor scenario, when the traffic is the UDP CBR, and with the LAA rate of 2 Mbps and the Wi-Fi rate of 1 Mbps.

any partial overlap of the transmitted frames from different nodes results in collisions; however, in experimental and ns-3 platforms the receiver may be able to decode packets which are partially overlapped. Because of this, for lower rates, we can notice difference between theoretical results on one side, and experimental and simulation results on the other side. However, this difference is reduced when systems use higher data rates, since devices become more sensitive to the interference. Additionally, differently from the theoretical model and experimental platform, in the simulator, LAA nodes are synchronized per subframe boundary, so there is a greater probability for them to collide among each other, then with Wi-Fi system. Hence, with lower rates, we do not notice a trend of degradation in the performance of LAA when increasing the number of interfering nodes, as we can notice in NI experiment and theoretical modeling results. However, for the higher data rates this trend is very clear also in the simulation, and it is the same as in theoretical modeling and experimental results.

VI. PERFORMANCE EVALUATION

In this section, we present the performance evaluation carried out with the implemented LTE unlicensed ns-3 models. We first analyze the behaviors of the LAA and LTE-U access schemes independently, as a function of the parameters on which they depend, and then we compare them to study their coexistence behavior.

A. IMPACT OF LAA PARAMETERS

1) IMPACT OF LAA ED THRESHOLD

The ED threshold is an essential parameter of the LBT mechanism since it directly influences when the LAA node detects the channel to be busy or idle, and consequently when it transmits. We analyze the impact in different scenarios, the simple and the indoor one, and with two different kinds of traffic, a CBR and FTP traffic. We show that the expected behavior of protecting Wi-Fi simply by lowering the LAA ED threshold is not so direct, and many other Wi-Fi and LAA implementation aspects intervene in determining the coexistence performance of both technologies.

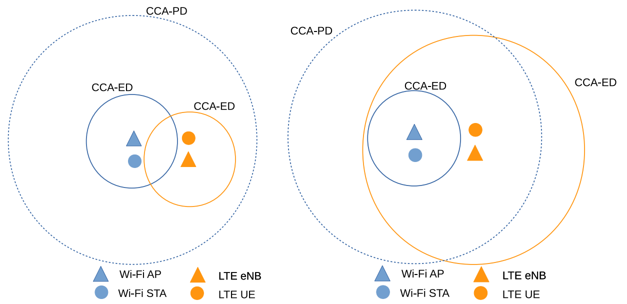
a: GENERAL BEHAVIOR

We start by analyzing the 3GPP indoor scenario in which the traffic performed is CBR over UDP. CBR rate per UE flow for LAA operator is 2 Mbps, and for Wi-Fi operator is 1 Mbps. First, we consider the ED threshold of LAA at −62 dBm, as Wi-Fi's, and then we lower it to −72 dBm. In Fig. 9a and Fig. 9b, we show the impact of LAA ED threshold on throughput and latency, and we compare the case of LAA over Wi-Fi, to the baseline Wi-Fi over Wi-Fi. **In this simulation configuration, we observe, as expected, a positive impact of lowering the LAA ED threshold on the Wi-Fi operator, while the LAA operator is negatively impacted. With this traffic type, both operators need to access the channel constantly, and due to the asymmetry in energy detection levels, Wi-Fi has more priority when accessing the channel compared to LAA. Based on the simulation traces, we observe that when lowering the ED threshold, LAA nodes are on average spending more time in backoff, and this makes that the average Wi-Fi throughput increases.**

b: DEPENDENCY ON THE TRAFFIC MODEL

We analyze now results with the 3GPP FTP Model 1. We first study the simple scenario case to well understand the multiple aspects that can affect performance. We compare the case when the ED threshold of LAA is set to −62 dBm, equal to that of the Wi-Fi AP, with the case when LAA ED threshold is set to −72 dBm. The distances, $d1$ and $d2$, are set in such a way that the BSs cannot detect each other when the LAA ED threshold is −62 dBm. In particular, $d1$ is 10 , and $d2$ is 30. We show the received power levels in this scenario in Table 11.

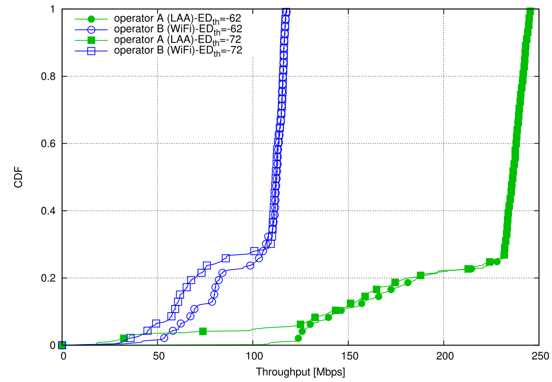
Note that when the LAA ED threshold is set to −72 dBm, the LAA eNB can energy detect the Wi-Fi AP and STA, but the AP and STA cannot detect the LAA node. We illustrate these two scenarios in Figure 10.



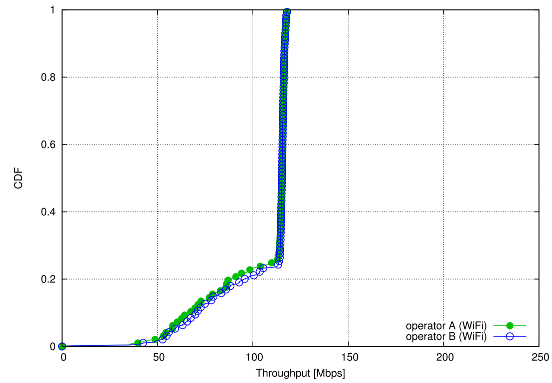
(a) LAA ED_{th} = -62 (b) LAA ED_{th} = -72 dBm

FIGURE 10. Illustration of the energy detection coverage when varying the LAA ED threshold in the scenario simple. Wi-Fi CCA-ED threshold is fixed to −62 dBm.

In Fig. 11, we show the impact of LAA ED threshold on throughput in simple scenario, and we compare the case of LAA over Wi-Fi (Fig. 11a) to the baseline Wi-Fi over Wi-Fi (Fig. 11b). When the energy detection thresholds of both technologies are set to −62 dBm, we notice a slight degradation of Wi-Fi performance wrt to the baseline case. On the other hand, we observe that when the LAA ED threshold is lowered to −72 dBm, and so LAA properly detects the Wi-Fi transmissions and backs off to them, **there is an unexpected negative impact on Wi-Fi performance.** Getting into the detail of the PHY layer traces we observe that when the LAA ED threshold is decreased from −62 dBm to −72 dBm, the amount of collisions decreases from 16.95% to 11.38%, and the LAA channel occupancy decreases, while the Wi-Fi channel occupancy increases and so its CW size. This means that, even if the overall amount of collisions reduces in the −72 dBm case, the Wi-Fi experiences more failures, and its performance is more affected compared to the −62 dBm case. **The reason for this behavior is not evident, and it depends on aspects that may be implementation specific and on the specific traffic model we are using.** When the LAA ED threshold is −72 dBm, LAA detects the activity of Wi-Fi in the channel, which forces a backoff until the channel is sensed to be idle. Immediately after the AP's transmission, the channel is idle during SIFS (16 μs), and after that the STA transmits the BA. LAA eNB backs off during the AP transmission, and also during the SIFS, since it is shorter than the initial CCA duration of 43 μs. As a result of that, LAA eNB initiates its transmission once the AP has transmitted the entire Aggregate MPDU (A-MPDU) and has received the corresponding BA. This would lead to an expected favorable behavior towards Wi-Fi, in case the Wi-Fi transmission is over. However, with the FTP model 1 we are using, the transmission of a single A-MPDU is not enough to transmit the FTP file of 0.512 MBytes. This means that once LAA has started its transmission, it is likely that Wi-Fi continues to transmit the following A-MPDU, since it does not energy detect the LAA node transmission. For the Wi-Fi AP, the previous transmission concluded successfully, so that in the new transmission it applies the previous transmission



(a) LAA over Wi-Fi scenario



(b) Baseline Wi-Fi over Wi-Fi scenario

FIGURE 11. Impact of LAA ED threshold, ED_{th} ∈ {−62, −72} dBm, evaluated in simple scenario using SNR-triggered Wi-Fi rate manager with the default FTP settings (λ_{LAA} = 5, λ_{Wi-Fi} = 2.5, file size=0.512 MB).

rate, when there was no interference by LAA. However, the new A-MPDU rate is most likely too high for the new interference conditions. Thus the STA is not able to decode the A-MPDU and does not send back the corresponding BA. From this point, the following actions taken by the Wi-Fi AP depend on the specific proprietary rate adaptation mechanism. According to the Wi-Fi implementation in ns-3, the Wi-Fi AP waits until the timer expires and then sends the Block Acknowledgment Request (BAR), but these messages are likely not to be received by the STA since the LAA transmission is ongoing. As soon as the Wi-Fi adaptation mechanism retransmits the next A-MPDU with a lower Modulation and Coding Scheme (MCS) that can be decoded by the STA, the Wi-Fi transmission starts to recover. However, some delay is inevitable, regardless of the proprietary rate adaptation algorithm, due to the lost A-MPDU and the time needed for the AP to resume the flow. Because of this delay the Wi-Fi performance drops, while the performance of LAA increases due to reduced collisions with Wi-Fi flows that are waiting for BA timeout. On the other hand, when LAA ED threshold is −62 dBm, it is likely that the LAA transmission starts in the middle of the AP transmission of the A-MPDU generating a collision. Even if counter-intuitive, this situation is better for Wi-Fi since LAA will most likely interfere with only some

MAC Protocol Data Unit (MPDU)s of the A-MPDUs, so that the STA will be aware of the A-MPDU and will send back the corresponding BA. Since the BA is typically sent with the lower transmission rate, there is a high probability that the AP can decode it successfully even if there is some interference by LAA. This BA provides an important information to the AP, about missed MPDUs and new interference, which leads to decrease the MCS of the following A-MPDUs. Thanks to this, and differently to the −72 dBm case, the Wi-Fi transmission continues, even though with a lower rate. The packet capture (PCAP) traces confirm these findings. Specifically, in the −62 dBm case, the maximum rate is used in 92.4% of transmissions, while in the −72 dBm case, it is in 99%. The BAR is sent 123 and 401 times when the ED threshold is, respectively, −62 dBm and −72 dBm case. **We conclude that the coexistence performance are not only affected by the access mechanism and ED procedure, but the impact of traffic model, Wi-Fi Distributed Coordination Function (DCF) and rate adaptation mechanism plays an important role.**

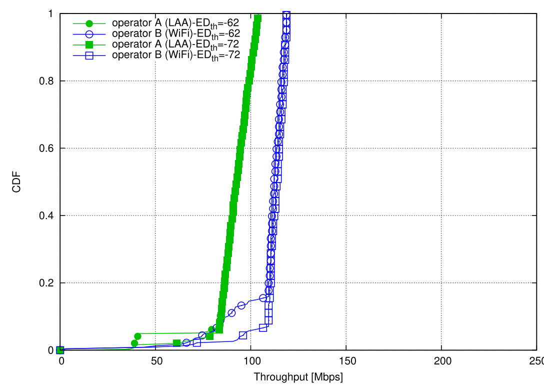
c: DEPENDENCY ON PACKET SIZE

To further confirm the conclusion discussed above, it is reasonable to expect that when flows can be sent within a single A-MPDU, the interplay between the rate adaptation mechanism and the LAA backoff will disappear. In Figures 12a and 12b, we show the results for a smaller file size of 0.0512 MB. We choose this file size because the maximum size of A-MPDU in 802.11n is 65535 bytes, thus in this way the file can be transferred during a single A-MPDU. We increase FTP lambdas to compensate for the lower file size. The results show the expected behavior that we were observing with the CBR traffic, i.e., Wi-Fi benefits from lower LAA ED threshold.

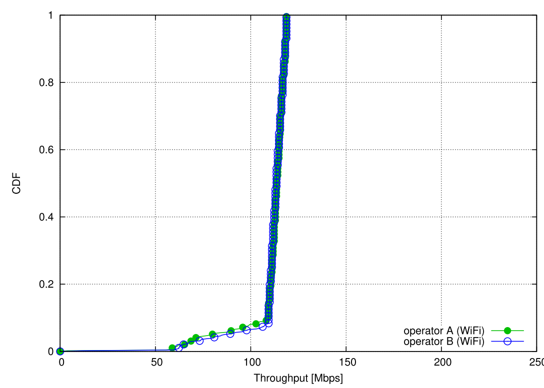
d: DEPENDENCY ON LAA NODE COORDINATION

Finally, we focus our attention on the more general 3GPP indoor scenario, when the traffic type is the 3GPP Model 1 FTP over UDP. In Figures 13a and 13b, we show the impact of LAA ED threshold on the throughput and latency. In this scenario, lowering the LAA ED threshold impacts negatively Wi-Fi, while it is impacting positively LAA. The channel occupancy of the LAA operator is 9.8% when $ED_{th} = -62$ dBm, 10% when $ED_{th} = -72$ dBm, and 10.3% when $ED_{th} = -82$ dBm. Besides the already described aspects, which depend on the traffic model and the rate adaptation algorithm, in this scenario we observe an additional effect, which depends on LAA network design. When lowering the ED threshold it becomes less likely that various LAA nodes transmit simultaneously, since they back off to each other, so that the channel occupancy of the LAA network increases. By lowering the LAA ED threshold, the number of collisions reduces (6.34%, 5.35% and 5.18% for ED_{th} of, respectively, −62, −72 and −82 dBm), but we get the side effect of an increased channel occupancy by LAA, which makes that the Wi-Fi nodes spend more time in backoff. The impact of lowering ED_{th} on the LAA network is positive, since the collisions with Wi-Fi are significantly reduced, and the reduction in collisions compensates the increase of time spent in the backoff. This effect should be taken into account when designing an LAA network. LTE is in fact capable of exploiting frequency reuse-1, thanks to interference management procedures inherent in its design (e.g., adaptive rate control, power control, Coordinated Multi- Point (CoMP), enhanced Inter-Cell Interference Coordination (eICIC)). Solutions of self-deferral have been proposed in 3GPP in order to take into account these aspects.

We reach then the following conclusion on the impact of the ED threshold. **In general, it is reasonable to expect that lowering the ED threshold will benefit the coexistence performance. However, this effect is not at all linear, and can be heavily impacted by aspects which have nothing to do with LAA access mechanism, but are related to scenario configurations, implementation issue and the traffic patterns. In addition, while LTE was designed to be able to reuse in frequency the channel, the LAA nodes of the same operator should be coordinated in order to control the LAA to LAA backoff mechanism, which also may affect**

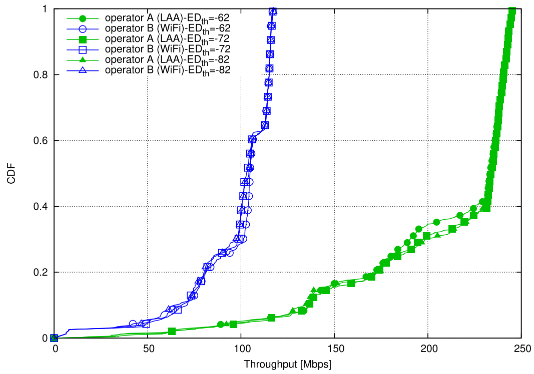


(a) LAA over Wi-Fi scenario (SNR-triggered Wi-Fi rate manager)

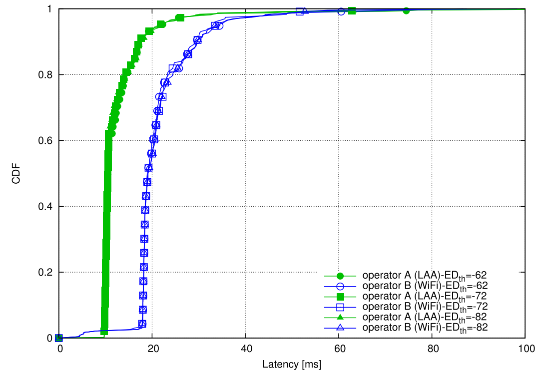


(b) Baseline Wi-Fi over Wi-Fi scenario (SNR-triggered Wi-Fi rate manager)

FIGURE 12. Impact of LAA ED threshold, $ED_{th} \in \{-62, -72\}$ dBm, evaluated in simple scenario using SNR-triggered Wi-Fi rate manager, with the modified FTP settings ($\lambda_{LAA} = 20$, $\lambda_{Wi-Fi} = 10$, file size=0.0512 MB).



(a) Throughput of LAA and Wi-Fi FTP flows



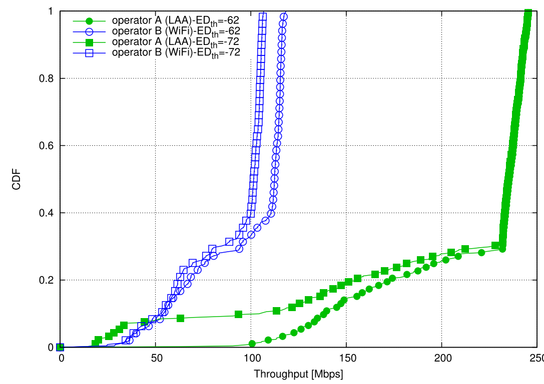
(b) Latency of LAA and Wi-Fi FTP flows

FIGURE 13. **Impact of LAA ED threshold, $ED_{th} \in \{-62, -72, -82\}$ dBm, evaluated in 3GPP indoor scenario when the traffic is FTP and Wi-Fi is using the SNR-triggered rate manager.**

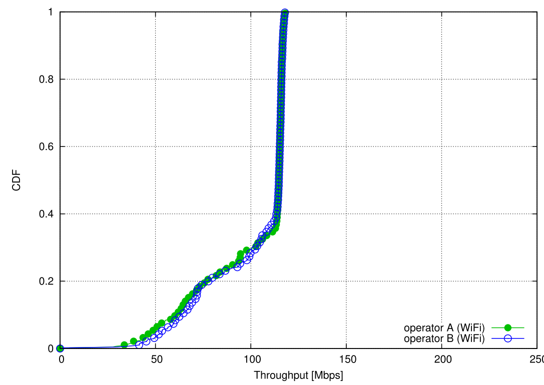
coexistence with Wi-Fi. For this, solutions like the *self-defer* have been proposed in standard.

2) IMPACT OF WI-FI RATE ADAPTATION ALGORITHM

Since the Wi-Fi standard does not specify any particular strategy for selecting the MCS, rate adaptation mechanisms are implementation specific, and can obey to different cost-functions, strongly impacting final coexistence performance. In our study, we use an SNR-triggered adaptation rate algorithm, which selects the highest transmission rate that allows to obtain a target frame delivery to achieve the target bit error rate (BER), by leveraging transmission mode based-specific SNR/BER curves. To understand better the impact of the rate adaptation mechanisms, we further analyze another representative Wi-Fi rate manager, Minstrel-HT, and compare its behavior in the coexistence scenario to that of SNR-triggered Wi-Fi rate manager. Minstrel-HT is a well-known rate adaptation mechanism that is used by many drivers in Linux kernel. Minstrel-HT keeps evaluating the delivery probability performance of every MCS by using look-around frames during normal operations, and selects on average the MCS with the best performance. In Fig. 14a and Fig. 14b, we show the coexistence results when Minstrel-HT is employed, instead of the SNR-triggered rate manager, in the simple scenario and when lowering the LAA ED threshold. We observe that with Minstrel, the throughput of a much larger number of flows that are transmitted with the highest rates is reduced when the LAA ED threshold is lowered, compared to the SNR-triggered rate manager, whose performance were already shown in Fig. 11. The reduction of the performance is due to the decrease in the MCS. On the other hand, we do not notice the impact of changing the LAA ED threshold on the flows that are transmitted with the lower rates. This is because, when the interference occurs, the Minstrel-HT adjusts the rate, which remains then similar during the whole simulation, so that the impact of interference is more time lasting than in case of the SNR-triggered Wi-Fi rate manager. Similar results, showing an impact of the rate adaptation, were presented by Google's



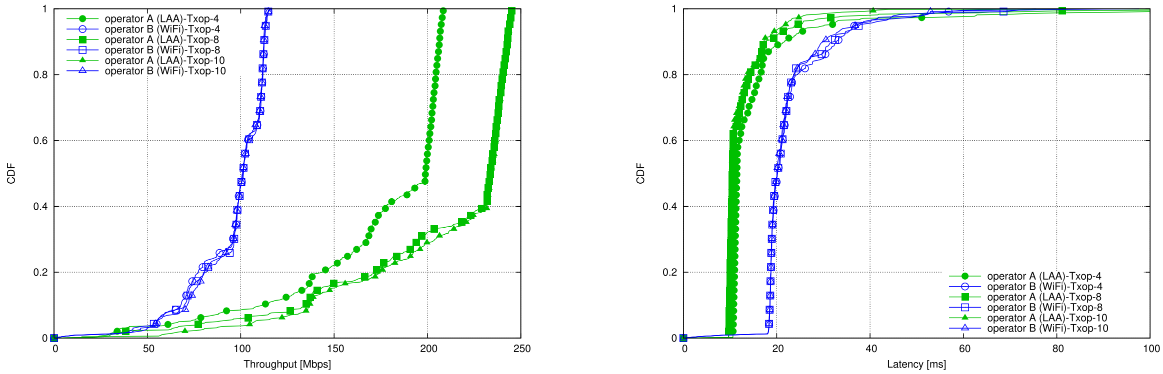
(a) LAA over Wi-Fi (Minstrel-HT)



(b) Baseline Wi-Fi over Wi-Fi (Minstrel-HT)

FIGURE 14. **Impact of LAA ED threshold, $ED_{th} \in \{-62, -72\}$ dBm, evaluated in simple scenario using Minstrel-HT Wi-Fi rate manager.**

initial investigation on Wi-Fi and LTE-U coexistence in [46], in case of coexistence between LTE-U and Wi-Fi. However, it was generally considered in literature that the existence of an LBT would eliminate the interplay between the Wi-Fi rate adaptation algorithm and channel access mechanism. In this paper, however **we show that the Wi-Fi rate adaptation may have a strong impact on coexistence, depending on**



(a) Throughput of LAA and Wi-Fi flows

(b) Latency of LAA and Wi-Fi flows

FIGURE 15. **Impact of LAA TxOP evaluated in 3GPP indoor scenario.**

the traffic model, not only in case of LTE-U, but also for LAA.

3) IMPACT OF LAA MAXIMUM TXOP LENGTH

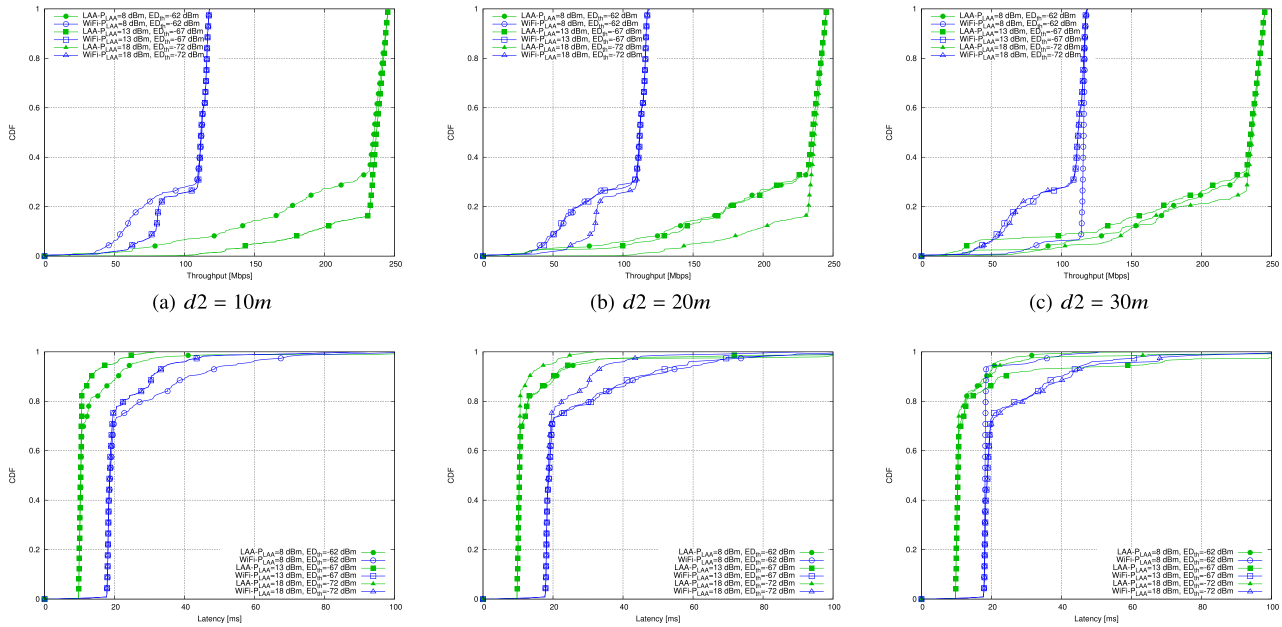
The maximum TxOP length or MCOT is another LAA parameter that needs to be carefully selected. 3GPP selects the TxOP length depending on the addressed application, with values ranging from 2 to 10 ms. In Figure 15, we show the impact of MCOT in the 3GPP indoor scenario. The results show that the impact on LAA is significant while on Wi-Fi it is not much pronounced. As expected, **LAA achieves better performance for higher values of MCOT.** This is due to the reduced waste of capacity due to reservation signals, and the decreased number of required accesses to the channel, which results in shortened accumulated backoff time. For example, in this simulation, the LAA channel occupancy is 10.1%, 9%, 8.8%, for MCOT of, respectively, 4, 8 and 10 ms. **Besides the channel occupancy, the MCOT also affects the probability of collisions.** In the previous example, when the MCOT is 4 ms, the LAA node starts to transmit and then releases the channel 6 times during the transmission of a single file. However, in case of 8 and 10 ms MCOT, this will happen only 3 times. The simulation traces confirm that in case of $MCOT = 4$ ms, the percentage of collisions is 4.78% and is higher than in case of $MCOT = 8$ ms and $MCOT = 10$ ms, when it is, respectively, 4.75 and 4.68%. When Wi-Fi is competing for the channel the impact is not so linear as for LAA. **In general, it is better for Wi-Fi when the MCOT is shorter. However, a shorter LAA MCOT also increases the overall channel occupancy by LAA and the probability of collisions, and consequently also the Wi-Fi's CW size. On the other hand, a longer MCOT increases the time Wi-Fi waits for LAA to complete its transmissions, but reduces the channel occupancy by LAA and so the number of collisions.**

4) IMPACT OF LAA TRANSMISSION POWER

In this section, we study the impact of the LAA transmission power on the coexistence performance. It is worth mentioning that the modification of the transmission power has an impact on the ED threshold that can be adopted. In particular, the ED threshold can be adapted depending on the available bandwidth and the maximum transmit power, as discussed in section 15.2.3.1 in [30]. We consider the simple scenario, with nodes at distance 10, 20 and 30 meters. We study three different power levels for LAA eNB, P_{LAA}, (8, 13, 18 dBm) considering the gain of 5 dbi, to which correspond three different LAA ED_{th} values (−62, −67 and −72 dBm), according to the ED adaptation rule discussed in [30]. The power of the Wi-Fi AP stays fixed at 18 dBm. Depending on the transmission power of the eNB, P_{LAA} and of the related energy detection threshold, the LAA eNB and Wi-Fi AP can either detect or not detect each other, in a symmetric or asymmetric way. In particular, the detection capabilities of each node, when considering only path loss, and eliminating the random aspects of the propagation, are summarized in Table 8: When the distance is 10 m, the eNB receives the emission of the AP, which is transmitted always at 18 dBm, at −54 dBm. So LAA sees and backoffs to Wi-Fi. On the other hand, Wi-Fi detects LAA transmission when they are emitted at 18 dBm and at 13 dBm, but not at 8 dBm, since they are received below threshold. When the distance is 20 m, again LAA detects Wi-Fi, but Wi-Fi only detects LAA when it transmits at the maximum power. Finally, when the distance is 30 m, LAA cannot detect Wi-Fi at −62 dBm, and Wi-Fi can never detect LAA, because it is energy detecting at −62 dBm. We discuss simulation results in Figure 16. When the distance between nodes is 10 m, coexistence performance is degraded when Wi-Fi cannot detect LAA, ans its access generates collisions and interference, so with $P_{LAA} = 8$ dBm. When P_{LAA} is higher, instead the performance is better and equivalent for both 13 and 18 dBm. A similar trend is observed with distance of 20 m. Here the coexistence performance is jeopardized, again, when Wi-Fi accesses the channel without detecting LAA. The interference is still quite high and so we see worse performance than for the case of 18 dBm, when Wi-Fi and LAA see each other. Finally, when the distance is 30 m, collision are generated by Wi-Fi in all the cases. However, the interference is lower due to the increased distance. As a result, of that the best performance

TABLE 8. How eNB and AP listen to each other depending on $d2$ and P_{LAA}. Wi-Fi $ED_{th} = -62$ dBm and $P_{Wi-Fi} = 18$ dBm.

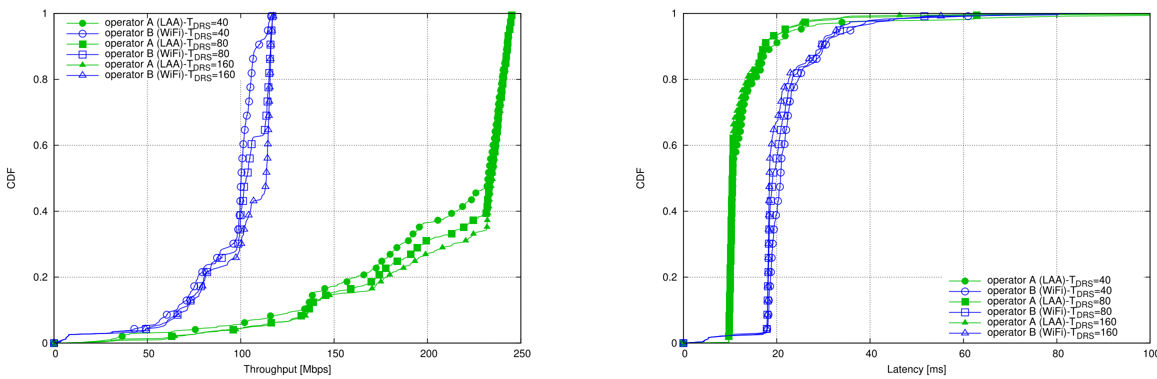
	How eNB listens to AP			How AP listens to eNB		
d2	$P_{LAA} = 18\ dBm$ $ED_{th} = -72\ dBm$	$P_{LAA} = 13\ dBm$ $ED_{th} = -67\ dBm$	$P_{LAA} = 8\ dBm$ $ED_{th} = -62\ dBm$	$P_{LAA} = 18\ dBm$	$P_{LAA} = 13\ dBm$	$P_{LAA} = 8\ dBm$
10 m	-54 dBm (yes)	-54 dBm (yes)	-54 dBm (yes)	-54 dBm (yes)	-59 dBm (yes)	-64 dBm (no)
20 m	-61 dBm (yes)	-61 dBm (yes)	-61 dBm (yes)	-61 dBm (yes)	-66 dBm (no)	-71 dBm (no)
30 m	-66 dBm (yes)	-66 dBm (yes)	-66 dBm (no)	-66 dBm (no)	-71 dBm (no)	-76 dBm (no)



(a) $d2 = 10m$ (b) $d2 = 20m$ (c) $d2 = 30m$

(d) $d2 = 10m$ (e) $d2 = 20m$ (f) $d2 = 30m$

FIGURE 16. Impact of varying the LAA transmission power along with LAA ED threshold evaluated in simple scenario with FTP traffic using SNR-triggered Wi-Fi rate manager with the default FTP settings ($\lambda_{LAA} = 5$, $\lambda_{Wi-Fi} = 2.5$, file size=0.512 MB), $d_1 = 10$ m, $d_2 = 10, 20, 30$ m.



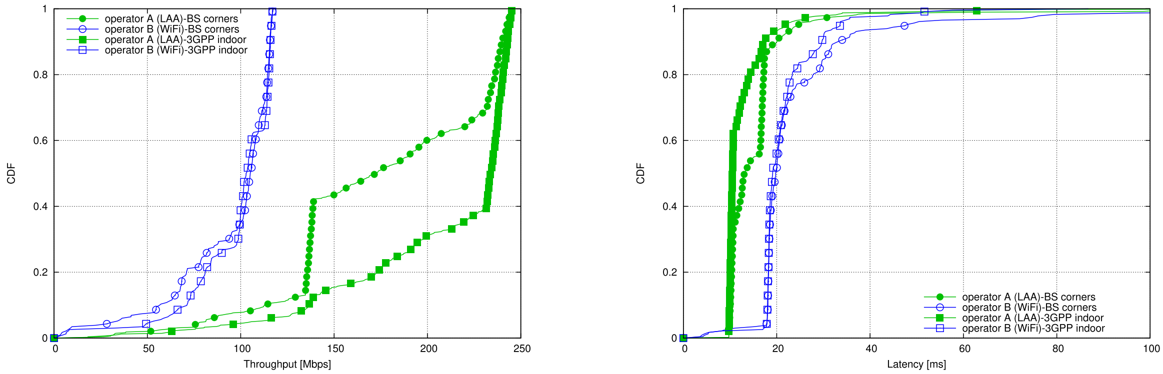
(a) Throughput of LAA and Wi-Fi flows (b) Latency of LAA and Wi-Fi flows

FIGURE 17. Impact of DRS evaluated in 3GPP indoor scenario.

is achieved when P_{LAA} is 8 dBm, while the worse one when P_{LAA} is 18 dBm. Those results are interesting in that show that any slight modification in scenario parameters can provide different effects in performance evaluation.

5) IMPACT OF DRS

As mentioned earlier, the periodicity of the DRS signaling, T_{DRS}, can be 40, 80, 160 ms. For RRM measurements, it would be beneficial to have a high periodicity of DRS signals. However, the DRS model does not capture these aspects in the simulator, but only its channel occupancy. As a result, Fig. 17 shows that **sending the DRS more frequently may have a negative impact, not only on a neighboring Wi-Fi but also on LAA network. The reason is that DRS is a quite expensive signaling, which may spare 1 ms transmission, in case it cannot be transmitted with data.** In such



(a) Throughput of LAA and Wi-Fi flows (b) Latency of LAA and Wi-Fi flows

FIGURE 18. Impact of hidden nodes evaluated by comparing performance in 3GPP indoor and BS corners scenario.

cases, it is much harder for Wi-Fi to achieve the highest data rates. In particular, while for $T_{DRS} = 160$ ms more than 55% of Wi-Fi flows obtain the maximum data rate of around 117 Mbps, for $T_{DRS} = 80$ ms the percentage of Wi-Fi flows to attain this rate drops to 35%, and for $T_{DRS} = 40$ ms this value is around 10%. This is due to the increased LAA occupancy time, and increased number of collisions, when T_{DRS} is low (i.e., high periodicity). LAA channel occupancy is 11.22%, 9.3% and 8.3% for the T_{DRS} of, respectively, 40, 80 and 160 ms. There are 4.26%, 4.07% and 3.65% collisions for, respectively, T_{DRS} equal to 40, 80 and 160 ms. The collisions are affecting the CW sizes of both, LAA and Wi-Fi operator, which results in a higher backoff time for both. Additionally, the LAA node enters into the backoff more often for lower T_{DRS}, since it accesses the channel more frequently, hence its delay and throughput performance degrade.

6) IMPACT OF HIDDEN NODES ON LAA AND WI-FI COEXISTENCE

To study the impact of hidden nodes, we compare the performance obtained in BS corners scenario to that of the 3GPP indoor scenario in Fig. 18b. We recall that a Wi-Fi device is capable of detecting other Wi-Fi devices at −82 dBm and LAA devices at −62 dBm. On the other hand, an LAA device energy detects all types of devices, Wi-Fi or LAA, at the same energy level of −72 dBm. Both networks are negatively impacted by the hidden nodes, in particular, the percentage of collisions increases from 4.06% in the indoor scenario, to 5.47% in the BS corners scenario. The collisions cause an increase in the CW size and the backoff, and consequently reduce the throughput of both Wi-Fi and LAA. The CW size is especially increased for Wi-Fi. The average backoff counter goes up to 244 slots in the indoor scenario, whereas in the BS corners scenario it reaches 735 slots. Due to the asymmetric detection levels, the number of LAA simultaneous transmissions increases, so that the average MCS for affected UEs reduces. As a result, the LAA network is more affected by the hidden node scenario than the Wi-Fi network.

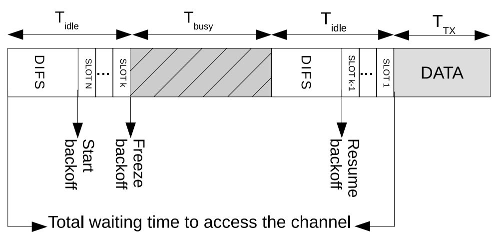
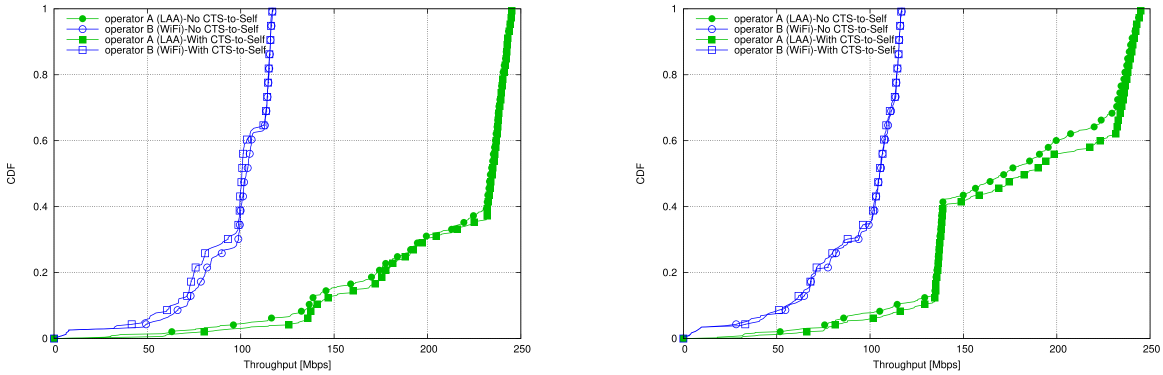


FIGURE 19. Illustration of time that Wi-Fi spends in backoff when the channel is busy during the backoff process. An initial value of backoff counter is N slots. After N-k slots the backoff is frozen due to detection of channel being busy.

7) IMPACT OF LAA CTS-TO-SELF

As we mentioned in section IV-B, and we analyzed in Sections VI-A.1 and VI-A.6 the performance degradation caused by the hidden nodes could be reduced by using the CTS-to-Self mechanism. CTS-to-Self would allow Wi-Fi to preamble detect LAA at −82 dBm or below. We evaluate the impact of CTS-to-Self in 3GPP indoor and BS corners scenario. Fig. 20 shows that the **CTS-to-Self improves the performance of the LAA network, while the impact on Wi-Fi is, as expected, negative, and depends on the scenario and the number of hidden nodes.**

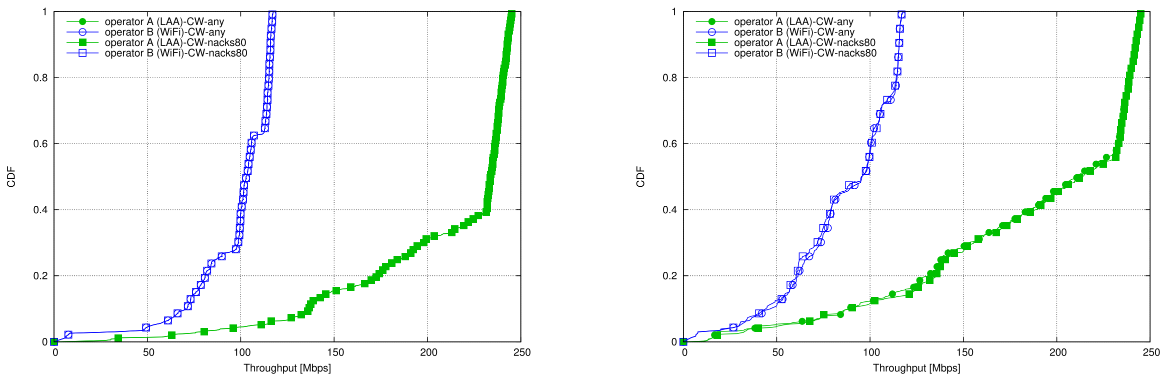
In 3GPP indoor scenario, collisions decrease from 2.68% to 0.43% when CTS-to-Self is active. This benefit is also reflected in terms of lower CW size for both LAA and Wi-Fi, e.g., when CTS-to-Self is not used, the maximum BO counter value of Wi-Fi reaches on average 512 slots, while when CTS-to-Self is used, its maximum value is on average around 32 slots. However, even if the CW size and collisions are reduced, the Wi-Fi performance is impacted negatively. This is mostly due to unnecessary backoffs to far away LAA nodes, which are detected in the range of [−82, −62] dBms, and which would not significantly affect the Wi-Fi communication even in case of collisions. Note that when performing the backoff, the actual time spent in backoff is composed of: the idle slots during which the backoff counter is decreased; and the channel busy slots, when the backoff counter is frozen



(a) 3GPP indoor scenario

(b) BS corners scenario

FIGURE 20. Impact of LAA CTS-to-Self.



(a) $\lambda = 5$

(b) $\lambda = 10$

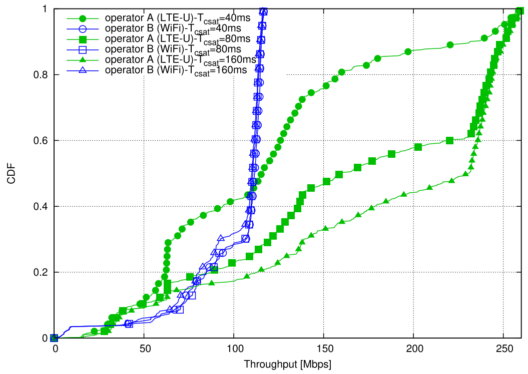
FIGURE 21. Impact of LAA Z parameter evaluated in 3GPP indoor scenario.

until the channel is found to be idle for the duration of eCCA defer period for LAA or DIFS for Wi-Fi. We recall how the backoff counter is frozen and resumed in Fig. 19. As a result, even if the average number of idle slots decreases, the number of busy slots is increased since Wi-Fi sees the channel more occupied.

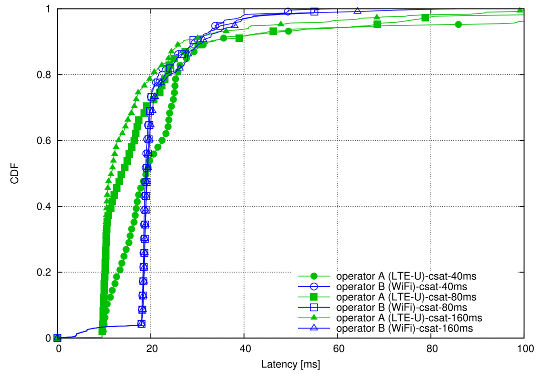
In the BS corners scenario, the trend is similar, but more accentuated since the number of hidden nodes increases. The CTS-to-Self mechanism is almost not impacting the Wi-Fi network, while it is significantly improving and protecting the LAA performance. Collisions drop from 2.75% to 8.09% collisions, when CTS-to-Self is used. In a scenario more affected by hidden nodes, the reduced number of collisions allowed by the introduction of CTS-to-Self is compensated by the extra time that Wi-Fi has to spend in backoff, due to the better detection capabilities. This makes that Wi-Fi performance results not affected by CTS-to-Self in this scenario, differently from the indoor.

8) IMPACT OF LAA CW UPDATE RULE (Z PARAMETER)

In Fig. 21, we show the impact of Z parameter on coexistence performance for different λ. Two CW update rules are compared, CW-nacks80 and CW-any. The CW-nacks80 is the default LAA LBT CW update rule which uses 80% threshold in order to increase the CW. The CW-any is the LAA LBT CW update rule according to which the CW is increased if any NACK belonging to a reference subframe is reported. The comparison results show that there is hardly any impact of the Z parameter on the coexistence performance, when considering $\lambda = 5$. This is mainly for the reasons explained in the Section IV-D. In particular, **the impact of Z parameter depends on the number of flows being scheduled in a single subframe, it also depends on the type of traffic being considered, and on the MAC scheduler algorithm.** For this reason, we evaluate the FTP Model 1 traffic also for a higher λ value in order to achieve more UEs to be scheduled in the same subframe. In Fig. 21b we show the performance when $\lambda = 10$. As expected, when $Z = 80\%$ LAA backs off less and enters in backoff less often, than the case $Z > 0$, while Wi-Fi finds the channel more frequently occupied, and enters more often in backoff. On the other hand, when Z is reduced, we note an increase in LAA backoff time, which results in a reduced number of collisions. There are 8.54% of collisions when $Z = 80\%$, and 8.23% when CW-any rule is used. **We conclude that reducing the Z parameter positively impacts Wi-Fi, while it negatively impacts LAA.**



(a) Throughput of LTE-U and Wi-Fi flows



(b) Latency of LTE-U and Wi-Fi flows

FIGURE 22. Impact of T_{CSAT} evaluated in 3GPP indoor scenario.

Notice that the impact of the Z policy as observed in Fig. 21 is marginal, also due to the maximum contention window value proposed by 3GPP for the class type 3 that we are considering in the simulations, which is 63. With a slot time of 9 μs, even when reaching the maximum contention window, due to collisions, the LAA eNB is normally in the condition to finalize its backoff count before the beginning of the following subframe, whatever the Z rule is. Consequently the impact is marginal.

B. IMPACT OF LTE-U PARAMETERS

1) IMPACT OF T_{CSAT}

In this section, we analyze the impact of T_{CSAT} parameter. As we mentioned earlier, T_{CSAT} represents the duration of the duty cycle, which includes ON and OFF time. This is one of the parameters that could be adaptively adjusted based on the MU measurements. Some of the values considered in industry are {40, 80, 160, 320, 640, 1280} ms. We will show in the following that the impact of T_{CSAT} depends on a scenario and traffic type. We consider the full buffer case, and a low traffic profile.

In Table 9, we show the impact of T_{CSAT} in the simple scenario when the traffic is full buffer CBR. The distances between nodes, d1 and d2, are selected in such a way that the nodes can energy detect each other (10 mt). Since the traffic is a full buffer traffic over UDP, then during the ON time, LTE-U occupies the channel during almost 100% of time. Thus, it is to expect that the share of the channel remains the same for any value of the T_{CSAT}. However, what changes depending on T_{CSAT} is the time that the LTE-U node needs to adjust the duty cycle and converge to 50% share, based on the medium utilization measurements.

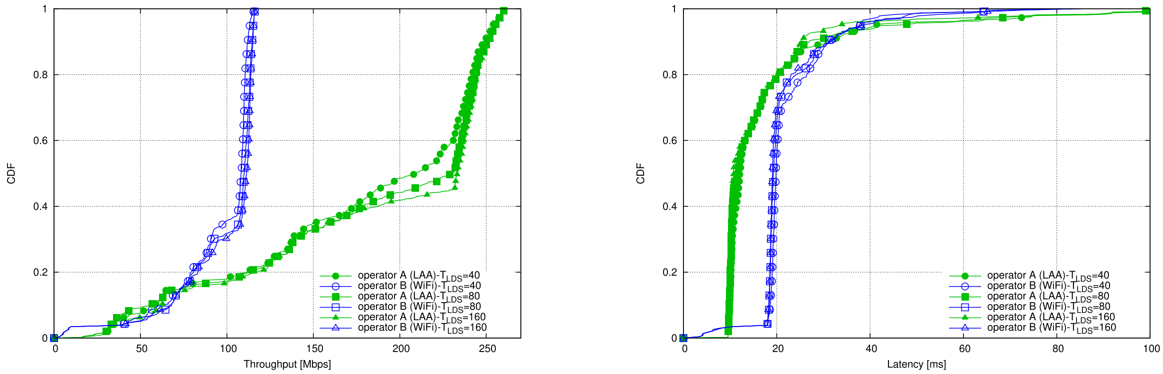
TABLE 9. Impact of T_{CSAT} in scenario simple, where $d1 = d2 = 10$ meters.

Measurement/T_{CSAT}	40	80	160
LTE-U throughput (Mbps)	198.29	214.5	218.97
Wi-Fi throughput (Mbps)	68.16	55.68	50.65
Average LTE-U duty cycle	0.5	0.58	0.58

TABLE 10. Impact of T_{CSAT} in scenario indoor, where $d1 = d2 = 10$ meters.

Measurements/T_{CSAT}	40	80	160
MU	0.133	0.125	0.107
Average LTE-U duty cycle	0.5	0.7465	0.873

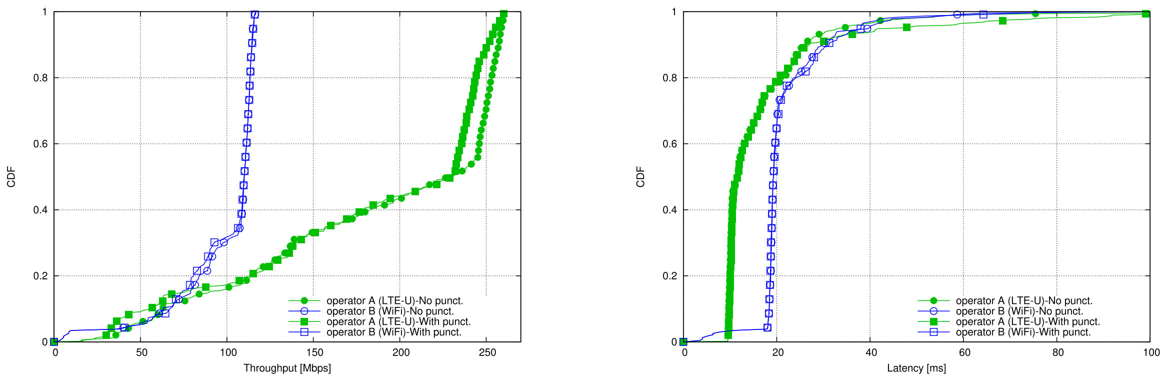
When the intensity of the traffic is lower, though, we observe different behaviors. In Fig. 22 we show results obtained for the 3GPP indoor scenario, with FTP traffic. We observe a negative impact on Wi-Fi performance when increasing T_{CSAT}. This is due to the traffic and duty cycle pattern, as we explain in the following. According to the exponential arrival process, for LTE-U operator, $\lambda = 5$, there is on average 1 file transfer every 0.2 second. Similarly, for Wi-Fi operator, $\lambda = 2.5$, the average file transfer will start every 0.4 seconds. In Table 10 we show the medium utilization and duty cycle values for different values of T_{CSAT}. We observe that for any value of T_{CSAT} the average MU is around 0.1, which is below the lower MU threshold, MU_{low}, which defaults to 0.4, as shown in Table 4. Because of this, the duty cycle during each simulation converges to its maximum value. Note that the effective LTE-U ON time increases with the increase of T_{CSAT}. Consequently, the number of transmissions by LTE-U increases. This is mainly because LTE-U can send more often MIB and LDS signaling, and the signaling is transmitted independently of data. For example, there are 3437, 5853 and 7362 MIB transmissions for T_{CSAT} of, respectively, 40, 80 and 160 ms. Note that the default periodicity for MIB is 10 ms for ON periods, while during OFF periods it drops to the minimum of 160 ms. We observe similar increment of LDS signaling, transmitted 999, 1167 and 1202 times for T_{CSAT} equal to, respectively, 40, 80 and 160. More signaling by LTE-U nodes introduces more collisions in the network. **We conclude that an increase of the T_{CSAT}, benefits the LTE-U network and not Wi-Fi, when the traffic in the network is low and the duty cycle is high.**



(a) Throughput of LTE-U and Wi-Fi flows

(b) Latency of LTE-U and Wi-Fi flows

FIGURE 23. **Impact of T_{LDS} in 3GPP indoor scenario with FTP Model 1 traffic.**



(a) Throughput of LTE-U and Wi-Fi flows

(b) Latency of LTE-U and Wi-Fi flows

FIGURE 24. **The impact of puncturing on FTP Model 1 traffic evaluated in 3GPP indoor scenario.**

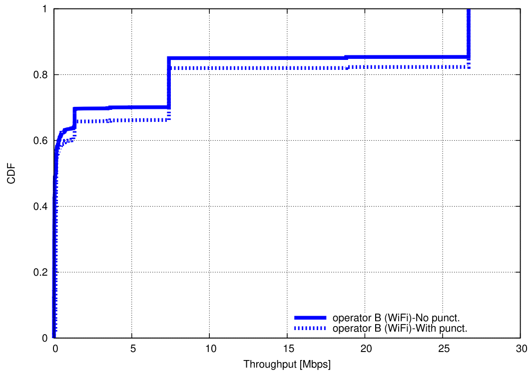
2) IMPACT OF T_{LDS}

As we mentioned earlier, LDS periodicity follows the specification of DRS, thus its periodicity can be of 40, 80 or 160 ms. Its synchronization functionality in the network is not modeled and we only model the channel occupancy of the signal and the collisions it generates. In Fig. 23, we show the impact of T_{LDS} on both, Wi-Fi and LTE-U. As expected, the more frequent the LDS, the higher the collision probability. We observe that there is 6.56%, 6.23% and 5.79% of collisions for T_{LDS} of respectively, 40, 80 and 160 ms. Also, LTE-U channel occupancy is higher for lower values of T_{LDS}, and is 9.4%, 8.2% and 7.6% for T_{LDS} of, respectively, 40, 80 and 160 ms. **Finally, similarly to LAA DRS, we conclude that T_{LDS} should be kept as low as possible to ensure a good coexistence performance.** Impact of LDS on Wi-Fi seems to be much weaker than that of DRS, in spite of the fact that DRS is sent with LBT. This is due to a higher channel occupancy in case of DRS, due to the potential need of reservation signal.

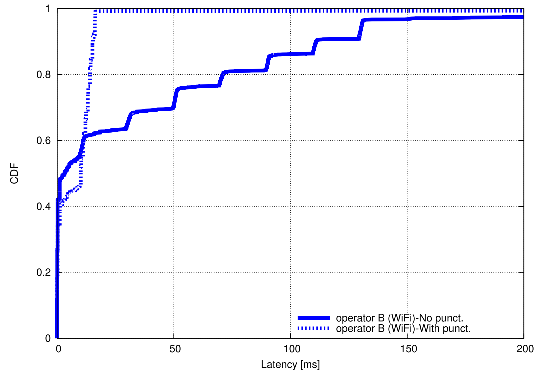
3) IMPACT OF LTE-U PUNCTURING

The concept of puncturing has been introduced to let low latency Wi-Fi traffic go through during the LTE-U ON periods. In Fig. 24, we show the impact on puncturing when both operators perform the FTP Model 1 traffic. We observe that for this type of traffic the puncturing is not playing an important role, and it is better not to puncture. **The reason is that the puncturing increases the probability of collisions, due to the impact of the OFF to ON transitions, when 1 ms puncturing is not enough to transfer the A-MPDU, which usually takes about 4 ms.** Collision traces show that there are 3.89% of collisions when there is no puncturing, and 4.16% when there is puncturing. When the traffic type is FTP, it is better for coexistence with Wi-Fi to let the LTE-U node finish its transmission and then have the Wi-Fi node transmit ideally without interruptions by LTE-U.

In Fig. 25, we show the impact on latency sensitive traffic performed by Wi-Fi nodes. In this scenario, Wi-Fi is transmitting a VoIP-like type of traffic, with a packet size equal to 160 bytes, sent every 20 ms, while LTE-U transmits a CBR traffic at the rate of 7 Mbps. Fig. 25b shows the latency per packet. When puncturing is not used there is 0.65 probability that the latency is lower than 20 ms, while in the case of puncturing, this probability reaches 0.95. The same effect can be observed for the throughput in Fig. 25a. These results show that, **for VoIP like traffic, puncturing facilitates that Wi-Fi finds on average the channel free more often, and reduces the need for backoff.**

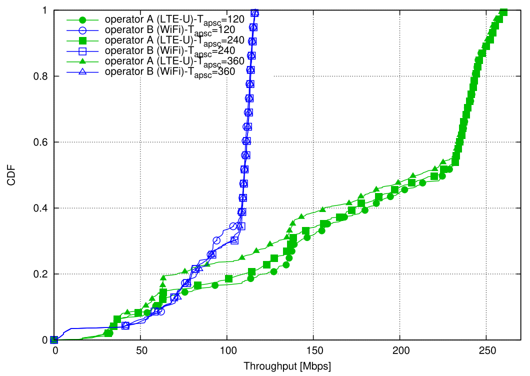


(a) Throughput of LTE-U and Wi-Fi flows

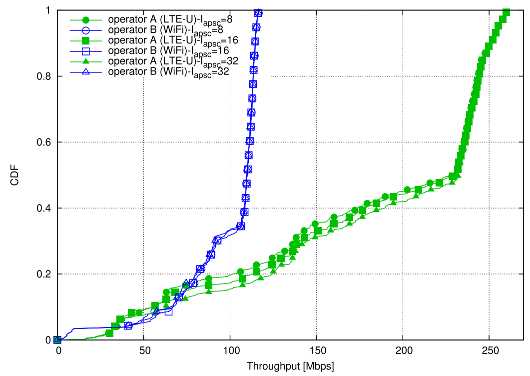


(b) Latency of LTE-U and Wi-Fi flows

FIGURE 25. The impact of puncturing on latency sensitive Wi-Fi traffic evaluated in 3GPP indoor scenario.



(a) The impact of duration of AP scan, T_{apsc}.



(b) The impact of AP scan interval, I_{apsc}.

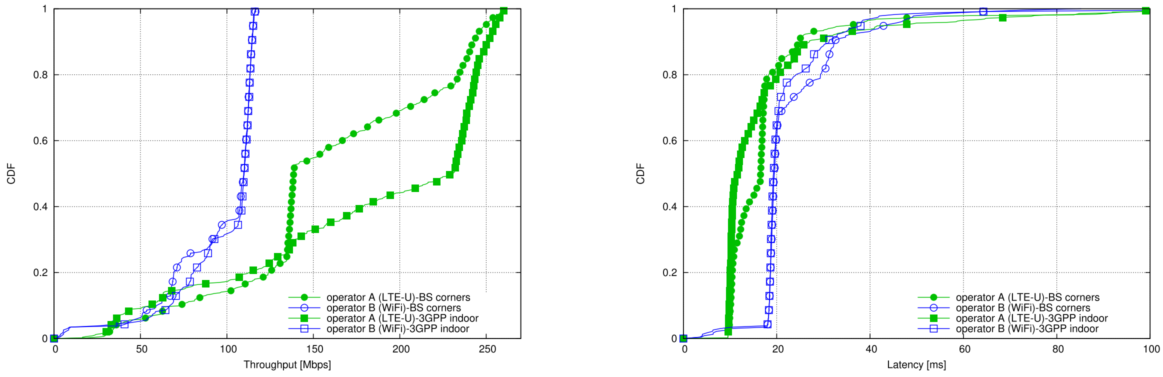
FIGURE 26. Impact of AP scan parameters evaluated in 3GPP indoor scenario.

4) IMPACT OF LTE-U AP SCAN

In this section, we analyze the impact of AP scan parameters, i.e., the AP scan duration, T_{apsc} and the AP scan interval, I_{apsc}. We show the results of the impact of these parameters in Figures 26a and 26b. We notice a negative impact on LTE-U performance when increasing the AP scan duration, due to an increased delay for the flows whose arrival time overlaps with the AP scan interval. Channel occupancy by LTE-U decreases when AP scan duration is increased, and is 8.3%, 8.1% and 7.7% when the AP scan period is, respectively, 120, 240 and 360. The impact on Wi-Fi is low since Wi-Fi observes on average the same activity of LTE-U during the regular CSAT transmissions. As LTE-U nodes perceive low channel utilization, around 0.12, the duty cycle converges to the maximum 0.875 value. The only difference is experienced by Wi-Fi flows which fall into AP scan periods, and which may experience the benefit of extended AP scan periods, as can be observed for few flows in Fig. 26a. While Wi-Fi sees less channel occupancy for higher T_{apsc}, it also experiences more collisions since it is more likely for it to collide with mandatory MIB and LDS that are sent during the AP scan periods. In Fig. 26b we observe, as the intuition suggests, that the less frequent the AP scan, the higher the performance of LTE-U.

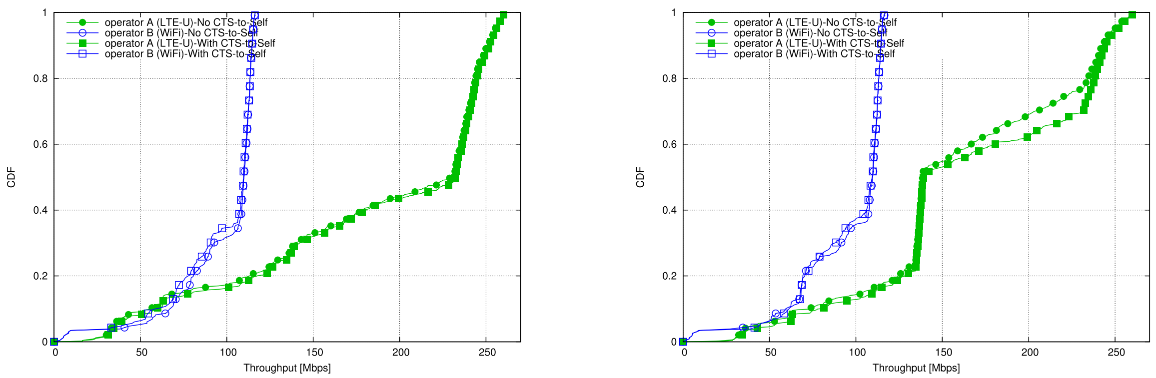
5) IMPACT OF HIDDEN NODES ON LTE-U AND WI-FI COEXISTENCE

Fig. 27 compares performance in the BS corner scenario, compared to the indoor one. The objective is to show the impact of an increased number of hidden nodes on LTE-U and Wi-Fi coexistence. Unlike LAA, LTE-U does not backoff to Wi-Fi, so that the Wi-Fi transmissions are more affected by LTE-U transmissions than they are when coexisting with LAA, in case that Wi-Fi is not able to properly sense the activity of LTE-U. In the BS corners scenario the average distance among nodes is higher than in the indoor scenario. In this context, the number of Wi-Fi nodes that cannot detect ongoing LTE-U transmissions, when their energy is lower than -62 dBm, increases. Since LTE-U does not backoff, Wi-Fi nodes that energy detect LTE-U nodes in the range $[-72, -62]$ dBm do not have channel access priority that they have when coexisting with LAA. As a result, Wi-Fi will be affected not only by the collisions that it causes, but also by the collisions generated by LTE-U nodes. The maximum size of the Wi-Fi backoff counter increases significantly in the BS corners scenario and is 530 slots, compared to the 42.25 slots in the indoor case. This confirms that the Wi-Fi transmissions are more affected by collisions in the BS corners scenario. **As an additional metric, we observe that the number of**



(a) Throughput of LTE-U and Wi-Fi flows (b) Latency of LTE-U and Wi-Fi flows

FIGURE 27. **Impact of hidden nodes evaluated by comparing the performance in 3GPP indoor and the BS corners scenario.**



(a) 3GPP Indoor scenario (b) BS corners scenario

FIGURE 28. **Impact of LTE-U CTS-to-Self.**

collisions in the BS corners scenario is higher when Wi-Fi coexists with LTE-U, than with LAA, which confirms that in a challenging scenario in terms of hidden nodes, LAA provides a more robust technology option than LTE-U.

6) IMPACT OF LTE-U CTS-TO-SELF

We evaluate the impact of the addition of the CTS-to-Self mechanism to LTE-U node on both, 3GPP indoor and BS corners scenario. Results are shown in Fig. 28. We observe a slightly negative impact of CTS-to-Self mechanism on Wi-Fi performance, since Wi-Fi backs off more, so the latency increases. We note that Wi-Fi is not impacted significantly by CTS-to-Self, because it is getting enough channel time when LTE-U is OFF. The percentage of collisions reduces in both scenarios, indoor and BS corners, when CTS-to-Self mechanism is employed. In the indoor scenario there are 6.23% collisions when CTS-to-Self is not used, compared to 4.44% when it is in use. Similarly, in the BS corners scenario there is 6.18% of collisions when CTS-to-Self is not employed, while there is 4.23% when CTS-to-Self is enabled. Among other metrics, we observe a significant reduction in CW size when CTS-to-Self is used in BS corners scenario. The backoff counter reaches values of around 530 slots in the case without CTS-to-Self, while when this mechanism is used it drops to 47 slots. In the indoor scenario, we do not observe a similar effect. However, as we discussed earlier, the rate control implementation may have an important influence. In some vendor's rate control implementation, the packet drop may result in severe coding rate backoff and even connection failures, and this is why this feature is in general recommended by WFA to be included in LTE-U products.

We observe that in both cases, LAA and LTE-U coexistence scenarios, the CTS-to-Self mechanism can protect LAA and LTE-U while having a minor negative impact on the Wi-Fi performance. The advantage for Wi-Fi is evident in scenarios with challenging hidden nodes conditions, since the increased latency produced by the augmented backoffs, is compensated by a significant collision reduction when the nodes are placed farther from APs.

C. LAA VS. LTE-U COEXISTING WITH WI-FI OR ANOTHER UNLICENSED LTE

In this section, we compare the coexistence performance of LAA and LTE-U with Wi-Fi or another LAA/LTE-U network. We evaluate performance when coexisting with Wi-Fi in both, the simple and the 3GPP indoor, scenarios. We create variants of the simple scenario by changing the parameter $d2$ (distance between the AP and the eNB) in order to examine different interference situations. In Table 11, we show the received power between BS/AP and their UE/STA, and between BS/AP and neighboring STA/UE as a function of $d2$. When $d2 = 10$ m, everyone can energy detect everyone. When $d2 = 30$ m, the scenario with LAA and Wi-Fi becomes asymmetric since the LAA node can energy detect the AP/STA, while AP/STA cannot energy detect the LAA node. Also, in the case of LTE-U and Wi-Fi coexistence, LTE-U can carrier sense Wi-Fi since it senses it up to CCA-PD threshold, while Wi-Fi cannot energy detect LTE-U. When $d2 = 50$ m, the scenario with LAA and Wi-Fi becomes symmetric, since at this distance they cannot anymore energy detect each other. On the other hand, LTE-U and Wi-Fi coexistence scenario is still asymmetric, since the AP/STA cannot energy detect LTE-U, while LTE-U is able to preamble detect the AP/STA.

TABLE 11. Simple scenario received power as a function of $d2$.

Distance (m)	BS<->BS (dBm)	BS<->own UE (dBm)	BS<->neighbor UE (dBm)
10	-54	-48	-48
20	-61	-48	-59
30	-66	-48	-65
50	-73.5	-48	-73.2
1000	-	-48	-

1) LAA VS. LTE-U: A SIMPLE SCENARIO WITH FULL BUFFER TRAFFIC

In Table 12, we show the coexistence performance comparison of LAA and LTE-U in a simple scenario (shown in Fig. 8), with full buffer CBR traffic over UDP. In particular, Table 12 shows the throughput achieved by: 1) Wi-Fi when coexisting with Wi-Fi, 2) Wi-Fi when coexisting with LAA, 3) LAA when coexisting with Wi-Fi, 4) Wi-Fi when coexisting with LTE-U and 5) LTE-U when coexisting with Wi-Fi. In a simple scenario, there is 1 UE per operator and 1 CBR flow per UE, and therefore, there is a single throughput value per operator. In general, we observe that when the nodes get closer (d2 decreases) the throughput decreases. This is due to the increased interference that the two networks generate to each other and due to the latency introduced by contention.

When $d2 = 10$ m, the transmitting nodes can see each other. In case of LTE-U over Wi-Fi scenario, Wi-Fi backs off properly to LTE-U, and LTE-U observes a high medium occupancy, due to Wi-Fi activity, and so it correctly reduces its duty cycle to 0.5. LTE-U channel occupancy is 46.57%. However, the collision probability is high, due to the LTE-U OFF to ON transitions. Additionally, the interferers are at sufficient distance to cause harmful interference to each other. There are 21% of collisions when LTE-U coexists with Wi-Fi. Still, we observe a slightly better performance of Wi-Fi when coexisting with LTE-U, compared to the baseline Wi-Fi over Wi-Fi scenario, where we do not observe any collision. This means that the interference generated by the LTE-U OFF to ON transitions is well compensated by the LTE-U OFF time, during which Wi-Fi can transmit without sharing the medium with any other network. When coexisting with LTE-U, Wi-Fi network occupies the channel 45.78%, while when coexisting with another Wi-Fi this value drops to only 24.4%, due to the time spent in backoff. Because of this, coexistence with Wi-Fi results in poorer performance than coexistence with LTE-U. As a result, **this is one interesting scenario configuration in which it is true the claim that LTE-U can be a better neighbor to Wi-Fi than Wi-Fi itself**.

When $d2 = 10$ m and LAA coexists with Wi-Fi, we note a negative impact on the Wi-Fi throughput. The reason is that the full buffer model makes LAA constantly compete for the channel. As soon as Wi-Fi releases the channel, LAA accesses and transmits for the MCOT duration, since it has always data available in the RLC buffer. Since the average Wi-Fi A-MPDU takes around 4 ms, and LAA MCOT is 8 ms, for channel access category 3, the channel share is unfair to Wi-Fi. In particular, we observe that the channel is occupied by LAA around 84% of the time, while Wi-Fi uses only 11% of the channel share. Note that, the channel occupancy of Wi-Fi is much lower than when it coexists with another Wi-Fi or LTE-U. On the other hand, we do not observe any collision when Wi-Fi coexists with LAA. **To sum up, in a simple scenario when the interferers can hear each other, $d2 = 10$ m, and a full buffer traffic model is performed, LTE-U is a better neighbor to Wi-Fi than LAA and than Wi-Fi itself. The LAA configuration parameter that makes the difference to jeopardize Wi-Fi, is the MCOT, considered for the channel access category we used in simulations, which is higher than the maximum Wi-Fi transmission opportunity.** Lower values of MCOT would benefit the coexistence with Wi-Fi, as already studied in previous sections.

When $d2 = 30$ m, the Wi-Fi transmitter does not detect the LAA/LTE-U signal since it is below Wi-Fi's CCA-ED threshold. Consequently, it does not backoff, which produces an increment in collisions, with respect to the 10 mt case, from 21% to 64.6%. On the other hand, both LTE-U and LAA detect Wi-Fi. Despite the increment of collisions, we observe an improvement in Wi-Fi performance of about 35%, due to the fact that its transmissions are not blocked during LTE-U ON periods. On the other hand, these collisions negatively impact LTE-U. In case of LAA/Wi-Fi, we notice worse coexistence performance than that of $d2 = 10$ m case. The reason for a significant degradation in Wi-Fi performance, and at the same time an increase of LAA performance, is twofold. First, there are a lot of collisions since Wi-Fi does not detect LAA. Second, while Wi-Fi is increasing its backoff and deferring its access to the channel due to failed transmissions, collisions and missed BAs, the LAA node occupies the channel even more often. There are 21% of collisions in this scenario, while at 10 m distance there were no collisions. LAA occupies the channel almost 93% of the time, while Wi-Fi occupies the channel only 2% of the time.

TABLE 12. LTE-U vs LAA throughput coexistence comparison in simple scenario with a full buffer traffic as a function of $d2$.

Distance $d2$ (m)	Wi-Fi in Wi-Fi/Wi-Fi (Mbps)	Wi-Fi in Wi-Fi/LAA (Mbps)	LAA in Wi-Fi/LAA (Mbps)	Wi-Fi in Wi-Fi/LTE-U (Mbps)	LTE-U in Wi-Fi/LTE-U (Mbps)
10	54.70	13.99	188.37	57.58	209.44
30	55.14	2.09	208.76	77.87	201.79
50	60.81	113.48	279.85	114.35	226.68
1000	115.26	115.28	279.85	115.31	273.34

When we further increase the distance to $d2 = 50$ m, the coexistence performance of both LAA and LTE-U improve, and this is because the interference generated to each other at the colliding packets is not high enough to cause a significant disruption. The performance of LTE-U cell increases even if there are more collisions, 73%. However, the LTE-U performance is upper bounded by its duty cycle since it preamble detects the Wi-Fi operator, and consequently, its duty cycle drops to 0.5. Therefore, LTE-U achieves over the unlicensed carrier only around 50% of the maximum achievable throughput per carrier, which is around 150 Mbps, so that, its total throughput is approximately 225 Mbps. In case of LAA/Wi-Fi, both operators reach almost the maximum throughput performance. LAA does not energy detect Wi-Fi, there are 56% collisions, but they do not harm Wi-Fi due to the distance. When Wi-Fi coexists with Wi-Fi, there are only 7% of collisions, but since Wi-Fi preamble detects the Wi-Fi their performance remains limited by backoff. As a result, when $d2 = 50$ m, LAA and LTE-U are better neighbors to Wi-Fi than Wi-Fi itself. LTE-U is a slightly better neighbor than LAA, but at the cost of significantly lower throughput than LAA.

Finally, when $d2 = 1000$ m, the transmitters cannot detect each other, and they are at a safe distance so they do not affect each other's transmissions. LTE-U observes no medium utilization, and so its duty cycle converges to its maximum value of 0.875 (20 ms out of 160 ms have to be OFF for MU monitoring), reaching the maximum throughput of 273 Mbps, which corresponds to the sum of approximately 150 Mbps achieved in the PCell plus about 123 Mbps achieved in SCell. In case of LAA coexisting with Wi-Fi, LAA does not energy detect Wi-Fi, so it achieves the maximum performance. The same happens when Wi-Fi coexists with another Wi-Fi.

As a summary, **in this simple scenario setup where we consider a full buffer traffic over UDP, and we only vary the distance of interferers, results show that we can easily set-up scenario configurations where, unexpectedly, LTE-U is a better neighbor to Wi-Fi than LAA and Wi-Fi itself. This is mainly due to the MCOT value chose by 3GPP for the channel access category** 3 **that we are considering. More favorable coexistence values would be achieved with lower MCOT.** Regarding ULTE performance, however, LAA is on average achieving better performance than LTE-U.

2) LAA VS. LTE-U: SIMPLE SCENARIO AND FTP UDP TRAFFIC

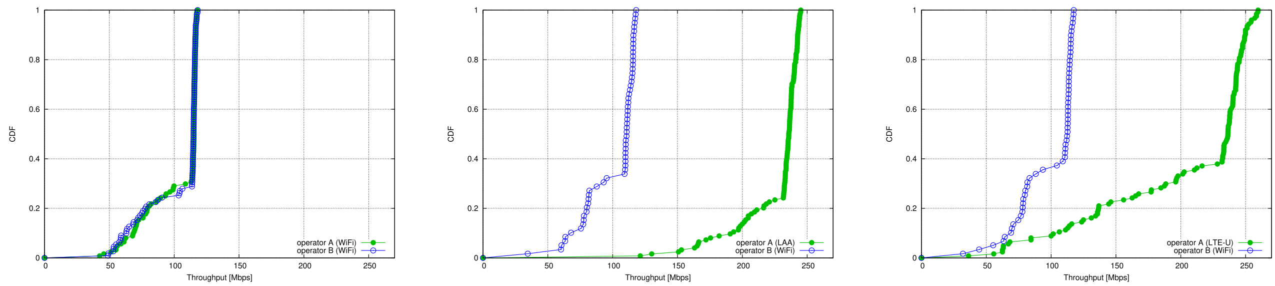
In Figures 29, 30 and 31, we show results for the simple scenario when traffic is FTP over UDP and distance d2 is equal to, respectively, 10, 30 and 50 m. In general, both ULTE technologies impact Wi-Fi throughput negatively for the lower values of d2. LAA is a slightly better neighbor to Wi-Fi at 10 m case, while LTE-U is better at coexisting than LAA at 30 m case. However, when $d2 = 50$ m both technologies are better neighbors to Wi-Fi than another Wi-Fi.

TABLE 13. CSAT measurements.

Distance	MU	Avg. duty cycle
10	0.2	0.86
30	0.21	0.83
50	0.18	0.86

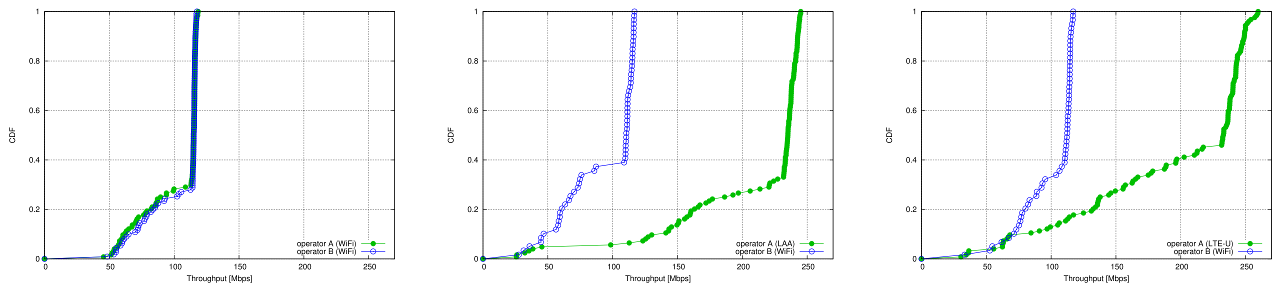
When $d2 = 10$ m, the LTE-U cell observes the average medium utilization of around 0.2. In Table 13, we show LTE-U CSAT measurements. We observe that with FTP traffic the medium utilization is low to appreciate a balanced share of the channel. We observe 6% of collisions when LTE-U coexists with Wi-Fi, while there are no collisions when Wi-Fi coexists with LAA or another Wi-Fi. **Because of collisions, the performance of the Wi-Fi cell is lower when coexisting with LTE-U, than when coexisting with LAA, even considering MCOT of 8 ms.** On the other hand, LAA impacts the Wi-Fi performance negatively because it occupies the channel more than it would another Wi-Fi network, and this causes an additional delay for some Wi-Fi flows. In particular, the channel occupancy of LAA network when coexisting with Wi-Fi is 8.91%, while the channel occupancy of a replaced Wi-Fi network is only 4.1%. **To sum up, when $d2 = 10$ m, and when, differently from before, we consider a bursty, non full buffer traffic model, Wi-Fi suffers degradation in performance when coexisting with both LTE-U and LAA. LTE-U performs worse than LAA since its duty cycle is upper bounded by 0.875 value, and LTE-U occupies the channel less than LAA, i.e. 8.1% of the channel time, and introduces more collisions**.

When $d2 = 30$ m, the negative impact of LTE-U over Wi-Fi decreases, since the power of the interfering signal is lower than the $d2 = 10$ m case. However, LAA impact over Wi-Fi becomes worse, due to an increased number of collisions, because Wi-Fi does not energy detect LAA. At this distance, there are 14.8% of collisions when LAA coexists with Wi-Fi, and 20.06% when LTE-U coexists with Wi-Fi. However, LTE-U occupies the channel less than LAA (8.6% of channel occupancy for LTE-U, against 9.6% for LAA). As a result, when $d2 = 30$ m, LTE-U is a slightly better neighbor to Wi-Fi, than LAA.



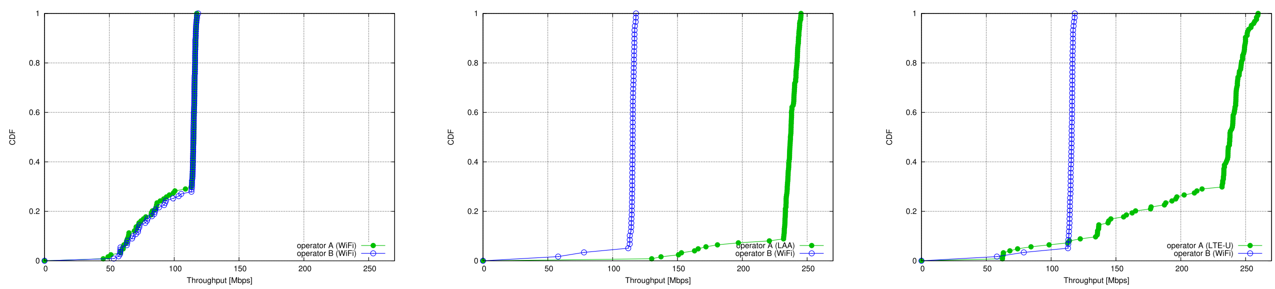
(a) Wi-Fi/Wi-Fi (b) LAA/Wi-Fi (c) LTE-U/Wi-Fi

FIGURE 29. **LTE-U vs LAA coexistence performance comparison in simple scenario when traffic is FTP over UDP. Distance $d2 = 10$ meters.**



(a) Wi-Fi/Wi-Fi (b) LAA/Wi-Fi (c) LTE-U/Wi-Fi

FIGURE 30. **LTE-U vs LAA coexistence performance comparison in simple scenario when traffic is FTP over UDP. Distance $d2 = 30$ meters.**



(a) Wi-Fi/Wi-Fi (b) LAA/Wi-Fi (c) LTE-U/Wi-Fi

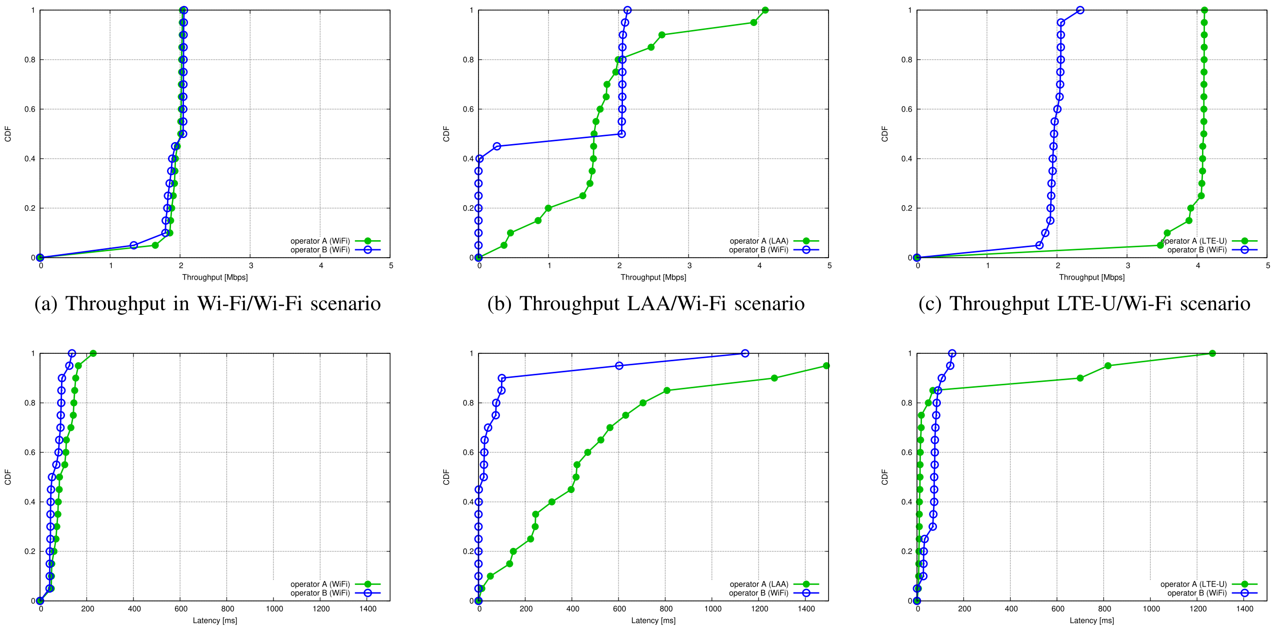
FIGURE 31. **LTE-U vs LAA coexistence performance comparison in simple scenario when traffic is FTP over UDP. Distance $d2 = 50$ meters.**

When $d2 = 50$, we observe that LAA and LTE-U are better neighbors to Wi-Fi than Wi-Fi itself. This is because, at this distance, Wi-Fi sees the other Wi-Fi and it backs off, while the interference is low compared to the useful signal. **There are then setups where the time lost during the backoff process affects more the performances of Wi-Fi than the interference itself.** LTE-U observes on average a low medium utilization of 0.18, due to the traffic model, so that the duty cycle again converges to its highest value, which is 0.875. On the other hand, LAA does not detect Wi-Fi at −72 dBm, and therefore it does not back off, neither reserves the channel. Thus, LAA attains a better performance.

As a result, we conclude from these results that **the coexistence performance does not only depend on the access mechanism itself. The apparent conclusion that LAA is a better neighbor to Wi-Fi than LTE-U is not always true: the received interference level, the detection capabilities of the eNB, or the traffic pattern, may make one technology perform better than the other, in such a way that it is not possible to claim that one technology is superior to the other in terms of coexistence.**

3) LAA VS. LTE-U:3GPP INDOOR SCENARIO WITH UDP CBR TRAFFIC

In Fig. 32 we show the performance of Wi-Fi, LAA and LTE-U networks evaluated in the indoor scenario when considering UDP CBR traffic of 4 Mbps of each flow of LAA or LTE-U operator, and 2 Mbps of Wi-Fi. Fig. 32 shows results of the following topologies: 1) the baseline Wi-Fi over Wi-Fi, 2) LAA over Wi-Fi and 3) LTE-U over Wi-Fi. In this scenario and with the proposed traffic model, we observe that LTE-U is definitely a better neighbor to Wi-Fi than Wi-Fi



(a) Throughput in Wi-Fi/Wi-Fi scenario (b) Throughput LAA/Wi-Fi scenario (c) Throughput LTE-U/Wi-Fi scenario

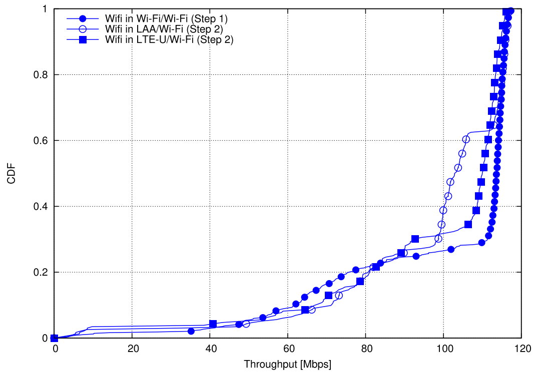
(d) Latency in Wi-Fi/Wi-Fi scenario (e) Latency in LAA/Wi-Fi scenario (f) Latency in LTE-U/Wi-Fi scenario

FIGURE 32. **LTE-U vs LAA coexistence comparison in 3GPP indoor scenario when traffic is UDP CBR.**

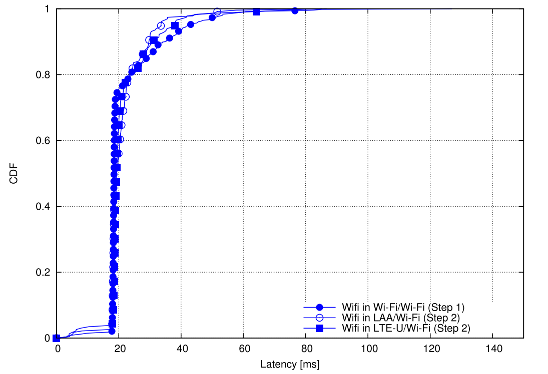
to itself, in terms of throughput, which can be observed in Figures 32a and 32c. In terms of latency, the performance of Wi-Fi in Wi-Fi over Wi-Fi scenario, and LTE-U over Wi-Fi is very similar, as shown in Figures 32d and 32f. Contrarily, LAA has extremely negative coexistence performance. Getting more into the detail of the statistics, the channel occupancy of Wi-Fi when it coexists with another Wi-Fi is 32.9%, with LAA is 19.1%, and with LTE-U is 23.3%. The channel occupancy of LAA is 80.3% and of LTE-U is 52.1%. LTE-U observes a high medium utilization of around 0.61 and its duty cycle drops to 0.5. There are 20% of collisions when Wi-Fi coexists with LAA, 11.29% when coexisting with another Wi-Fi and 10.71% when coexisting with LTE-U. Based on these stats, we observe that LAA offers extremely poor coexistence performance, because it occupies the channel much more than the other technologies. The reason is that for each LAA or LTE-U flow, one UDP packet arrives every 2 ms to RLC queues. Every time a new packet is available, LAA attempts to access the channel, and when it gets it, it cannot fill all the subframe capacity, because only one MAC PDU is available to be sent. As a result, the LAA transmission opportunity is not used at its best, and the channel is not efficiently occupied during 1 ms. To this we need to add the reservation inefficiency to access the channel with LAA. The spectral efficiency of this access is extremely low. The channel occupancy increases, then, dramatically, compared to Wi-Fi, and this jeopardizes the coexistence performance. This effect, though, is not present in LTE-U, where the channel can be used continuously during the ON period. As a result, **we conclude from these simulation results, that the coexistence performances are highly affected by the traffic pattern, besides that by the channel access approach. In particular, when considering an unbursty traffic model that does not allow to take full advantage of the capacity of the subframe, and of the transmission opportunity, LAA occupies the channel for 1 ms, to transmit little data, while Wi-Fi to transmit the same data would occupy the channel in the order of μs. In this case, the coexistence performance is significantly poorer than LTE-U.** This problem in LAA could be reduced at MAC scheduler level, by not allowing access to the unlicensed channel with small packets, or without having enough data to transmit to fill the transmission opportunity. Also, we have to consider that this kind of LAA scheduling inefficiencies in unlicensed access will be less evident with New Radio, since this novel technology will allow enough flexibility through the concept of the flexible Transmission Time Interval (TTI)s, to use more appropriately the scheduling opportunities.

4) LAA VS. LTE-U: 3GPP INDOOR SCENARIO WITH FTP UDP TRAFFIC

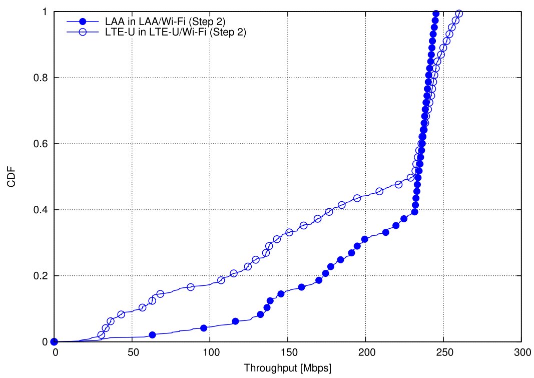
Fig. 33 shows LTE-U vs. LAA coexistence performance, in the 3GPP indoor scenario, when the traffic is FTP over UDP. **In this set-up, we finally observe some of the results that one would expect when comparing LTE-U and LAA. In fact, this setup was the one selected for evaluation in 3GPP TR36.889.** Let us first go through some statistics. The Wi-Fi channel occupancy is 5.5% when coexisting with LAA, 5.9% when coexisting with LTE-U, and 7% when coexisting with another Wi-Fi. We also observe 0.11% of collisions when coexisting with Wi-Fi, 1.9% when coexisting with LAA, and 4.01% when coexisting with LTE-U. From



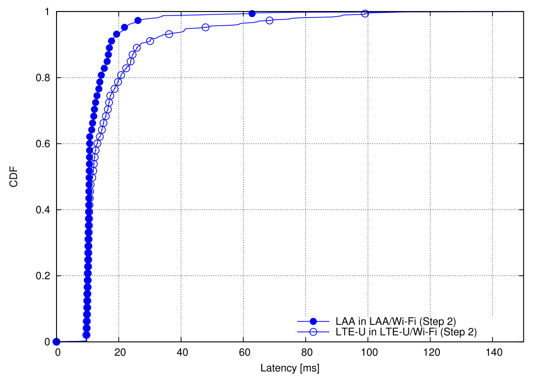
(a) Wi-Fi throughput when coexisting with Wi-Fi, LTE-U and LAA



(b) Wi-Fi latency when coexisting with Wi-Fi, LTE-U and LAA



(c) LAA and LTE-U throughput when coexisting with Wi-Fi



(d) LAA and LTE-U latency when coexisting with Wi-Fi

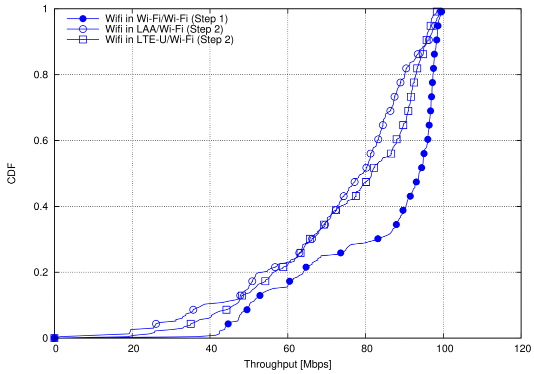
FIGURE 33. LTE-U vs LAA coexistence comparison in 3GPP indoor scenario when traffic is FTP over UDP.

the figure, we observe that for the flows with higher data rates, the throughput significantly reduces when coexisting with LAA (see section VI-C.2). For this kind of flows, there is a high chance of losing a complete A-MPDU and the corresponding BAs. The impact on these higher data rates flows, mainly depends on Wi-Fi's adaptation rate mechanism. Wi-Fi flows with lower and medium rate are positively impacted by LAA LBT mechanism, since in the coexistence there are not unnecessary backoffs to far away nodes. The negative impact of LTE-U on Wi-Fi is mainly due to the increased number of collisions, and similarly to the LAA case, there is a negative impact on the flows with the higher data rates since there is more probability to lose A-MPDUs due to too high MCS in interference situations. However, we see that both LAA and LTE-U positively impact the Wi-Fi performance for the flows transmitted with the lower MCS.

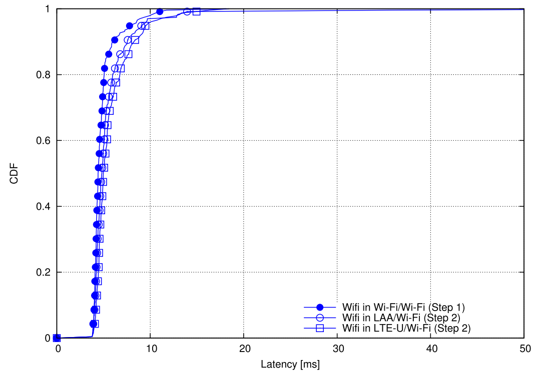
Differently to what happens with the CBR UDP traffic model, we observe here that LAA achieves better performance than LTE-U concerning the throughput and the latency. LAA occupies the channel 9.3% of the time, while LTE-U only 8.3%. It is not only the channel occupancy the reason why LTE-U achieves worse performance, it is also due to OFF times during which the transmission stops and the delay of the flow increases. We note this effect even if the LTE-U duty cycle converges quickly to its maximum value of 0.875. (min OFF time is 20 ms).

These results obtained in the indoor scenario are aligned with those obtained in the simple scenario discussed in Section VI-C.2. What is generating a great difference in coexistence behavior, with respect to what we observed in previous section, is the pattern of packet arrivals at application level. **The arrival of data per burst that we get with the FTP UDP model, allows LAA to take advantage of the full capacity of the transmission opportunity, and, consequently avoid to use inefficiently the transmission opportunity as it happens with less bursty traffic models like the CBR shown in the previous section. When LAA uses properly its transmission opportunity capacity, its channel occupancy becomes more similar to that of Wi-Fi, and consequently, the coexistence improves. In general, we observe that LAA coexistence performance is more sensitive than LTE-U's to the characteristic of the traffic model.**

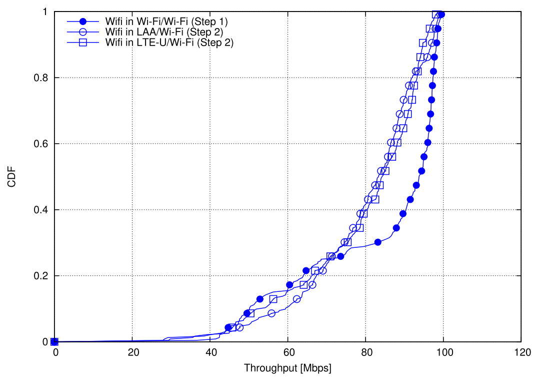
The results that we have obtained in this section are similar to those obtained by 3GPP in TR36.889, since the traffic model, the scenario set-up and the LTE configuration is the same. In particular, here we are simulating an FTP application over UDP and RLC-UM, which is similar to what is simulated



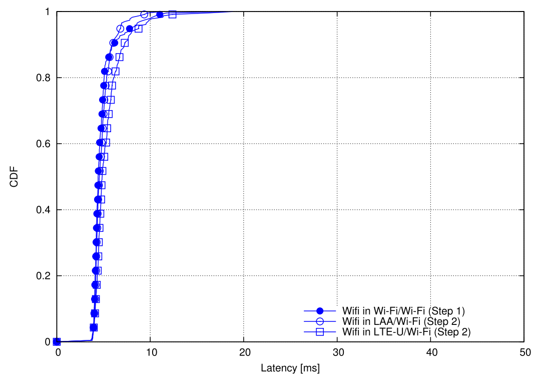
(a) Wi-Fi throughput when coexisting with Wi-Fi, LAA and LTE-U, and LTE RLC mode is RLC-AM



(b) Wi-Fi latency when coexisting with Wi-Fi, LAA and LTE-U, and LTE RLC mode is RLC-AM



(c) Wi-Fi throughput when coexisting with Wi-Fi, LAA and LTE-U, and LTE RLC mode is RLC-UM



(d) Wi-Fi latency when coexisting with Wi-Fi, LAA and LTE-U, and LTE RLC mode is RLC-UM

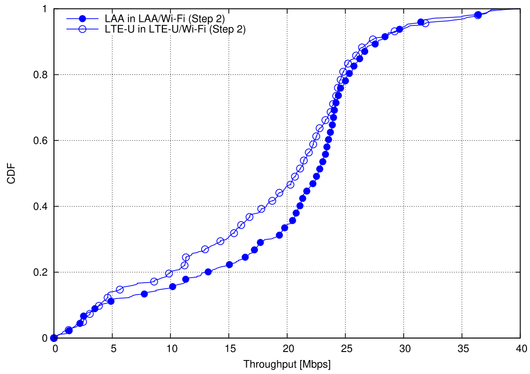
FIGURE 34. **Wi-Fi performance when coexisting with Wi-Fi, LAA and LTE-U, the traffic is FTP over TCP, and LTE RLC mode is RLC-AM or RLC-UM.**

in 3GPP groups, where normally only PHY and MAC are modeled. However, FTP applications in reality never run over UDP, but normally they do over TCP. This is why in next subsection we further study the impact of TCP and different RLC implementations.

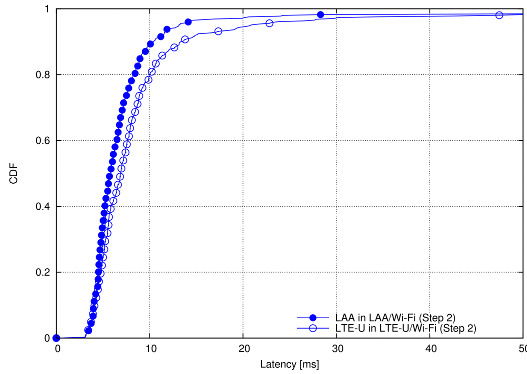
5) LAA VS. LTE-U: 3GPP INDOOR SCENARIO WITH FTP TCP TRAFFIC

In the current Internet, file transfers are typically run over TCP. In simulations where we simulated the FTP application operating over UDP, the RLC protocol at LTE was configured to be RLC-UM, to avoid retransmissions at both link and transport layers. However, TCP commonly runs over a reliable link, which is supported by RLC-AM in LTE networks. We, therefore, test the FTP over TCP and RLC-AM. In this case, **the coexistence of two windows, TCP and RLC, generates a flow control effect that can alter the data arrival pattern as compared with the bursty arrival rate observed when FTP is run over UDP.** Because of this, to better understand this effect, we further simulate as well TCP over RLC-UM. Note that, since our simulation study is focused on the coexistence in an unlicensed band for DL only, the TCP ACKs in ULTE are transmitted in the licensed band without contention. In Fig. 34, we show the Wi-Fi performance for TCP over RLC-AM and RLC-UM, and in Fig. 35 we show the performance of LAA and LTE-U.

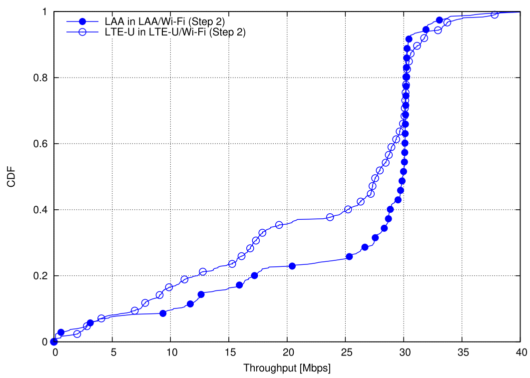
In Fig. 34, we observe that the throughput of Wi-Fi is significantly lower than for the FTP over UDP traffic model. When RLC-AM is used, both ULTE technologies impact Wi-Fi throughput negatively. This can be observed in Fig. 34a. This performance degradation is due to the additional contention that LAA and LTE-U cause because they occupy the channel much more than in case of FTP over UDP. In particular, LAA occupies the channel 16.4% of the time, LTE-U 12.3%, while another Wi-Fi occupies it 8.3%. **TCP is affected by longer Round Trip Time (RTT) due to the inherent latencies of the LTE protocol stack. These longer RTT in LTE could cause transmission timeouts, which results in the shrink or reset of the TCP congestion window, which may drop down to few or even only one segment. Once this happens, LTE resources are underutilized, since the subframe (i.e., 1 ms long) is the minimum granularity in LTE for resource allocation.** Thus, resources are in general less efficiently used in ULTE than in Wi-Fi, which holds the channel only the amount of airtime that corresponds to the size of the data to transmit. Additionally, when coexisting with LAA, there are 3.5% of collisions, when coexisting with LTE-U, there are 5.1%



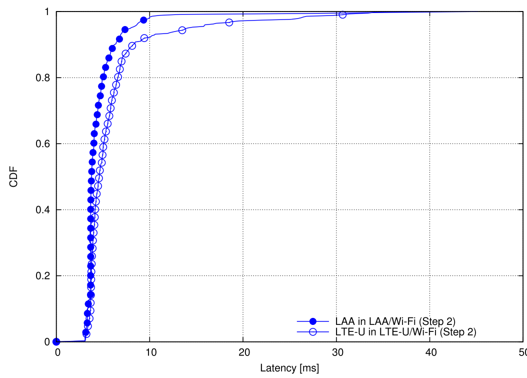
(a) LAA vs LTE-U throughput when coexisting with Wi-Fi and employing RLC-AM



(b) LAA vs LTE-U latency when coexisting with Wi-Fi and employing RLC-AM



(c) LAA vs LTE-U throughput when coexisting with Wi-Fi and employing RLC-UM



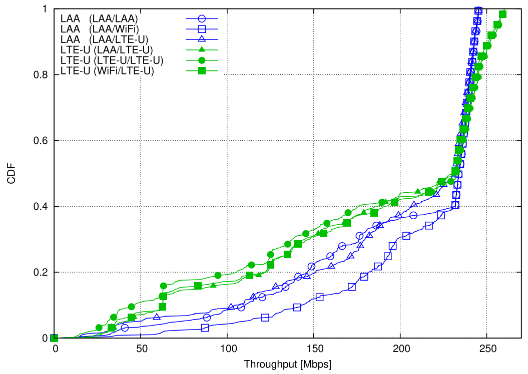
(d) LAA vs LTE-U latency when coexisting with Wi-Fi and employing RLC-UM

FIGURE 35. Performance of LAA and LTE-U when the traffic is FTP over TCP, and LTE RLC mode is RLC-AM or RLC-UM.

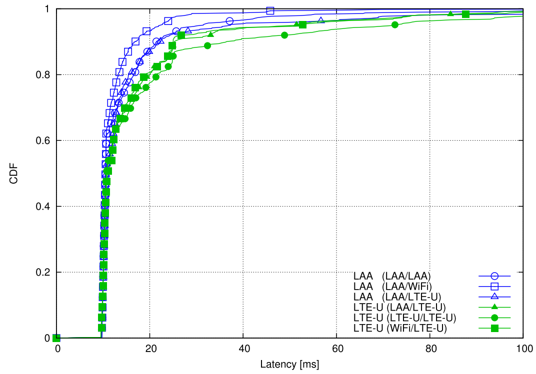
and when coexisting with another Wi-Fi, there are 0.88% of collisions.

When RLC-AM is used, we observe that the Wi-Fi throughput is better when coexisting with LTE-U than with LAA, even if there are more collisions when coexisting with LTE-U. The reason for this is that LAA holds the channel much more than LTE-U, which increases the time Wi-Fi spends in backoff, and thus its delay. We notice the same effect for all the flows, independently from the rate at which they are transmitted. When RLC-UM is used, the Wi-Fi throughput curves intersect, and the impact of both ULTE technologies on Wi-Fi is similar. This is shown in Fig. 34c. The channel occupancy of LAA and LTE-U is much lower from that of RLC-AM case, i.e., LAA occupies the channel 8% of the time, and LTE-U 8.1%. There are also less collisions when coexisting with LAA (2.7%), than when coexisting with LTE-U (4.37%). However, these coexistence statistics are still poor when compared to the Wi-Fi over Wi-Fi case, when we observe 4.1% of channel occupancy time, and only 0.88% of collisions.

Concerning the LAA and LTE-U results, in Fig. 35 we observe that LAA achieves significantly better performance than LTE-U regarding throughput and latency, for both RLC implementations. The reason is that both, TCP and RLC-AM, are sensitive to delays, which are much more pronounced in LTE-U due to OFF periods. As a final observation, from Fig. 35, we notice that the LAA/LTE-U FTP over TCP throughput is significantly lower than that of FTP over UDP. In particular, depending on the segment size and file size, TCP requires multiple RTT to transmit the data. Due to LTE protocol stack delays, RTT is higher in LTE than in Wi-Fi. In particular, the RTT when transmitting one FTP file of 0.512 MBytes in LTE is around 15 ms. 3-4 ms are required for the TCP segment to be transmitted from the eNB and received at the UE. Then a TCP ACK is generated and approx. 12 ms are required to transmit it, without contention, because the uplink traffic is transmitted in a licensed band. When the UE detects the ACK in the RLC queue, or has something to transmit, the UE RLC sends a Buffer Status Report (BSR) to the eNB MAC. From this moment, it takes 4 ms for the BSR to reach the eNB MAC. Then, the eNB receives the BSR and has to schedule and generate an Uplink (UL) DCI. It takes additional 4 ms before the UL DCI is received at the UE, with the information for it to transmit. When the UE receives the UL DCI, it takes additional 4 ms before the TCP ACK reaches the end destination. These delays are standard LTE delays. To transmit files of 0.512 Mbytes with TCP segment size of 1440 bytes, and using a somewhat aggressive initial congestion window of 10 segments, we found by examining traces that we need about 10 RTTs of at least 12 ms,



(a) LAA and LTE-U throughput when coexisting with LAA, LTE-U, and Wi-Fi



(b) LAA and LTE-U latency when coexisting with LAA, LTE-U and Wi-Fi

FIGURE 36. Performance of LAA and LTE-U when coexisting with LAA, LTE-U and Wi-Fi in indoor scenario, when the traffic is 3GPP FTP M1.

sometimes more or less, depending on buffer occupancy of each component carrier and timings involved. As we are focusing on a DL only, this RTT length is accentuated by the fact that traffic is not sent in the UL. This means that every time that UE has to send a TCP ACK in UL, it needs first to send a BSR from the UE RLC to the eNB MAC and then wait for the UL DCI. This handshake is expensive from a latency standpoint. If there was data in UL, the TCP ACK could be piggybacked to the data, and this would shorten the RTT since the UE would not have to request and wait for the UL DCI grant, which takes around 8 ms. These TCP performance trends not only are confirmed with LAA and LTE-U scenarios, but also with LTE in general. The issue with TCP in LTE networks was discussed in [47]. However, in case of LTE-U and LAA these delays are further increased due to discontinuous LBT or LTE-U transmissions, and subframes being wasted due to reservation, backoff, puncturing, and OFF periods.

6) LAA VS. LTE-U: THE IMPACT ON WI-FI BEACONS

In this section, we study the impact that different LTE technologies may have on the Wi-Fi beacons. Several critics have been raised by industry that coexistence with ULTE technologies may increase the percentage of beacons that are lost, or not correctly received by Wi-Fi, or received in a non-timely fashion. These effects may jeopardize the Wi-Fi association procedures. We have instrumented the simulator with traces to track events of collisions with Wi-Fi beacons. Wi-Fi network sends one beacon every 102,4 ms. We have evaluated the impact on percentage of lost beacons, and standard deviation of the beacon interval, for all the scenarios and traffic models considered in the paper (indoor, simple, BS corner and hidden node scenario, with FTP over UDP and FTP over TCP, DP CBR; in the simple scenario we have considered different distance situation between the nodes). Due to space constraints, and without loss of generality, based on the observation of the gathered results, we only represent a subset of these results, while the rest can be reproduced by the interested reader using the scripts available in the public repository of this work. We consider the indoor scenario with FTP traffic over UDP. In this scenario we observe that when Wi-Fi coexists with Wi-Fi or with LAA, thanks to the implementation of LBT assessment, no beacons are lost. However, the contention of the channel results in a standard deviation of approximately 13 ms for the coexistence with Wi-Fi, 8 ms with LAA. Coexistence with LTE-U in turn results in 1,49% of lost beacons and approximately 12 ms of standard deviation of the beacon interval. These results show that LAA does not affect Wi-Fi association performance more than Wi-Fi already does, while LTE-U increases of less than 2 points the probability of not receiving a beacon, and introduces the same delay to receive it. Similar results are obtained in the other scenarios.

7) LAA VS. LTE-U: LAA/LTE-U COEXISTENCE PERFORMANCE WITH ANOTHER LAA/LTE-U NETWORK

In Fig. 36, we illustrate LAA and LTE-U performance in terms of throughput and latency, when coexisting with another unlicensed technologies of the same type and compare this case with the cases when they coexist with the other unlicensed LTE technology, and with Wi-Fi. Similarly to the procedure followed in previous sections, to evaluate coexistence of LAA/LTE-U and Wi-Fi, we have evaluated coexistence in both simple and indoor scenarios, and with both FTP and CBR traffic models. However, due to space constraints, and without loss of generality, we only represent in this section results for the most general indoor scenario, with FTP traffic model. Scripts to reproduce also the other scenarios are available for the interested reader in the public repository of the work.

LTE-U, when coexisting with Wi-Fi, works by preamble detecting the Wi-Fi headers received from the surrounding APs. In case of coexistence with LAA, we consider that LTE-U has knowledge on the number of surrounding eNBs, through the Automatic Neighbor Relation (ANR) SON function. In this way, it is able to accordingly adjust the duty cycle.

Results show that Wi-Fi is the best neighbor to both LAA and LTE. On the other hand, the performance of LAA and LTE-U when coexisting with each other are similar. In particular, LTE-U has a slightly better performance when coexisting with Wi-Fi and LAA than with LTE-U. On the other hand, it is hard to claim if LAA coexists better with itself or with LTE-U, since the CDF curves cross in many points. It is interesting to note that LTE-U performance is more stable since it depends mainly on the duty cycle which in all three cases converges quickly to 0.5. Differently, LAA depends on the availability of the channel, and since LAA and LTE-U are occupying channel on average more than Wi-Fi, (8.62% for LAA, and 8.2% for LTE-U, 5.26% for Wi-Fi), its performance quickly degrades when coexisting with these two technologies.

D. SUMMARY OF FINDINGS AND SUGGESTIONS FOR FUTURE WORK

In the paper, we have presented a detailed analysis of the performance of ULTE technologies through an accurate simulation campaign, run over a high fidelity, standard compliant network simulator. While discussing the results, we have tried to highlight the main aspects that the simulation insights were reveling. In what follows, we summarize the main findings here.

- The main message that we want to convey in the paper, after this very extensive collection of results, is that there is a general belief that LAA is superior to LTE-U in terms of coexistence. This is true in some setups, as those described in section VI.C.3. However, studying also the impact of other aspects like the interference level (distance among nodes), the detection capability of the nodes, the details of LTE-U CSAT algorithm, the selection of the LAA parameters (e.g. MCOT), the traffic pattern injected in the network (if CBR, bursty or full buffer), it is possible to see that the conclusion is not at all straightforward and the absolute superiority of one access mechanism over the other, cannot be claimed. The common thought in industry and literature that LTE-U is necessarily a worse neighbor to Wi-Fi than LAA is, is also not always true. We have shown and discussed setups, scenario configurations, and traffic patterns, where LTE-U coexists much more fairly with Wi-Fi than LAA.
- Coexistence performance is highly sensitive to factors that affect the channel occupancy (e.g. control signals), and in some cases even more than to the parameter choices of the LBT CCA and backoff algorithms.
- Channel occupancy, and consequently coexistence, is not only affected by the behavior of the PHY-MAC layers, and of the LAA access in particular, which have been evaluated in 3GPP RAN1 and literature, but also by other aspects, related with upper layer protocols, such as TCP and RLC. However, no other previous study has included evaluations of TCP performance, to our knowledge.
- The characteristic of the traffic plays a very important role in coexistence performance, much more than it has been highlighted up to date in 3GPP studies or in other references. For instance, a bursty traffic pattern, such as the FTP run over a UDP or raw transport, may be a best-case scenario for coexistence in LAA scenarios, because inefficiencies of LAA in accessing the channel, due to the resource allocation granularity of 1 ms, can be amortized when transmissions are bursty. Alternatively, less bursty traffic models, or other transport protocols, e.g., TCP, may cause LAA to occupy the channel more frequently and inefficiently and impact the coexistence with other technologies.
- The proprietary rate control in Wi-Fi, can have a very important role in the final coexistence performance.
- There has been much attention on the importance of the ED threshold definition for LAA. However, the expected result that it is always beneficial that the LAA ED threshold is lowered, is untrue in many cases. We have shown unexpected effects, which could not be revealed without the support of a high fidelity network simulator.
- Some design parameters of both LAA and LTE-U may impact on coexistence more than expected: the expensive control messages which need to be sent in unlicensed, like DRS and LDS, the long delays required in LAA to update the contention window, the MCOT definition, the puncturing. In particular, the MCOT appears to be a very important parameter, which for two out of four channel access procedures, has been set to a value quite higher (8 or 10 ms) than the average Wi-Fi transmission opportunity. This leads to a clearly unfair behavior to Wi-Fi, in case of full buffer traffic.
- We have presented in general encouraging results for LTE-U. However, the reader should take into account that we have implemented and studied the Qualcomm's CSAT, which is only one possible implementation of CSAT, and definitively an excellent one, including many interesting features to achieve fair coexistence, which are not mandatory according to LTE-U specifications.

For future research, we recommend the design of smart MAC scheduling approaches capable of solving the inefficiency and granularity issues in LAA resource allocation, which are highlighted in cases of applications run over TCP, or in the case of constant bit rate applications, such as voice. In addition, we recommend investigating the effectiveness of the HARQ based collision detection approach. Moreover, the development roadmap of the simulator may include future evolutions of LAA related with uplink transmissions, i.e., Release 14 eLAA, as well as the MulteFire technology to develop LTE entirely in unlicensed band, without an anchor in the licensed band [4].

VII. CONCLUSIONS

While 3GPP prioritizes LAA and its successors for both, downlink and uplink access in unlicensed spectrum, different options for unlicensed technologies have been under development, and validating and comparing them, becomes essential for both, vendors and network operators. In this work, we have provided a detailed comparison study of the two predominant technologies for LTE in unlicensed, LAA and LTE-U. We have done so by building a full stack, specs-compliant network simulator in the popular ns-3 simulator, and we have open its access to favor results reproducibility. A considerable portion of this work elaborated on examining each of these technologies, its advantages and limitations. Some meaningful and unexpected conclusions have been generated by the analysis of the intense simulation campaign that we have carried out, showing that some of the common thoughts in industry and academia, with respect to these two technologies, are not necessarily true. Many aspects like the considered traffic patterns, the simulation setups, the proprietary implementation choices for both LTE and Wi-Fi, play a significant role in the coexistence performance, besides the specific details of the channel access procedures that have long been under discussion.

ACRONYMS

3GPP	3rd Generation Partnership Project
LTE	Long Term Evolution
LTE-A	The Long Term Evolution Advanced
ANR	Automatic Neighbor Relations
AP	Wi-Fi Access Point
BS	Base Station
CCA	Clear Channel Assessment
eCCA	Extended CCA
CCA-CS	CCA-Carrier Sensing
CCA-ED	CCA Energy Detection
CCA-SD	CCA Signal Detection
CSAT	Carrier Sense Adaptive Transmission
LTE-U	LTE Unlicensed
PCell	Primary Cell
SCell	Secondary Cell
SDL	Supplemental DownLink
SIB	System Information Broadcast
STA	Wi-Fi Station
CA	Carrier Aggregation
LBT	Listen-Before-Talk
SC	Small cell
UE	User Equipment
eNB	Evolved Node B
DRS	Discovery Reference Signal
DS	Discovery Signal
OFDM	Orthogonal Frequency Division Modulation
FTP	File Transfer Protocol
ACK	Acknowledgment
CTS	Clear to send
LAA	Licensed-Assisted Access
LDS	LTE-U Discovery Signal
CDF	Cumulative Distribution Function
Wi-Fi	A trademark of Wi-Fi Alliance, used to refer to a technology based on the IEEE 802.11 standards or Wi-Fi Alliance specifications
CW	Contention Window
DCF	Distributed Coordination Function
IEEE	Institute of Electrical and Electronics Engineers
DIFS	Distributed Coordination Function Interframe Space
MIB	Master Information Block
SIB1	System Information Block Type 1
CSI-RS	Channel State Information - Reference Signal
PDCCH	Physical Downlink Control Channel
PDSCH	Physical Downlink Shared Channel
CRS	Cell-Specific Reference Signal
PSS	Primary Synchronization Signal
SSS	Secondary Synchronization Signal
RAN	Radio Access Network
ETSI	European Telecommunications Standards Institute
QoS	Quality of Service
eLAA	Enhanced LAA
feLAA	Further Enhanced LAA
PLMN	Public Land Mobile Network
EDCA	Enhanced Distributed Channel Access
TxOP	Transmission Opportunity
MCOT	Maximum Channel Occupancy Time
ED	Energy Detection
HARQ	Hybrid Automatic Repeat Request
NACK	Negative Acknowledgement
CSMA/CA	Carrier Sense Multiple Access/ Collision Avoidance
PD	Preamble Detection
PUSCH	Physical Uplink Shared Channel
PUCCH	Physical Uplink Control Channel
SRS	Sounding Reference Signal
DMTC	Discovery signals Measurement Timing Configuration
CBR	Constant Bit Rate
TTI	Transmission Time Interval
MIMO	Multiple Input Multiple Output
PHY	Physical Layer
MAC	Medium Access Control
MPDU	MAC Protocol Data Unit
A-MPDU	Aggregate MPDU
BA	Block Acknowledgment
BAR	Block Acknowledgment Request
TCP	Transmission Control Protocol
UDP	User Datagram Protocol
CAM	Channel Access Manager
RLC	LTE Radio Link Control
RLC-UM	RLC Unacknowledged Mode
RLC-AM	RLC Acknowledged Mode
DCI	Downlink Control Information
UL	Uplink
DL	Downlink
MCS	Modulation and Coding Scheme
RTT	Round Trip Time

Minstrel-HT	Minstrel supporting High Throughput (802.11n rates)
ULTE	Unlicensed LTE
NR	New Radio
LWA	LTE-WLAN Aggregation
LWIP	LTE-WLAN Radio Level Integration with IPsec Tunnel
IPsec	Internet Protocol Security
SON	Self-Organizing Network

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