Baena *et al. EURASIP Journal on Wireless Communications and Networking* (2020) 2020:224
https://doi.org/10.1186/s13638-020-01834-x

EURASIP Journal on Wireless Communications and Networking

RESEARCH Open Access

Assessing the impact of DRS signaling in unlicensed indoor coexistence scenarios

Eduardo Baena*, Sergio Fortes and Raquel Barco

Abstract
The use of unlicensed bands is one of the most promising features envisaged to increase capacity in 5G. However, this poses multiple challenges associated with the operation when coexisting networks are present, such as WiFi. Previous coexistence analyses have been focused on the user-plane data-related transmissions and mainly based on abstract models. Meanwhile, the effects of the shared channel signaling defined by the standards have been mostly disregarded, particularly for ultra-dense scenarios. This paper assesses how the shared data channel signaling mechanisms influence the performance of the coexisting technologies operating unlicensed bands in indoor environments. Based on this analysis, some DRS signaling modifications are envisaged to additionally enhance the service provision and fairness towards WiFi in these scenarios.

Keywords: Unlicensed band, Coexistence, LAA, eLAA, WiFi, Optimization, Signaling

1 Introduction

The rapid proliferation of user devices with access to mobile broadband, such as smartphones or tablets, represents a challenge for both the deployment and operation of new cellular networks. Emerging services with high bandwidth demand (such as 16K video) make necessary to expand the existing capacity of Long-Term Evolution (LTE) standards by including new spectrum for 5G. Among all possible candidates, the unlicensed bands represent a key opportunity for mobile operators to provide additional radio resources.

Standardization organizations have been actively working on adding unlicensed band operation capacity to LTE technologies, and several approaches have been already designed, mainly Licensed Assisted Access (LAA) [1], *enhanced LAA* (eLAA) [2], FeLAA, and MulteFire [3]. LAA only includes downlink carrier aggregation in the unlicensed band, keeping standard licensed LTE link for general signaling. eLAA adds to this scheme the addition of unlicensed uplink carriers, while keeping the downlink equal to LAA. With FeLAA, carrier aggregation and dual connectivity were added. MulteFire entirely operates in the unlicensed band while sharing many common mechanisms and characteristics with LAA/eLAA. Recently, the sub-7-GHz (with possible extension to mmwave) unlicensed band is in the process of standardization under the name 5G New Radio-Unlicensed (NR-U) [4] with two flavors: non-stand-alone operation (similar to LAA) and stand-alone (alike MulteFire).

In recent years, the coexistence of WiFi and LAA has been widely explored in the literature both from an analytical point of view and at a simulation level. In these works, two main options for a fair coexistence are presented: on the one hand, methods of communication between technologies that allow their cooperation in random access are suggested [5], and on the other hand, techniques for adapting channel access mechanisms based on contention (adaptive window modulation, Energy Detection Threshold, etc.) are proposed [6].

Following the cooperative approach, the authors in [7] present and validate (through simulations) an algorithm that improves coexistence. Based on Admission Control mechanism, the proposed scheme reduces the signaling but it makes use of an inter-technology communication, where the exact number of WiFi sessions is required, which is unlikely to happen in commercial systems.

*Correspondence: ebm@ic.uma.es
Departamento de Ingeniería de Comunicaciones, Universidad de Málaga, Andalucía Tech, Campus de Teatinos s/n, 29071, Málaga, Spain

On the other hand, under a non-cooperative paradigm, [8] makes a comprehensive study of the channel access performance using Markov chain models. Nevertheless, in this paper, several aspects have been overlooked: firstly, the chosen evaluation metric, i.e, "Normalized Saturation Throughput," does not take into account the effects of layer segmentation beyond the channel access. Also, the signal processing in the channel (MIMO) has not being taken into account. This fact makes its results, although indicative, to not reflect many of the effects they would have on the end user's service perception. Similarly, the article [9] shows in detail many of the aspects of the non-cooperative coexistence with the full-stack layer simulator ns3, including a preliminary assessment of the performance and an outline of the importance of Discovery Reference Signals but with no further details of their impact neither proposing signaling adaptations, modifications, or enhancements. Finally, as a complement to these, and focusing more specifically on signaling, the work [10] performs an exhaustive study of the signaling methods involved in LAA as a fundamental aspect to be further explored. In addition, [11] introduces a method to avoid signaling collisions, although at the expense of a decrease in LTE performance and overlooking the inevitable impact on WiFi.

Thus, as far as the authors are aware, there is not yet an exhaustive study of the impact of Unlicensed Shared CHannel in-band signaling (and the technologies that inherit LAA standard) in an environment of indoor non-cooperative coexistence with WiFi. This paper presents the influence that sending such signaling has on the performance of both Licensed Assisted 3GPP-based technologes and WiFi and proposes a possible compensation modification that can serve as a basis for further designs of the 5G NR-U standard.

The present work main contributions are, firstly, a novel assessment of the impact of downlink shared channel control signaling for the indoor ultra-dense coexistence scenario in the unlicensed 5 GHz band and, secondly, an improved DRS signaling modification to mitigate the negative effect of this signaling and enhance the service performance (up to 10%) and fairness towards WiFi (up to 25%).

The article is structured as follows. Firstly, in Section 2, an introduction to the channel access mechanisms available for coexistence in unlicensed bands is provided. Secondly, Section 3 draws a brief overview of signaling procedures for physical downlink shared channel. Then, in Section 4, an exhaustive performance assessment is done including a summary of the simulation and scenario setup and signaling configuration that impact coexistence between LAA and WiFi. Afterwards, in Section 5, some standard DRS signaling recommendations and a novel DRS modification are proposed. Finally, in Section 6, the conclusions and future work are given.

2 Coexistence mechanisms in unlicensed bands

Analyzing the effects of the coexistence is essential to spot differences among the different mechanisms used to access the channel. While 3GPP-based standard radio transmissions are continuous in time and subject to centralized scheduling at the eNodeB, WiFi has been designed for opportunistic/asynchronous access among its users and therefore is ideally matched for the unlicensed spectrum. This fundamental difference between centralized 3GPP-based operation and distributed WiFi access makes contention techniques necessary to coexist in the same band [12].

In this regard, the LAA, eLAA, and MulteFire standards implement a Listen Before Talk (LBT) mechanism. LBT defines a Clear Channel Assessment procedure (CCA). Such mechanism is based on the sensing of the level of occupancy of the channel state, or Energy Detection (ED). This is performed during a *defer period*, checking whether any signal is present above a certain threshold (regardless of its technology of origin). In case the channel is detected as "free" during an initial CCA (iCCA) period, the LAA station is allowed to transmit for a Maximum Channel Occupancy Time (MCOT). Otherwise, *enhanced CCA* (eCCA) is activated and the station waits for a "backoff" time given by contention window (CW) size determined by maximum CW_{max} and minimum CW_{min} number of time slots.

Before standardization by 3GPP, several variants or categories (CAT) of LBT have been considered for study. Here, while CAT1 (no LBT), CAT2 (without backoff), and CAT3 (fixed window backoff) have been discarded for having a negative impact on coexisting technologies, CAT4 has been established as a proper method to access channel in a fair way [12]. Thus, just this category is the one considered in the subsequent versions of the standard [4]. Besides, within this CAT4, and based on different configuration values for the CW size and the MCOT, four priorities have been proposed [1] as shown in Table 1. For example, for priority 1, the contention window is smaller (between 3 and 7 slots), i.e., the transmitter waits less time to try to transmit again but the maximum time which can be occupied once the channel is found free (i.e., MCOT)

Table 1 3GPP LBT CAT4 priority class

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

is limited to 2 ms. Consistently, in priority 4, the waiting time to access the channel is longer (CW from 15 to 1024 slots), but once the channel is granted, its MCOT is increased up to 8 ms.

By comparison, in the WiFi standards [13] (IEEE 802.11), the most widespread channel access is the Distributed Coordination Function (DCF) based on CSMA/CA (Carrier Sensing Multiple Access with Collision Avoidance). Such a mechanism, which includes sensing of the channel before any transmission, can be classified in turn as an LBT technique. In WiFi DCF, two CCA sensing functions are defined: Carrier Sense (CCA-CS), which detects and decodes WiFi preambles of other transmitters, and Energy Detect (CCA-ED) for non-WiFi signals. Although they operate simultaneously, different thresholds are set for each function. When the channel is "empty" for a DCF Inter Frame Space (DIFS) period duration, the WiFi station sends the whole frame. If it is "busy," a random timer (with backoff count) is activated. Such timer only decreases its value when the channel has been sensed free during slot period, and once it expires, the WiFi station can transmit. Moreover, every time a frame is correctly decoded at the receiver, an ACK is sent after a Short Inter Frame Space (SIFS). Otherwise, if ACK is not received correctly, the backoff period is increased exponentially.

3 Signaling procedures for physical downlink shared channel

In LAA, the physical downlink shared data channel (*PDSCH*) has several signaling mechanisms controlled by specific signals such as Cell-specific Reference Signal (*CRS*) and Channel State Information Reference Signal (*CSI-RS*), which are used for coherent demodulation and channel estimation at User Equipment (UE) side, and the primary and secondary synchronization signals (PSS/SSS) to get synchronized to the base station [14]. From the CSI-RS embedded in data transmissions over the PDSCH (with adaptable periodicity from 5 to 80 ms), the UE estimates the interfering signal/noise ratio (*SINR*). Such SINR measurement (which may vary in each band of the spectrum) is then translated into a channel quality indicator or CQI which is sent to the eNodeB as a CQI feedback vector. The highest modulation and coding scheme (MCS) that the eNodeB can use to transmit data to the UE while maintaining a block error rate (BLER) below a given target (typically 10%) is then selected from this vector. Such process is called Link Adaptation with Channel Quality Indication [14], and it is an essential part of Radio Resource Management (*RRM*).

Similarly, for LAA and eLAA [14], the functions of cell detection, synchronization, and RRM measurements over the PDSCH in the unlicensed downlink band are performed by Discovery Reference Signals (DRS). These are, in turn, composed of PSS/SSS and CRS/CSI-RS signals with a transmission within a periodically occurring time window called the DRS measurement timing configuration (DMTC) occasion with a duration of 6 ms and a configurable period of 40/80/160 ms. However, to reduce its collision probability, such transmission is also subject to the contention mechanism protocol LBT.

In case some user-plane downlink data is scheduled during a DMTC window, DRS are embedded within the data transmission. Otherwise, the DRS are sent by themselves, what is denominated as *stand-alone* DRS. According to the model such as [15], stand-alone DRS are transmitted using over a single subframe occupying 14 OFDM symbols (1 ms). Therefore, DRS are the main signaling mechanism in the downlink shared channel and they will be the main focus of the posterior assessment, particularly in terms of their periodicity and related LBT transmission impact.

4 Impact evaluation

In this section, the impact of the presented signaling mechanisms on unlicensed downlink shared channel is assessed. To do so, and in accordance to the technical report TR.38.889 [12], the main Key Performance Indicators (KPIs) to evaluate coexistence of LAA and WiFi networks to be analyzed are as follows:

- *User Perceived Throughput (UPT)*—the data rate (in Mbit/s) defined as the amount of bits received correctly at UE/STA for each packet divided by the time between the packet submission in the transmitter and its successful reception in the UE/STA.
- *Latency*—time measured from the packet delivery in the transmitter to its successful and complete reception at the MAC layer of the receiver (including retransmissions).

Besides, another crucial aspect highlighted by 3GPP and which concerns the different stakeholders involved in the coexistence of unlicensed wireless technologies is the concept of *fairness*. According to the standard definition [12], fairness is established as the capability of a 3GPP-defined network (e.g., LAA) to not impact a coexistent non-3GPP technology (e.g., WiFi) more than an additional non-3GPP technology network using the same carrier would do it, both in terms of throughput and latency. For example, a scenario with both LAA and WiFi using the same carrier is expected to allow a better performance for WiFi than a scenario with two competitive WiFi networks in the same carrier.

On the basis of this formal definition of the standard, two formulations are proposed in order to be able to quantify "fairness" effectively. In this context, the baseline for the assessment of fairness is the scenario where

Table 2 Simulation parameters

Parameter	LAA	WiFi
Standard version	Rel.13	802.11n
Channel access specifications	CWmin = 15	CWmin = 15
	CWmax = 63 Cw update rule: 80% HARQ-NACK MCOT = 8 ms	CWmax = [63, 1023]
MCS	Adaptive SINR	Adaptive SINR
Freq. /BW [MHz]	5180 / 20	5180 / 20
Max TX power [dBm]	BS: +18, MS: +18	BS: +18, MS: +18
Antenna gain [dBi]	BS: +5, MS: 0	BS: +5, MS: 0
Energy Detect Threshold [dBm]	ED (−724 dBm)	Preamble detection, ED = −82, −72 dBm
Antenna configuration	MIMO 2 × 2	MIMO 2 × 2
Fixed minimum sensing duration	34 us	43 us
Cell selection	RSRP for LAA UEs	RSS for WiFi STAs
Distance-dependent pathloss, shadowing and fading	ITU InH IEEE	ITU InH IEEE
UE dropping	Randomly dropped and within small cell coverage	Randomly dropped and within small cell coverage
UE noise figure	9 dB	9 dB

two WiFi operators coexist (named WiFi-WiFi Case or W+W). Thus, W+W case is compared to the same environment but where LAA eNodeBs replace the Access Points (APs) from one of the WiFi operators identified as the Wifi+LAA or W+L case. As a result, fairness can be measured based on a performance comparison with a scenario where at least two WiFi operators coexist (W+W), with another where APs from one of the WiFi operators are substituted by LAA eNodeBs (W+L).

In this way, the ratio of UPT comparison (see Eq. 1) establishes the reference W+W case in the denominator, meaning that to achieve fairness it has to be higher than the unit, otherwise implies the introduction of LAA eNB negatively impacts WiFi.

$$\rho_{upt} = \frac{\overline{\mathbf{UPT}}\,(\text{WiFi})_{W+L}}{\overline{\mathbf{UPT}}(\text{WiFi})_{W+W}}. \tag{1}$$

On the other hand, regarding delay fairness ratio (Eq. 2), W+W performance in the numerator means that in case the ratio is smaller than the unit, the delay has deteriorated when coexisting. Thus, a value larger than 1 indicates an improvement (less delay) with respect to W+W considering it fairer.

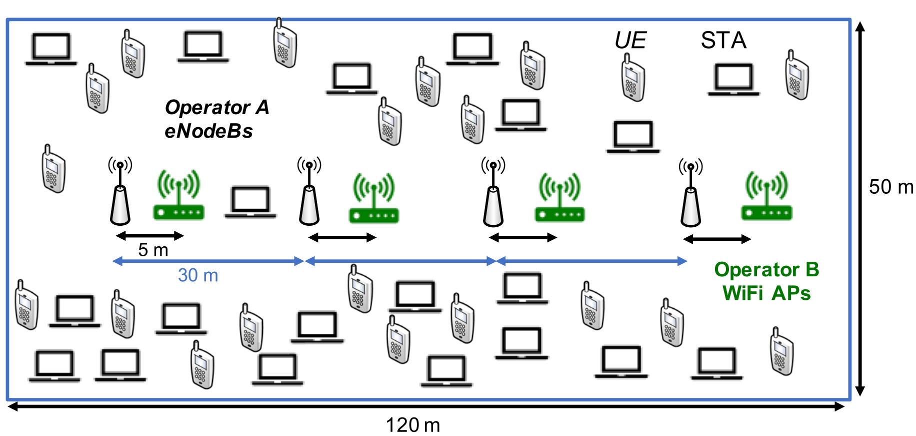


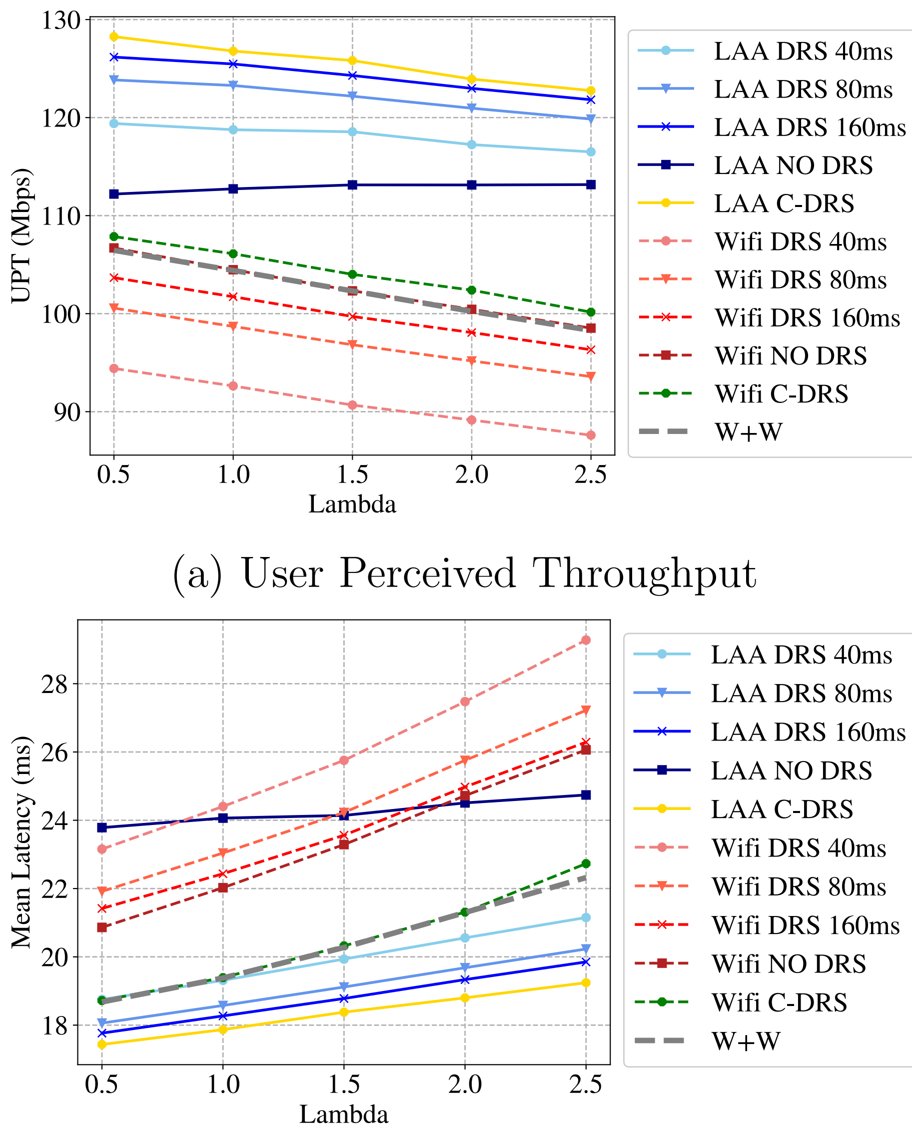
Fig. 1 Ultra-dense indoor coexistence scenario

$$\rho_{lat} = \frac{\overline{\mathbf{Lat}}(\text{WiFi})_{W+W}}{\overline{\mathbf{Lat}}(\text{WiFi})_{W+L}}. \tag{2}$$

4.1 Simulation and scenario

To have a realistic system model of both technologies, the widely used ns3 simulator [16] has been chosen. This tool is extensively applied within the field of wireless networks research and development for all kind of analysis. Particularly, its WiFi and LTE modules have been commissioned by relevant stakeholders of the industry, providing a very complete and faithful multilayer simulation of both technologies.

The modeled ultra-dense indoor environment is the one proposed by 3GPP to perform coexistence assessments [12]. Such standard establishes the transmission power determined by ETSI for simulated equipment (18 dBm), the bandwidth (20 MHz), and the shared downlink channel (5180 MHz) used by both technologies, as well as the channel access parameters as determined by the standardization bodies in each case (e.g., ED Threshold, Maximum Transmission Time, Slot Time) presented in Table 2. The simulated channel model corresponds to Indoor Hotspot or InH [12] as stated by 3GPP.

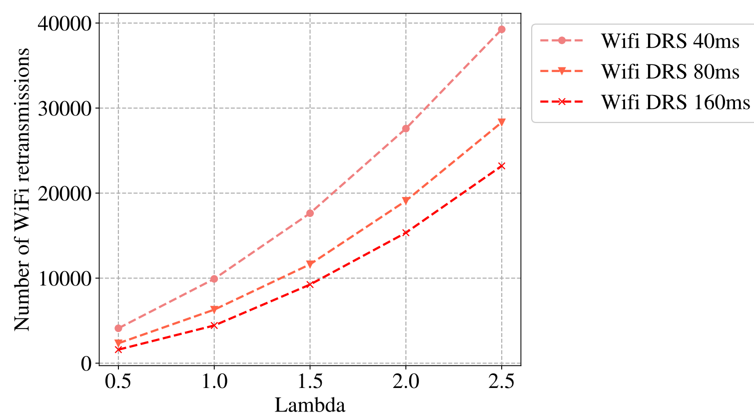


(b) Mean end to end Latency

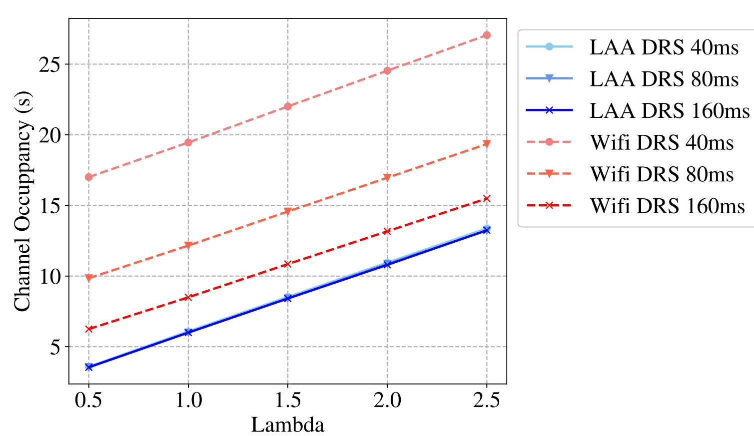
Fig. 2 Performance comparison of the different signaling approaches

As represented in Fig. 1, the simulated scenario covers an area of 120 × 50 m where two operators are running four WiFi 802.11n APs and four LAA eNodeBs (or four additional WiFi in the W+W case), respectively. Connected to these base stations, twenty users per operator are randomly placed all over the layout. The simulated traffic is File Transfer Protocol (FTP) model I with 0.5 MB file size as described in the 3GPP coexistence assessment [12]. According to this model, the service requests follow a Poisson distribution with *lambda* intensity ranging from 0.5 to 2.5 (file transmission requests per second per operator). A separate file generation mechanism controlled by lambda (i.e., traffic load) is introduced in each operator network, and all files originate from a server in the network backhaul to one of the users (STA/UE). Concerning the performance evaluation, both described KPIs (UPT and Mean Delay) have been calculated at the Internet Protocol (IP) layer with a packet size of 1480 bits and have been averaged over 50 random user distributions with 500 s duration runs each.

The main configuration details described in Table 2 have been defined following the 3GPP indications as well as the most common parameters used both in the bibliography and expected in the considered scenario [14]. In this way, all LAA eNodeBs are set according to parameters established by LBT CAT4 priority 3, which is defined for best-effort traffic [14] as the most appropriate option for FTP traffic. On the Radio Link Control (RLC) layer, acknowledged mode (AM) and proportional fair (PF) scheduling schemes are established. Lastly, the transmissions of both LAA and WiFi implement MIMO 2 × 2 and 64-QAM with code rate 0.9258 as the most complex available constellation corresponding to a value of MCS 28.



(a) Number of WiFi Retransmissions



(b) WiFi/LAA channel occupancy

Fig. 3 DRS periodicity impact

4.2 Impact of DRS measurement timing configuration

The performance of the presented scenario (W+L) is assessed for all the DMTC allowed by the standard (40, 80, and 160 ms) and for various levels of traffic demand as shown in Fig. 2. By comparison of all standard signaling configurations, it can be observed that more frequent DRS transmissions (particularly for the 40-ms DMTC) degrade both latency and UPT for LAA. It is also noticeable how WiFi suffers a significant performance degradation specially with higher DRS frequencies.

Such adverse impact is caused due to the rise in the number of collisions produced in the channel when stand-alone DRS are delivered, making WiFi stations to increase their retransmissions as it can be observed in Fig. 3a. Then, once the airtime is saturated with these retransmissions, both technologies are negatively affected (Fig. 3b)

Each time an eNodeB transmits a stand-alone DRS with a duration of 1 ms, it usually does so in the time between transmissions from other Access Points. If they are far enough away, they may suffer the effect of "hidden nodes" [17] and try to transmit in that time interval. The interference caused activates the retransmission mechanism of the WiFi AP that tries to retransmit the interfered frame over and over again, feeding back new collisions. Thus, both technologies suffer a decrease in end-to-end perfor-

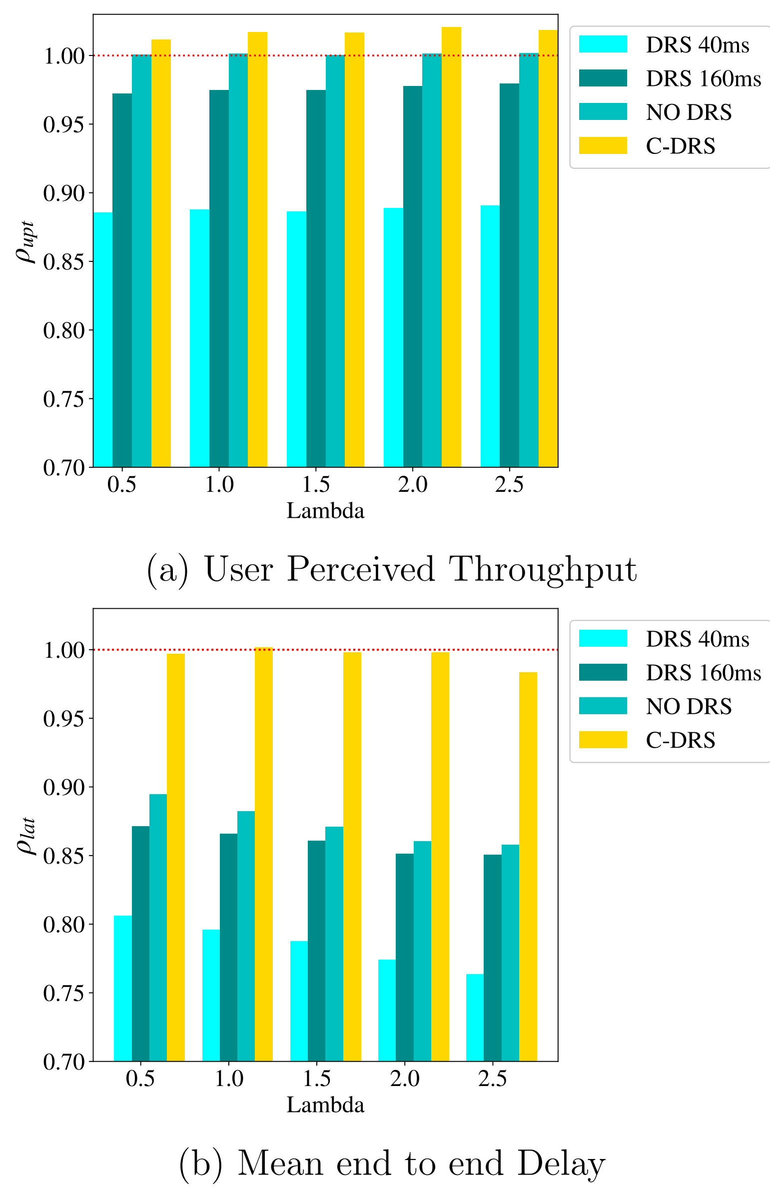


Fig. 4 Fairness comparison

mance that can be clearly spotted in Figs. 3 and 4 (static and mobility enabled scenarios, respectively).

Moreover, to fully assess coexistence impact with a more detailed view, fairness should be analyzed. To that end, as evidenced in Fig. 2, the latency deteriorates in the W+L coexisting case in comparison to W+W. Such degradation is mainly due to differences in their allowed transmission times (LAA MCOT versus WiFi TxOP) depending on each technology specifications. As stated in the standard, LBT CAT4 priority 3 has an MCOT duration of 8 ms; meanwhile, WiFi best-effort traffic does not have a fixed time, but its transmissions are considerably shorter (less than 1 ms per IP packet for [18]). In this way, longer granted transmission times will tend to be more inherently more unfair than the ones occupying less airtime.

4.3 Impact of DRS suppression

Given the intrinsic unfairness of the standard signaling in downlink shared channel, the need for improved schemes with respect to the ones considered is pointed out. As a first approach, to avoid the collisions produced by standalone DRS and reducing the negative effect on the coexistence with WiFi, their suppression (i.e., not transmitting them) is proposed.

This scheme (also named as “NO DRS” case) impacts two functions of stand-alone DRS: the support to coarse synchronization and the channel quality measurement. On the former, since synchronization is not considered its main functionality and having also the support of the licensed link, no impacts are envisaged in this regard [19]. Considering the latter, the absence of CQI feedback implies that the eNodeB starts to send data with the lowest MCS for every LBT MCOT transmission. This can be observed in Fig. 5 where the MCS histogram is displayed for the cases with DRS enabled (Fig. 5a) and supressed (Fig. 5b), showing a predominance of the lowest MCS when DRS are not present. Once the MCOT and the associated data transmission has started, the UE will be able to estimate the channel through the CRS signals embedded in the data transmission itself [20]. Then, a MCS matching the state of the channel will be assigned. However, if no other adjustment is made, this “Slow Start” will be repeated for every MCOT sent (see Fig. 6), thus implying an increase in the transmission time and channel occupancy for the same amount of data (see Fig. 3b). As shown in Fig. 2 (“LAA NO DRS” case), this implies a UPT decrease and a delay increase in LAA, resulting in a worse performance compared to the previous DRS periodicity configuration cases.

Figure 2 shows that the performance of DRS suppression is less sensitive to the traffic intensity, approaching the one obtained by DRS-enabled configurations for high traffic situations. This is due to the fact that having a higher number of data transmissions in the downlink

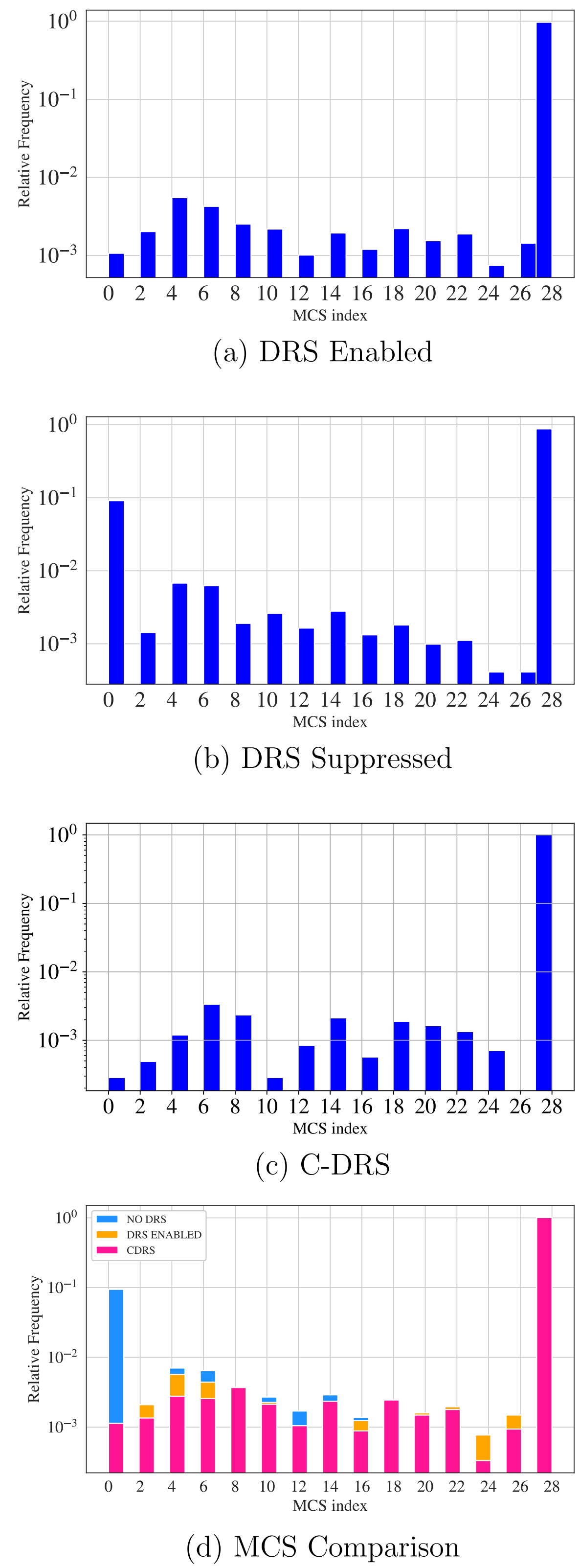


Fig. 5 MCS histogram DRS impact analysis

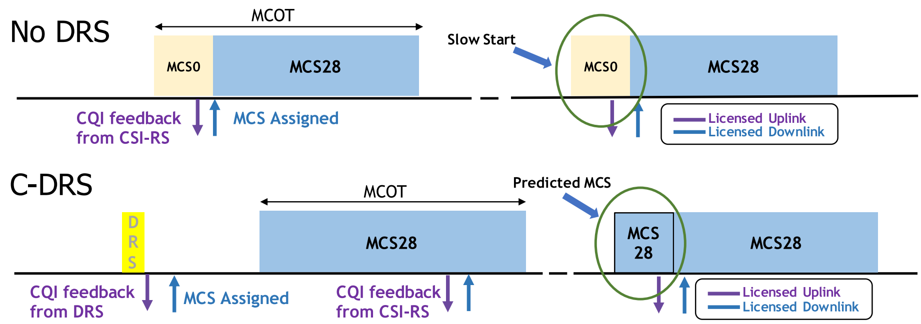


Fig. 6 Proposed CDRS compensation method

(including their embedded CRS) avoids the "need" for DRS stand-alone transmissions, and thus alleviating the "Slow Start" degradation. In terms of fairness, the suppression of DRS is a better approach than any of the standard periodicities as it minimizes the impact on WiFi reaching a more similar performance with respect to W+W scenario.

In short, the coexistence fairness with WiFi is improved but at the cost of worsening LAA performance (see Fig. 4a, b). Therefore, it is necessary to find a compromise solution to enhance LAA performance at the minimum or zero negative impact on WiFi when both technologies experience high traffic demand. Furthermore, it should be noted that in case of non-dense coexistence (e.g., scenario with 2 AP/eNodeB with 4 users each), the negative effects on the WiFi are not expected to be as significant since it decreases both the probability of hidden nodes and the total number of sent stand-alone DRS.

5 DRS modification to improve performance and fairness: C-DRS

The proposed solution to overcome the impact of suppressing DRS signals during dense coexistence (even with low load traffic) aims to tackle directly the "Slow start" effect described in Fig. 6: When stand-alone DRS are disabled ("NO DRS" case), each transmission determined by MCOT sent with the lowest MCS and once the CQI feedback is sent over the licensed uplink, the MCS value is updated. This effect occurs at the beginning of each LBT-based transmission affecting the overall performance. To avoid this harmful effect, a modification called Compensated DRS (C-DRS) covers the lack of channel estimation in "NO DRS" case assigning the last stored MCS for that particular UE at the beginning of every transmission performed in downlink. Thus, as presented in the "C-DRS" case from Fig. 6, instead of starting the transmission with the lowest index, an MCS matching the last perceived channel condition is assigned.

Assuming the low mobility that characterizes the 3GPP indoor scenario [21], such assignment should not lead to a high number of losses in the transmissions and the SINR value would remain close to the previous ones. However, in case of fast changing channel conditions in a high loaded scenario if the assigned MCS does not match the SINR level, some losses might happen (Fig. 7a). Nevertheless, once the transmission of user data over the shared channel has been established, the MCS is promptly readjusted based on the CSI-RS signaling embedded in the user-plane downlink data. Moreover, when losses reach 80% of NACKs at RLC layer, the stand-alone DRS opportunistic transmission mechanism is re-enabled with 160 ms period. It is worth noting that C-DRS method does not introduce any extra degree of complexity since the mechanism only needs to store the last CSI feedback or keep its validity until next CSI feedback arrival. The impact on WiFi is then reduced while improving LAA performance by means of a better CQI estimations (Fig. 7b). If there is no licensed uplink channel for signaling, blind estimation should be used or it should be sent through the common unlicensed uplink channel via LBT.

In order to fully assess the benefits of the proposed C-DRS modification, all the performance results have been re-evaluated to cover all the casuistry associated to the proposed coexistence scenario. Simulations have been carried out with different numbers of base stations per operator (1, 4) and with different user ratios per BS (1:1, 20:1). In addition, two different load situations have been taken into account, one with low load (lambda = 0.5) and another with high load (lambda = 3). In this way, it is possible to determine when it is most advantageous to use the various signaling configurations proposed. Furthermore, these scenarios have in turn been evaluated under two mobility conditions: a static one where users do not change their initial random position (Figs. 8, 10, 12, and 14) and another with enabled mobility where users follow a RandomWalk2D model [22] with 3 km/h user speed [21] (Figs. 9, 11, 13, and 15).

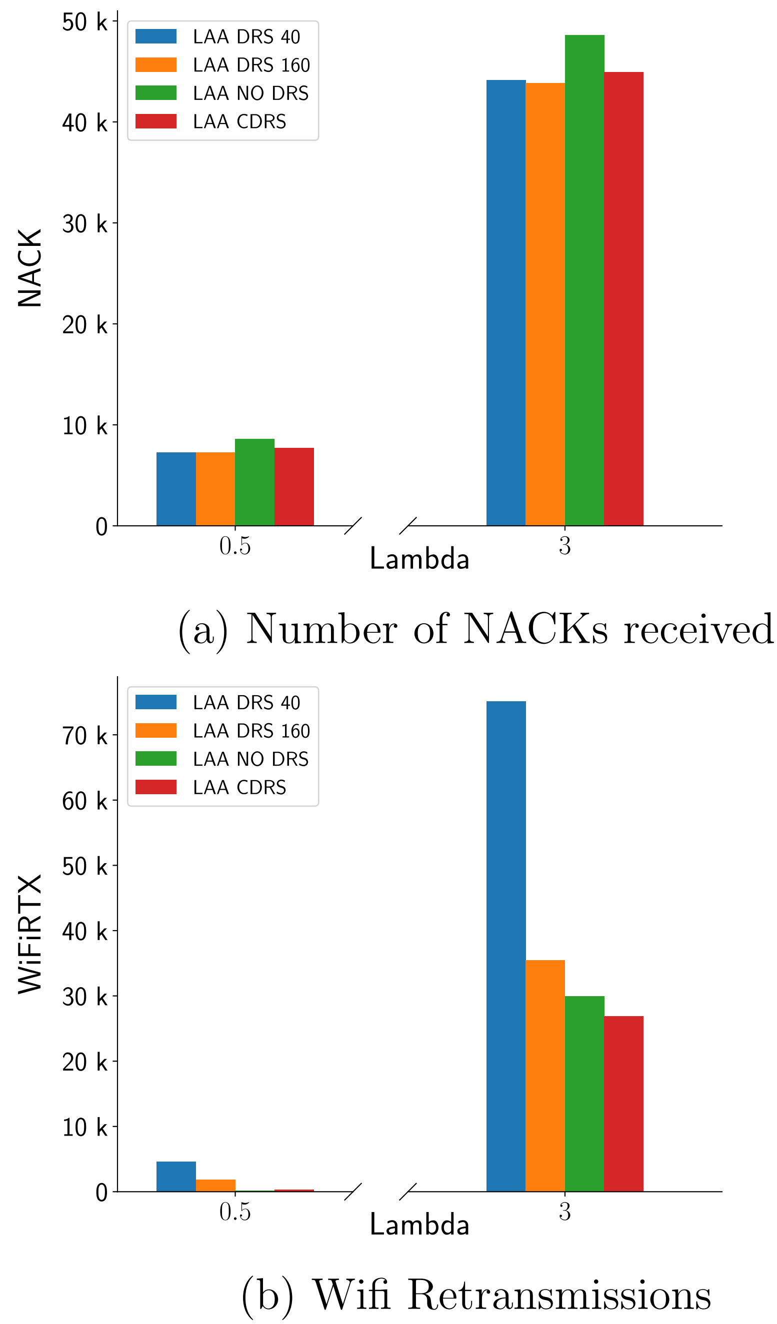


Fig. 7 Collision analysis

5.1 Density impact

In general, the coexistence has better fairness properties in low density environments with low load (Figs. 12a, c and 14a, c) than in high loaded and dense (Figs. 12b and 14b). The reason behind is a more intensive use of the channel and the diversity of relative positions between users making the collision probability more significant. In most scenarios, the fairness of CDRS modification is equal or higher than the rest due to a reduction in collision probability caused by the reduction of the DRS sent-alone signals (Fig. 4a, b). When density is low, a similar behavior is maintained regardless of its load condition (Figs. 8a, 9a, 10a, and 11a). All DRS configuration options offer similar performance since the fewer terminals are operating the less collision probability. Thus, in case of high load and density, an improvement is shown when “NO DRS” and “C-DRS” (Figs. 8d and 9d) are applied.

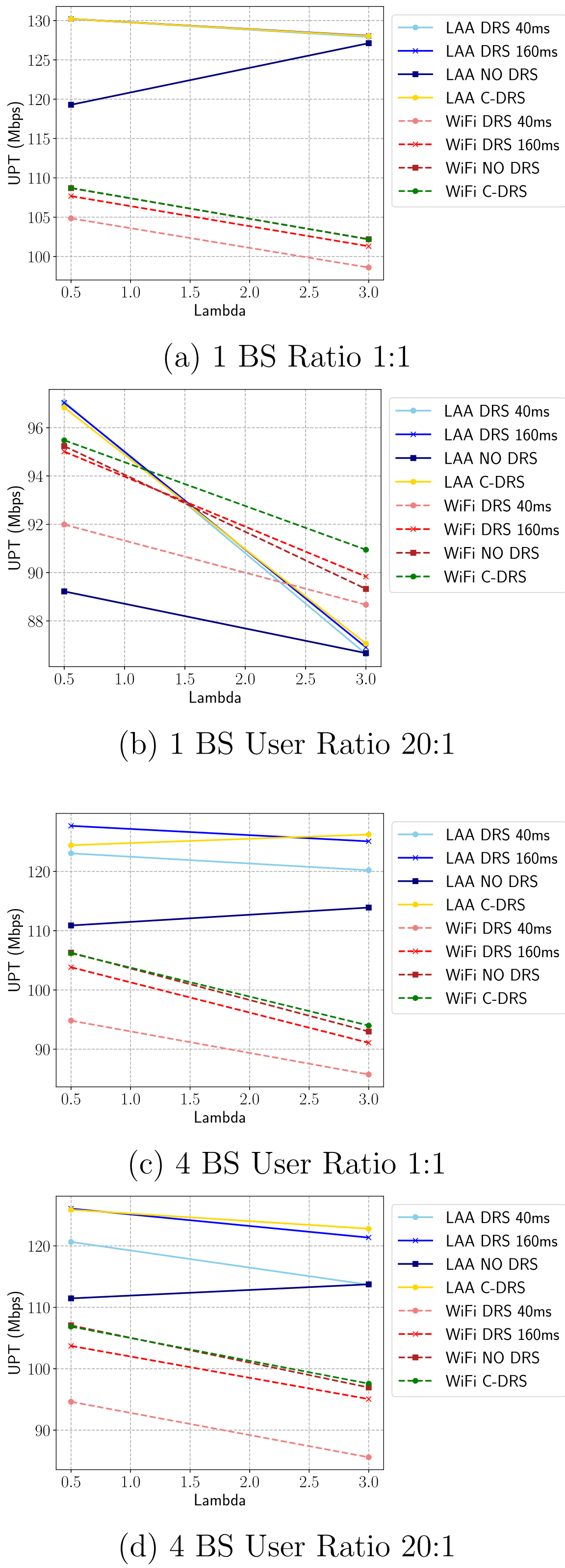


Fig. 8 Static scenario density UPT results

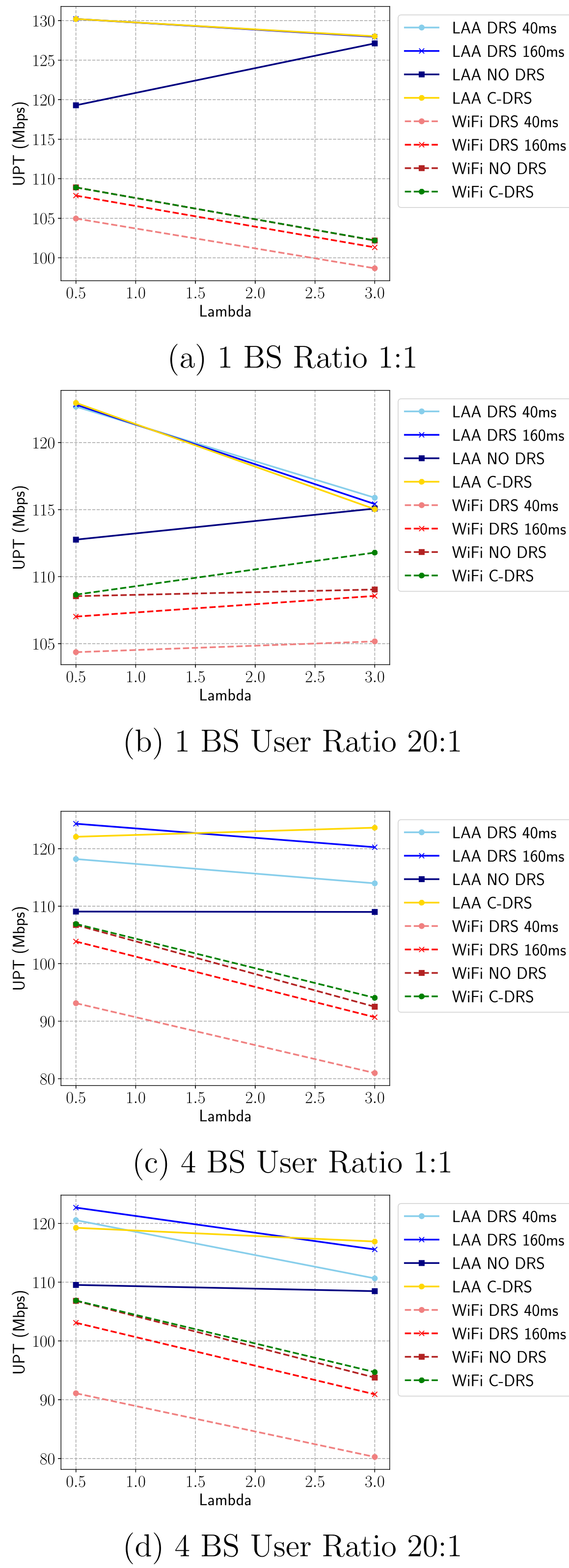


Fig. 9 Scenario density UPT results (ped. mobility)

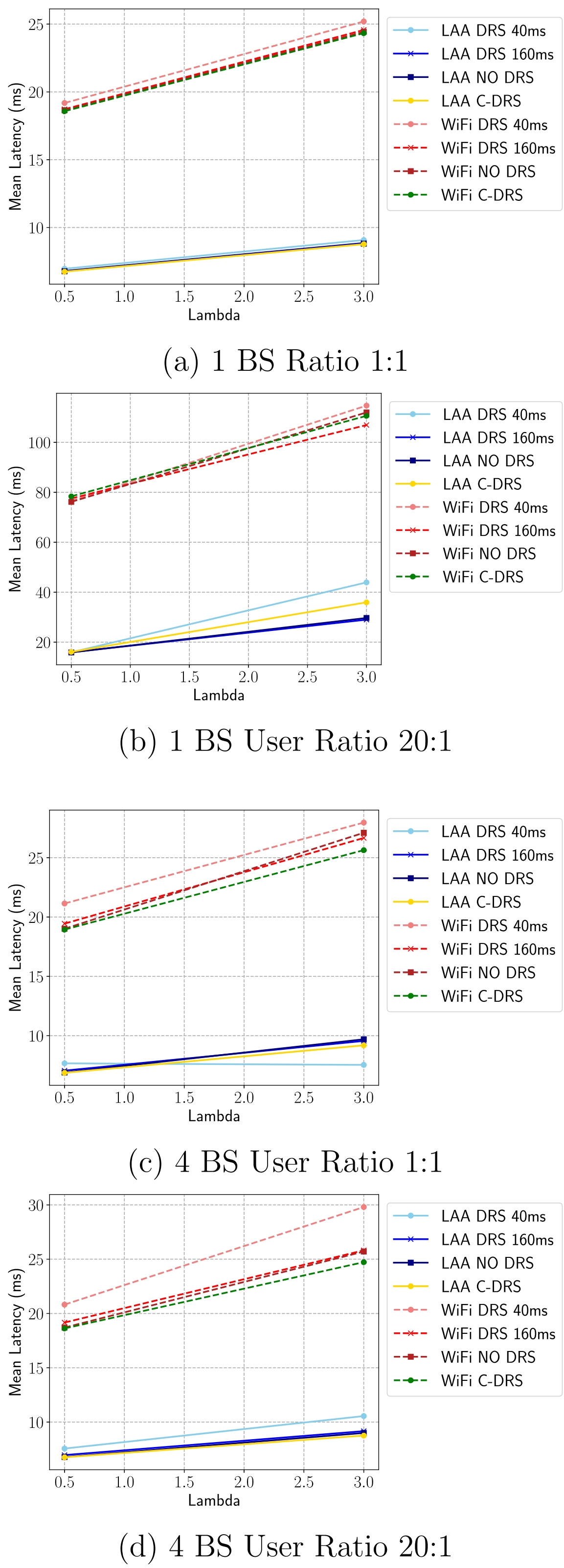


Fig. 10 Static scenario latency density results

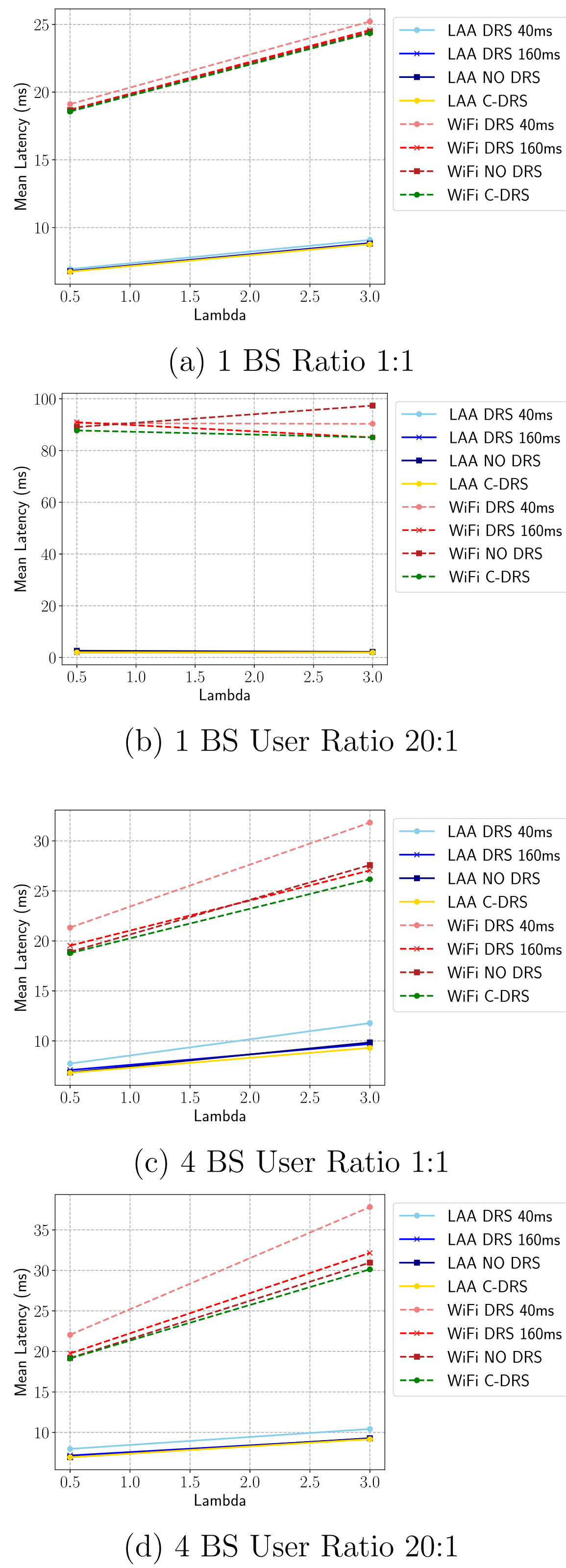


Fig. 11 Scenario density latency results (ped. mobility)

As the number of users increases, it is observed that the behavior is increasingly different, especially concerning fairness degree and LAA performance. The option with the lowest fairness performance (Figs. 12b, 13b, 14b, and 15b) is produced when there are few BSs with a high traffic load. In such a case, the collision probability is considerably increased due to the rise in the number data transmissions (the channel is more saturated) without a reliable mechanism to detect the hidden nodes of another technology.

Last but not least, the performance of C-DRS with respect to the impact over WiFi analyzed in Fig. 7 is revealed to a greater or lesser extent in any scenario. In particular, when there is a high density, its improvement with respect to the rest of the signaling options is much more remarkable (Figs. 12, 13, 14, and 15).

5.2 Mobility impact

According to the results obtained from simulations, mobility has a rather limited impact in the scenarios proposed. Especially when there are few BSs, the coexistence affects each technology in a different manner (Figs. 9 and 11). Moreover, being a WiFi protocol which is more adapted to the contention channel, it better responds in static environments since it does not implement handovers (Figs. 8a, b and 9a, b). This is particularly evident when there is a high load and density in with fewer BSs (Fig. 8b). However, the most noticeable effect introduced by the mobility is the gain margin introduced by C-DRS with respect to the rest of the options. In this case, such margin is reduced by the CQI mismatch produced when UEs are moving around (Figs. 9c, d and 11c, d).

In general terms, as traffic load increases, the throughput decreases almost linearly in both LAA and WiFi thus raising its average latency. When the mobility scenario is enabled as shown in Figs. 9 and 11, the results present a very similar trend compared to the static scenario at a lesser degree of accuracy. This is mainly due to mismatches in the channel state measurements taken when DRS are not present ("NO DRS" case) or being estimated (C-DRS case). This effect can be better verified in Fig. 5c, d where the MCS histograms show a higher MCS allocation. On the basis of fairness evaluation (Fig. 4), the C-DRS method achieves better WiFi UPT (Fig. 4a) and a lower latency (Fig. 4b) compared to W+W case for all the different traffic conditions. With enabled user mobility, we see that the fairness ratio is reduced compared with the static case. However, C-DRS modification outperforms other methods in terms of both throughput (Fig. 13) and latency (Fig. 15).

To sum up, applying the proposed C-DRS modification in the 3GPP coexistence scenario, there is a 10% performance improvement over the worst case of standard DRS

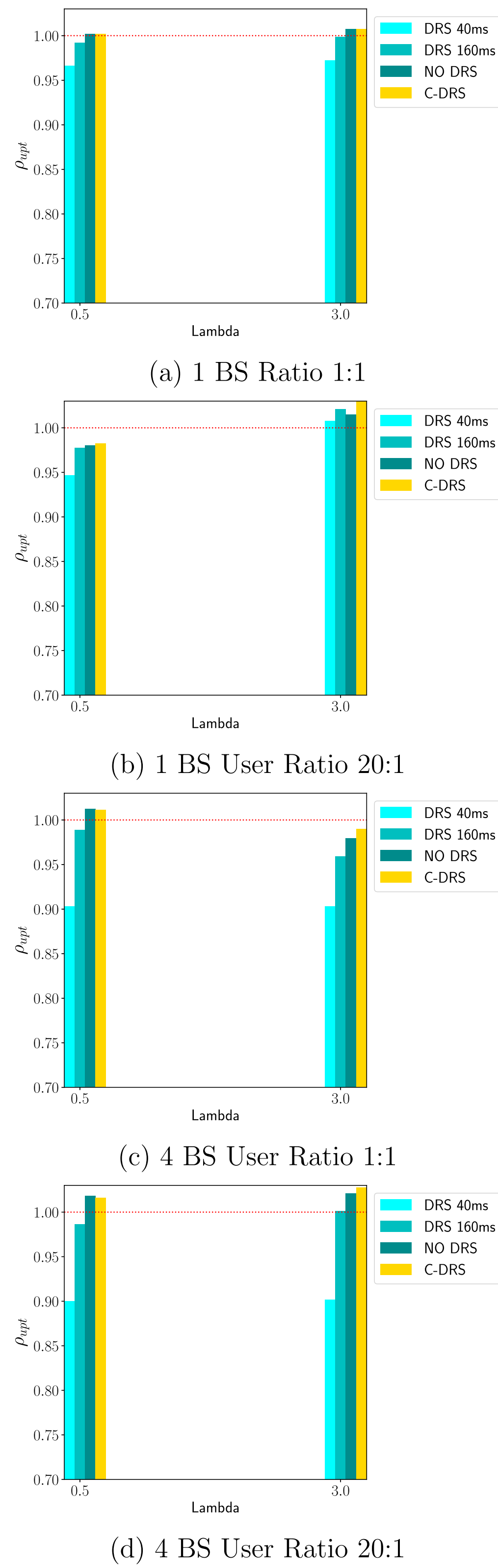


Fig. 12 Static scenario density UPT fairness results

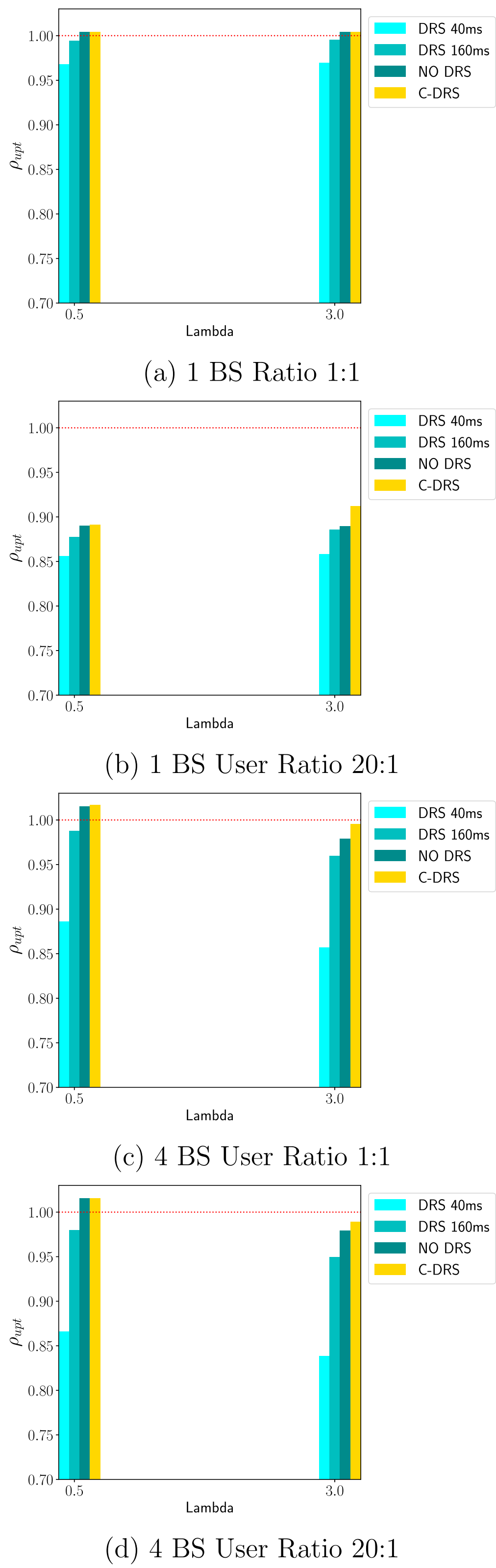


Fig. 13 Scenario density UPT fairness results (ped. mobility)

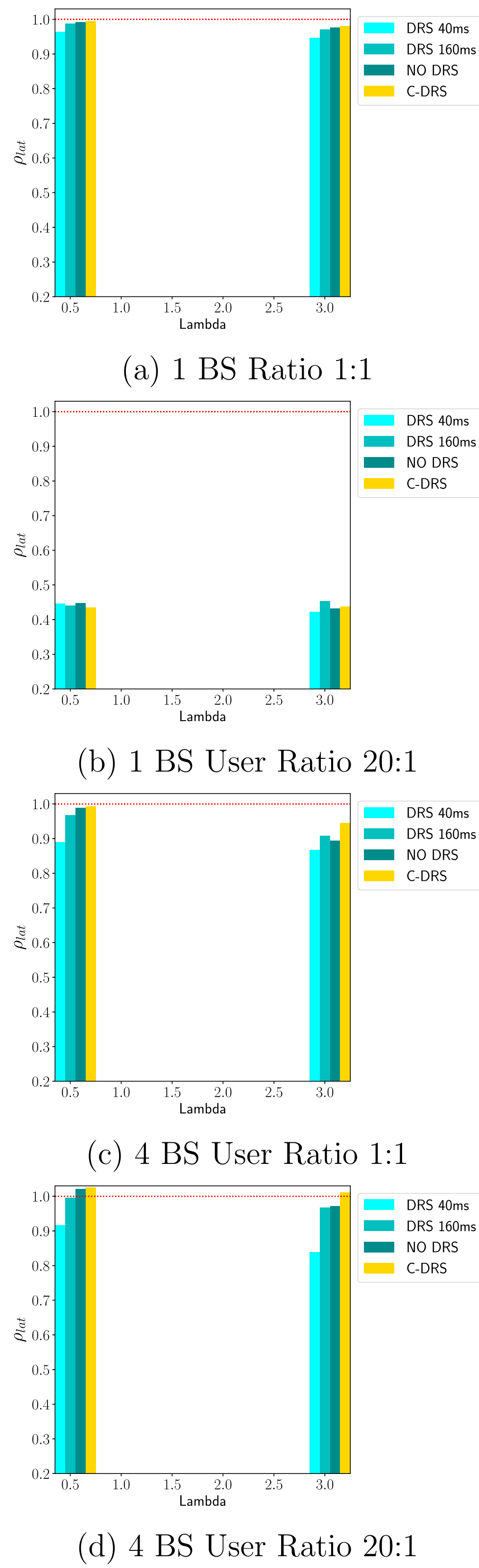


Fig. 14 Static scenario density delay fairness results

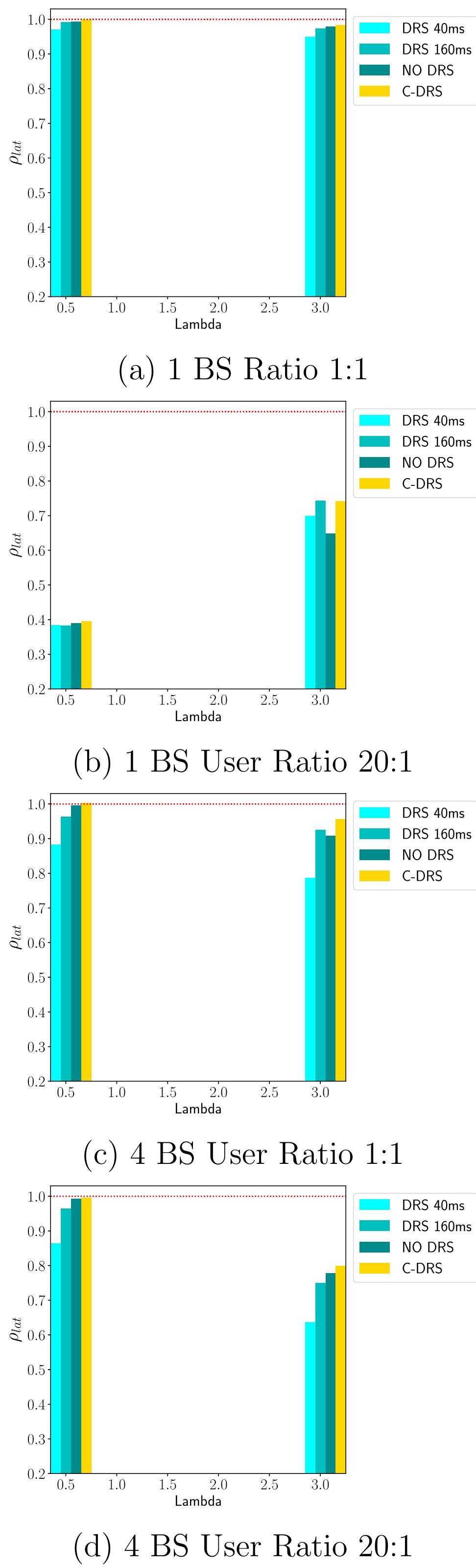


Fig. 15 Scenario density delay fairness results (ped. mobility)

signaling configuration (Fig. 2) and an increase of up to 25% in fairness (Fig. 4).

6 Conclusions and outlook

This research paper has assessed the coexistence issues of LAA and WiFi in 5G ultra-dense scenarios, with a specific focus on the impact of signaling in the shared downlink channel. Given the deficiencies identified in LAA signaling standard in terms of fairness towards WiFi and performance, different approaches have been proposed. As a first alternative, it has been shown how the suppression of periodic stand-alone DRS can improve fairness towards WiFi at the expense of producing a degradation of LAA performance.

To avoid this adverse effect, a modification of the shared channel signaling called C-DRS has been proposed and described. Its application results in a better assignment of the MCS than the one made with the standards defined for LAA. Thus, it has been depicted how this method shows better results both in terms of LAA performance and fairness towards WiFi that could be applied in indoor ultra-dense coexistence scenarios which have been proved to be specially beneficial. This mechanism has proven to improve LAA performance by 10% and fairness with respect to WiFi by 25%.

Further works would consider additional dynamic environmental conditions to drive further coexistence optimizations of the signaling in the physical downlink shared channel which may be applied for future standards operating in unlicensed bands. These include the application of directional LBT methods for mmwaves [23] or the use of contention methods for the uplink signaling channel as in NR-U stand-alone mode.

Abbreviations

3GPP: 3rd Generation Private Public Partnership; ACK: ACKnowledgement signal; AM: Acknowledged mode (RLC); AP: Access Point; BS: Base station; CCA: Clear Channel Assessment procedure; CQI: Channel quality indicator; CSI: Channel State Information; CSI-RS: Channel State Information Reference Signal; CRS: Cell-specific Reference Signal; C-DRS: Compensated Discovery Reference Signal; CSMA/CA: Carrier Sense Multiple Access with Collision Avoidance; CW: Contention window; DCI: Downlink control information; DMTC: DRS measurement timing configuration; DRS: Discovery Reference Signal; eCCA: Enhanced Clear Channel Assessment procedure; eLAA: Enhanced Licensed Assisted Access; eNodeB: LTE base station; ETSI: European Telecommunications Standards Institute; FeLAA: Further Enhanced Licensed Assisted Access; FTP: File Transfer Protocol; HARQ: Hybrid automatic repeat request; KPI: Key Performance Indicator; LAA: Licensed Assisted Access; LBT: Listen Before Talk; LTE: Long-Term Evolution; MCOT: Maximum Channel Occupancy Time; MCS: Modulation and coding scheme; MIMO: Multiple input multiple output; NACK: Negative-ACKnowledgement signal; NR-U: 5G New Radio Unlicensed; OFDM: Orthogonal frequency division multiplexing; PF: Proportional fair; PDSCH: Physical downlink shared channel; RLC: Radio Link Control; RRM: Radio Resource Management; SRS: Sounding reference signal; SINR: Signal-to-interference-plus-noise ratio; STA: WiFi station; TxOP: Transmission opportunity; UE: User Equipment; UPT: User Perceived Throughput; WiFi: Wireless fidelity (i.e 802.11 standards)

Acknowledgements

This work has been carried out in the framework of the Horizon 2020 project ONE5G (ICT-760809) receiving funds from the European Union. The authors would like to acknowledge the contributions of their colleagues in the project, although the views expressed in this contribution are those of the authors and do not necessarily represent the project.

Authors' contributions
E.B developed the simulator add-ons, carried out the simulations, proposed the solution, and wrote the manuscript. S.F contributed to the interpretation of the results and review of the manuscript. R.B reviewed the manuscript and supervised the project. The authors read and approved the final manuscript.

Funding
This work is partially funded by Junta de Andalucía (Research Project of Excellence P12-TIC-2905) and the Ministry of Economy and Competitiveness (TEC2015-69982-R).

Availability of data and materials
The data and source code that support the findings of this study are available from the corresponding author, upon request.

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

Received: 13 October 2019 Accepted: 2 October 2020
Published online: 02 November 2020

References

1. 3GPP news, Evolution of LTE in release 13 (2015). http://www.3gpp.org/news-events/3gpp-news/1628-rel13
2. RP-170848, 3GPP TSG RAN 75 Meeting, New Work Item on enhancements to LTE operation in unlicensed spectrum (Release 15) (2017)
3. Multefire, MulteFire Release 1.1 Technical Overview. White paper, MulteFire Alliance (2018). https://www.multefire.org/wpcontent/uploads/MulteFire_Release-1.1_WhitePaper_03DEC2018.pdf. Accessed 15 Jan 2020
4. Feasibility Study on 6 GHz for LTE and NR in Licensed and Unlicensed Operations (Release 16), Standard 3GPP TR 37.890, V0.7.0 (2019)
5. K. M. Metwaly, K. G. Seddik, M. Y. ElNainay, in *2017 IEEE Wireless Communications and Networking Conference (WCNC)*. A Cooperative Scheme for the Coexistence of the LTE and WiFi Systems, (San Francisco, 2017), pp. 1–6. https://doi.org/10.1109/WCNC.2017.7925657
6. A. Mukherjee, J. Cheng, S. Falahati, H. Koorapaty, D. H. Kang, R. Karaki, L. Falconetti, D. Larsson, Licensed-assisted access lte: coexistence with ieee 802.11 and the evolution toward 5g. IEEE Commun. Mag. **54**(6), 50–57 (2016)
7. M. Maule, D. Moltchanov, P. Kustarev, M. Komarov, S. Andreev, Y. Koucheryavy, Delivering fairness and qos guarantees for lte/wi-fi coexistence under laa operation. IEEE Access. **6**, 7359–7373 (2018)
8. N. Bitar, M. O. Al Kalaa, S. J. Seidman, H. H. Refai, On the coexistence of LTE-laa in the unlicensed band: modeling and performance analysis. IEEE Access. **6**, 52668–52681 (2018)
9. B. Bojovic, L. Giupponi, Z. Ali, M. Miozzo, Evaluating unlicensed LTE technologies: LAA vs LTE-U. IEEE Access. **7**, 89714–89751 (2019)
10. J. Zhang, M. Wang, M. Hua, T. Xia, W. Yang, X. You, Lte on license-exempt spectrum. IEEE Commun. Surv. Tutorials. **20**(1), 647–673 (2018)
11. J. Xu, Y. Sun, Y. Ji, Y. Tian, in *2016 International Conference on Networking and Network Applications (NaNA)*. A Time and Frequency Division Algorithm for Control Signaling Collision Avoidance in Standalone LTE-unlicensed Networks, (Hakodate, 2016), pp. 12–16. https://doi.org/10.1109/NaNA.2016.34
12. Study on NR-based access to unlicensed spectrum (Release 15), Standard 3GPP TR 38.889, V13.0.0 (2018)
13. G. Bianchi, Performance analysis of the ieee 802.11 distributed coordination function. IEEE J. Sel. Areas in Commun. **18**(3), 535–547 (2000). https://doi.org/10.1109/49.840210
14. 3GPP, Physical layer procedures for shared spectrum channel access. Technical specification (TS) 37.213, 3rd Generation Partnership Project (3GPP) (2020). https://www.3gpp.org/ftp//Specs/archive/37_series/37.213/37213-g30.zip. Accessed 15 Jan 2020. Version 16.3.0
15. B. Bojovic, L. Giupponi, Z. Ali, M. Miozzo, Evaluating unlicensed LTE technologies: LAA vs LTE-u. IEEE Access. **7**, 89714–89751 (2019). https://doi.org/10.1109/ACCESS.2019.2926197
16. G. F. Riley, T. R. Henderson, in *Modeling and Tools for Network Simulation*. The ns-3 network simulator (Springer Berlin Heidelberg, 2010), pp. 15–34
17. M. J. Saeed, M. Merabti, R. J. Askwith, Hidden and Exposed Nodes and Medium Access Control in Wireless Ad-Hoc Networks. presented at PGNet2006 (2006)
18. IEEE Computer Society LAN MAN Standards Committee, Wireless LAN medium access control (MAC) and physical layer (PHY) specifications. IEEE Standard. **802**, 11 (1999)
19. Q. Wang, C. Mehlführer, M. Rupp, in *21st Annual IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC 2010)*. Carrier frequency synchronization in the downlink of 3GPP LTE (IEEE, Istambul, 2010)
20. M. Meidlinger, Q. Wang, in *Proc of the 19th International Conference on Systems, Signals and Image Processing (IWSSIP 2012)*. Performance evaluation of LTE advanced downlink channel estimators, (Vienna, 2012), pp. 252–255
21. M. Maternia, et al., 5g ppp use cases and performance evaluation models. 5G PPP, Whitepaper, vol. 1 (2016)
22. T. Camp, J. Boleng, V. Davies, A survey of mobility models for ad hoc network research. Wirel. Commun. Mob. Comput. **2**(5), 483–502 (2002). https://doi.org/10.1002/wcm.72
23. N. Patriciello, S. Lagén, B. Bojovic, L. Giupponi, Nr-u and ieee 802.11 technologies coexistence in unlicensed mmwave spectrum: models and evaluation. IEEE Access. **8**, 71254–71271 (2020)

Publisher's Note