Novel LAA Waiting and Transmission Time Configuration Methods for Improved LTE-LAA/Wi-Fi Coexistence over Unlicensed Bands

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ABSTRACT Long Term Evolution-Licensed Assisted Access (LTE-LAA) has been pointed out as a key solution to cope with the increasing amounts of data traffic and the scarcity of the licensed spectrum. The 3rd Generation Partnership Project (3GPP) has standardised LAA to operate over the 5 GHz unlicensed spectrum which is mainly occupied by Wi-Fi. It is a challenging problem to ensure a fair coexistence between these technologies. Several studies have been proposed in the literature to allow a fair LAA/Wi-Fi coexistence. In this work, various methods are proposed to adapt/select the waiting times for LAA based on the activity statistics of the existing Wi-Fi network. The main novelty is that the knowledge of the existing Wi-Fi activities is exploited to tune the boundaries of the Contention Window (CW) for LAA and to select fixed waiting times for LAA. Moreover, a dynamic method is proposed to adapt the Transmission Opportunity (TxOP) times for LAA based on the Hybrid Automatic Repeat Request (HARQ) feedbacks. The methods are evaluated using ns-3 network simulator based on the 3GPP fairness definition. We show that selecting fixed waiting times for LAA based on the existing Wi-Fi activities is more friendly to the existing Wi-Fi and provides better total aggregated throughputs for both coexisting networks compared to the 3GPP Category 4 Listen Before Talk (Cat 4 LBT) algorithm. Moreover, the proposed dynamic TxOP method is more friendly to the existing Wi-Fi and provides better total aggregated throughputs compared to the fixed TxOP period approach of the 3GPP Cat 4 LBT scheme.

INDEX TERMS Licensed assisted access, LTE/Wi-Fi coexistence, ns-3, Unlicensed spectrum, Wi-Fi.

I. INTRODUCTION

UNLICENSED spectrum bands have inspired researchers as a promising solution for the licensed spectrum shortage given the current exponential increase in demand for wireless data and services. The licensed spectrum is scarce and costly, and no longer provides simple ways to increase the mobile networks capacities. A significant amount of spectrum of approximately 600 MHz is available for various purposes over the unlicensed 5 GHz band [1], [2]. This unlicensed available spectrum has recently attracted the industry and researchers to be utilised for Long Term Evolution (LTE) deployments. Thus, LTE has been recently deployed to operate over unlicensed bands

providing enhanced mobile networks capacities [3], [4]. This same concept is likely to be introduced as well in the future 3GPP specification for 5G New Radio Unlicensed (5G NR-U) and therefore still constitutes a research topic of recent interest [5], [6].

However, unlicensed spectrum bands are mainly occupied by Wi-Fi networks. Despite the fact that deploying LTE over unlicensed bands achieves higher throughput and more capacity, a few issues need to be considered while deploying these heterogeneous technologies (i.e., LTE and Wi-Fi) in a shared spectrum band [4], [7], since special attention needs to be paid to coordinate this coexistence over the same unlicensed spectrum band [8]. In particular, the difference

in the Medium Access Control (MAC) layers between LTE and Wi-Fi creates a challenging problem given that Wi-Fi follows a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) mechanism while LTE has no sensing scheme for transmission. Considering this heterogeneous coexistence between LTE and Wi-Fi, Wi-Fi may experience a lower opportunity to access the unlicensed channel since Wi-Fi nodes have to check the channel availability before transmitting their own data, thus potentially leading to a performance degradation for Wi-Fi [9], [10].

The key idea of coexistence between LTE and Wi-Fi networks over unlicensed bands is to increase LTE network capacity but not to degrade the performance of the existing (Wi-Fi) networks. As a result, different requirements need to be taken into account to design an unlicensed LTE such that it allows a fair coexistence with Wi-Fi over unlicensed bands. 3GPP TR 36.889 describes the "fairness" between the coexisting networks (i.e., LTE and Wi-Fi) over the unlicensed 5 GHz band as the ability of an LTE network not to impact the existing network (i.e., Wi-Fi) active on the same carrier more than an additional Wi-Fi network in terms of throughput and latency [4].

Two main approaches have been proposed in the literature to achieve a fair coexistence between these heterogeneous technologies [3], [4]. In particular, for some markets, such as Europe and Japan, a Listen Before Talk (LBT) protocol for Clear Channel Assessment (CCA) is required for accessing unlicensed bands, while in other markets, such as USA and China, there is no need for such protocol. LTE-Unlicensed (LTE-U), which does not need an LBT protocol, was the first version of LTE over unlicensed bands and was proposed by the industry consortium LTE-U Forum [11]. LTE-U was aimed at allowing a quick deployment of LTE networks in 5 GHz bands in those countries that do not require an LBT protocol by reusing mechanisms already available in the 3GPP standard. The three main mechanisms on which LTE-U relies are carrier selection, ON/OFF switching and Carrier Sense Adaptive Transmission (CSAT) to adapt the Duty Cycle (DC) of the transmissions [12], [13]. However, LTE-U is unable to fully meet the requirement of fair coexistence as defined in 3GPP TR 36.889. As a result, the 3rd Generation Partnership Project (3GPP) in Release 13 proposed LTE-Licensed Assisted Access (LTE-LAA) for Supplementary Down-Link (SDL) where an LBT protocol is required for transmission over unlicensed bands [4].

A. PREVIOUS RELATED WORK
Due to the increasing interest in spectrum sharing between LTE and Wi-Fi networks over unlicensed bands, various studies have been recently devoted to implement different spectrum sharing mechanisms enabling a fair coexistence between these two heterogeneous technologies. A comparison between the coexistence of LTE-U/Wi-Fi and LTE-LAA/Wi-Fi scenarios is provided in [14]. The simulation results show that coexisting LAA with Wi-Fi achieves better performance than deploying LTE-U with Wi-Fi over the un-

licensed 5 GHz band. A numerical analysis is performed for LTE and Wi-Fi networks in [15]. The numerical results show that coexisting both technologies over the same unlicensed band without any modification to the existing protocols can severely degrade the Wi-Fi performance. The impact of the DC parameter on LTE-U/Wi-Fi coexistence over unlicensed bands is studied in [16] where different blank subframes are deployed within the LTE-U frame allowing Wi-Fi transmissions. The simulation results show that by deploying more blank subframes over the LTE frame, a higher Wi-Fi throughput can be achieved. The performance of LTE-U/Wi-Fi coexistence is investigated in [17] by exploiting the knowledge of the activity statistics of the existing Wi-Fi network to select a fixed DC for LTE-U. The simulation results show that the total aggregated throughputs for the coexisting networks can be improved by selecting both the DC value and the location of the blank subframes of LTE-U based on the Wi-Fi activity statistics. In [18], an hyper access point (HAP) is proposed that allows LTE-U take advantage of the Wi-Fi point coordination function protocol by dedicating a contention-free period to LTE-U users and allowing a contention period for traditional Wi-Fi users. In [19], a listen-before-talk access mechanism featuring an adaptive distributed control function protocol is proposed, whereby the backoff window size is adaptively adjusted according to the available licensed spectrum bandwidth and the Wi-Fi traffic load to satisfy the quality-of-service requirements of small cell users and minimise the collision probability of Wi-Fi users.

On the other hand, the fairness of LTE-LAA/Wi-Fi coexistence has been widely studied in the literature [20]. An LTE-LAA module has been developed for ns-3 network simulator in [21] to investigate the performance of LTE-LAA/Wi-Fi coexistence scenario. The simulation results show that the fairness depends on the design parameters of the LBT algorithm for LAA. The work reported in [7] indicated that the transmission times of LTE evolved Node B (eNB) should be fixed at the beginning of the Distributed coordination function Inter-frame Space (DIFS) of Wi-Fi Access Point (AP) and the CCA period of LTE eNB should be shorter than DIFS period leading to no collisions between LTE and Wi-Fi networks. In [16] and [22], an LTE muting scheme is considered where LTE eNBs follow a predetermined muting pattern allowing the transmission of LTE nodes. The impact of the LBT design parameters for LTE-LAA/Wi-Fi coexistence is investigated in [23]. In particular, an alternative approach to increase the LAA Contention Window (CW) is proposed based on the observed number of free slots during a specific time interval. The results show that the standard algorithm outperforms the proposed one. An adaptive LBT scheme for LAA based on Markov chain model is proposed in [24]. Specifically, a partially-randomised initial Clear Channel Assessment (iCCA) scheme and an adaptive CW size scheme are considered for the LBT algorithm of LAA based on the detection by the LAA system. The simulation results

show that the proposed strategy is effective for LAA to achieve the fairness in the downlink scenario for LAA/Wi-Fi coexistence. A CW size adjusting method within an enhanced LBT algorithm of LAA is proposed in [25]. The CW size is adjusted based on the exchanged information from the neighbor nodes of the considered scenario. The simulation results show that the proposed scheme achieves better performance compared to the fixed scheme of LBT for the various coexistence scenarios. In [26], a fair downlink traffic management scheme is proposed for LAA/Wi-Fi networks to tune the minimum CW values and to assign feasible weights for LAA eNBs under different traffic loads. The simulation results show that the proposed scheme improves the aggregated utility of LAA/Wi-Fi networks but the Wi-Fi throughput decreases slightly compared to the static approach of minimum CW configuration. In [27], a CW adjustment method is proposed based on a simple gradient approach enabling a fair coexistence between LTE-LAA and Wi-Fi networks but the authors did not provide an analytical throughput model for the proposed method. An adaptive LBT algorithm is proposed in [28] where the different design parameters of LBT are adapted dynamically based on the varying traffic load and the CW size of the existing Wi-Fi system. In [29], a modified model to investigate the Energy Detection (ED) threshold of LAA is proposed. The numerical and experimental results show that the fairness between LTE-LAA and Wi-Fi networks depends on the channel access parameters such as ED threshold and Transmission Opportunity (TxOP) period of LAA. In [30], the fundamental trade-off between co-channel interference and collision probability is investigated and addressed by means of a power allocation rule with double water-filling lines, which achieves the complete set of Pareto optimal solution by means of the weighted Tchebycheff method. In [31], a joint licensed and unlicensed resource block allocation scheme is proposed to maximise the energy efficiency of LAA taking into account fair resource sharing between LTE and WiFi networks. In [32], an adaptive p-persistent channel access scheme for LAA (named p-LAA protocol) is proposed to balance the trade-off between throughput and fairness for the coexistence network. A Q-learning algorithm is proposed in [33] to adjust the TxOP periods for Wi-Fi and LAA based on the current traffic load or expected capacity. The simulation results show that the proposed algorithm can achieve fairness while maintaining high throughput when the algorithm is applied. The work presented in [34] provides a Markov chain model analysis for LAA/Wi-Fi coexistence scenario where the data are transmitted in a single transmission opportunity backoff. The numerical results show that the proposed model provides better performance for Wi-Fi network and for LAA networks in dense deployments.

B. CONTRIBUTIONS

In this work, we focus on LTE-LAA given that it represents the most promising unlicensed LTE approach to achieve

fairness between LTE and Wi-Fi networks because it is generally more fair to Wi-Fi compared to LTE-U. Current studies mostly focus on the design of mechanisms that enable a fair coexistence between LTE-LAA and Wi-Fi over unlicensed bands. Considering the latest LBT algorithm of 3GPP, Category 4 (Cat 4) LBT algorithm, it can be noticed that the coexistence performance of LTE-LAA/Wi-Fi over the unlicensed 5 GHz band does not perfectly match the fairness definition as described by 3GPP TR 36.889 [4], as it was shown in the results reported in [14]. Specifically, a Wi-Fi performance degradation can be noticed due to this heterogeneous coexistence between LTE-LAA and Wi-Fi networks. This degradation is due to some potential drawbacks of the 3GPP Cat 4 LBT algorithm which are described in Section II and that are addressed and overcome by the methods proposed in this work. The main novelty of the methods proposed and analysed in this work is the exploitation of the activity statistics of the Wi-Fi network for an adequate configuration and operation of the LTE-LAA method. As opposed to previous related work, where the activity statistics of the Wi-Fi network are not taken into account, the methods proposed in this work exploit the availability of this information in order to optimise the performance not only of LTE-LAA but also of the Wi-Fi network itself.

The main contributions of this work are as follows:

1) Two dynamic CW methods for LAA are proposed to improve the performance of LAA/Wi-Fi coexistence based on the 3GPP fairness definition. In particular, the activity statistics of the existing Wi-Fi network are exploited to set the upper bounds of the LAA CW, as opposed to the 3GPP Cat 4 LBT method, which considers a limited set of fixed upper bounds for the LAA CW.

2) Unlike the 3GPP Cat 4 LBT algorithm which considers a dynamic CW scheme based on the Hybrid Automatic Repeat Request (HARQ) reports to adapt the upper bound of the LAA CW, a static CW method for LAA is proposed where the activity statistics of the existing Wi-Fi network are exploited to select a single fixed upper bound for the LAA CW instead of using variable upper bounds for the LAA CW size.

3) A fixed waiting time method for LAA is proposed where the activity statistics of the Wi-Fi network are used to set fixed waiting times for LAA before transmission instead of following a CW-based approach.

4) Various variants are proposed to select the lower bound of the CW of LAA based on the minimum and mode of the activity statistics of the existing Wi-Fi network. Moreover, a fixed waiting time method for LAA is proposed based on these variants as well.

5) A novel dynamic TxOP period approach is proposed where the observed Wi-Fi transmission pattern is exploited to configure the maximum TxOP length for LAA using a dynamic scheme.
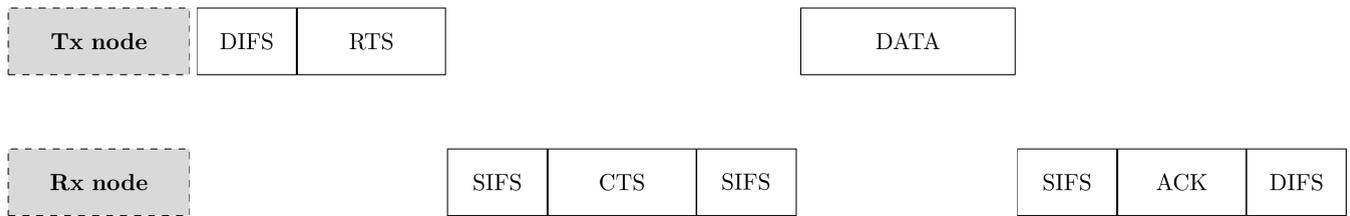
Tx node	DIFS	RTS				DATA	

Rx node			SIFS	CTS	SIFS			SIFS	ACK	DIFS

FIGURE 1. Wi-Fi MAC scheme [12].

The remainder of this work is organised as follows. First, Section II describes the channel access mechanisms in Wi-Fi and LTE-LAA technologies. In addition, the 3GPP Category 4 (Cat 4) LBT algorithm is introduced. Various methods are presented in Section III to adapt/select the waiting times for LAA. Section IV presents a dynamic approach to configure the transmission times for LAA. The considered methodology, simulation environment and used model are described in Section V. Section VI presents and analyses the obtained simulation results. Finally, the conclusions are summarised in Section VII.

II. COEXISTENCE OF WI-FI AND LTE-LAA: MAC PROTOCOL MECHANISMS

This section introduces a review of Wi-Fi and LTE-LAA technologies to highlight the main features and the basic differences between both technologies.

A. WI-FI TECHNOLOGY

Wi-Fi technology employs a Distributed Coordination Function (DCF) protocol which uses carrier sensing to maximise the throughput while preventing packet collisions. DCF is mainly based on the CSMA/CA MAC protocol [12]. In particular, if there is a Wi-Fi node that has data to transmit, it needs to sense the channel firstly to be idle for a DCF Inter-frame Space (DIFS) duration. If the channel is clear, it will transmit a Request-To-Send (RTS) to the destination node. Then, the destination will send a Clear-To-Send (CTS) if it is ready to receive data. The Wi-Fi node will transmit its data when the sender node receives the CTS message. In addition, the destination will send an Acknowledgment (ACK) to the sender node for the successful data reception after a Short Inter-frame Space (SIFS) time. On the other hand, if the channel is not clear, the node keeps monitoring the medium until it becomes idle for a DIFS time, then it picks a random backoff time and counts down (in particular, a random number of time slots which is within a CW that has lower and upper bounds as shown in Table 1). When the backoff timer reaches zero, the Wi-Fi node can perform the transmission for a maximum time determined by the Transmission Opportunity (TxOP) parameter as shown in Table 1. The process is illustrated in Fig. 1. It is worth noting that, given the Wi-Fi MAC protocol, Wi-Fi nodes may be unable to access the channel if it is heavily and selfishly used by other technologies in the same channel.

TABLE 1. Access categories for IEEE 802.11n [35, Table 7-37] and IEEE 802.11ac [36, Table 8-105].

Access category	CW_{min}	CW_{max}	TxOP
Background	15	1023	1 frame
Best effort	15	1023	1 frame
Video	7	15	3.008/6.016 ms
Voice	3	7	1.504/3.264 ms

B. LTE-LAA TECHNOLOGY

In some countries, such as Europe and Japan, the regulations require an LBT protocol to be used for transmission over unlicensed bands. As a result, 3GPP proposed in Release 13 a new version of LTE which supports an LBT protocol for the Down-Link (DL) transmission over unlicensed bands [4]. In Release 14, the Up-Link (UL) scenario was considered in the context of enhanced LAA (eLAA). LTE-LAA uses the Carrier Aggregation (CA) concept in the DL to combine the LTE spectrum in the licensed band with the spectrum in the unlicensed band, thus providing higher data rates, better user experience and enhanced capacity [4]. Aggregating licensed and unlicensed carriers is a key milestone towards 5G.

The licensed LTE MAC protocol has no frame for collision detection and this is the key difference between LTE and Wi-Fi technologies. This requires a modification for the LTE air interface in order to include an LBT algorithm within the LTE MAC. Coexisting LTE with Wi-Fi over the same unlicensed band without any fair mechanism can degrade the Wi-Fi performance given the lack of an LBT mechanism in LTE (since it was designed assuming exclusive access to the spectrum) and the fact that Wi-Fi nodes would frequently sense the channel as busy before attempting any transmission, thus preventing their access to the channel. As a result, an LBT algorithm for LAA was introduced in 3GPP Release 13, which is referred to as Category 4 (Cat 4) LBT [4], [37].

The 3GPP Cat 4 LBT algorithm is similar to the Wi-Fi DCF protocol as it can be seen in Fig. 2. In this algorithm, a CCA period is considered to check the availability of the channel before transmission. In particular, an LAA eNB is allowed to transmit its own data after sensing the channel to be free for an initial CCA (iCCA) period (e.g., $34\mu s$); otherwise, the extended CCA (eCCA) stage starts. During
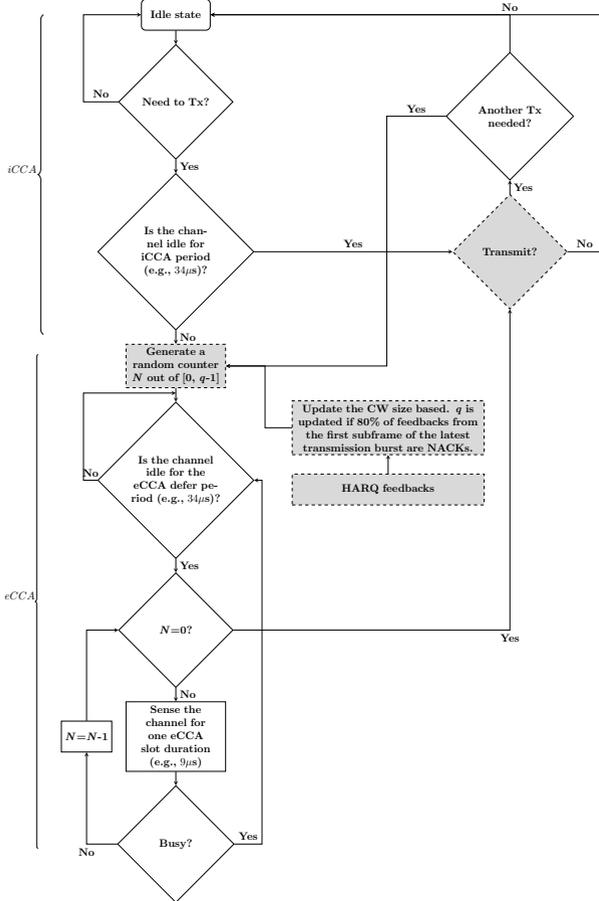
FIGURE 2. 3GPP Cat 4 LBT algorithm [4].

TABLE 2. Channel access priority classes for LAA [37].

Channel access priority class	CW_{min}	CW_{max}	TxOP
1	3	7	2 ms
2	7	15	3 ms
3	15	63	8/10 ms
4	15	1023	8/10 ms

feedbacks from the first subframe of the latest transmission are Negative Acknowledgments (NACKs). The upper bound of the CW $q - 1$ is again updated to 63 if another 80% of HARQ feedbacks are NACKs. Otherwise, the upper bound of the CW $q - 1$ is reset to the initial value (i.e., 15). Thus, the upper bound of the LAA CW $q - 1$ for class 3 varies between {15, 31, 63}.

There are a few drawbacks of the 3GPP Cat 4 algorithm which considers the HARQ feedbacks to update the LAA CW [38], [39]. In particular, the LAA CW size will not be updated if less than 80% of the users suffer from the collision since the collision remains undetected below this threshold. Moreover, the algorithm only considers the detection of the first subframe of the transmission to update the CW size but the collisions from other subframes are neglected. Furthermore, the performance of LAA/Wi-Fi coexistence is affected by the configuration of the LBT parameters such as the CW and the TxOP length of LAA [40]–[42]. However, it can be noted that the adaptation approach of the LAA CW in the standard Cat 4 LBT algorithm does not take into account the activity statistics of the existing technology (i.e., Wi-Fi) and it configures the upper bound of the LAA CW to be 15, 31 or 63 (for class 3) regardless of the existing Wi-Fi activity patterns. Moreover, the Cat 4 LBT algorithm allows LAA eNBs to transmit, after the channel availability check, for a fixed TxOP period. It can be noted that this static TxOP approach is not the most efficient approach for a fair coexistence between LAA and Wi-Fi networks where the LAA TxOP length is kept fixed for all transmissions regardless of the HARQ feedbacks. Therefore, to enhance the performance of the current Cat 4 LBT algorithm, different methods are proposed in this work to update/select the LAA CW boundaries. The dashed shaded boxes in Fig. 2 highlight the procedure of the standard Cat 4 LBT that will be modified to include these proposed methods. In addition, a novel method is proposed to configure the TxOP length in a dynamic manner which will be included instead of the dashed shaded diamond in Fig. 2. All these methods are described below.

the eCCA stage, a backoff process starts by selecting a random number $N \in [0, q - 1]$, where N indicates the number of idle slots that need to be observed before transmission, while $q - 1$ represents the upper bound of the CW, which varies according to an exponential backoff. In particular, the channel is observed by LAA eNB for a time equal to N multiplied by the CCA slot time period (e.g., $9\mu s$). When the channel is free, another eCCA period (e.g., $9\mu s$) begins and N is decreased by one if the channel is clear. When N decrements to zero, the LAA eNB starts the transmission for a fixed configurable Transmission Opportunity (TxOP) time, which can be up to 10 ms depending on the channel access priority class (see Table 2 and [37, Table 15.1.1-1] for details). If the LAA eNB needs another transmission, the eCCA stage is repeated again. However, the value of N is related to the channel access priority class which categorises the traffic type. In particular, the CW size $q - 1$ is initialised with CW_{min} and it is exponentially increased based on Hybrid Automatic Repeat Request (HARQ) feedbacks. Table 2 provides the values of CW_{min} and CW_{max} for each channel access priority class. For example, for the priority class 3, the initial value of the upper bound of the CW, $q-1$, is 15 and it is updated to 31 by doubling q if 80% of HARQ

III. METHODS TO ADAPT LTE WAITING TIMES
In this section, various methods are presented to adapt/select the lower and upper bounds of the LAA CW, which determine the waiting times of LTE-LAA, based on the Wi-Fi activity statistics. In addition, various methods are described to select fixed waiting times for LAA eNB.
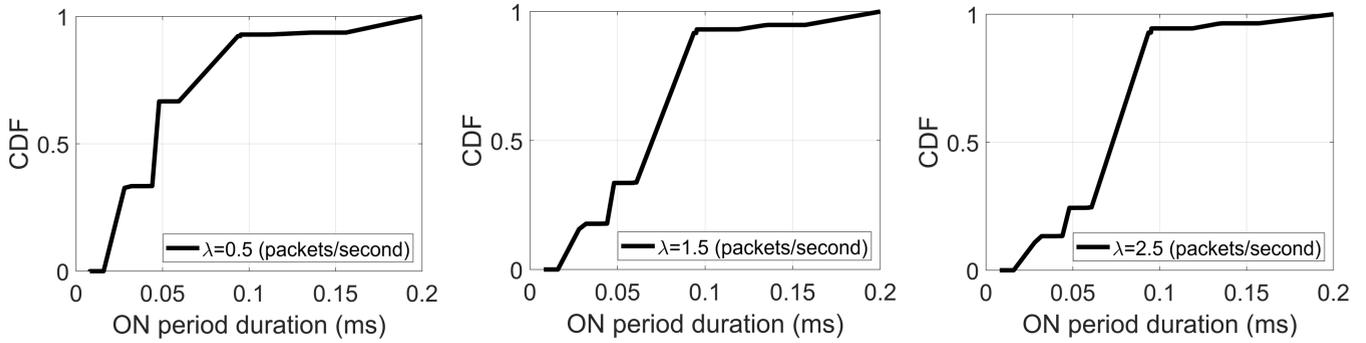
FIGURE 3. CDFs of the ON Wi-Fi times under different traffic loads and a packet size of 0.5 MB (this is the packet size at the application layer, see Section V).

A. DYNAMIC CW (DynCW) METHODS

As stated before, the standard 3GPP Cat 4 LBT algorithm follows a similar contention mechanism to that of Wi-Fi technology aiming to achieve a fair coexistence between LTE-LAA and Wi-Fi networks. In specific, LAA updates the upper bound of the CW, $q-1$, by doubling q from 15 to 31 and to 63 based on the HARQ feedbacks when the channel is sensed to be busy. It is worth noting that this increase in the upper bound of the LAA CW is heuristic and ignores the actual ON/OFF activities of the existing Wi-Fi network which may lead to an inefficient spectrum utilisation. In particular, if the channel is sensed to be busy by the LAA eNB, the upper bound of the CW is doubled, which in many cases may lead to longer waiting times than the actual occupancy times of the Wi-Fi transmissions, then LAA would wait a long time before re-accessing a channel that could actually be empty since a long time ago. This behavior would degrade the LAA performance by increasing latencies and reducing throughputs for LAA. As a result, considering the activity statistics of the existing technology (i.e., Wi-Fi) should provide a more efficient channel access mechanism since the LAA waiting times would be aligned with the actual occupancy times of the Wi-Fi network, thus reducing the latency and increasing the throughput for LAA. Two adaptation methods for the upper bound of the CW of LAA, $q-1$, are proposed here based on the activity statistics of the existing Wi-Fi network [43].

It is worth mentioning that the existing Wi-Fi activity statistics can be estimated by the LTE system without any coordination between the coexisting networks and this can be performed based on the energy detection sensing decisions of the LAA algorithm [12], [44], [45]. In particular, LAA eNB can periodically sense the Wi-Fi channel state when LAA is not transmitting to estimate the Wi-Fi ON time periods. After observing the ON Wi-Fi channel state for a sufficient large number of ON periods, the LAA network can compute the Cumulative Distribution Function (CDF) for the ON time periods of the existing Wi-Fi network. This CDF, which describes the activity pattern of the existing Wi-Fi network, can be exploited to adapt the upper bound of the CW of LAA in an efficient manner instead of following

TABLE 3. Upper bound CW values ($q-1$) of LAA under different traffic loads (9 μs slots).

Percentile point	λ (packets/second)		
	0.5	**1.5**	**2.5**
100%	23	23	23
99%	22	22	21
95%	19	18	14
75%	8	10	10
50%	6	8	9
25%	3	6	7

the standard adaptation method as specified by the 3GPP Cat 4 LBT algorithm which doubles the q value regardless of the activity statistics of the existing Wi-Fi network.

To illustrate the proposed method, Fig. 3 shows the CDFs of the Wi-Fi ON times estimated by the LTE network. In addition, Table 3 provides the corresponding values of the upper bound of the LAA CW, $q-1$, for different percentile points of the CDFs under different traffic loads. Fig. 3 is used to compute the values in Table 3 by dividing the ON times of each percentile point by the LAA slot duration (9 μs) and rounding the result to the nearest integer toward infinity (i.e., ceil function). For example, for $\lambda = 1.5$ packets/second, the 50% percentile point corresponds to a Wi-Fi ON time of around 70 μs, which divided by 9 μs and ceiled results in the value $q-1 = 8$ shown in Table 3 for the 50% percentile and $\lambda = 1.5$ packets/second. All the provided values in Table 3 are calculated following the same procedure. It is worth mentioning that a percentile point of 100% in a theoretical CDF model is not feasible generally since the corresponding ON time would tend to infinity. However, the CDF that is used by LAA for the CW adaptation is based on empirical observations of Wi-Fi ON times, which necessarily have a finite maximum and this value is selected as the 100% percentile point. This approach allows various adaptation methods. Two dynamic adaptation methods for the LAA CW are discussed below.

Notice that the CDF of the Wi-Fi ON times will be affected not only by the packet inter-arrival times as illustrated in Fig. 3 but also by other network conditions such as the

number of Wi-Fi APs, LTE-LAA eNBs and total number of users. If any of these network conditions change, the CDF of the Wi-Fi ON times will change as well. However, the LTE-LAA system will not be required to have any prior knowledge of these conditions. Note that the estimation of the required CDF and the resulting percentile points can be implemented as an online, real-time learning process. Any changes in the network conditions will automatically result in a change in the estimated CDF and the resulting percentile points. The proposed methods will thus adapt automatically to the new network conditions every time these change.

1) Dynamic CW with 3 adaptation points (DynCW-3)

Three adaptation points are defined in this method for the CW of LAA. These points are at the 50% (median value), 95% and 100% (maximum value) percentiles of the CDF of the existing Wi-Fi ON time periods. This method is implemented by setting the first upper bound of the LAA CW, $q-1$, to be the median (i.e., 50% value) Wi-Fi ON time. The reason behind choosing this value to be the starting point of the upper bound of the LAA CW is that in 50% of cases the Wi-Fi ON times will be shorter than this value and in the other 50% of cases they will be longer. Thus, the median value is considered a reasonable starting point. If the LAA transmission fails, this means that the 50% percentile time is not long enough to find a clear channel for LAA transmission and in such case the upper bound of the CW, $q-1$, will be increased to the 95% percentile point. In most cases, LAA should find an idle Wi-Fi channel after the new waiting time and therefore can transmit. For those cases where Wi-Fi has very long transmissions, the upper bound of the LAA CW will finally be updated to the 100% percentile point (maximum value), thus hopefully leading to a successful transmission in the next attempt. For this method, it can be noticed that the actual LAA waiting times are adapted based on the existing Wi-Fi traffic statistics.

2) Dynamic CW with 2 adaptation points (DynCW-2)

Two adaptation points are defined in this method for the CW of LAA. This method is implemented based on the Wi-Fi activity statistics as well. In particular, it defines the first maximum CW value at the 50% percentile (median value) point and finally at the 100% percentile (maximum value) point. The motivation of this method is to allow for a faster convergence to the optimum value of LAA CW, in case it needs to be increased, and therefore provide better performance for LAA by reducing latencies and increasing throughputs.

3) Illustrative examples of DynCW-3 and DynCW-2 methods

Table 4 depicts the maximum CW values using Cat 4 LBT, DynCW-3 and DynCW-2 methods under different traffic loads. For example, for $\lambda = 0.5$ packets/second, the maximum LAA CW values are {6, 19, 23} and {6, 23} for DynCW-3 and DynCW-2 methods, respectively, as observed from Table 3. On the other hand, the maximum LAA CW

TABLE 4. Upper bound CW values $(q-1)$ of LAA using Cat 4 LBT, DynCW-3 and DynCW-2 methods under different traffic loads (9 μs slots).

λ (packets/second)	Cat 4 LBT	DynCW-3	DynCW-2
0.5	{15, 31, 63}	{6, 19, 23}	{6, 23}
1.5	{15, 31, 63}	{8, 18, 23}	{8, 23}
2.5	{15, 31, 63}	{9, 14, 23}	{9, 23}

TABLE 5. Upper bound CW values $(q-1)$ of LAA using StatCW method under different traffic loads (9 μs slots).

Percentile point	λ (packets/second)		
	0.5	1.5	2.5
100%	23	23	23
95%	19	18	14
50%	6	8	9

values for the standard 3GPP Cat 4 LBT algorithm are fixed regardless of the existing Wi-Fi activity statistics and they vary between {15, 31, 63}. It can be seen that the 3GPP Cat 4 LBT values of the upper bound LAA CW are significantly larger than those provided by the proposed methods for the different traffic loads. Thus, the 3GPP method may lead to unnecessarily long waiting times for LAA and therefore a degraded performance.

B. STATIC CW (StatCW) METHOD

We propose here a new static method to select the upper bound of the LAA CW based on the activity statistics of the existing Wi-Fi network instead of updating the upper bound of the LAA CW dynamically [46]. In particular, the 50% (median value), 95% or 100% (maximum value) percentile point of the CDF of the ON Wi-Fi times are considered as fixed upper bounds of the LAA CW. In this proposed method, $q-1$ is considered to be a static value that is selected as the corresponding value for the percentile point of the CDF of the ON Wi-Fi times divided by the CCA slot duration (9 μs). Table 5 shows corresponding values of the LAA CW, $q-1$, for these percentile points of the CDF of the ON Wi-Fi times under different traffic loads. Therefore, the upper bound of the LAA CW is fixed and there are no different sizes for the CW size as specified in the 3GPP Cat 4 LBT algorithm where the upper bound of the CW could be 15, 31 or 63. The main motivation of this method is to allow a faster convergence to the prospective optimum LAA CW, thus further reducing LAA waiting times that should lead to lower latency and higher throughput for LAA.

C. FIXED WAITING TIME (FWT) METHOD

In the 3GPP Cat 4 LBT algorithm, the channel is observed by the LAA eNB for a time equal to N multiplied by the CCA slot time period (e.g., 9 μs) where N is a uniform random number within the interval $N \in [0, q-1]$ and

$q-1$ is the upper bound of the LAA CW, which is updated based on HARQ feedbacks to 15, 31 and 63. It can be noted that the number of idle slots that need to be observed by the eNB is random and constrained by the upper bound of the LAA CW. The random choice for the number of idle slots that need to be observed by the LAA eNB before transmission may not be the most appropriate approach since such random choice is somehow arbitrary and independent of the actual Wi-Fi activity statistics. This suggests that a fixed waiting time, if properly configured based on the Wi-Fi activity statistics, may lead to a more efficient operation, which motivates the idea considered in this subsection. This knowledge of the existing Wi-Fi network activity statistics can be exploited to allow the LAA eNB to wait a fixed (rather than random) amount of slots before attempting a new transmission. Setting a fixed waiting time, if properly configured, should allow a faster convergence to the optimum operating point than dynamic approaches. Therefore, in order to enhance the 3GPP Cat 4 LBT algorithm, we propose a new method with a fixed waiting time before transmission for LAA based on the activity statistics of the existing Wi-Fi network. The dashed shaded boxes in Fig. 2 highlight the procedure of the 3GPP Cat 4 LBT algorithm that need to be modified to implement the proposed Fixed Waiting Time (FWT) method for LAA.

Notice that three key changes to the 3GPP standard approach are considered in this method. Firstly, there is no backoff process, which to some extent reduces the complexity of the algorithm since random number generators are not required in this case. Secondly, there is no adaptation of the LAA CW based on the received HARQ reports (in fact, there is no CW in this case), which also contributes to simplify the algorithm and reduce its complexity. Thirdly, the knowledge of the activity statistics of the existing Wi-Fi network is required to set a fixed waiting time before transmission for the LAA eNB. The LAA eNB waiting time is set as N multiplied by the CCA slot time (9 μs) where N can be set based on the percentile point of the CDF for the ON time periods of the existing Wi-Fi network divided by the CCA slot time (9 μs) as shown in Table 5.

D. VARIANTS OF THE PROPOSED WAITING TIME ADAPTATION METHODS

The previous proposed dynamic and static CW methods, including the standard 3GPP Cat 4 LBT algorithm, consider various implementations to adapt/select the upper bound of the LAA CW. All these methods propose different approaches to tune the upper bound of the LAA CW but they have not proposed any strategy to adapt/select the lower bound of the LAA CW. Exploiting the knowledge of the activity statistics of the existing Wi-Fi network to select the lower bound of the LAA CW may provide a more efficient channel access mechanism for LAA. Various methods are proposed here to select the lower bound of the CW of LAA based on the activity statistics of the existing Wi-Fi network. The ideas suggested in this section to select the lower bound

of the CW can also be applied to the FWT method, thus leading to new variants of this method as well.

1) Variants based on shortest (minimum) Wi-Fi ON time
It can be noted that the lower bound of the LAA CW in the methods discussed so far (including the Cat 4 LBT and proposed CW-based methods) is set to zero regardless of the HARQ feedbacks or even of the activity statistics of the existing Wi-Fi network. This value means that the LAA eNB may start the backoff process by selecting a random number $N \in [0, q-1]$, which could be zero or any small value within the interval $[0, q-1]$. This selection process may not be efficient for LAA transmission since this small value of N may not be long enough to find a clear channel given that it may lead to shorter waiting times than the actual occupancy times of the Wi-Fi transmissions, and as a result LAA would attempt to access a channel which is not free, thus leading to a backoff process repetition and therefore degrading the performance of the coexisting networks. Consequently, new variants of the methods discussed so far are here proposed by selecting the lower bound of the LAA CW based on the minimum ON activity time of the existing Wi-Fi network. Thus, the LAA eNB starts the backoff process by selecting a random number $N \in [N_{Min}, q-1]$, where N indicates the number of idle slots that need to be observed before transmission, N_{Min} is the lower bound of the CW and $q-1$ represents the upper bound of the CW. The value of N_{Min} is obtained as the minimum ON activity time of the Wi-Fi Network divided by the LAA slot duration (e.g., 9 μs) and rounding the result to the nearest integer toward infinity (i.e., ceil function), while the upper bound of the CW, $q-1$, is selected as discussed for each proposed method in Sections III-A and III-B.

The motivation of these variants is that selecting any random number by the LAA eNB below N_{Min} may not be a wise decision since the channel will likely still be busy (i.e., in use by a Wi-Fi transmission) within that time period. Therefore, to minimise the number of unfruitful backoffs, the minimum waiting time of the considered methods is adapted according to the minimum Wi-Fi ON activity time.

2) Variants based on most frequent (mode) Wi-Fi ON time
The variants proposed in this section select the lower bound of the LAA CW based on the most frequent occurring ON time of the existing Wi-Fi network (i.e., the mode of the ON times). In particular, the LAA eNB starts the backoff process by selecting a random number $N \in [N_{Mode}, q-1]$ where N indicates the number of idle slots that need to be observed before transmission, N_{Mode} is the lower bound of the CW and $q-1$ represents the upper bound of the CW. The value of N_{Mode} is obtained as the mode of the ON activity time of the Wi-Fi network divided by the LAA slot duration (e.g., 9 μs) and rounding the result to the nearest integer toward infinity (i.e., ceil function), while the upper bound of the CW, $q-1$, is selected as discussed for each proposed method in Sections III-A and III-B. The motivation for this variant is
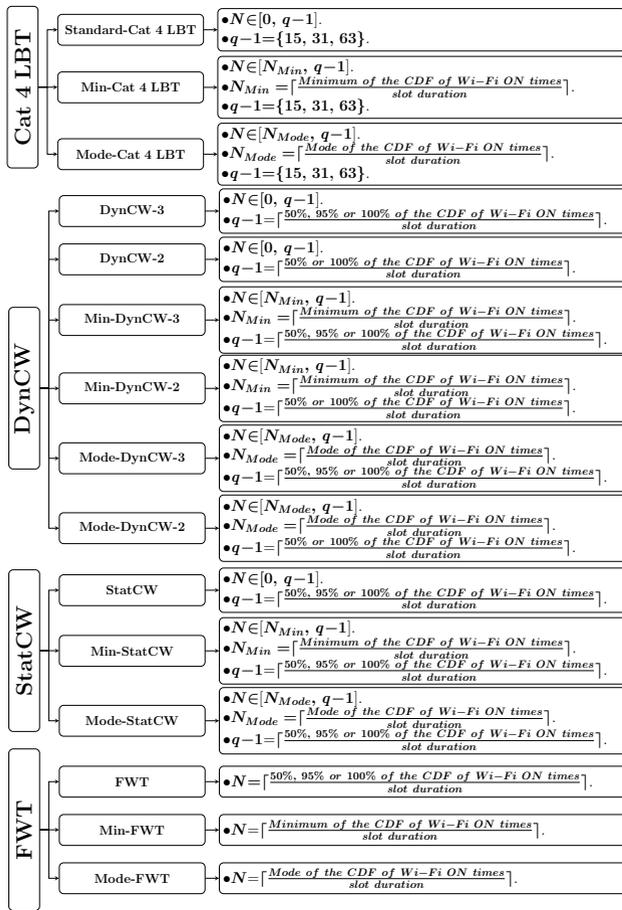
Cat 4 LBT

Standard-Cat 4 LBT
- $N \in [0, q-1]$.
- $q-1 = \{15, 31, 63\}$.

Min-Cat 4 LBT
- $N \in [N_{Min}, q-1]$.
- $N_{Min} = \lceil \frac{Minimum\ of\ the\ CDF\ of\ Wi-Fi\ ON\ times}{slot\ duration} \rceil$.
- $q-1 = \{15, 31, 63\}$.

Mode-Cat 4 LBT
- $N \in [N_{Mode}, q-1]$.
- $N_{Mode} = \lceil \frac{Mode\ of\ the\ CDF\ of\ Wi-Fi\ ON\ times}{slot\ duration} \rceil$.
- $q-1 = \{15, 31, 63\}$.

DynCW

DynCW-3
- $N \in [0, q-1]$.
- $q-1 = \lceil \frac{50\%,\ 95\%\ or\ 100\%\ of\ the\ CDF\ of\ Wi-Fi\ ON\ times}{slot\ duration} \rceil$.

DynCW-2
- $N \in [0, q-1]$.
- $q-1 = \lceil \frac{50\%\ or\ 100\%\ of\ the\ CDF\ of\ Wi-Fi\ ON\ times}{slot\ duration} \rceil$.

Min-DynCW-3
- $N \in [N_{Min}, q-1]$.
- $N_{Min} = \lceil \frac{Minimum\ of\ the\ CDF\ of\ Wi-Fi\ ON\ times}{slot\ duration} \rceil$.
- $q-1 = \lceil \frac{50\%,\ 95\%\ or\ 100\%\ of\ the\ CDF\ of\ Wi-Fi\ ON\ times}{slot\ duration} \rceil$.

Min-DynCW-2
- $N \in [N_{Min}, q-1]$.
- $N_{Min} = \lceil \frac{Minimum\ of\ the\ CDF\ of\ Wi-Fi\ ON\ times}{slot\ duration} \rceil$.
- $q-1 = \lceil \frac{50\%\ or\ 100\%\ of\ the\ CDF\ of\ Wi-Fi\ ON\ times}{slot\ duration} \rceil$.

Mode-DynCW-3
- $N \in [N_{Mode}, q-1]$.
- $N_{Mode} = \lceil \frac{Mode\ of\ the\ CDF\ of\ Wi-Fi\ ON\ times}{slot\ duration} \rceil$.
- $q-1 = \lceil \frac{50\%,\ 95\%\ or\ 100\%\ of\ the\ CDF\ of\ Wi-Fi\ ON\ times}{slot\ duration} \rceil$.

Mode-DynCW-2
- $N \in [N_{Mode}, q-1]$.
- $N_{Mode} = \lceil \frac{Mode\ of\ the\ CDF\ of\ Wi-Fi\ ON\ times}{slot\ duration} \rceil$.
- $q-1 = \lceil \frac{50\%\ or\ 100\%\ of\ the\ CDF\ of\ Wi-Fi\ ON\ times}{slot\ duration} \rceil$.

StatCW

StatCW
- $N \in [0, q-1]$.
- $q-1 = \lceil \frac{50\%,\ 95\%\ or\ 100\%\ of\ the\ CDF\ of\ Wi-Fi\ ON\ times}{slot\ duration} \rceil$.

Min-StatCW
- $N \in [N_{Min}, q-1]$.
- $N_{Min} = \lceil \frac{Minimum\ of\ the\ CDF\ of\ Wi-Fi\ ON\ times}{slot\ duration} \rceil$.
- $q-1 = \lceil \frac{50\%,\ 95\%\ or\ 100\%\ of\ the\ CDF\ of\ Wi-Fi\ ON\ times}{slot\ duration} \rceil$.

Mode-StatCW
- $N \in [N_{Mode}, q-1]$.
- $N_{Mode} = \lceil \frac{Mode\ of\ the\ CDF\ of\ Wi-Fi\ ON\ times}{slot\ duration} \rceil$.
- $q-1 = \lceil \frac{50\%,\ 95\%\ or\ 100\%\ of\ the\ CDF\ of\ Wi-Fi\ ON\ times}{slot\ duration} \rceil$.

FWT

FWT
- $N = \lceil \frac{50\%,\ 95\%\ or\ 100\%\ of\ the\ CDF\ of\ Wi-Fi\ ON\ times}{slot\ duration} \rceil$.

Min-FWT
- $N = \lceil \frac{Minimum\ of\ the\ CDF\ of\ Wi-Fi\ ON\ times}{slot\ duration} \rceil$.

Mode-FWT
- $N = \lceil \frac{Mode\ of\ the\ CDF\ of\ Wi-Fi\ ON\ times}{slot\ duration} \rceil$.

FIGURE 4. Proposed methods to adapt LTE waiting times and their variants.

that adjusting the LTE-LAA minimum waiting times based on the most frequent Wi-Fi ON time might potentially lead to a more efficient coexistence between LTE-LAA and Wi-Fi networks in the same unlicensed channel, and this motivates the consideration of this variant in this work.

Fig. 4 summarises the complete set of methods that can be used to adapt the LTE-LAA waiting times, including both the 3GPP Cat 4 LBT method and the methods proposed in this work, along with the possible variants.

IV. METHOD TO ADAPT LTE TRANSMISSION TIMES

Spectrum regulators impose constraints on the maximum transmission duration for any wireless communications system operating over unlicensed channels. As a result, a predefined transmission period (TxOP) for LAA eNB is mandatory for transmissions over unlicensed bands. This transmission period determines for how long an LTE-LAA transmission may last, after which the transmission must finish (even if there are more data to transmit) in order to allow other users to access the unlicensed channel. The standard 3GPP Cat 4 LBT algorithm implements a configurable but fixed TxOP parameter that depends on the channel access priority class (see Table 2 and [37, Table

15.1.1-1] for details). This duration of TxOP, once selected, will remain constant during the LAA eNB operation.

This static scheme for the transmission of LAA over unlicensed bands may be unsuitable since a fixed TxOP may not lead to an efficient spectrum utilisation. In particular, the unlicensed channel may suffer from different traffic conditions and a dynamic TxOP scheme would be more efficient for spectrum utilisation, thus leading to better performance for the coexisting networks. In specific, when the Wi-Fi traffic load is low, the channel can be expected to be idle for longer time periods and these periods can be exploited for LAA transmissions for longer intervals, thus providing better performance (i.e., using longer TxOP period). On the other hand, a shorter TxOP period for LAA would be more suitable when the Wi-Fi traffic load is high since the use of a long TxOP period in such cases would lead to more collisions in the channel and degrade the performance for the coexisting networks. As a result, the static TxOP period scheme may not be the most suitable scheme for an efficient coexistence between LTE-LAA and Wi-Fi networks over unlicensed spectrum bands. Thus, a novel scheme is proposed here to adapt the TxOP period for LAA dynamically in order to improve the performance of the coexisting networks. The dashed shaded diamond in Fig. 2 highlights the procedure of the 3GPP Cat 4 LBT algorithm that will be modified to implement the proposed dynamic TxOP method for LAA.

The new proposed method selects the TxOP for LAA based on the current size of the CW for LAA, which is a parameter readily available in any practical implementation of LAA [47]. The 3GPP Cat 4 LBT algorithm adapts the size of the CW for LAA based on the HARQ feedbacks, which reflect incorrect data transmission due to a congestion or a collision in the channel. Therefore, the current CW size can be seen as an indication of the current level of congestion in the unlicensed channel and used to adapt the TxOP accordingly. The proposed method considers two adaptation points for the maximum TxOP period of LAA as shown in Table 6, where the TxOP can dynamically range from 4 ms to 20 ms. This range of values for the TxOP has been selected to illustrate the full potential benefits of the method proposed in this section, but can be adjusted, where required, to specific local spectrum regulations, or optimised for specific ranges of traffic loads. According to the adaptation points shown in Table 6, when the LAA CW size is 15 (i.e., the minimum LAA CW size), the TxOP parameter is set to its maximum value of 20 ms. Otherwise, the TxOP period parameter is set to 4 ms, which is the minimum TxOP period considered. The reason behind choosing the maximum TxOP period (20 ms) for the lower value of the CW size is that the lower CW size is associated with low volume of Wi-Fi traffic, therefore a longer LAA transmission should be reasonable in this case since this low volume of Wi-Fi traffic means more idle times in the channel, which can be exploited for LAA transmissions by setting TxOP period to its maximum value,

TABLE 6. Value of the selected TxOP period as a function of the LAA CW size for the dynamic TxOP method.

CW Size	TxOP Period
15	20 ms
31	4 ms
63	4 ms

thus improving the LAA performance without degrading the Wi-Fi performance. On the other hand, the LAA CW size is increased to 31 or 63 in the 3GPP Cat 4 LBT algorithm due to the channel congestion or transmission collisions, therefore the TxOP period is set here to its minimum value (4 ms) in order to reduce this congestion/collision, thus providing better performance for LAA and not degrading the performance of the existing network (i.e., Wi-Fi).

It is worth mentioning that the proposed dynamic approach for the TxOP period of LAA is based on the traffic statistics of the coexisting networks through the received HARQ feedbacks. Thus, the key change between the 3GPP standard and the proposed approach is the use of a dynamic TxOP period instead of a static one. This dynamic adaptation for the TxOP of LAA can achieve better alignment between Wi-Fi idle times and LTE-LAA transmission times, thus reducing the number of collisions and achieving a better performance for the coexisting networks compared with the 3GPP Cat 4 LBT algorithm, which considers a fixed TxOP period for LTE-LAA transmissions regardless of the congestion/collision over the unlicensed channel. In addition, the proposed approach can be easily implemented in a real system without adding any significant modifications to current commercial products since the approach is mainly based on the LAA CW parameter which is a readily available in any practical implementation of LAA.

V. SIMULATION METHODOLOGY AND SETUP

The indoor scenario defined in [4] is considered in this work to verify the effectiveness of the proposed methods in providing a fair coexistence between LTE-LAA and Wi-Fi networks over unlicensed bands in terms of throughput and latency. In particular, the proposed methods are evaluated based on the 3GPP definition of fairness, where the LAA network should not impact the Wi-Fi network performance more than an additional Wi-Fi network operating on the same carrier in terms of throughput and latency.

In order to estimate the activity statistics of the existing Wi-Fi network, two Wi-Fi networks are deployed together over the same unlicensed band. The CDF of the ON times of the existing Wi-Fi network can be estimated for this scenario and exploited to adapt/select the CW boundaries, the transmission waiting times and the transmission opportunity time for LAA. In particular, various statistical values can be evaluated from this CDF such as the percentile point at the 50%, 95% and 100% of the CDF. In addition, the minimum and mode can be evaluated from the CDF as well. These

various statistical values are used in the implementations of the different proposed methods. Afterwards, one of these deployed Wi-Fi networks is replaced with an LTE-LAA network allowing an LTE-LAA/Wi-Fi coexistence scenario and assessing the validity of the various proposed methods. The LTE-LAA/Wi-Fi coexistence scenario is compared with the Wi-Fi/Wi-Fi scenario in order to determine how the introduction of an LTE-LAA network operating with the proposed methods affects and existing Wi-Fi network with respect to the introduction of an additional Wi-Fi network, therefore providing an accurate assessment of the coexistence fairness as defined by the 3GPP.

The methodology for evaluating the coexistence performance of LTE-LAA and Wi-Fi follows the 3GPP TR 35.889 simulation conditions except the updating rule of the LAA CW, where the proposed CW methods are implemented. In addition, a dynamic TxOP approach is implemented instead of the static TxOP approach of the 3GPP to assess the validity of the proposed dynamic TxOP method. In this study, all methods are evaluated using the event driven simulator ns-3 with LAA extension [48]. This simulator is an open source simulator and it allows researchers to share their contributions [4], [49]. In this simulator, WifiNetDevice can coexist with other NetDevices and an LTE module was implemented and developed by the LENA project to evaluate the performance of issues in LTE systems such as radio resource management algorithms, cognitive LTE systems and DL/UL MAC schedulers [50].

In this work, an indoor scenario in a single floor building is adopted as specified by 3GPP by considering two operators; operator A (Wi-Fi) and operator B (LAA) using the same 20 MHz channel over the unlicensed 5 GHz band [4]. The LAA/Wi-Fi indoor scenario is shown in Fig. 5. Operator A (Wi-Fi) deploys four APs while operator B (LAA) deploys four eNBs. All the base stations (i.e., APs and eNBs) are equally spaced and centred along the shorter dimension of the building. Moreover, each operator deploys 20 stations (STAs)/User Equipments (UEs) randomly distributed in a one floor building with a rectangular area. All base stations (i.e., APs and eNBs) and users (i.e., STAs and UEs) are equipped with two antennas for 2x2 Multiple Input Multiple Output (MIMO) operation. The traffic is modelled as a File Transfer Protocol (FTP) Model 1 operating over User Datagram Protocol (UDP) considering DL scenario. This model simulates file transfers according to a Poisson process with an arrival rate of λ packets/second. The file size considered is 0.5 MB with different recommended arrival rates ($\lambda = 0.5, 1.5, 2.5$ packets/second), which are simulated to generate different load levels [4]. Notice that the packet size of 0.5 MB is the size of the Protocol Data Unit (PDU) at the application layer. The ns-3 simulator implements the whole set of layers of the protocol stack and these packets are split into smaller pieces of data for transmission according to the PDU size at each level of the protocol stack. The details of the employed simulation parameters are shown in Table 7 along with the 3GPP reference scenario.
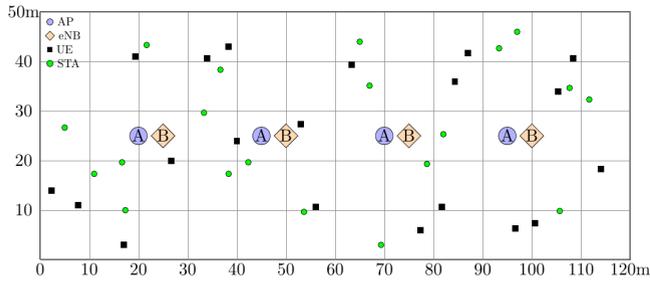
FIGURE 5. Indoor layout with two operators (operator A and operator B) with 4 cells per operator and 5 STAs/UEs per cell.

	3GPP TR 36.889	ns-3 simulator
Network layout	Indoor scenario	Indoor scenario
System bandwidth	20 MHz	20 MHz
Carrier frequency	5 GHz	5 GHz (Ch.36)
Max. total BS Tx power	18/24 dBm	18 dBm
Max. total UE Tx power	18 dBm	18 dBm
Pathloss, shadowing & fading	ITU InH	IEEE 802.11n
Antenna pattern	2D omni-D	2D omni-D
Antenna height	6 m	6 m for LAA
UE antenna height	1.5 m	1.5 m for LAA
Antenna gain	5 dBi	5 dBi
UE antenna gain	0 dBi	0 dBi
UE dropping	Randomly	Randomly
Traffic model	FTP model 1 & 3	FTP model 1

The coexisting Radio Access Technologies (RATs) detect each other based on an Energy Detection (ED) principle. Wi-Fi nodes can detect other Wi-Fi nodes at –82 dBm and LAA nodes at –62 dBm. On the other hand, LAA nodes can detect Wi-Fi nodes at –72 dBm. This means that Wi-Fi will defer to weaker Wi-Fi signals sensed on the channel compared to LTE signals, which are detected at –62 dBm. It is worth noting that the selected decision thresholds can have a significant impact on the performance of both coexisting networks in some scenarios. As extensively investigated and shown in [51], a careful selection of the thresholds can lead to an improved performance. This aspect, however, is out of the scope of this work and thus the default values presented above, which are defined in [4], are here considered. The parameter that describes the maximum length of transmission for LAA (i.e., the TxOP) is configurable and is set to be 8 ms in the Cat 4 method, CW methods and FWT methods. On the other hand, the TxOP parameter is configured dynamically within the dynamic TxOP method. The CW size is adapted as defined in Section II-B for the 3GPP Cat 4 LBT method and in Section III for the proposed CW selection methods.

The performance of the considered LTE-LAA/Wi-Fi coexistence methods is evaluated based on the main performance metrics described in 3GPP TR 36.889 (i.e., throughput and latency). Throughput is measured as the amount of data correctly transmitted within a specified time period as observed at the Internet Protocol (IP) layer, while latency is measured as the time elapsed since the packet leaves the transmitter until it reaches the receiver.

VI. SIMULATION RESULTS

In this section, the performance of LTE-LAA and Wi-Fi networks is analysed using the proposed methods. The results are shown in terms of the individual throughputs and latencies for each network as well as the total aggregated throughput for both networks. To validate the performance of the proposed methods, the fairness definition as specified by 3GPP is considered based on the throughput and latency for 95% of the users. The results at various percentiles (90%, 95% and 100%) were evaluated in the context of this work and it was observed that the main trends and conclusions are similar in all cases. However, only the results for the 95%

percentile case are provided here for the sake of brevity.

A. DYNAMIC CW (DynCW) METHODS

The coexistence of LTE-LAA and Wi-Fi networks is analysed here when LTE-LAA implements the proposed dynamic CW methods. The throughputs for the existing Wi-Fi network (i.e., operator A) under different traffic loads (i.e., different arrival rates) for various methods are presented in Fig. 6. The reference case represents a homogeneous scenario where the existing Wi-Fi network (operator A) coexists with another Wi-Fi network (operator B), while the other cases correspond to heterogeneous coexistence scenarios (i.e., Wi-Fi and LAA) where operator A is a Wi-Fi network and operator B is an LTE-LAA network. Based on the 3GPP fairness definition, an ideal LAA coexistence mechanism should allow the Wi-Fi network achieve at least the same performance as in the reference case without (ideally) experiencing any performance degradation. It can be seen that operating LAA using the Cat 4 LBT algorithm leads to a lower throughput performance for the Wi-Fi network than in the reference case for all traffic loads, which contradicts the 3GPP fairness definition. Compared to the 3GPP Cat 4 LBT method, the proposed dynamic CW methods (in particular the DynCW-2 method) achieve a comparable Wi-Fi throughput performance under low traffic loads ($\lambda = 0.5$ packets/second) and a slightly better performance under higher traffic loads ($\lambda = 1.5$ and 2.5 packets/second). Even though it can be seen from Fig. 6 that the fairness definition in terms of Wi-Fi throughput is not fully met with the proposed dynamic CW methods (DynCW-3 and DynCW-2 methods) for the different traffic loads, the proposed dynamic CW methods degrade the throughput performance of the existing Wi-Fi network to a lesser extent and therefore can be considered to be more friendly to Wi-Fi networks than the 3GPP Cat 4 LBT method. It is worth noting that the DynCW-2 method in general outperforms DynCW-3; this suggests that the two-point adaptation process of the CW performed by DynCW-2
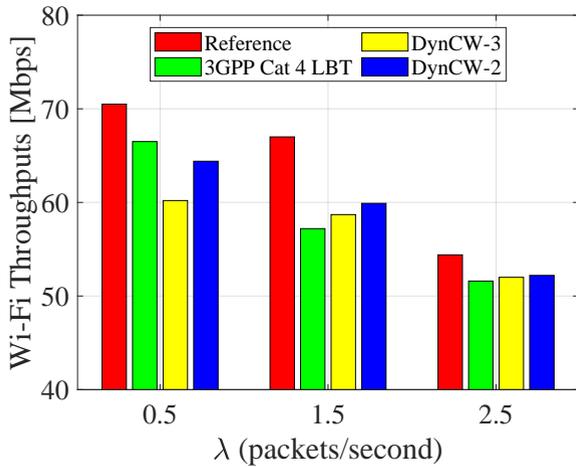
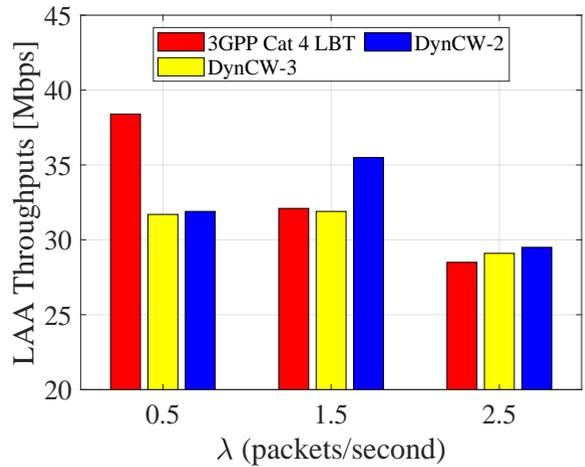**FIGURE 6.** Wi-Fi throughput performance of the proposed dynamic CW methods.

FIGURE 8. LTE-LAA throughput performance of the proposed dynamic CW methods.
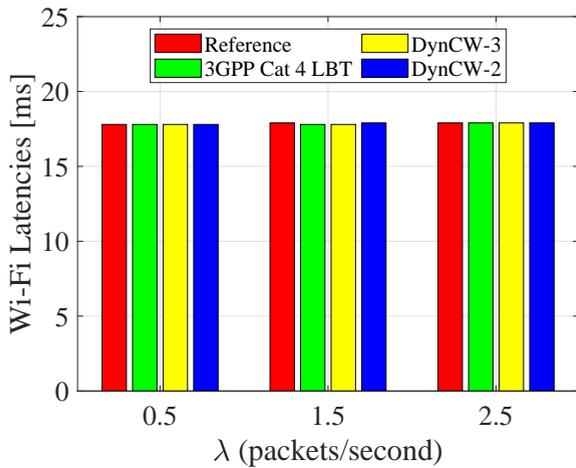

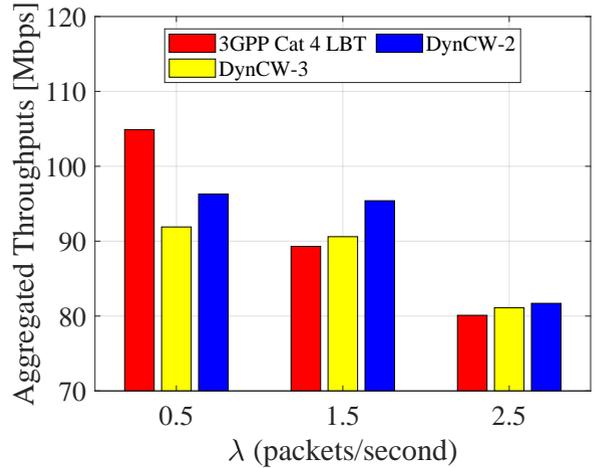**FIGURE 7.** Wi-Fi latency performance of the proposed dynamic CW methods.

FIGURE 9. Aggregated throughput performance of the proposed dynamic CW methods.

allows a faster convergence to an appropriate CW size when this is required by the Wi-Fi traffic conditions.

Fig. 7 shows the Wi-Fi latency performance under different traffic loads for the various methods. It can be noted that all methods lead to a similar latency performance as the reference case, which means that the latency experienced by the existing Wi-Fi network is not significantly affected by the presence of other (Wi-Fi or LTE-LAA) networks.

The LAA throughput performance is illustrated in Fig. 8. It can be noticed that the proposed methods achieve better LAA throughputs compared to the standard Cat 4 LBT method as the traffic load increases. The LAA throughputs are improved using the proposed methods due to the smart selection of the upper bound of the LAA CW based on the Wi-Fi activity statistics. This approach in the proposed dynamic CW methods allows the LAA eNB to access the channel faster than the Cat 4 LBT method, thus removing unnecessary waiting times for the LTE-LAA network and

providing better LAA throughputs. As high traffic demands are expected in the future, high performance at high values of λ is therefore more desirable.

Finally, the total aggregated throughputs for both coexisting networks (i.e., Wi-Fi and LAA) are shown in Fig. 9. It can be seen that the proposed dynamic CW methods achieve better total aggregated throughputs compared to Cat 4 LBT at higher traffic loads. Specifically, the performance improvement in the total aggregated throughputs using the DynCW-3 method compared to the Cat 4 LBT method is 1.5% (1.3 Mbps) and 1.2% (1 Mbps) for $\lambda = 1.5$ and 2.5 packets/second, respectively. Moreover, the performance improvement in the total aggregated throughputs using the DynCW-2 method compared to the Cat 4 LBT method is 6.8% (6.1 Mbps) and 2% (1.6 Mbps) for $\lambda = 1.5$ and 2.5 packets/second, respectively. Overall, it can be noticed that the proposed dynamic CW methods can achieve a slightly better performance (for both Wi-Fi and LTE-LAA networks)

TABLE 8. Wi-Fi/LAA throughput performance [Mbps] for 95% of users using the StatCW method at different percentile points of the CDF of Wi-Fi ON times.

Percentile	λ (packets/second)		
point	0.5	1.5	2.5
100%	80.9/31.1	62.4/33.9	53.5/27.9
95%	74.1/31.8	60.0/32.3	52.5/28.2
50%	59.9/30.6	57.7/29.5	51.9/28.1

TABLE 9. Wi-Fi latency performance [ms] for 95% of users using the StatCW method at different percentile points of the CDF of Wi-Fi ON times

Percentile	λ (packets/second)		
point	0.5	1.5	2.5
100%	17.9	17.8	17.9
95%	17.9	17.9	17.9
50%	17.9	17.8	17.9

compared to the standard Cat 4 LBT method under high traffic loads and therefore constitute more convenient co-existence approaches in such scenario (in particular the DynCW-2 method).

B. STATIC CW (StatCW) METHOD

The performance of LTE-LAA and Wi-Fi networks is analysed here using the proposed static CW method. The throughputs for the coexisting networks (i.e., Wi-Fi and LAA) for the different percentile points at 50%, 95% and 100% of the CDF of the ON times of the existing Wi-Fi network using the proposed static CW method are provided in Table 8. It can be seen that for the different traffic loads (i.e., different arrival rates) the 100% percentile point (maximum value) achieves the best performance in terms of Wi-Fi throughput with a rather constant performance in terms of LAA throughput. Table 9 provides the Wi-Fi latencies at the different percentile points of the CDF using the proposed static CW method. It can be seen that all percentile points (i.e., 50%, 95% and 100%) provide comparable performances in terms of Wi-Fi latency. Thus, the 100% percentile point of the ON Wi-Fi times will be considered to select the upper bound of the LAA CW in the proposed static CW method since this choice leads to the best Wi-Fi performance (LTE-LAA performance is unaffected by the selected percentile point).

The Wi-Fi throughput performance of the proposed static CW method is presented and compared to the reference and 3GPP Cat 4 LBT cases in Fig. 10. It can be observed that the proposed static CW method achieves better throughput for the existing Wi-Fi network (i.e., operator A) for all traffic loads compared to the standard Cat 4 LBT method. In addition, it provides better throughput for the existing Wi-Fi network compared to the reference case at lower traffic loads ($\lambda = 0.5$ packets/second) and comparable throughput performance at medium and higher traffic loads ($\lambda = 1.5$ and 2.5 packets/second). Even though the fairness require-
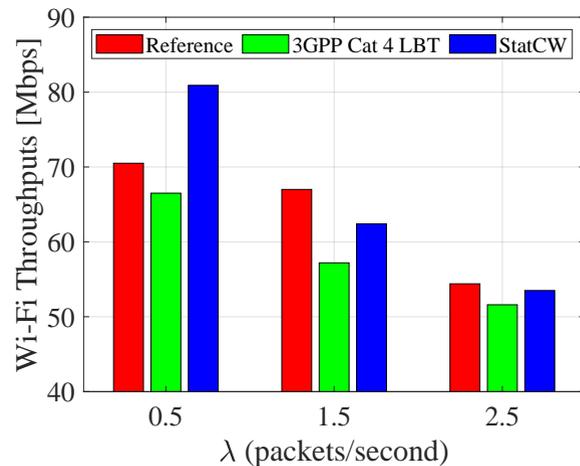
FIGURE 10. Wi-Fi throughput performance of the proposed static CW method.
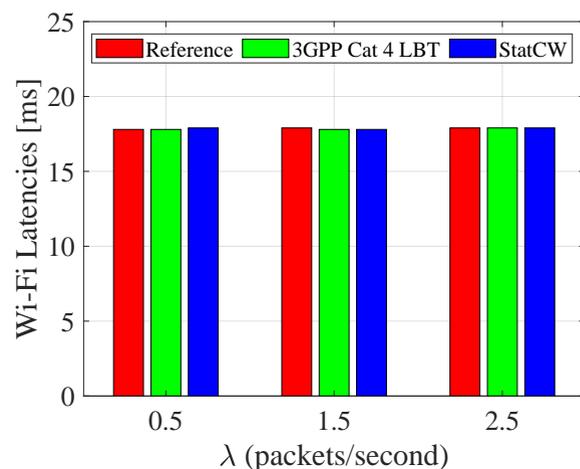
FIGURE 11. Wi-Fi latency performance of the proposed static CW method.

ment in terms of throughput is not fully met for all traffic loads (concretely, for $\lambda = 1.5$ packets/second), the proposed static CW method provides a very close approximation, with a noticeably better performance than the standard Cat 4 LBT method. Comparing the results shown in Figs. 6 and 10, it can be noted that the static CW method provides in general a better Wi-Fi throughput performance than the dynamic CW method as well.

The latencies of the existing Wi-Fi network are presented in Fig. 11 for the reference, Cat 4 LBT and static CW methods under different traffic loads. Comparable latencies for all traffic loads can be seen compared to the reference case. As a result, both Cat 4 LBT and static CW methods do not degrade the existing Wi-Fi performance in terms of latency.

The throughputs for LAA (i.e., operator B) using the Cat 4 LBT and static CW methods under different traffic loads are presented in Fig. 12. Comparing this figure with the
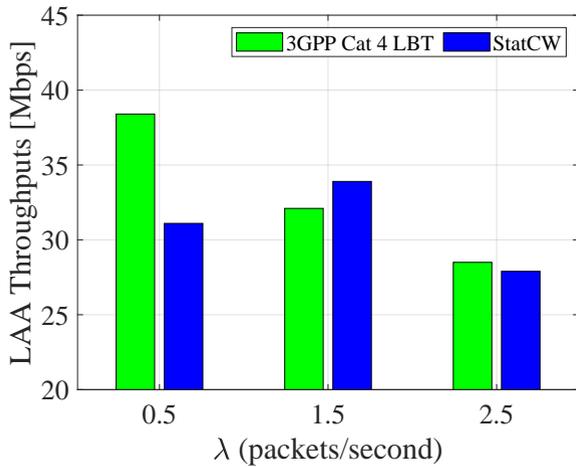
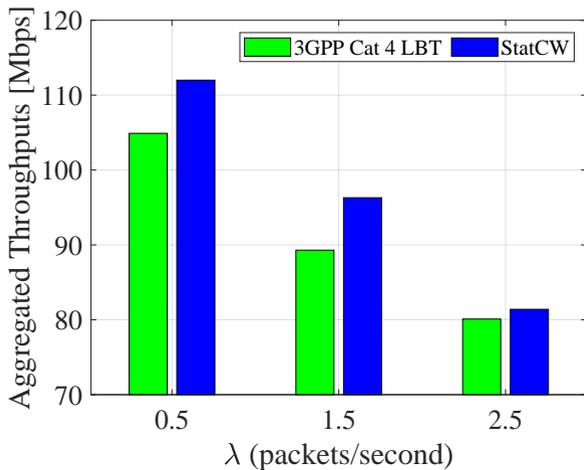**FIGURE 12.** LTE-LAA throughput performance of the proposed static CW method.

FIGURE 13. Aggregated throughput performance of the proposed static CW method.

results shown in Fig. 8 for the dynamic CW methods, it can be noted that the LAA throughput performance is quite comparable in both cases, with the LAA throughput for the static CW method being slightly lower than that attained by the best dynamic CW method. This slight reduction of the LAA throughput with the static CW method compared to the dynamic CW method is the price to be paid in order to achieve a better Wi-Fi throughput performance that, as shown in Fig. 10 for the static CW method, meets more closely the 3GPP definition of fairness. The existence of a tradeoff between the Wi-Fi and LAA throughput performances seems reasonable. However, it is interesting to note that the slightly degraded LAA throughput of the static CW method with respect to the dynamic CW method leads to a comparatively larger improvement of the Wi-Fi throughput. This can be clearly seen by comparing the total aggregated throughput of the static CW method (shown in Fig. 13) with the total aggregated throughput of the dynamic CW methods

(shown in Fig. 9). The static CW method outperforms the 3GPP Cat 4 LBT method in terms of aggregated throughput for all traffic loads (including $\lambda = 0.5$ packets/second, where the performance of the best dynamic CW method was still lower than that of the 3GPP Cat 4 LBT). Moreover, the performance improvements of the static CW method with respect to the Cat 4 LBT method are greater than those achieved by the best dynamic CW method, concretely 6.8% (7.1 Mbps), 7.8% (7 Mbps) and 1.6% (1.3 Mbps) for $\lambda = 0.5$, 1.5 and 2.5 packets/second, respectively.

Based on the obtained results, it can be concluded that the static CW method not only is more convenient than the 3GPP Cat 4 LBT method but also than the best dynamic CW method in terms of fairness. In general, the static CW method allows the Wi-Fi network experience a higher throughput performance that is closer to the scenario of fair coexistence as defined by the 3GPP. On the other hand, the LTE-LAA performance remains quite stable and, as a result, the overall aggregated performance of both networks is significantly higher with the static CW method.

C. FIXED WAITING TIME (FWT) METHOD
The performance of LTE-LAA and Wi-Fi networks is investigated here using the proposed FWT method for LAA. Fig. 14 depicts the throughputs for the existing Wi-Fi network under different traffic loads for the reference, Cat 4 LBT and fixed waiting times methods. It can be seen that the proposed FWT method provides better throughput for the existing Wi-Fi network for all traffic loads compared not only to the standard Cat 4 LBT method but also to the reference case. This means that the existing Wi-Fi network (operator A) experiences a better throughput performance when the coexisting network (operator B) is an LTE-LAA network using the proposed FWT method than when it is another Wi-Fi network. This means that the proposed FWT method not only meets the 3GPP fairness requirement in terms of throughput but in fact leads to an improved throughput performance for the existing Wi-Fi network when an LTE-LAA network is introduced (compared to the introduction of another Wi-Fi network). This may be explained by the ability of the proposed FWT method to select a suitable amount of waiting time before attempting a transmission such that there is a high chance to find a free channel without waiting unnecessarily long times, which can in turn be ascribed to the selection of such waiting time based on the Wi-Fi activity statistics.

Fig. 15 presents the latencies of the existing Wi-Fi network for the reference, Cat 4 LBT and FWT methods under different traffic loads. It can be seen that all methods provide comparable latencies for all traffic loads. As a result, both Cat 4 LBT and FWT methods do not degrade the performance of the existing Wi-Fi network in terms of latency.

Fig. 16 depicts the throughputs for LAA (i.e., operator B) using the Cat 4 LBT and FWT methods under different traffic loads. It can be seen that the significant throughput
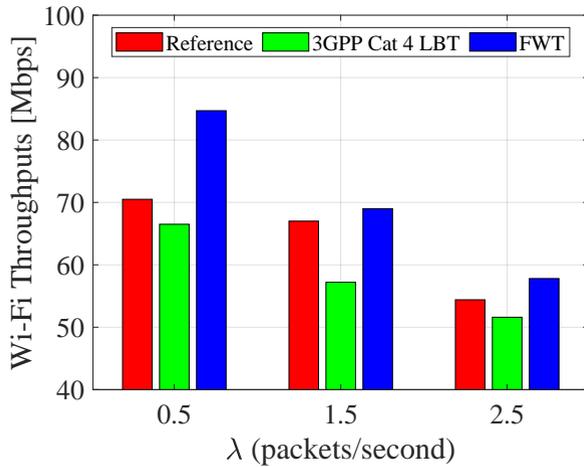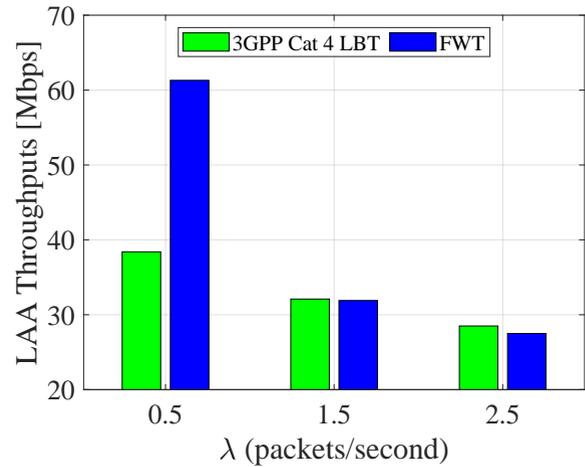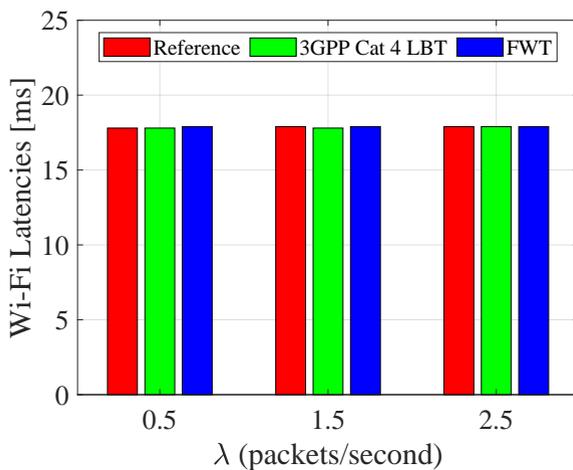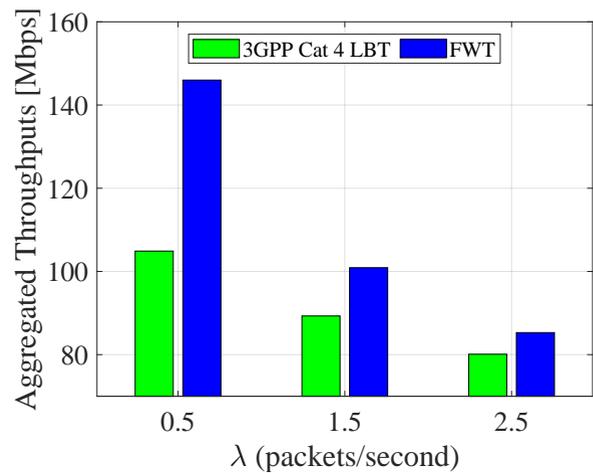
performance improvements for the existing Wi-Fi network provided by the FWT method (as observed in Fig. 14) are not obtained at the expense of the LTE-LAA throughput performance, which is comparable under medium and higher traffic loads ($\lambda = 1.5$ and 2.5 packets/second) and even better at lower traffic loads ($\lambda = 0.5$ packets/second). As a result, the total aggregated throughput of both networks is significantly enhanced as it can be appreciated in Fig. 17, which shows very significant throughput performance improvements with respect to the 3GPP Cat 4 LBT algorithm of 39.2% (41.1 Mbps), 13% (11.6 Mbps) and 6.5% (5.2 Mbps) for $\lambda = 0.5$, 1.5 and 2.5 packets/second, respectively. These improvements are larger than those observed for the dynamic and static CW methods analysed in the previous sections and can be explained by the ability of FWT to select an adequate waiting time, which ultimately results in a reduced number of collisions between both coexisting networks and consequently in an improved performance for

both networks, thus making the proposed FWT method a more suitable candidate for LTE-LAA.

D. VARIANTS OF THE PROPOSED WAITING TIME ADAPTATION METHODS

The performance of LTE-LAA and Wi-Fi networks is here analysed when the minimum and mode variants of the proposed waiting time adaptation methods are considered. Fig. 18 shows the throughput of the existing Wi-Fi network under different traffic loads for all the waiting time adaption methods considered in this work, including the 3GPP Cat 4 LBT and proposed methods, both in their standard versions and with the minimum and mode variants. It can be noticed that the minimum variants either provide a similar Wi-Fi throughput performance as the original versions of the respective method or, in some cases, lead to a slight throughput performance degradation, but in no case the minimum variants lead to a throughput performance improvement in
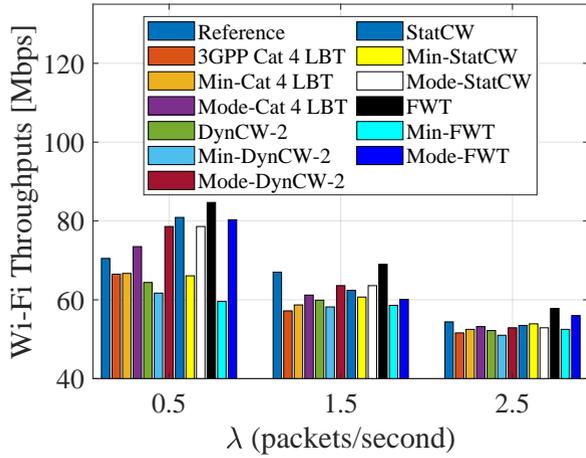
FIGURE 18. Wi-Fi throughput performance of the proposed methods and their variants.
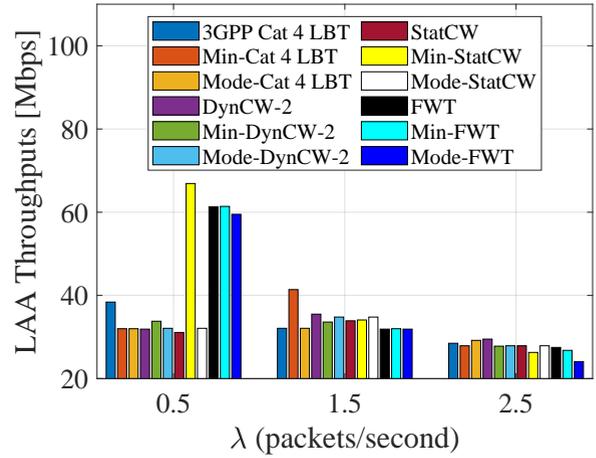

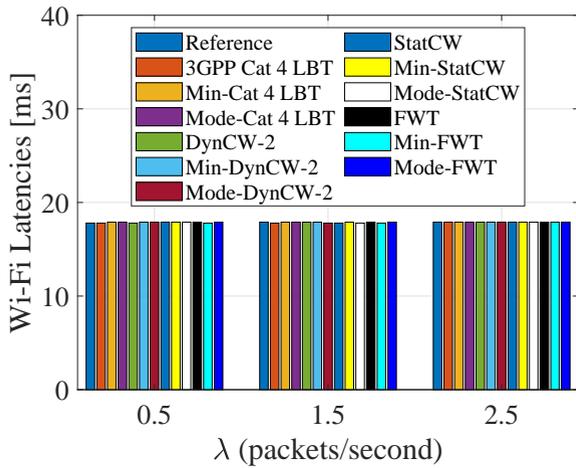**FIGURE 20.** LTE-LAA throughput performance of the proposed methods and their variants.

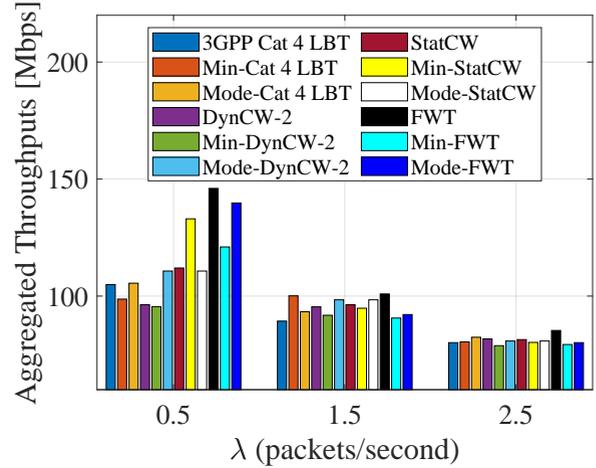**FIGURE 19.** Wi-Fi latency performance of the proposed methods and their variants.

FIGURE 21. Aggregated throughput performance of the proposed methods and their variants.

the Wi-Fi network. These results indicate that the minimum variants are not suitable for a fair coexistence of the LTE-LAA network with the existing Wi-Fi network. The mode variants lead in most cases to higher Wi-Fi throughputs than their minimum counterparts, however they do not necessarily perform better than the standard versions of their respective methods (if fact, the mode variant leads to a higher throughput for all traffic loads only for the 3GPP Cat 4 LBT and DynCW-2 methods). As it can be observed in Fig. 18, the best Wi-Fi throughput performance for all traffic loads is attained with the FWT method in its standard version.

Fig. 19 presents the latencies of the considered methods and their variants under different traffic loads. As it can be appreciated, and in line with the latency performance results presented in previous sections, comparable latencies are obtained with all methods and for all traffic loads.

Fig. 20 presents the LTE-LAA throughput performance

attained by the various methods and variants under different traffic loads. The performances observed in this figure can largely be explained based on the trends discussed for the Wi-Fi throughput performance in Fig. 18, noting the existence of a performance trade-off between the Wi-Fi and LTE-LAA networks such that an increase in the Wi-Fi throughput can usually be associated with a corresponding decrease in the LTE-LAA throughput and vice versa.

The aggregated throughput performances of both Wi-Fi and LTE-LAA networks for the various methods considered in this work and their variants are shown in Fig. 21. As in previous figures, there are some specific cases where one of the variants provides a better performance than the original version of the corresponding method, however there is no clear trend that can guarantee an improved performance in all cases when a variant is employed.

When jointly taking into account all the methods considered in this work to select/adapt the waiting times of

LTE-LAA and their variants, it becomes apparent that the FWT method (in its standard version) is the most suitable candidate. On the one hand, the FWT method is the only candidate that in all cases (i.e., all traffic loads) ensures that the Wi-Fi throughput performance will not be degraded (with respect to the reference case) by the introduction of an LTE-LAA network, and therefore leads to a fair coexistence. As a matter of fact, and interestingly, the introduction of an LTE-LAA network using the proposed FWT method results indeed in a higher throughput performance for the existing Wi-Fi network than the introduction of another Wi-Fi network, as observed in Fig. 18. On the other hand, the FWT method yields the highest aggregated throughput between both networks. Therefore, the proposed FWT method is the only method out of all the methods considered in this work (including the 3GPP Cat 4 LBT method) that guarantees a fair coexistence with the existing Wi-Fi network (and in fact improves its performance) while at the same time providing the highest aggregated throughput between both networks.

E. LTE TRANSMISSION TIMES ADAPTATION METHOD

The performance of LTE-LAA and Wi-Fi networks is investigated here using the proposed dynamic TxOP period method. Fig. 22 depicts the throughputs for the existing Wi-Fi network under different traffic loads for the homogeneous coexistence (i.e., Wi-Fi and Wi-Fi) and the heterogeneous coexistence (i.e., Wi-Fi and LTE-LAA) scenarios. In particular, the 3GPP Cat 4 LBT method with various static TxOP periods is considered for Wi-Fi/LAA coexistence. Moreover, the proposed dynamic TxOP approach is investigated for the Wi-Fi/LAA coexistence scenario as well. It can be seen that the standard Cat 4 LBT method achieves lower Wi-Fi throughputs compared to the reference case for the different static TxOP periods for all traffic loads. The proposed dynamic TxOP method, when compared to the static TxOP method, provides a comparable Wi-Fi throughput performance for $\lambda = 1.5$ and 2.5 packets/second, and a slightly better throughput for $\lambda = 0.5$ packets/second, which in all cases is lower than the throughput experienced by the Wi-Fi network in the reference case. These results indicate that the proposed dynamic TxOP method does not provide in general an improved fairness for the existing Wi-Fi network.

The corresponding latencies for the existing Wi-Fi network are depicted in Fig. 23. It can be noticed that all methods achieve very similar performance in terms of Wi-Fi latency. As a result, the Cat 4 LBT method using a static TxOP approach and the proposed dynamic TxOP method do not degrade the existing Wi-Fi latency.

Fig. 24 presents the LAA throughput performance for the Wi-Fi/LAA coexistence scenario using the static approach of Cat 4 LBT and using the proposed dynamic TxOP approach. For low traffic loads ($\lambda = 0.5$ packets/second), it can be noticed that the dynamic TxOP method provides the same throughput as the static TxOP method with a 20 ms TxOP. This can be explained by the fact that, under low traffic loads, the channel is sparsely used, long idle times are
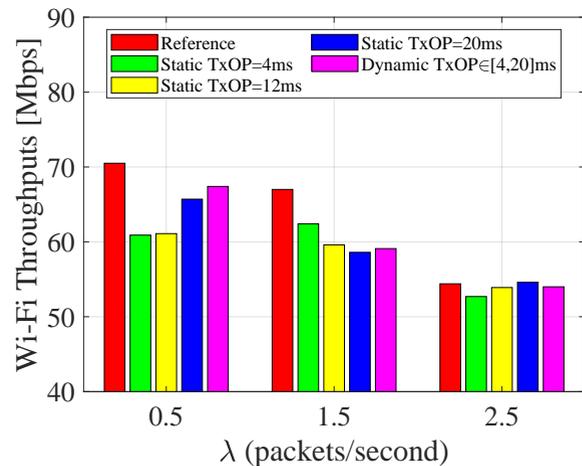

FIGURE 22. Wi-Fi throughput performance of the proposed dynamic TxOP period method.
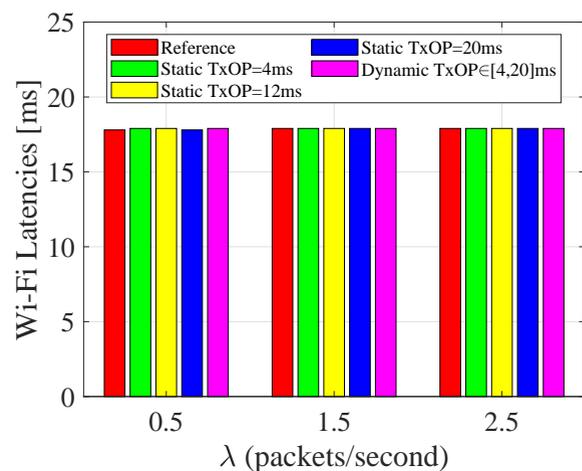

FIGURE 23. Wi-Fi latency performance of the proposed dynamic TxOP period method.

frequent and collisions are unlikely to occur. As a result, the vast majority of transmissions are performed with the lowest value of the CW (i.e., 15) and therefore most of the time the dynamic TxOP method selects the highest TxOP available (i.e., 20 ms as illustrated in Table 6). In this scenario of low traffic load ($\lambda = 0.5$ packets/second), the dynamic TxOP method is equivalent to the static TxOP method with a 20 ms TxOP and, as a result, both methods achieve the same throughput. Notice that the achieved throughput is the highest attained for $\lambda = 0.5$ packets/second, which indicates that a constant selection of a 20 ms TxOP in such a case is the optimum choice when it comes to the LTE throughput.

For medium traffic loads ($\lambda = 1.5$ packets/second), Fig. 24 shows that the static TxOP method is unable to achieve the same throughput as the proposed dynamic TxOP method. This is because under this higher traffic load, the channel usage increases and so does the number of collisions. As a result, a constant 20 ms TxOP is not the optimum
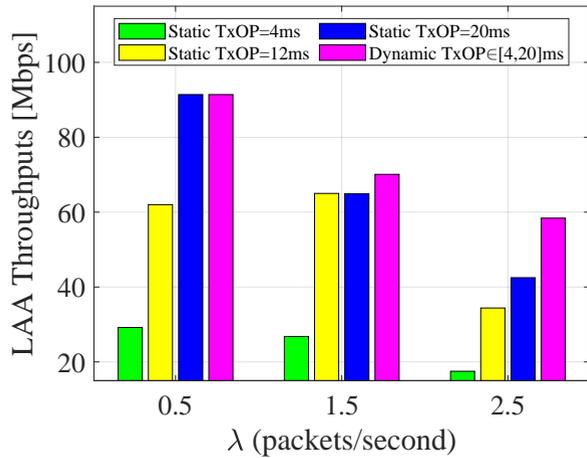
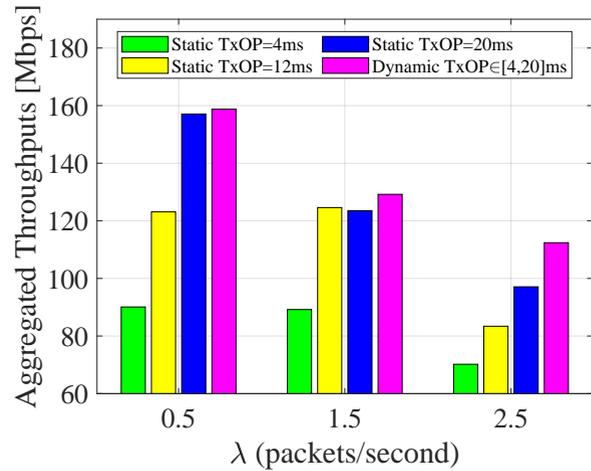**FIGURE 24.** LTE-LAA throughput performance of the proposed dynamic TxOP period method.

FIGURE 25. Aggregated throughput performance of the proposed dynamic TxOP period method.

choice anymore since this long transmission time will lead to more frequent collisions and therefore a lower throughput (this is also suggested by the fact that, under a static TxOP, the same throughput is obtained for 12 ms and 20 ms TxOP, showing that there is no benefit from performing longer transmissions). In this scenario, and as a result of the presence of some collisions in the channel, the CW will be increased sometimes from the lowest value (i.e., 15) to the next value (i.e., 31) and, when this occurs, the proposed dynamic TxOP method will accordingly reduce the TxOP from 20 ms to 4 ms in order to reduce the likelihood of more frequent channel collisions. As appreciated in Fig. 24, this dynamic adaption of the TxOP performs well and leads to a higher throughput for the LTE-LAA network than any of the static configurations. This is also confirmed for higher traffic loads ($\lambda = 2.5$ packets/second), where it can be clearly appreciated that the proposed dynamic TxOP yields a significantly improved throughput performance as a result of this smart adaption of the TxOP length to the instantaneous occupancy activity in the Wi-Fi channel.

The total aggregated throughputs for the coexisting networks (i.e., Wi-Fi and LTE-LAA) for the various methods under different traffic loads are depicted in Fig. 25. The results presented in Fig. 25 show not only that the proposed dynamic TxOP method provides the highest aggregated throughput for all traffic loads compared to the standard Cat 4 LBT method based on a static TxOP configuration, but also obtains more significant performance improvements with respect to the static TxOP method as the traffic load increases. Specifically, the performance improvement in the total aggregated throughputs for both networks using the dynamic TxOP method compared to the static TxOP method for $\lambda = 2.5$ packets/second is 60.1% (42.2 Mbps), 34.8% (29 Mbps) and 15.8% (15.3 Mbps) for a static TxOP period of 4, 12 and 20 ms, respectively.

F. DISCUSSION

The methods proposed in this work fall into two categories, namely those focused on the LTE-LAA waiting times and those focused on the LTE-LAA transmission times. For the first category, the results presented in Section VI-D concluded that the FWT method is the most convenient approach within its category since it is the only method out of all the methods considered in this work (including the 3GPP Cat 4 LBT method) that guarantees a fair co-existence with the existing Wi-Fi network (i.e., it does not produce a degradation more significant than that caused by another Wi-Fi network) while at the same time provides the highest aggregated throughput between both networks when compared to the rest of methods in the same category. For the second category, a method has been proposed based on the dynamic adaption of the TxOP length, which is unable to improve the fairness offered by the 3GPP Cat 4 LBT method but yields a higher aggregated throughput between both networks, in particular as a result of a significantly enhanced throughput for the LTE-LAA network.

Following the performance evaluation carried out individually for the methods in each category, a natural question is which of these methods would be more convenient in a practical coexistence scenario. This question can be answered based on the Wi-Fi throughput results shown in Fig. 26 and the total aggregated throughputs shown in Fig. 27, which compare together the main results shown in previous sections. As it can be appreciated, the FWT method is the only method that can fully meet the fairness requirement as defined by the 3GPP. Thus, this method may be more appealing to scenarios where the Wi-Fi and LTE-LAA networks are owned by different operators, where the LTE-LAA operator is strictly required to avoid causing unacceptable performance degradation to the Wi-Fi operator. On the other hand, the dynamic TxOP method provides the highest aggregated throughput at the expense of a slightly
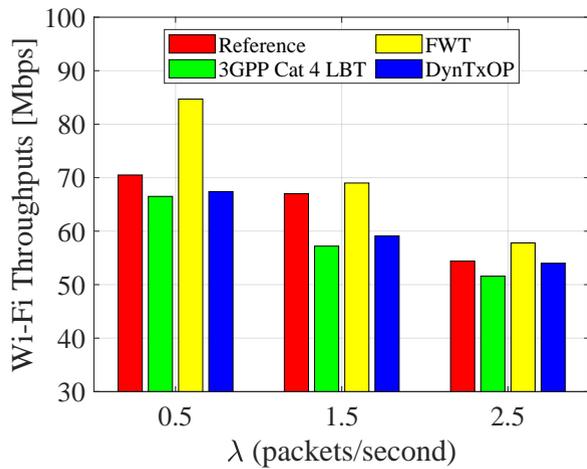
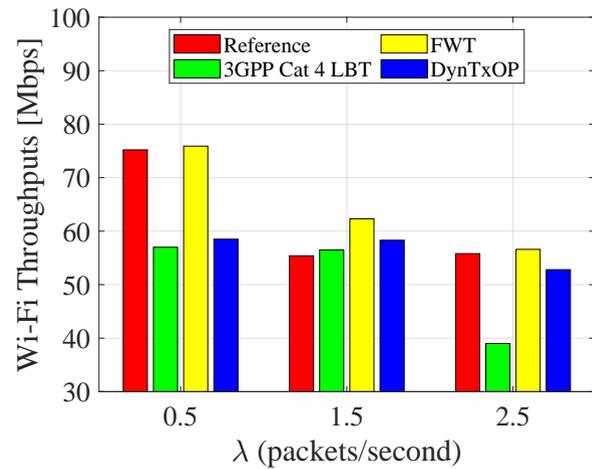**FIGURE 26.** Wi-Fi throughput performance of selected methods (5 STAs/UEs per AP/eNB).

FIGURE 28. Wi-Fi throughput performance of selected methods (10 STAs/UEs per AP/eNB).
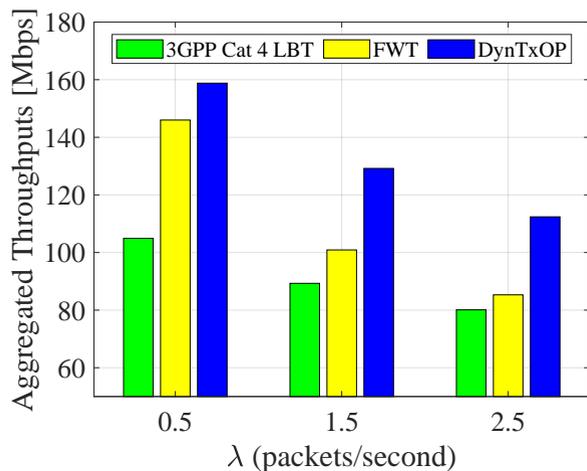

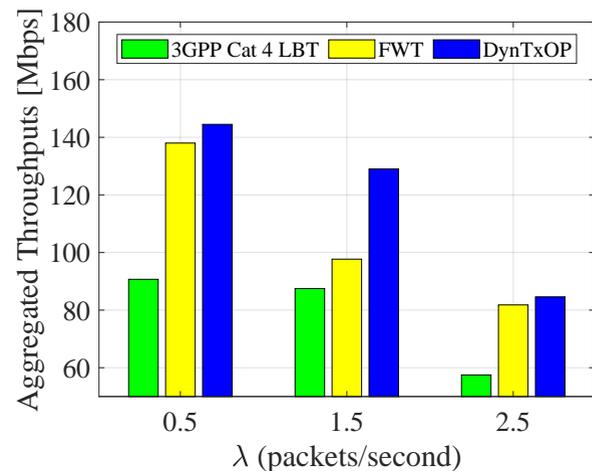**FIGURE 27.** Aggregated throughput performance of selected methods (5 STAs/UEs per AP/eNB).

FIGURE 29. Aggregated throughput performance of selected methods (10 STAs/UEs per AP/eNB).

degraded Wi-Fi throughput and thus it may be more suitable to scenarios where both networks are owned by the same operator, for example where a mobile cellular operator offers Wi-Fi hotspots to its clients and therefore the ultimate interest is in maximising the overall aggregated throughput (i.e., the total capacity) of the owned network infrastructure.

Finally, it is worth noting that, while in this work the traffic load has been varied by modifying the packet inter-arrival rates at the application layer (λ = 0.5, 1.5 and 2.5 packets/second), this can also vary based on the network scale (i.e., number of Wi-Fi APs, LTE-LAA eNBs, users). While the numerical results may change for different network conditions, the main conclusions of this study remain the same. In order to illustrate this, Figs. 28 and 29 show the counterparts of Figs. 26 and 27 when the total number of users in the system is doubled. As it can be appreciated, the main conclusions discussed above for the methods proposed in this work are also valid under larger network scales.

VII. CONCLUSION

Current studies aim to enable a fair coexistence between LTE-LAA and Wi-Fi networks over unlicensed spectrum bands. The current 3GPP Cat 4 LBT algorithm does not perfectly meet the fairness definition given by 3GPP. In particular, a Wi-Fi throughput degradation can be noticed due to deploying LTE-LAA with Wi-Fi over the same unlicensed band. Different design parameters of the LBT algorithm play a key role in this heterogeneous coexistence such as the waiting and transmission times for LAA. Therefore, novel methods have been proposed to tune the waiting and transmission times for LAA as an alternative to the traditional contention window-based approach and the fixed configuration of the TxOP period for LAA proposed by the 3GPP. The obtained simulation results have shown that, for LAA/Wi-Fi coexistence, selecting fixed waiting times for LAA based on the knowledge of the activity statistics of the existing Wi-Fi network achieves better performance

compared to the contention window-based approach of the standard 3GPP Cat 4 LBT algorithm, and moreover it also results in less complex coexistence mechanisms. In addition, the dynamic TxOP period method achieves better performance compared to the fixed TxOP period approach of the standard Cat 4 LBT algorithm. The most convenient method to use depends on the particular business scenario and target of the network operator as discussed in this work but, in any case, the proposed methods can provide significant performance improvements compared to the standard 3GPP Cat 4 LBT method.

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