Dynamic Contention Window Methods for Improved Coexistence Between LTE and Wi-Fi in Unlicensed Bands

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***Abstract*—Recently, the 3rd Generation Partnership Project (3GPP) announced standards that permit the Licensed-Assisted Access (LAA) of Long Term Evolution (LTE) to operate over unlicensed spectrum bands. This permission, which is a part of the 5G specifications, is due to the scarcity of the licensed spectrum and the increased use of wireless networks and services. However, these unlicensed bands are mainly occupied by 802.11 based WLAN devices. Thus, challenges arise for the efficient coexistence mechanism to share the same unlicensed band by LAA and Wi-Fi to maintain the quality of service and manage the interference among users. In this work, we propose new variable contention window (CW) methods for LAA to enable the coexistence of LTE and Wi-Fi in a fair manner based on the Wi-Fi statistics. The main novelty of this work is that the knowledge of Wi-Fi activity statistics is exploited to adapt the CW of LAA more effectively. These methods are evaluated based on the 3GPP fairness definition for such coexistence mechanisms under various traffic loads. We show that the fairness depends on the LAA CW size. Further, through simulation results, we show that the proposed schemes are more friendly to the existing Wi-Fi network, in particular for the higher traffic loads, compared with the existing Category 4 Listen-Before-Talk (Cat 4 LBT) algorithm defined in the 3GPP standard and provide higher total throughputs for both coexisting networks, improving the overall network performance.**

***Index Terms*—Coexistence mechanism; Contention window; Licensed-Assisted Access; Listen-Before-Talk .**

I. Introduction

With the increased demand on wireless services and applications, research is focusing on techniques that manage and utilise the spectrum more efficiently. One of the promising techniques to deal with the increasing data traffic and the lack of available spectrum is spectrum sharing [1]. As a result of the limited availability of licensed spectrum, the large amount of accessible unlicensed spectrum and the growing demands in cellular systems have attracted researchers to expand the operations of Long Term Evolution (LTE) into the unlicensed bands (specifically the 5 GHz band) [2].

LTE technology has been recently developed to enable the coexistence with Wi-Fi devices over the 5 GHz unlicensed band. Many benefits can be achieved by this coexistence such as higher throughput, more capacity, and better performance in dense deployments [3]. On the other hand, the difference in the MAC layers and the lack of coordination between these two technologies are challenging problems [4]. Wi-Fi technology employs Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) to provide efficient access to the unlicensed bands. In specific, each Wi-Fi node should sense the channel to determine if it is idle or not before transmission [5]. Then, the transmission starts if the channel is idle, otherwise a random back-off timer is selected and the transmission starts when the timer decreases to zero. On the other hand, there is no sensing scheme in LTE as it is a centralised network. Thus, sharing the unlicensed band with LTE without any coordination degrades the performance of the existing technology (i.e., Wi-Fi) because of the heterogeneous wireless protocols between these two technologies [6].

The 3rd Generation Partnership Project (3GPP) Release 13 proposed the use of LTE in the unlicensed spectrum, which is called LTE Licensed-Assisted Access (LTE-LAA). LAA aggregates the primary carrier in the licensed band and the secondary carrier in the unlicensed band [2]. LAA can provide higher capacity, lower latency, better coverage and lower operational costs compared to the traditional offloading of cellular traffic to Wi-Fi networks [7]. Moreover, it allows LTE not to degrade the throughput performance of Wi-Fi nodes when these two technologies coexist over the 5 GHz unlicensed band. These benefits can be achieved by using a Listen-Before-Talk (LBT) mechanism before transmission and modifying the LTE air interface accordingly [8].

The fairness between LTE and Wi-Fi networks over the 5 GHz unlicensed band is described by 3GPP TR 36.889 as the capability of an LTE network not to impact the existing Wi-Fi network active on the same carrier more than an additional Wi-Fi network in terms of throughput and latency [2], [9]. Hence, when designing LAA, this definition should be taken into account to achieve an effective coexistence with Wi-Fi. Using an LBT algorithm for LTE-LAA is necessary for a fair coexistence between LTE and Wi-Fi in the 5 GHz band. Moreover, the design of this LBT algorithm plays a critical role in this fairness [10].

Due to the different advantages of deploying LTE with Wi-Fi over the 5 GHz band, there have been several studies in the literature on the coexistence mechanisms for LTE and Wi-Fi networks. As part of this evolution, different scenarios of LTE have been developed to coexist with Wi-Fi over the unlicensed 5 GHz band. LTE-U was the first version of LTE over unlicensed spectrum, which does not use any LBT mechanism, while the last version is LTE-LAA. A comparative performance analysis of existing coexistence approaches (i.e., LTE-U versus LTE-LAA) is presented in [11]. In [12], different coexistence mechanisms such as static muting, LBT, and Request-

To-Send/Clear-To-Send (RTS/CTS) have been implemented, and the results show that the RTS/CTS method provides the best performance compared to the other mechanisms. In [13], LBT-based techniques are implemented and evaluated using different Energy Detection (ED) thresholds, and the results show that the ED threshold plays a key role in the coexistence performance. In addition, the authors in [14] proposed a fair LBT algorithm to allocate the idle Wi-Fi periods by taking into account the system throughput and fairness. In [15], a distributed algorithm was proposed to adapt the detection thresholds of LAA based on the Cat 4 LBT procedure from the perspective of collisions. The simulation results show that the proposed algorithm improves the coexistence performance.

Despite the aim to enable a fair coexistence between LAA and Wi-Fi, the Category 4 LBT (Cat 4 LBT) algorithm proposed in the 3GPP standard [2] fails, as it will be shown in this work, to fully achieve the fairness requirements under high traffic loads. In this context, the main objective of this study is to propose new CW methods for LAA to improve the performance of the coexistence mechanism of LAA and Wi-Fi networks in a fair manner based on the Wi-Fi activity statistics. The main idea of the proposed scheme, which is a novel contribution of this work, is to update the LAA CW based on the knowledge of Wi-Fi statistics. We first analyse the Wi-Fi statistics for the ON time periods. We then analyse the coexistence of LAA and Wi-Fi using new proposed methods that exploit such knowledge. Finally, we compare the performance of the proposed scheme with the latest LBT algorithm (i.e., Cat 4 LBT). Via simulation, we show that the proposed schemes can achieve better performance and are more friendly than Cat 4 LBT scheme to Wi-Fi devices, leading to an improved performance for both LAA and Wi-Fi.

The rest of the paper is organised as follows. In Section II, the Cat 4 LBT algorithm is introduced. In Section III, two new dynamic CW methods that can be adopted to update the CW for LAA are presented. In Section IV, the methodology and the simulation setup for evaluating the coexistence performance are provided. In Section V, the simulation results are discussed. Finally, in Section VI, the conclusions are drawn.

II. Category 4 LBT Algorithm

Different LBT algorithms for LTE-LAA have been proposed in the literature to achieve a fair coexistence between LTE and Wi-Fi. Currently, Cat 4 LBT algorithm has been introduced in LTE Release 13 for the downlink transmissions [2]. The Cat 4 LBT procedure is depicted in Fig. 1. It can be seen that there is a similarity between this algorithm in LAA and the LBT algorithm in Wi-Fi. The main underlying idea is that the LAA eNodeB (eNB) should sense the channel to determine if it is idle or not, by performing a Clear Channel Assessment (CCA), which is similar to the CSMA/CA scheme in Wi-Fi. Data transmission can proceed if the channel is clear for the initial CCA (iCCA) (e.g., 34μs); otherwise, the extended CCA (eCCA) begins. In the eCCA stage, the LAA eNB starts a backoff process by selecting a random number $N\in[0,\ q\text{-}1]$, which defines the number of idle slots that are needed to be observed before transmission, where q varies according to an exponential backoff and represents the upper bound of the CW. Then, the channel is checked to be free or not for an eCCA period (e.g., 34μs). When the channel is free, another eCCA duration (e.g., 9μs) takes part and decrements N if the channel is sensed to be free. The counter is decremented every time a CCA slot is deemed to be unoccupied. When N reaches zero, the LAA eNB can begin its transmission. If the LAA eNB needs another transmission, the eCCA stage is performed. The initial value for the upper bound of the CW size q-1 is 15 and it is updated based on the Hybrid Automatic Repeat Request (HARQ) feedbacks. In particular, if 80% of feedbacks from the first subframe of the latest transmission burst are NACKs, HARQ declares a collision and q is doubled to leed to a new maximum CW of q-1 = 31. Then, q-1 is again updated to be 63 if another 80% of HARQ feedbacks are NACKs. Otherwise, q-1 is reset to 15. Thus, it is worth mentioning that the adaptation of the upper bound of the CW here does not take into account the Wi-Fi traffic statistics, and the maximum CW value, q-1, varies between $\{15,\ 31,\ 63\}$ regardless of the Wi-Fi traffic statistics.

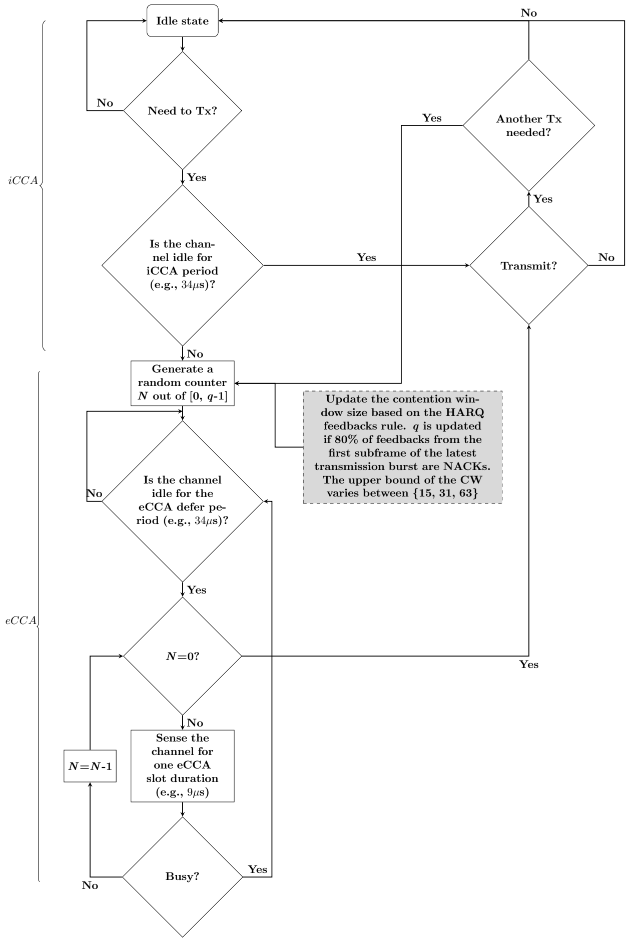

Fig. 1. Cat 4 LBT algorithm [2].

To improve the performance of this algorithm, new methods are proposed in this work. The dashed highlighted box in Fig. 1 highlights the procedure of Cat 4 LBT that we will modify to include the proposed dynamic CW methods, which are described in the next section.

III. Proposed Methods

The default 3GPP Cat 4 LBT algorithm implements a contention mechanism similar to that of Wi-Fi networks with the aim to make the LAA network behave similar to another Wi-Fi network and meet this way the fairness requirements as defined in [2]. When a transmission is not possible due to the channel being busy, LAA updates the upper bound of the CW, q-1, by successively doubling its value from 15 to 31 and finally to 63. This increase ratio is heuristic and independent on the actual ON/OFF activity times of the Wi-Fi network. As a result, the LAA contention for the channel can be expected to be inefficient. When LAA finds the channel to be busy in its first attempt to transmit and updates q by doubling its value, this necessarily leads to new waiting times much longer than the previous value of q. If these new waiting times are comparatively longer than the actual channel occupancy times of the Wi-Fi network, then LAA would unnecessarily wait a long time before re-attempting transmission on a channel that was actually vacated a long time ago. This would unnecessarily lead to increased latencies and reduced throughputs for LAA, and consequently a degraded performance. On the other hand, an adaption of the upper bound for the CW q that takes into account the Wi-Fi activity statistics (e.g., the distribution of the ON times) should lead to LAA waiting times that are better aligned with the actual channel occupancy times of the Wi-Fi network and therefore should provide a more efficient access to the channel (i.e., lower latency and higher throughput). In this context, this work proposes new methods to adapt the upper bound of the CW, q-1, based on the knowledge of the Wi-Fi traffic statistics.

The LAA network can estimate the Wi-Fi traffic statistics from the sensing decisions based on energy detection [5] without the need for any coordination mechanism with the Wi-Fi network. This estimation can be performed by the LAA network by periodically sensing the Wi-Fi channel state when LAA is not transmitting (i.e., during the idle periods of the LAA network) in order to make an estimation of the Wi-Fi ON times. Once a sufficiently large number of Wi-Fi ON times has been observed in the channel, the LAA network can then compute the Cumulative Distribution Function (CDF) of the ON times of the existing Wi-Fi network. This CDF characterises the activity pattern of the Wi-Fi network and can be exploited to efficiently adapt the maximum CW of LAA, instead of following the heuristic approach of the 3GPP Cat 4 LBT method based on simply doubling the value of q. The procedure is illustrated in Fig. 2, which shows an example of the CDF of the Wi-Fi ON times estimated by the LAA network, and Table I, which shows the corresponding values of the maximum CW, q-1, for several percentile points of the CDF. The values of Table I are computed from Fig. 2 by dividing the ON times corresponding to each percentile point by the LAA slot duration (9μs) and rounding the result to the nearest integer towards infinity (i.e., ceil function). For example, for λ = 0.5 packets/second, which is the example considered in Fig. 2, the 75% percentile point corresponds to a Wi-Fi ON time of around 65μs, which divided by 9μs and ceiled leads to the value q-1 = 8 shown in Table I for the 75% percentile and λ = 0.5. The rest of values are obtained

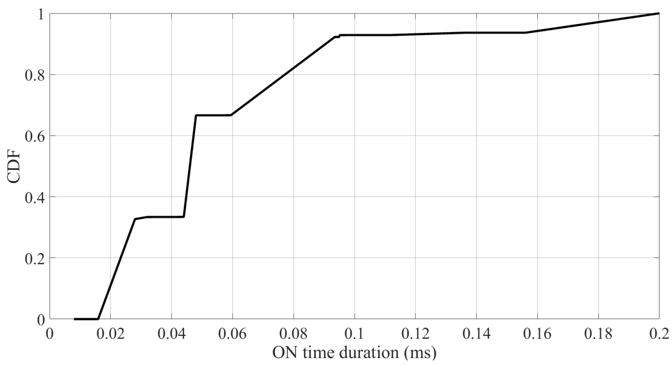

Fig. 2. CDF of the ON times of the existing Wi-Fi network for a packet inter-arrival rate of λ = 0.5 packets/second and a packet size of 0.5 MB/packet.

TABLE I
The maximum CW values (q-1) under different traffic loads (9μs slots)

Percentile point	λ **0.5**	**1.5**	**2.5**	**3.0**
100%	23	23	23	23
99%	22	22	21	21
95%	19	18	14	13
75%	8	10	10	10
50%	6	8	9	9
25%	3	6	7	7

following the same principle. Notice that a percentile point of 100% in a theoretical CDF model would in general be not feasible since the corresponding ON time would tend to infinity. However, the CDF used by the LTE-LAA system to adapt the maximum CW is based on empirically observed Wi-Fi ON times, which will necessarily have a finite maximum. This maximum Wi-Fi ON time is the value used to compute the maximum CW value for the 100% percentile point in a practical implementation.

This approach allows for several adaptation strategies. In this work, we consider the following two methods:

1) Method A: This method defines three adaptation points at the 50% (median value), 95% and 100% (maximum value) percentiles of the CDF of Wi-Fi ON times. The first maximum CW value for LAA, q-1, is set to the median Wi-Fi ON time since 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. Therefore, the median value appears to be a reasonable starting point for the maximum CW of LAA. If an LAA transmission attempt fails, then the maximum CW q-1 is increased to the 95% percentile, which means than only in 5% of the cases the maximum waiting time would not be enough to find the Wi-Fi channel idle when LAA re-attempts a transmission. In most cases, LAA should find an idle Wi-Fi channel after the new waiting time and therefore should be able to transmit. In those few cases where a very long Wi-Fi transmission takes place, then the maximum CW is finally updated to the 100% percentile point (maximum value), which should lead with high certainty (in theory) to a successful transmission in the next attempt. Notice that, with this method, the actual LAA waiting times are adapted in accordance with the Wi-Fi traffic statistics. For example, for λ = 0.5 Wi-Fi packets/second, the maximum CW values with this method will be q-1 = {6, 19, 23}, while for λ = 2.5 packets/second they will be q-1 = {9, 14, 23}, thus adapting the LAA contention mechanism to the actual Wi-Fi channel traffic patterns. On the other hand, 3GPP Cat 4 LBT would always use q-1 = {15, 31, 63} regardless of the Wi-Fi traffic activity. Note that, in this example, the 3GPP Cat 4 LBT values of q-1 are significantly larger than those provided by the proposed method, even for large traffic loads, which appears to corroborate the observation that the 3GPP method may potentially lead to unnecessarily long waiting times for LAA.

2) Method B: This method is similar to Method A but defines only two adaption points for the maximum contention window, first at the 50% percentile (median value) and finally at the 100% percentile (maximum value). The motivation of this method is to hopefully allow for a faster convergence to the optimum CW for LAA, in case it needs to be increased, and therefore reduce LAA waiting times, virtually leading to reduced latency and increased throughput.

IV. Methodology and Simulation Setup

The new methods proposed in this work are evaluated based on the main definition of fairness as defined by 3GPP, which requires that the LAA network should not impact the Wi-Fi network more than an additional Wi-Fi network operating on the same carrier. For the estimation of the Wi-Fi statistics, instead of deploying an LTE network on the same carrier as the existing Wi-Fi network, two Wi-Fi networks have been deployed to investigate the impact of such homogeneous coexistence (i.e., Wi-Fi and Wi-Fi) on the existing Wi-Fi network. Then, the CDF for the ON time periods of the existing Wi-Fi network can be evaluated. As a result, this CDF can be exploited to update the LAA CW following either of the two proposed methods. Afterwards, one of the Wi-Fi networks is replaced with an LTE-LAA network to have an LAA/Wi-Fi coexistence scenario and assess this way the coexistence performance.

The methodology for evaluating the coexistence performance of LTE-LAA and Wi-Fi follows the 3GPP TR 36.889 except for the updating rule of the CW, where the proposed CW methods have been implemented. In this study, the methods are evaluated with the NS-3 simulator with LAA extension [16]. In particular, we adopt an indoor scenario as specified by 3GPP [2] and consider two operators: operator A (Wi-Fi) and operator B (LAA) using the same 20 MHz channel over the 5 GHz band. As it can be seen from Fig. 3, each operator deploys 4 Access Points (APs)/eNBs and 20 Stations (STAs)/User Equipments (UEs) randomly distributed in a one-floor building with a rectangular area. Moreover, this model simulates file transfers arriving according to Poisson prosses with arrival rate λ. Traffic is modelled as a File Transfer Protocol (FTP) to operate over User Datagram Protocol (UDP) where FTP Model 1 has been implemented considering the downlink scenario. The file size is 0.5 MB with different Poisson arrival rates (λ = 0.5, 1.5, 2.5, 3.0 packets/second) [2]. The details of the simulation scenario are compared to the 3GPP model in Table II.

In addition, all the nodes (i.e., APs/eNBs/STAs/UEs) are equipped with two antennas for 2x2 MIMO operation. The two ED thresholds for Wi-Fi are -62 dBm to detect the LAA signal and -82 dBm to detect the Wi-Fi signal. On the other hand, the LAA ED threshold is -72 dBm. The transmission opportunity length (i.e., TxOP) is fixed at 8 ms.

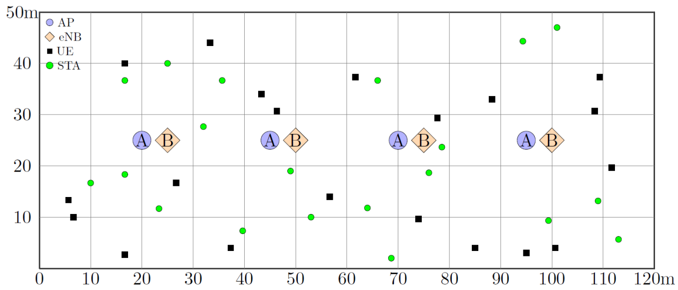

Fig. 3. 3GPP indoor topology with two operators (operator A and operator B) with 4 APs/eNBs per operator.

TABLE II
3GPP TR 36.889 versus NS-3

Unlicensed channel model	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)
Total BS Tx power	18/24 dBm	18 dBm
Total UE Tx power	18 dBm	18 dBm
Pathloss, shadowing & fading	ITU InH	IEEE 802.11ax
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

To validate the proposed CW methods, the performance is compared with the method defined by the 3GPP standard (described in Section II) based on the two relevant fairness metrics (throughput and latency). Throughput is defined as the amount of data that can be transferred from one location to another in a given amount of time as observed at the IP layer, while latency is measured as the time elapsed since the packet leaves the transmitter until it reaches the receiver. In the next section, we present the simulation results for these various methods.

V. Simulation Results

In this section, the performance of LAA and Wi-Fi networks in an indoor scenario is analysed using the proposed CW methods. We present the tables of individual throughputs and latencies for LAA and Wi-Fi networks and the total aggregated throughputs for both networks. To assess the performance of the proposed methods, the 3GPP definition of "fairness" is here considered based on the throughput and latency for 95% of the users. We evaluated the throughput at various percentiles (90%, 95% and 100%) and the main trends and conclusions are applicable in all cases, but we show here only the results for the 95% percentile for the sake of brevity.

In Table III, the throughputs for the existing Wi-Fi network (i.e., operator A: Wi-Fi) for the various methods considered at different arrival rates (i.e., different traffic loads) are presented. The reference case (Ref) represents the throughput for operator A (Wi-Fi) when it coexists with another operator B (Wi-

TABLE III
OPERATOR A: WI-FI THROUGHPUTS FOR 95% OF USERS USING DIFFERENT CW METHODS FOR DIFFERENT TRAFFIC LOADS

λ	**0.5**	**1.5**	**2.5**	**3.0**
Throughput [Mbps]	70.5 (Ref)	67.0 (Ref)	54.4 (Ref)	53.0 (Ref)
	66.5 (Cat 4)	59.9 (Method B)	52.2 (Method B)	47.3 (Method B)
	64.4 (Method B)	58.7 (Method A)	52.0 (Method A)	46.9 (Method A)
	60.2 (Method A)	57.2 (Cat 4)	51.6 (Cat 4)	45.5 (Cat 4)

TABLE IV
OPERATOR A: WI-FI LATENCIES FOR 95% OF USERS USING DIFFERENT CW METHODS FOR DIFFERENT TRAFFIC LOADS

λ	**0.5**	**1.5**	**2.5**	**3.0**
Latency [ms]	17.8 (Ref)	17.9 (Ref)	17.9 (Ref)	17.9 (Ref)
	17.8 (Cat 4)	17.8 (Cat 4)	17.9 (Cat 4)	17.9 (Cat 4)
	17.8 (Method A)	17.8 (Method A)	17.9 (Method A)	17.9 (Method A)
	17.8 (Method B)	17.8 (Method B)	17.9 (Method B)	17.9 (Method B)

TABLE V
OPERATOR B: LAA THROUGHPUTS FOR 95% OF USERS USING DIFFERENT CW METHODS FOR DIFFERENT TRAFFIC LOADS

λ	**0.5**	**1.5**	**2.5**	**3.0**
Throughput [Mbps]	38.4 (Cat 4)	35.5 (Method B)	29.5 (Method B)	27.2 (Method B)
	31.9 (Method B)	32.1 (Cat 4)	29.1 (Method A)	25.9 (Method A)
	31.7 (Method A)	31.9 (Method A)	28.5 (Cat 4)	25.6 (Cat 4)

TABLE VI
TOTAL THROUGHPUTS FOR 95% OF USERS FOR BOTH OPERATORS USING DIFFERENT CW METHODS FOR DIFFERENT TRAFFIC LOADS

λ	**0.5**	**1.5**	**2.5**	**3.0**
Throughput [Mbps]	104.9 (Cat 4)	95.4 (Method B)	81.7 (Method B)	74.8 (Method B)
	96.3 (Method B)	90.6 (Method A)	81.1 (Method A)	72.8 (Method A)
	91.9 (Method A)	89.3 (Cat 4)	80.1 (Cat 4)	71.1 (Cat 4)

Fi), while the other cases correspond to coexistence scenarios where operator B is an LTE-LAA network. The 3GPP fairness definition requires the Wi-Fi throughput in the coexistence scenarios to be no lower than that of the reference case. In general, it is observed that Cat 4 LBT method performs worse than the reference case (i.e., operator A: Wi-Fi and operator B: Wi-Fi) for all traffic loads. Thus, coexisting LAA with Wi-Fi using Cat 4 LBT method impacts the existing Wi-Fi network, which conflicts with the fairness definition. On the other hand, the proposed variable CW methods (i.e., Method A and Method B) provide better performance than Cat 4 LBT method for the different traffic loads except for λ = 0.5. Thus, the proposed methods are more friendly than the Cat 4 LBT method for the existing Wi-Fi network, which means that they degrade Wi-Fi (i.e., operator A) throughput less than the Cat 4 LBT method when LAA coexists with Wi-Fi networks on the same unlicensed frequency band. In general, in Method A and Method B, the fairness condition in terms of throughput (Table III) is not fully met for the different traffic loads but they provide better throughputs for the existing Wi-Fi network compared to the Cat 4 LBT method for the higher traffic loads. In particular, Method B, which follows the {50%, 100%} criterion, provides better performance for the different traffic loads than Method A, which follows the {50%, 95%, 100%} criterion to update the LAA CW.

Table IV is the counterpart of Table III for the latency, and presents the Wi-Fi latencies for the various methods considered with different traffic loads. It can be noticed that the various CW methods, including Cat 4 LBT method, do not degrade the latency performance for the existing Wi-Fi network. There are comparable latencies for all traffic loads compared to the reference case.

In Table V, we present the LAA throughputs for the different methods considered with different traffic loads. It can be seen that as λ increases, the proposed methods provide better LAA throughputs compared to the Cat 4 LBT method. This improvement in LAA throughputs is due to the fact that the maximum value of the upper bound of LAA CW size is 23 for the proposed CW methods. On the other hand, for Cat 4 LBT, the maximum value of the upper bound of LAA CW is 63. Thus, the proposed CW methods allow the eNB to access the channel faster than Cat 4 LBT method, thus improving the LAA throughput performance. Since we can expect high traffic loads as traffic demands increase in the future, high performance at high values of λ is therefore more desirable.

Finally, Table VI depicts the total aggregated throughputs for both networks (i.e., LAA and Wi-Fi). It can be seen that the proposed methods provide better total throughputs compared to Cat 4 LBT at higher traffic loads.

Overall, it is observed that the proposed methods can achieve better performance compared to the Cat 4 LBT method under higher traffic loads for both LAA and Wi-Fi networks.

VI. CONCLUSION

Current research aims to implement mechanisms to enable the coexistence of LTE-LAA and Wi-Fi in a fair manner. The latest 3GPP LBT algorithm, which is Category 4 LBT, does not perfectly match the main definition of fairness as described by the 3GPP standard and there is a degradation in the Wi-Fi performance due to this coexistence. The CW size plays a significant role in the performance of the coexistence mechanism. Therefore, novel dynamic CW methods are proposed to update the CW of LAA based on the knowledge of Wi-Fi activity statistics to provide more fair coexistence. These methods are implemented based on the fairness definition provided by 3GPP. The obtained results demonstrate that the proposed methods can enable a more fair coexistence in terms of throughput and latency than the Category 4 LBT algorithm defined by the 3GPP standard. Moreover, these methods provide better total aggregated throughput for both coexisting networks (i.e., Wi-Fi and LTE-LAA). Therefore, we can conclude that the considered schemes are more fair towards Wi-Fi than the Cat 4 LBT scheme.

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