Static Contention Window Method for Improved LTE-LAA/Wi-Fi Coexistence in Unlicensed Bands

Moawiah Alhulayil* and Miguel López-Benítez*†
* Department of Electrical Engineering and Electronics, University of Liverpool, United Kingdom
† ARIES Research Centre, Antonio de Nebrija University, Spain
{M.M.Alhulayil, M.Lopez-Benitez}@liverpool.ac.uk

***Abstract*—The 3rd Generation Partnership Project (3GPP) has recently defined a Licensed Assisted Access (LAA) scheme to enable Long Term Evolution (LTE) networks to use unlicensed frequency bands. However, the unlicensed bands are mainly occupied by the Wi-Fi technology. Hence, achieving fairness between LAA using LTE (LTE-LAA) and Wi-Fi in the unlicensed bands is a primary challenge. The 3GPP has recently standardised in Release 13 a Listen Before Talk (LBT) algorithm to ensure the fairness among these two technologies (LTE and Wi-Fi) over the unlicensed bands. In this paper, we focus on the downlink performance of LTE-LAA and Wi-Fi with different traffic loads. To achieve not only better fairness but also higher total aggregated throughputs for the coexisting networks, a static Contention Window (CW) selection method based on the fairness definition is proposed. The main novelty of this work is that the knowledge of Wi-Fi activity statistics is exploited effectively to select the CW of LAA. We show that the fairness between LAA and Wi-Fi networks depends on the LAA CW size adaptation criterion. Simulation results validate that the proposed method is effective in LAA/Wi-Fi coexistence scenario, can improve fairness performance and provide higher total aggregated throughputs for both coexisting networks compared with the current Category 4 LBT (Cat 4 LBT) algorithm defined in the 3GPP standard.**

***Index Terms*—Contention window; LAA/Wi-Fi coexistence, Licensed-Assisted Access; Listen-Before-Talk; Unlicensed bands.**

I. Introduction

Recently, due to the dramatic usage of mobile devices to access the internet, including smartphones, tablets and laptops, spectrum sharing has attracted researchers as a key solution for the cost and the scarcity of the licensed spectrum. Unlike the licensed spectrum, an unlicensed spectrum is free to access by anyone as long as a transmit power constraint is satisfied [1]. On the other hand, this spectrum is mainly occupied by the Wi-Fi technology. Due to the wide available unlicensed spectrum over the unlicensed 5 GHz band, Long Term Evolution (LTE) networks have been recently deployed to operate over the unlicensed spectrum [2].

Wi-Fi technology defines a Distributed Coordination Function (DCF) for sharing access to the channel based on the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) scheme [3]. In particular, each Wi-Fi node should listen to the channel before transmission to check the channel availability. If the channel is sensed to be idle for a DCF inter-frame space (DIFS) time, the transmission will proceed. If the channel is busy, the node defers its transmission and it will wait until the end of the transmission and then it will wait an additional DIFS time and generate a random back-off timer. When the back-off timer decreases to zero, the node starts transmission. However, LTE has a centralized control architecture (i.e., no sensing scheme). Thus, deploying LTE with Wi-Fi without any coexistence mechanisms in the unlicensed spectrum will affect Wi-Fi performance severely due to LTE transmission.

Fair coexistence with the existing technology (i.e., Wi-Fi) should be taken into account when deploying LTE in unlicensed spectrum. For this reason, the 3GPP Release 13 proposed the last version of LTE in the unlicensed spectrum which is called LTE Licensed-Assisted Access (LTE-LAA) [2]. The main challenge of LAA is how to guarantee a fair coexistence with the existing technology (i.e., Wi-Fi). 3GPP TR 36.889 defined the fairness between LAA and Wi-Fi in the 5 GHz unlicensed band as the capability of LAA operator not to impact the existing Wi-Fi operator active on the same carrier more than an additional Wi-Fi operator in terms of throughput and latency. Thus, to achieve a fair coexistence between LAA and Wi-Fi in the unlicensed spectrum, this definition should be taken into account while designing LAA. Therefore, 3GPP has standardised Listen-Before-Talk (LBT) algorithm as the default channel access algorithm for LAA to meet the fairness definition.

LTE and Wi-Fi coexistence has been vastly discussed in the literature. The first version of LTE in unlicensed frequency which is LTE-U has been discussed in [4] and the results show that coexisting LTE-U with Wi-Fi without using LBT scheme degrades the performance of both technologies. A comparison between LTE-LAA and LTE-U (non 3GPP standard) is presented in [5]. A simple LBT algorithm for LAA is adopted in [6] and the results show that the Contention Window (CW) and the Clear Channel Assessment (CCA) parameters play a significant role in coexisting LAA with Wi-Fi over the unlicensed bands. Mathematical models based on Markov chain for LAA and Wi-Fi coexistence are provided in [7]. An analytical model based on Markov chain for LAA and Wi-Fi coexistence to update the LAA CW using a fixed CW size approach is provided in [8]. An LBT algorithm for LAA to update the CW size for LAA based on the exchanged information among the nodes is proposed in [9]. A mathematical model analysis for LAA and Wi-Fi coexistence based on Markov chain and Category 4 LBT (Cat 4 LBT) algorithm is proposed in [10], where the authors propose a CW size adaption based on slot utilisation. Optimal Constant Contention Window (OCCW) and fixed periodic LBT (P-LBT) methods based on Cat 4 LBT are proposed in [11] where the results show that these methods achieve better performance for LAA/Wi-Fi networks compared with the Cat 4 LBT algorithm.

To the best of our knowledge, current research aims to implement mechanisms that enable the coexistence of LTE-LAA and Wi-Fi in a fair manner. Taking the latest LBT algorithm which is Cat 4 LBT, it should be noticed that the coexistence performance of LTE-LAA and Wi-Fi in the 5 GHz band does not perfectly match the main definition of the fairness as defined by the 3GPP TR 36.889 [2] and there is a degradation in the Wi-Fi performance due to this coexistence. This degradation is due to a few potential drawbacks in the Cat 4 LBT algorithm which are described in the next section.

The key contributions of this paper are as follows:

1) Unlike the Cat 4 LBT algorithm which uses the Hybrid Automatic Repeat Request (HARQ) collisions declaration to update the CW size, we propose a new scheme that uses the main definition of fairness as described by 3GPP by exploiting the Wi-Fi activity statistics for the ON time periods to select the LAA CW.

2) We consider a static CW method to select the CW for LAA based on the Wi-Fi activity statistics instead of using a variable CW size between $\{15, 31, 63\}$ as in the Cat 4 LBT scheme.

The paper is structured as follows. The Cat 4 LBT procedure is presented in Section II. In Section III, a new static CW method to select the LAA CW size for a fair coexistence between LTE-LAA and Wi-Fi is introduced, where we first analyse the Wi-Fi statistics for the ON time durations. In Section IV, the methodology, simulation environment and used model are presented. In Section V, Performance evaluation results are presented and discussed, where we compare the proposed method with the Cat 4 LBT results. Finally, the conclusions are summarized in Section IV.

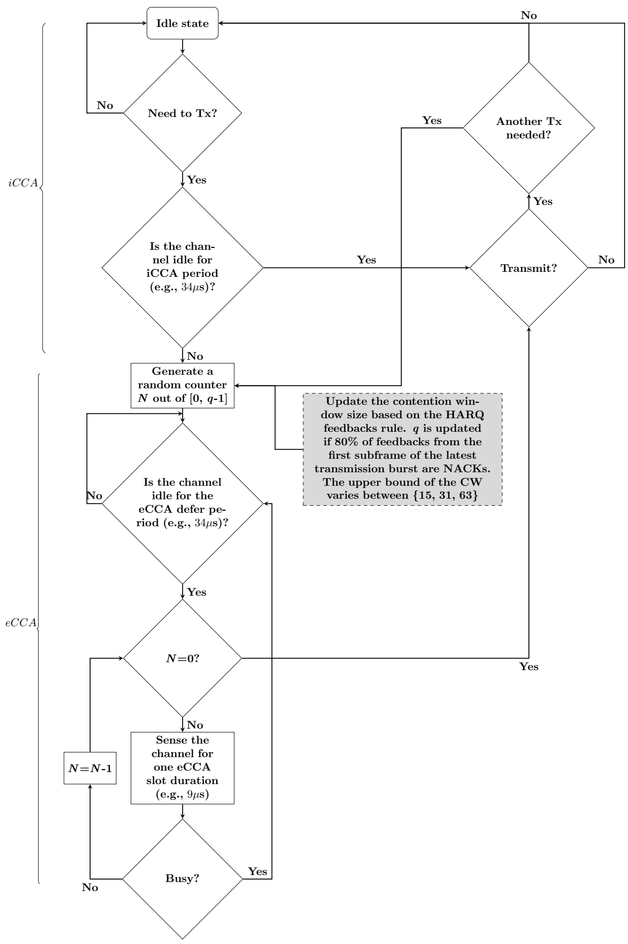

Fig. 1. Cat 4 LBT algorithm [2].

II. Category 4 LBT Algorithm

3GPP evaluated different algorithms for LBT to coexist LAA with Wi-Fi in the unlicensed spectrum. The eventual algorithm selected was Cat 4 LBT algorithm which is very similar to the LBT principle used by the IEEE 802.11 networks. In general, LAA performs a CCA to access the unlicensed band and the LAA CW for the Evolved NodeB (eNB) is adjusted with a variable size based on the HARQ ACK feedback. The procedure is shown in Fig. 1. Specifically, the LAA eNB may transmit the data after sensing the channel to be idle for the initial CCA (iCCA) (e.g., 34μs) duration; otherwise, the extended CCA (eCCA) stage begins. In an eCCA, the channel is observed by the LAA eNB for the duration of a random backoff factor N multiplied by the CCA slot time duration (e.g., 9μs). N defines the number of observed idle slots that need to be sensed before transmission and it is randomly selected as $N \in [0,\ q\text{-}1]$ and the value is stored in a counter, while q-1 represents the upper bound of the CW, which varies according to an exponential backoff. When the channel is free, another eCCA duration (e.g., 9μs) starts and decrements N if the channel is free. When N reaches zero, the LAA eNB begins the transmission. If the LAA eNB needs another transmission, the eCCA stage is performed again. The CW size q-1 is initialised with 15 and it is exponentially increased based on the HARQ Acknowledgment Control Response (ACK) feedbacks. In particular, if 80% of the HARQ feedbacks from the first subframe of the latest transmission are negative ACKs (NACKs), q is doubled and the CW size is updated to be q-1 = 31. Then, the CW size is update again to be 63 if 80% of the HARQ feedbacks are still NACKs. Otherwise, the CW size is reset to the minimum (i.e., q-1 = 15) upon the absence of 80% NACKs condition. Thus, in Cat 4 LBT, the LAA CW size, q-1, varies between $\{15, 31, 63\}$.

There are a few drawbacks of the existing scheme to update the upper bound of the LAA CW size in Cat 4 LBT algorithm based on the HARQ feedbacks [11]–[13]. The 80% threshold is normally hard to meet since LTE is capable of scheduling multiple nodes in a single subframe. In particular, if less than 80% of the users suffer from the collision, then the collision will be undetected and the LAA eNB will not update its CW size. Moreover, due to the integral latencies of the LTE transmission protocol stack, the method detects the collision during the first subframe of the transmission in order to update the CW size. Thus, the collisions from other subframes are neglected.

However, the performance of LAA and Wi-Fi networks when coexisting in the unlicensed band is highly affected by how the LBT parameters are configured. Thus, it is worth mentioning that the Cat 4 LBT algorithm implies that the LAA eNB adapts the upper bound of its CW between $\{15, 31, 63\}$

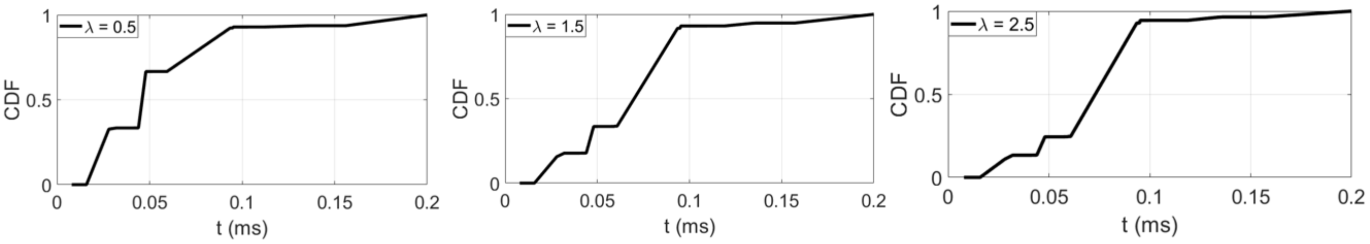

Fig. 2. CDFs of the ON times of the existing Wi-Fi network for different packet inter-arrival rates (λ) and a packet size of 0.5 MB/packet.

based on the HARQ feedbacks and does not take into account the traffic statistics of the existing Wi-Fi network.

Therefore, to enhance the performance of Cat 4 LBT algorithm, a new method with a static CW size for LAA is 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 static CW method, which is described in the next section.

III. The static CW method

As specified by 3GPP, the Cat 4 LBT procedure resembles the CSMA/CA of Wi-Fi. The LAA eNB needs to sense the channel for at least an iCCA duration followed by eCCA stage. If the channel is still busy after these stages, the LAA eNB has to update the upper bound of the CW from 15 to 31 and finally to 63 based on the NACKs feedbacks. It can be noticed that this adaptation ignores the ON/OFF activity statistics of the existing Wi-Fi network. Thus, this scheme is expected not to be a fair scheme to the existing technology (i.e. Wi-Fi). In particular, when the LAA eNB finds the channel to be busy for the first transmission, it updates its CW size by doubling the q value leading to a longer deferral time compared with the previous q value. If the new deferral time is longer than the actual channel occupancy times of the Wi-Fi network, then LAA eNB does not need to wait a long time before accessing the channel which was vacated a long time ago. This unutilised time degrades the performance of LAA by increasing the latencies and reducing the throughputs. As a result, selecting the upper bound of the LAA CW based on the activity statistics of the existing Wi-Fi network should lead to LAA waiting times that are comparable to the actual channel occupancy times of the Wi-Fi network, thus providing better performance (i.e., lower latency and higher throughput). In this work, we propose a new method for the upper bound of the CW, q-1, based on the Wi-Fi traffic statistics.

The Wi-Fi activity statistics can be estimated by the LAA network based on the energy detection protocol [3] without any coordination between the two technologies. In particular, the LAA network estimates the Wi-Fi activity statistics by performing a periodic sensing for the Wi-Fi channel state when the LAA is idle in order to estimate the Wi-Fi ON periods. The LAA network can compute the Cumulative Distribution Function (CDF) of the ON time periods of the existing Wi-Fi network after observing the channel for a sufficient large number of Wi-Fi periods. Instead of updating the maximum LAA CW size by doubling the value of q based on the NACKs feedbacks as described in the 3GPP Cat 4 LBT algorithm, this CDF of the ON times of the existing Wi-Fi network can be exploited to configure the LAA CW size. The procedure is illustrated in Fig. 2, which shows the CDFs of the Wi-Fi ON times estimated by the LAA network for different traffic loads, and Table I, which shows corresponding values of the maximum CW, q-1, for several percentile points of the CDF for different traffic loads. It can be noticed that the values in Table I are evaluated based on Fig. 2 by dividing the ON times corresponding to each percentile point by the slot duration of LAA (9μs) and rounding the result to the nearest integer towards infinity (i.e., ceil function). For example, for $\lambda = 0.5$ packets/second, the 100% percentile point corresponds to a Wi-Fi ON time of round 200μs, which divided by 9μs and ceiled leads to the value q-1 = 23 shown in Table I. All the values in Table I are evaluated based on the same procedure. It is worth mentioning that the percentile point of 100% in a theoretical CDF model is not feasible because the corresponding ON time would tend to infinity. On the other hand, LAA updates the CW size based on the CDF of the ON Wi-Fi times that are empirically observed, which have a finite maximum. Moreover, this maximum time of Wi-Fi On time is the value used to compute the maximum CW values for the 100% percentile point in a practical implementation.

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

Percentile point	λ 0.5	1.5	2.5
100%	23	23	23
95%	19	18	14
50%	6	8	9

This approach describes the proposed adaptation strategy. In this work, we propose a replacement to the Cat 4 LBT standard based on HARQ to update the LAA CW with a more realistic channel activity statistics based mechanism. The proposed method introduces two key changes to the standard approach. Firstly, it replaces the HARQ based approach with one based on the ON Wi-Fi times. Secondly, instead of an exponential increase of q to update the LAA CW and reset it to the minimum value, the LAA CW is fixed based on the ON Wi-Fi times. In particular, we consider the percentile point at the 50% (median value), 95% or 100% (maximum value) of the CDF of the ON Wi-Fi times to be the CW for LAA. In particular, q is a static value selected as the correspondent value for the percentile point of the CDF divided by the CCA slot time (9μs). Hence, there are no different sizes for the LAA CW as in the 3GPP Cat 4 LBT where the maximum CW varies between {15, 31, 63}. Moreover, in this method, the maximum CW, q-1, is selected based on the fairness definition. Note that the 3GPP Cat 4 LBT variable values of q-1 are not the optimum values, thus leading to unsuccessful channel access or unnecessarily long waiting times for LAA. The motivation of this method is to allow for the optimum CW for LAA and reduce LAA waiting times leading to lower latency and higher throughput.

IV. Methodology and Simulation Setup

The proposed method in this work is evaluated based on the 3GPP definition of fairness, where the LAA network should not impact the existing Wi-Fi network more than an additional Wi-Fi network operating on the same carrier in terms of throughput and latency.

To estimate the traffic statistics of the existing Wi-Fi network, two Wi-Fi networks are deployed together to investigate the impact of coexisting two Wi-Fi networks on the existing Wi-Fi network. The CDF for the ON times of the existing Wi-Fi network can be estimated in this scenario. The CDF is then evaluated to get the percentile point at the 50%, 95% and 100% of the CDF and set the LAA CW. Finally, one of the Wi-Fi networks is replaced with an LAA network to allow LAA/Wi-Fi coexistence and assess the validity of the proposed method.

We evaluate the coexistence performance of LTE-LAA and Wi-Fi following the 3GPP TR 36.889 simulation conditions except the updating rule of the CW, where the proposed LAA CW method is implemented. In this work, we evaluate the performance for LTE-LAA and Wi-Fi networks using an event-driven simulator NS-3 with LAA extension [14]. Specifically, we consider an indoor scenario with two operators; operator A (Wi-Fi) and operator B (LAA) using the same 20 MHz channel in the 5 GHz band. Fig. 3 provides an overview for the LAA/Wi-Fi indoor scenario. Both operators deploy four small cells (4 APs/eNBs). The base stations (i.e., APs and eNBs) are equally spaced. Each operator deploys 20 stations (STAs)/User Equipments (UEs) randomly distributed in a one floor building with a rectangular area. In addition, this model simulates file transfers arriving according to a Poisson process with arrival rate λ. In experiments, we have implemented the File Transfer Protocol (FTP) to operate over User Datagram Protocol (UDP). In particular, FTP Model 1 has been implemented considering the downlink scenario. A file size of 0.5 MB is considered with different recommended arrival rates ($\lambda = 0.5$, 1.5, 2.5 packets/second) [2], which are simulated to generate different load levels to show interesting performance differences. The details of the simulation scenario are compared to the 3GPP model in Table II.

Moreover, all the nodes (i.e., APs/eNBs/STAs/UEs) are equipped with two antennas for 2x2 Multiple Input Multiple Output (MIMO) operation. The Wi-Fi nodes detect each others at -82 dBm and they detect the LAA nodes at -62 dBm. On the other hand, LAA nodes detect the Wi-Fi nodes at -72 dBm. The maximum Transmission Opportunity (TxOP) length is configurable and defaults to 8 ms.

To validate the proposed static CW method, the performances for Wi-Fi and LTE-LAA are compared with the 3GPP standard (i.e., Cat 4 LBT) based on the main performance

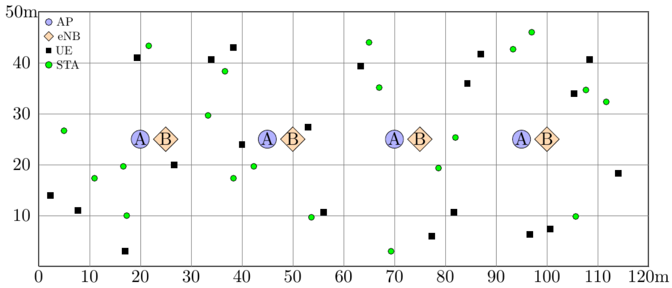

Fig. 3. Indoor layout with two operators (operator A and operator B) with 4 cells per operator and 5 STAs/UEs per cell.

TABLE II
3GPP TR 36.889 versus NS-3

	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 802.11n
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

metrics described in the 3GPP TR 36.889 (i.e., throughput and latency). Throughput is the amount of data transferred from one location to another in a specified period 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 two methods.

V. Simulation Results

The performance of LTE-LAA and Wi-Fi networks is analysed in this section using the proposed static CW method. We provide the main performance metrics as described in the 3GPP TR 36.889 [2] where the tables of individual throughputs and latencies for LAA and Wi-Fi networks and the total aggregated throughputs for both networks are presented. The fairness definition of the 3GPP is considered based on the throughput and latency for 95% of the users. However, we evaluated the throughput and latency at various percentiles (90%, 95% and 100%) and the main trends are applicable for all cases, but we provide here only the results for the 95% percentile for the sake of brevity.

In Table III, the throughputs for Wi-Fi and LAA netwroks for the different percentile points at 50%, 95% and 100% of the CDF considered using the proposed static CW method are presented. It can be seen that for the different arrival rates the 100% criterion provides the best performance in terms of Wi-Fi throughput with a comparable performance in terms of LAA throughput. On the other hand, Table IV presents the latencies of the existing Wi-Fi network at the different percentile points of the CDF using the static CW method. All of the different percentile points provide a comparable performance in terms

TABLE III
WI-FI/LAA THROUGHPUTS FOR 95% OF USERS USING THE STATIC CW METHOD AT DIFFERENT PERCENTILE POINTS OF THE CDF

Performance	Percentile point	λ 0.5	1.5	2.5
Throughput [Mbps]	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 IV
OPERATOR A: WI-FI LATENCIES FOR 95% OF USERS USING THE STATIC CW METHOD AT DIFFERENT PERCENTILE POINTS OF THE CDF

Performance	Percentile point	λ 0.5	1.5	2.5
Latency [ms]	100%	17.9	17.8	17.9
	95%	17.9	17.9	17.9
	50%	17.9	17.8	17.9

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

λ	**0.5**	**1.5**	**2.5**
Throughput [Mbps]	80.9 (Stat. CW)	67.0 (Ref)	54.4 (Ref)
	70.5 (Ref)	62.4 (Stat. CW)	53.5 (Stat. CW)
	66.5 (Cat 4)	57.2 (Cat 4)	51.6 (Cat 4)

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

λ	**0.5**	**1.5**	**2.5**
Latency [ms]	17.9 (Stat. CW)	17.9 (Ref)	17.9 (Ref)
	17.8 (Cat 4)	17.8 (Cat 4)	17.9 (Cat 4)
	17.8 (Ref)	17.8 (Stat. CW)	17.9 (Stat. CW)

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

λ	**0.5**	**1.5**	**2.5**
Throughput [Mbps]	38.4 (Cat 4)	33.9 (Stat. CW)	28.5 (Cat 4)
	31.1 (Stat. CW)	32.1 (Cat 4)	27.9 (Stat. CW)

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

λ	**0.5**	**1.5**	**2.5**
Throughput [Mbps]	112.0 (Stat. CW)	96.3 (Stat. CW)	81.4 (Stat. CW)
	104.9 (Cat 4)	89.3 (Cat 4)	80.1 (Cat 4)

of latency. As a result, it is worth mentioning that we will consider the percentile point at the 100% (maximum value) of the CDF to select the CW for LAA in our proposed method.

In Table V, the throughputs for the existing Wi-Fi network (i.e., operator A: Wi-Fi) for the various methods considered at different arrival rates are presented. The reference case (Ref) represents the case where operator A (Wi-Fi) coexists with another Wi-Fi operator (i.e., operator B: Wi-Fi), while the other two cases correspond to coexistence scenario where operator B is an LAA network. The 3GPP fairness definition requires the throughput and latency of the existing Wi-Fi network (i.e., operator A) 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 for all traffic loads. Thus, coexisting LAA with Wi-Fi using Cat 4 LBT method impacts the existing Wi-Fi network throughput which conflicts with the 3GPP fairness definition. On the other hand, the static CW method proposed in this work provides better throughput than Cat 4 LBT method for all traffic loads and it achieves better throughput for the existing Wi-Fi network (i.e. operator A) compared with the reference case throughput at $\lambda = 0.5$. Thus, the static CW method is more friendly than Cat 4 LBT method for the existing Wi-Fi network, which means that it degrades the existing Wi-Fi throughput less than Cat 4 LBT method when LAA and Wi-Fi coexist together at the same unlicensed frequency band. In general, in the static CW method, the fairness condition in terms of throughput is not fully met for all traffic loads but it achieves better throughputs for the existing Wi-Fi network compared to the Cat 4 LBT method.

Table VI presents the latencies of the existing Wi-Fi network for the various methods considered with different traffic loads. It can be seen that there are comparable latencies for all traffic loads compared to the reference case. Thus, the Cat 4 LBT and the static CW methods do not degrade the latency performance for the existing Wi-Fi network.

Table VII presents the LAA throughputs for the two methods (i.e., Cat 4 LBT and static CW) considered with different traffic loads. 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. It can be seen that as λ increases the static CW method achieves LAA throughputs comparable to the Cat 4 LBT method, which is the price to be paid for enabling a more fair coexistence with Wi-Fi as required by the 3GPP standard.

Table VIII presents the total aggregated throughputs for both networks (i.e., LAA and Wi-Fi). It can be seen that the proposed method provides better total aggregated throughputs compared to Cat 4 LBT for all traffic loads.

The benefits of our proposed method are more noticeable when the number of STAs/UEs per cell increases. As it can be seen from Fig. 4, the throughput degradation for the existing Wi-Fi network due to doubling the number of contenders up to 40 (10 STAs/UEs per cell) using the proposed static CW method is less than the throughput degradation using Cat 4 LBT method. Fig. 5 shows the latencies for the existing Wi-Fi network using different methods (Reference, Cat 4 LBT and Static CW). It can be observed that all methods achieve comparable latencies.

Furthermore, we evaluate different LBT methods (i.e., Cat 4 LBT and static CW) coexistence scenario with $\lambda = 2.5$ and 10 STAs/UEs per cell (40 in total) as shown in Table IX. From the simulation results, it can be seen that our static CW method outperforms Cat 4 LBT method in terms of fairness and achieves a comparable performance in terms of latency for the different percentiles of users (i.e. 50%, 90% and 95%). For example, for 95% of users, the static CW method outperforms Cat 4 LBT method by 11.8 Mbps in terms of the existing Wi-Fi throughput, which shows a consistent performance improvement by the proposed method even at

TABLE IX
SYSTEM PERFORMANCE IN WI-FI/WI-FI AND WI-FI/LAA COEXISTENCE SCENARIOS WITH 10 STAS/UES PER CELL (40 IN TOTAL) AND $\lambda = 2.5$

Performance	Method	**Reference**		**Static CW**		**Cat 4 LBT**	
	% users	Wi-Fi	Wi-Fi	Wi-Fi	LAA	Wi-Fi	LAA
Throughput [Mbps]	50%	113.9	113.2	100.4	106.8	99.2	107.7
	90%	66.3	59.2	57.8	31.8	54.0	39.7
	95%	55.8	51.5	50.8	17.4	39.0	18.5
Latency [ms]	50%	18.4	18.5	19.6	20.6	19.7	20.6
	90%	18.0	18.1	18.1	18.1	18.0	18.1
	95%	18.0	18.0	18.0	18.0	17.9	18.0

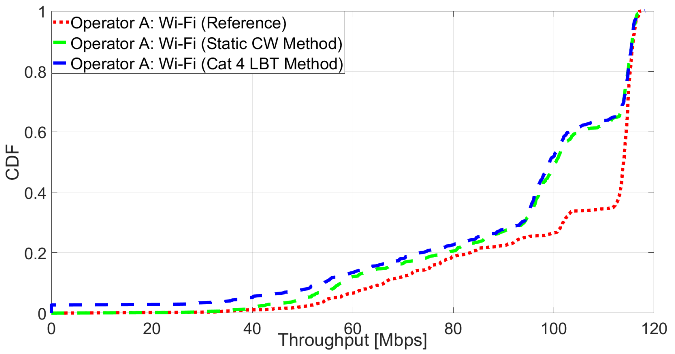

Fig. 4. Throughput performance of the existing Wi-Fi operator for Wi-Fi/Wi-Fi and Wi-Fi/LAA coexistence scenarios with 10 STAs/UEs per cell ($\lambda = 2.5$).

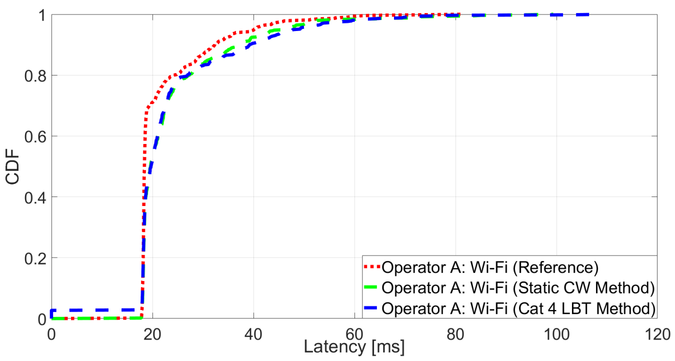

Fig. 5. Latency performance of the existing Wi-Fi operator for Wi-Fi/Wi-Fi and Wi-Fi/LAA coexistence scenarios with 10 STAs/UEs per cell ($\lambda = 2.5$).

high traffic loads.

Overall, it is observed that the proposed method can achieve a more fair coexistence compared to the Cat 4 LBT method for all traffic loads and provide a better overall aggregated performance for both LTE-LAA and Wi-Fi networks.

VI. CONCLUSION

The 3GPP Cat 4 LBT algorithm considers the HARQ feedbacks of the most recent transmission criterion to update the CW size of LAA to achieve fairness while coexisting Wi-Fi and LAA networks over unlicensed bands. This algorithm does not perfectly match the fairness definition as described by the 3GPP where LAA should not impact Wi-Fi services more than an additional Wi-Fi network. In particular, the LAA CW rule plays a significant role in this fairness. As a result, a novel static CW method is proposed to select the LAA CW size based on the knowledge of Wi-Fi traffic statistics to achieve a more fair coexistence. The obtained simulation results show that the proposed static CW method can enable a more fair coexistence than the Category 4 LBT algorithm in terms of throughput and latency. In addition, the proposed method provides higher total aggregated throughput for both coexisting networks (i.e., Wi-Fi and LTE-LAA).

ACKNOWLEDGMENT

Moawiah Alhulayil would like to thank the support of a PhD scholarship from the Applied Science University in Jordan.

REFERENCES

[1] F. Teng, D. Guo and M. L. Honig, "Sharing of Unlicensed Spectrum by Strategic Operators" in *IEEE Journal on Selected Areas in Communications*, vol. 35, no. 3, pp. 668-679, March 2017.

[2] 3GPP TR 36.889, "Study on Licensed-Assisted Access to Unlicensed Spectrum (Release 13)," V13.0.0, June 2015.

[3] L. S. Committee *et al.*, "Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications," *IEEE-SA Standards Board*, 2013.

[4] R. Zhang, M. Wang, L. X. Cai, Z. Zheng, X. Shen and L. Xie, "LTE-unlicensed: the future of spectrum aggregation for cellular networks," in *IEEE Wireless Communications*, vol. 22, no. 3, pp. 150-159, June 2015.

[5] M. Alhulayil and M. López-Benítez, "Coexistence Mechanisms for LTE and Wi-Fi Networks over Unlicensed Frequency Bands," *2018 11th International Symposium on Communication Systems, Networks & Digital Signal Processing (CSNDSP)*, Budapest, Hungary, 2018, pp. 1–6.

[6] J. Jeon, H. Niu, Q. Li, A. Papathanassiou and G. Wu, "LTE with listen-before-talk in unlicensed spectrum," *2015 IEEE International Conference on Communication Workshop (ICCW)*, London, United Kingdom, 2015, pp. 2320–2324.

[7] C. Chen, R. Ratasuk and A. Ghosh, "Downlink performance analysis of LTE and WiFi coexistence in unlicensed bands with a simple listen-before-talk scheme," in *Proc. IEEE Vehicular Technology Conference (VTC Spring)*, May 2015, pp. 1–5.

[8] Y. Song, K. W. Sung and Y. Han, "Coexistence of Wi-Fi and Cellular With Listen-Before-Talk in Unlicensed Spectrum," in *IEEE Communications Letters*, vol. 20, no. 1, pp. 161–164, Jan. 2016.

[9] T. Tao, F. Han and Y. Liu, "Enhanced LBT algorithm for LTE-LAA in unlicensed band," *2015 IEEE 26th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*, Hong Kong, China, 2015, pp. 1907–1911.

[10] Fanrong Hao, Chang Yongyu, Hongdou Li, Jian Zhang and Wei Quan, "Contention window size adaptation algorithm for LAA-LTE in unlicensed band," *2016 International Symposium on Wireless Communication Systems (ISWCS)*, Poznan, Poland, 2016, pp. 476–480.

[11] A. Mbengue and Y. Chang, "LBT Enhancement for LTE-LAA Fair Coexistence," in *International Journal of Future Generation Communication and Networking*, vol. 10, no. 1, pp. 71–82, 2015.

[12] R. Ali *et al.*, "Fair and Efficient Channel observation-based Listen-Before Talk (CoLBT) for LAA-WiFi Coexistence in Unlicensed LTE," in *2018 Tenth International Conference on Ubiquitous and Future Networks (ICUFN)*, Jul 2018, pp. 154–158.

[13] Z. Ali, L. Giupponi, J. Mangues-Bafalluy and B. Bojovic, "Machine learning based scheme for contention window size adaptation in LTE-LAA," in *2017 28th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*, Montreal, QC, Canada, 2017, pp. 1–7.

[14] L. Giupponi *et al.*, "Simulating LTE and Wi-Fi coexistence in unlicensed spectrum with ns-3," in *arXiv preprint arXiv*, vol. 1604.06826, April 2016.