LTE/Wi-Fi Coexistence in Unlicensed Bands Based on Dynamic Transmission Opportunity

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***Abstract*—With the rapid proliferation of smart devices, the demand for more licensed spectrum bands arises. Due to the scarcity of the licensed spectrum, the 3rd Generation Partnership (3GPP) has recently deployed Long Term Evolution (LTE) networks using the Licensed Assisted Access (LAA) scheme over unlicensed bands. On the other hand, the Wi-Fi technology is the main technology that operates over these unlicensed bands. Thus, the major concern is to attain a fair coexistence mechanism between these coexisting technologies (i.e., LTE and Wi-Fi). In this paper, we focus on the downlink scenario under different traffic loads to study the effect of the maximum Transmission Opportunity (TxOP) period for LTE-LAA in the performance of LTE-LAA/Wi-Fi coexistence. A dynamic TxOP period method is proposed to provide better fairness and higher total aggregated throughputs for the coexisting networks based on the Hybrid Automatic Repeat Request (HARQ) reports. The novelty of this work is that the existing HARQ reports are exploited to update the TxOP period for LAA in a dynamic manner. We show that the TxOP period plays a key role in the coexistence between LTE-LAA and Wi-Fi networks over unlicensed bands. The simulation results show that the proposed dynamic TxOP method improves the fairness and achieves higher total aggregated throughputs for both coexisting networks as compared to the static TxOP period used by the standard Category 4 LBT (Cat 4 LBT) method defined by 3GPP.**

***Index Terms*—Category 4 LBT; LTE-LAA/Wi-Fi coexistence; Licensed Assisted Access; Transmission Opportunity; Unlicensed spectrum.**

I. Introduction

By 2021 a seven fold increase in data traffic for mobile services is expected [1]. Thus, due to this dramatic increase in data traffic over cellular networks, mobile network operators face a challenging problem to cope with such huge volume of traffic with the limited licensed spectrum [2]. To deal with the growing demand for wireless broadband access, unlicensed spectrum has been recently considered for Long Term Evolution (LTE) operation by the 3rd Generation Partnership Project (3GPP) in LTE Release 13 [3]. In particular, LTE has been deployed with the existing technology (i.e., Wi-Fi technology) over the unlicensed 5 GHz band.

Due to the differences between LTE and Wi-Fi Medium Access Control (MAC) layer techniques, a lack of coordination among these technologies leads to major challenges for a fair coexistence scheme design. In particular, Wi-Fi follows a contention based MAC protocol for sharing the spectrum between Wi-Fi nodes. A Distributed Coordination Function (DCF) based on the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) scheme is implemented. Specifically, Wi-Fi nodes access the spectrum when the channels are sensed to be unoccupied for a DCF Inter-Frame Space (DIFS) period, and a backoff process starts if there is a collision. Thus, deploying LTE with Wi-Fi over unlicensed bands without modification will lead to a severe degradation in Wi-Fi performance due to LTE transmissions.

To cope with the differences between the coexisting technologies (i.e., LTE and Wi-Fi), the coexistence mechanism design aims to achieve a fair spectrum sharing between these technologies. 3GPP Release 13 proposed LTE over unlicensed bands which is called LTE Licensed Assisted Access (LTE-LAA) [3]. In particular, the fairness between LTE-LAA and Wi-Fi networks over the unlicensed 5 GHz band is defined in [3] as the capability of LTE-LAA not do degrade the existing Wi-Fi performance active on the same carrier more than an additional Wi-Fi operator in terms of throughput and latency. Thus, Category 4 Listen Before Talk (Cat 4 LBT) has been recently adopted in LAA networks as a downlink access method achieving a fair coexistence between LTE-LAA and Wi-Fi [4].

The two versions of LTE over unlicensed bands have been widely discussed in the literature. The unlicensed LTE (LTE-U) is the first version of LTE over unlicensed bands and it does not need a LBT mechanism while LTE-LAA is the most recent one. An exhaustive comparison between LTE-U and LTE-LAA by deploying them with Wi-Fi over the unlicensed 5 GHz band is provided in [5]. The simulation results show that LTE-LAA can enable a more fair coexistence (in terms of throughput and latency) than LTE-U. Several mechanisms have been proposed in the literature for spectrum sharing between LTE and Wi-Fi [6]–[9].

To the best of the author's knowledge, current researches aim to implement mechanisms enabling a fair coexistence between LTE and Wi-Fi networks over unlicensed bands by focusing on some design parameters that play a significant role in LAA and Wi-Fi coexisting such as the Contention Window (CW), Clear Channel Assessment Energy Detection (CCA-ED) and the maximum Transmission Opportunity (TxOP) period [10], [11]. Specifically, fixed and adaptive CW methods are analysed in [12] and [13] where the CW size is updated based on the channel state. Dynamic and static CW methods are proposed in [14] and [15] for LAA based on the activity statistics of the existing Wi-Fi network for improved coexistence between LAA and Wi-Fi over unlicensed bands. A CW method for LAA based on the mutual information between the nodes for a fair coexisting between LAA and Wi-Fi is proposed in [16]. On the other hand, an enhanced LAA (eLAA) practical technique is proposed in [17] by exploiting the inherent TxOP reservation using the Clear to Send to Self (CTS-to-Self) frame. The results show that the proposed technique improves eLAA throughput without severely degrading the per-user Wi-Fi throughput. A Markov chain model is analysed in [18] for LAA/Wi-Fi coexisting scheme with TxOP transmitted in a single transmission opportunity backoff. The results show that the proposed LBT model achieves better performance for the existing Wi-Fi network and for dense LAA deployments.

This work extends the current state of the art by proposing a novel method to dynamically adapt the TxOP based on the observed Wi-Fi transmission pattern. The key contribution of this paper is a new dynamic scheme to configure the maximum TxOP length for LAA, unlike the Cat 4 LBT algorithm where the the LAA TxOP length is configurable but fixed. We consider dynamic TxOP lengths for LAA by exploiting the existing Hybrid Automatic Repeat Request (HARQ) collision declarations to update the TxOP length.

The rest of this work is organised as follows. First, Section II presents Cat 4 LBT algorithm. The dynamic TxOP method proposed enhancing the LAA and Wi-Fi networks over the unlicensed 5 GHz band is presented in Section III. Section IV presents the methodology, simulation environment and used model. Section V presents and analyses the obtained simulation results. Finally, Section VI summarises and concludes this work.

II. Category 4 LBT Algorithm

The algorithm that has been selected by 3GPP for LAA/Wi-Fi coexistence over unlicensed bands is Cat 4 LBT. This algorithm is very similar to the LBT scheme used by the IEEE 802.11 networks. The procedure of Cat 4 LBT is illustrated in Fig. 1. Specifically, LAA Evolved NodeB (eNB) should observe the channel availability before transmitting its own data. The channel is considered to be busy if the energy level measured in the channel exceeds a certain threshold; otherwise, the channel is considered to be idle. The LAA eNB may transmit the data if the time of channel's idle period equals the duration of the initial CCA (iCCA) (e.g., 34μs). On the other hand, if the channel is busy, the extended CCA (eCCA) stage begins by generating a random backoff counter *N*. In the eCCA stage, the LAA eNB observes the channel to be idle for the backoff counter *N* multiplied by the CCA slot time duration (e.g., 9μs). *N* is a random integer number with a uniform distribution chosen from [0, *q*-1] and it defines the number of observed idle slots, while *q*-1 represents the upper bound of the CW and it varies according to an exponential backoff. When the channel is idle, the channel has to be sensed for another eCCA duration (i.e., 9μs) and *N* is decremented by one if the channel is sensed to be idle. When *N* equals zero, the LAA eNB starts its transmission with a fixed and configurable maximum Transmission Opportunity (TxOP) period upward to 20 ms. Otherwise, if the channel is sensed to be busy during the eCCA defer period, the LAA eNB keeps monitoring the channel until an idle duration equal to the eCCA defer period appears. For any new transmission, the eCCA stage is repeated again. The upper bound of the CW (i.e., *q*-1) is initialised with 15 and it is increased exponentially based on the HARQ Acknowledgement Control Response (ACK) feedbacks. Specifically, *q* is doubled if 80% of the HARQ feedbacks are negative ACKs (NACKs) and the CW size will be *q*-1=31. Then, *q* is doubled again and the CW size will be *q*-1=63 if 80% of the HARQ feedbacks are still NACKs. On the other hand, after each successful transmission, the upper bound of the CW returns to its initial value (i.e., *q*-1=15). Overall, for Cat 4 LBT, the upper bound of the CW size typically varies within the set {15, 31, 63}.

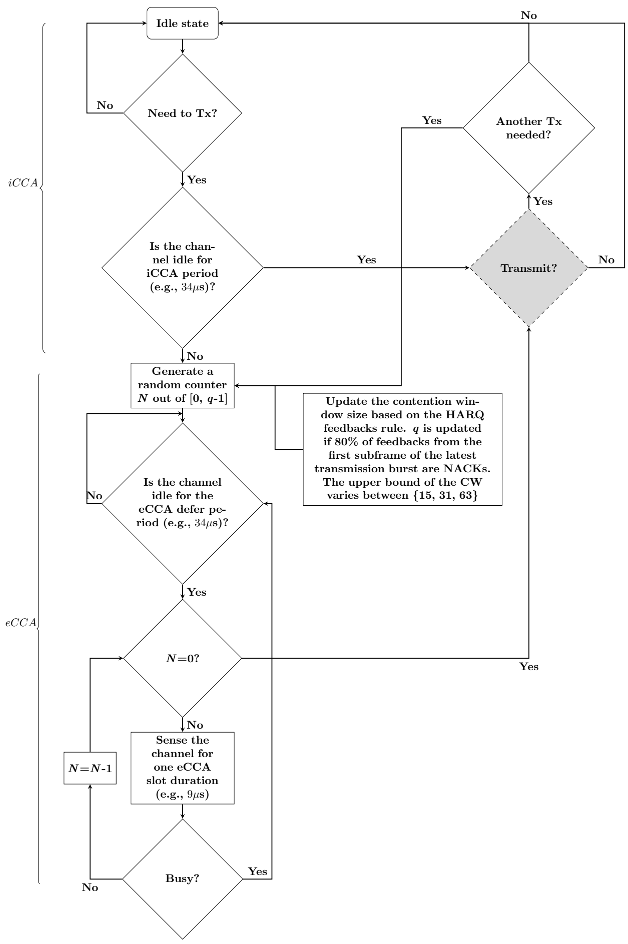

Fig. 1. Cat 4 LBT algorithm [3].

The LBT parameters play a key role in the performance of the LAA and Wi-Fi networks when coexisting over unlicensed bands. As mentioned before, the Cat 4 LBT algorithm allows LAA eNB to transmit its own data after performing the channel availability check. Then, an LAA eNB can start the transmission for a fixed configurable TxOP length upward to 20 ms. Thus, it is worth mentioning that the Cat 4 LBT algorithm keeps the LAA TxOP length to be static for all transmissions regardless of the NACK feedbacks. Therefore, to enhance the performance of the Cat 4 LBT algorithm, a new method with a dynamic TxOP period for LAA is proposed in this work. The dashed highlighted diamond in Fig. 1 highlights the procedure of Cat 4 LBT that will be modified to include the proposed dynamic TxOP method, which is described in the next section.

III. Proposed Dynamic TxOP Method

Wi-Fi nodes transmit their own data over unlicensed spectrum bands by following a contention-based LBT algorithm. As a result, if an LAA eNB transmits its data without a limited TxOP period, this will prevent the Wi-Fi nodes from accessing the unlicensed channel. Every time an LAA eNB gains access to the unlicensed channel, the transmission duration must not exceed a predefined time period (i.e., the TxOP). This is typically required by spectrum regulators in order to prevent that a single system monopolises the unlicensed spectrum. In the Cat 4 LBT mechanism defined by 3GPP, the TxOP parameter is configurable (from 4 to 20 ms) but fixed, meaning that once set to a valid value it will remain constant during the LAA eNB operation. In this work, we argue that this approach is unsuitable since a fixed TxOP may not be able to lead to the most efficient exploitation of the channel under varying traffic conditions. Concretely, when the Wi-Fi traffic load is low, the unlicensed channel can be expected to remain idle for longer time intervals and this can be exploited by the LAA eNB to obtain a better performance by transmitting for longer intervals (i.e., using higher values for the TxOP parameter). On the other hand, when the Wi-Fi traffic load is high, more Wi-Fi transmissions can be expected to take place and in this case a long TxOP for the LAA eNB could potentially lead to more collisions in the channel and therefore a degraded performance for both Wi-Fi and LAA networks; in such a case, a shorter TxOP for LAA would be more suitable. In summary, we argue that a static TxOP period may not be the most suitable choice for an efficient coexistence between Wi-Fi and LTE-LAA networks over unlicensed channels and, as a result, we propose a novel method to adapt dynamically the TxOP parameter for the LAA LBT mechanism in order to improve the overall performance.

This work proposes a new method to dynamically select the employed TxOP period based on the current size of the LAA CW, which is a parameter readily available in any practical implementation of LAA. The default Cat 4 LBT mechanism adapts the size of the LAA CW based on the received NACK reports, which indicate an erroneous transmission of data and therefore can be interpreted as a potential situation of congestion/collision in the channel. Concretely, when 80% or more of the received reports are NACK, the size of the CW is doubled (typically from 15 to 31 and finally to 63, if needed) with the aim to reduce the number of collisions in the channel and allow a more efficient coexistence with other users of the unlicensed spectrum. The method proposed in this work adapts the value of the TxOP period based on the current value of the CW as shown in Table I, where two adaptation points for the TxOP period are defined. The first maximum TxOP period for LAA is set to be 20 ms (i.e., the maximum TxOP period specified by 3GPP) when the CW size is 15 (minimum CW size). Otherwise, the maximum TxOP period for LAA is set to be 4 ms (i.e., the minimum TxOP period specified by 3GPP) for larger CW sizes. This approach is motivated by the observation that a lower value of the LAA CW will in general be associated with a low/moderate volume of traffic from the Wi-Fi network and thus with the availability of longer idle times in the channel, therefore a longer TxOP should allow a more efficient data transmission for the LAA system without a noticeable degradation of the Wi-Fi traffic. When the LAA LBT mechanism increases the CW, this can be interpreted as a potential situation of congestion/collision in the unlicensed channel caused by a higher number of transmissions and in such a case it is sensible to reduce the TxOP so that LAA transmissions will be shorter, thus reducing the probability of collision with other Wi-Fi nodes. Notice that collisions have a degrading effect for all users (both Wi-Fi and LTE-LAA nodes), therefore reducing the number of collisions will always improve the overall network performance for all users, which motivates the proposed dynamic TxOP method.

TABLE I
Value of the TxOP period as a function of the CW size

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

The key change proposed to the 3GPP standard approach is the replacement of the static TxOP period with a dynamic scheme based on the received HARQ feedbacks as described above. Hence, there is no static period for LAA TxOP as in the 3GPP Cat 4 LBT algorithm, where the LAA TxOP period is fixed. Instead, with the proposed method, the TxOP period is selected based (implicitly) on the traffic statistics of the coexisting networks through the received NACK reports. The proposed method is aimed at better aligning the durations of the LTE-LAA transmissions with the actual Wi-Fi idle times in the unlicensed channel so that a better efficiency is achieved by reducing the potential number of collisions, which should result in better throughput and latency. In order to achieve this better alignment between Wi-Fi idle periods and LTE-LAA transmission periods, a dynamic adaptation of the LAA TxOP is proposed, which can be expected to outperform the default 3GPP Cat 4 LBT method, which is based on a fixed TxOP period. Notice that the proposed method is based on the LAA CW, which is a parameter readily available in any practical implementation of LAA and therefore can be easily implemented in a real system without adding any significant complexity and without any complex modifications of current commercial products.

IV. Methodology and Simulation Environment

In order to verify the effectiveness of the proposed method in improving the coexistence performance in terms of throughput and latency, we consider an indoor scenario which has been defined in [3]. The proposed method is investigated based on fairness as defined by the 3GPP. In particular, LTE-LAA should not impact Wi-Fi services more than an additional Wi-Fi network on the same carrier in terms of throughput and latency as explained in Section I. While there are other definitions of fairness (e.g., Jain's fairness index [19]), this work will focus exclusively on the 3GPP definition of fairness mentioned above.

In this study, the coexistence performance of LTE-LAA and Wi-Fi networks following the simulation conditions in [3] is evaluated by considering the static TxOP period scheme, then

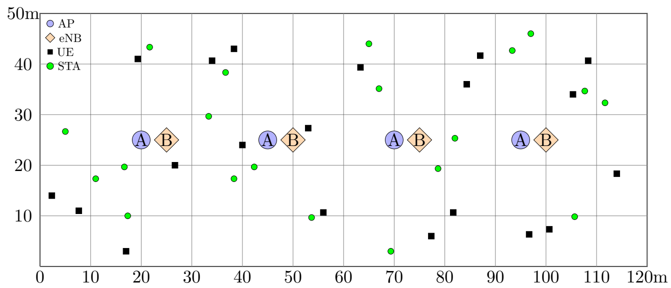

Fig. 2. Indoor layout with two operators (operator A and operator B) with 4 cells per operator and 5 STAs/UEs per cell.

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 802.11ax
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

by using the proposed dynamic TxOP period scheme. The performance of LTE-LAA and Wi-Fi networks is evaluated using NS-3 simulator with LAA extension [20]. As shown in Fig. 2, we consider an indoor scenario in a single floor building with two operators using the same 20 MHz channel in the unlicensed 5 GHz band. Operator A (Wi-Fi) deploys four Access Points (AP) 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) that are randomly distributed within a rectangular area. The traffic model considered here is File Transfer Protocol (FTP) Model 1 considering downlink scenario. FTP is implemented to operate over User Datagram Protocol (UDP). This model simulates file transfers following 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) representing different traffic loads [3]. More details of simulation parameters are shown in Table II compared with the 3GPP model. 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. On the other hand, the ED threshold for Wi-Fi nodes to detect each others is -82 dBm while LAA nodes detect each others at -72 dBm. In addition, the ED threshold for LAA nodes to detec the Wi-Fi nodes is -72 dBm.

In order to validate the proposed dynamic TxOP period method, the performance of LTE-LAA and Wi-Fi networks is evaluated and compared with the static TxOP period method (i.e., the standard Cat 4 LBT algorithm) based on the fairness definition of the 3GPP. Specifically, the throughputs and latencies are evaluated for the coexisting networks. Throughput is defined as the amount of data transferred from one node to another node within a period of time as observed at IP layer. On the other hand, latency is the time needed for a packet to transfer from the transmitter to the receiver. In the next section, the simulation results for the proposed method are presented.

V. Simulation Results

In this section, the performance of LTE-LAA and Wi-Fi networks is analysed using the proposed dynamic TxOP period approach. The individual throughputs for Wi-Fi and LTE-LAA networks are provided and the total aggregated throughputs for both networks are presented as well. The simulation results for the proposed approach are compared with the Cat 4 LBT algorithm results (i.e., the 3GPP standard). However, we consider the fairness definition as defined by the 3GPP based on the throughput and latency for 95% of the users. In order to validate the proposed approach, two deployments are investigated; Case A: Wi-Fi with Wi-Fi (Reference case) and Case B: Wi-Fi and LTE-LAA. The homogenous coexistence between Wi-Fi networks (i.e., Reference case) is considered as a reference to evaluate the new proposed LTE-LAA mechanism.

The throughputs for the existing Wi-Fi network (i.e., operator A (Wi-Fi)) for both Wi-Fi/Wi-Fi (Reference) and Wi-Fi/LAA coexistence scenarios at different arrival rates are provided in Fig. 3. The 3GPP Cat 4 LBT algorithm with different static TxOP periods and the proposed dynamic TxOP approach are considered for the Wi-Fi/LAA coexistence scenario. It is worth mentioning that the throughput and latency for the existing network (i.e., operator A (Wi-Fi)) should be no lower than that of the reference case based on the 3GPP fairness definition. In general, it can be seen that Cat 4 LBT performs worse than the reference case for the different static TxOP periods for the different traffic loads. Thus, the Cat 4 LBT algorithm does not perfectly match the fairness definition. On the other hand, the proposed dynamic TxOP method provides a comparable throughput compared to Cat 4 LBT method for the different traffic loads. In addition, it achieves better throughput at $\lambda = 0.5$ packets/second compared to the different static TxOP periods of Cat 4 LBT method.

Fig. 4 depicts the latencies for the existing Wi-Fi operator for Wi-Fi/Wi-Fi (Reference) and Wi-Fi/LAA coexistence scenarios at different traffic rates. It can be seen that the Cat 4 LBT method using the different TxOP periods and the proposed dynamic TxOP method including the reference method achieve comparable latencies. As a result, Cat 4 LBT and the proposed dynamic TxOP period method do not degrade the performance of the existing Wi-Fi network in terms of latency.

The LAA throughputs of Wi-Fi/LAA coexistence scenario at different traffic rates are provided in Fig. 5. It can be noticed that as λ increases the LAA throughput improves by increasing the static TxOP period for Cat 4 LBT algorithm. This improvement is due to allowing LAA to transmit for longer time over the unlicensed channel. For low traffic load (i.e., $\lambda = 0.5$ packets/second), it can be seen that the proposed dynamic TxOP period method achieves better throughput than

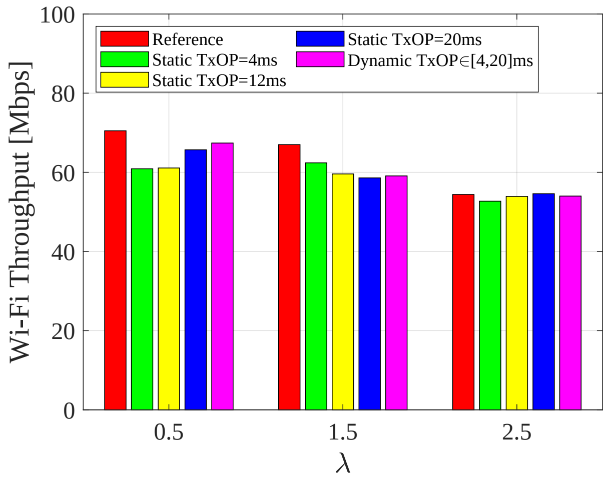

Fig. 3. Throughput performance of the existing Wi-Fi operator for Wi-Fi/Wi-Fi (Reference) and Wi-Fi/LAA coexistence scenarios with 5 STAs/UEs per cell under different arrival rates.

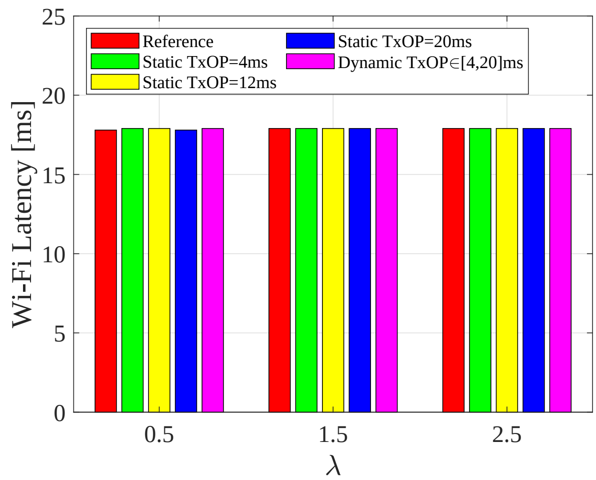

Fig. 4. Latency performance of the existing Wi-Fi operator for Wi-Fi/Wi-Fi (Reference) and Wi-Fi/LAA coexistence scenarios with 5 STAs/UEs per cell under different arrival rates.

Cat 4 LBT method for TxOP periods equal to 4 ms and 12 ms, and a comparable throughput for 20 ms. On the other hand, for higher traffic loads (i.e., $\lambda = 1.5$ and 2.5 packets/second), the dynamic TxOP period method achieves better throughputs compared to all static TxOP periods of the Cat 4 LBT method. These results show that the proposed dynamic TxOP method can lead to an overall throughput performance improvement for LAA.

Fig. 6 depicts the total aggregated throughputs for both networks (i.e., Wi-Fi and LAA) of the Wi-Fi/LAA coexistence at different traffic loads. It can be seen that, for all traffic loads, the proposed method provides better aggregated throughputs compared to the Cat 4 LBT method. Moreover, it can be noticed that as λ increases, the improvement in the total aggregated throughputs increases. As high traffic loads can be expected in the future, the proposed method is considered to be more beneficial compared to the Cat 4 LBT method.

Furthermore, in order to highlight the benefits of the

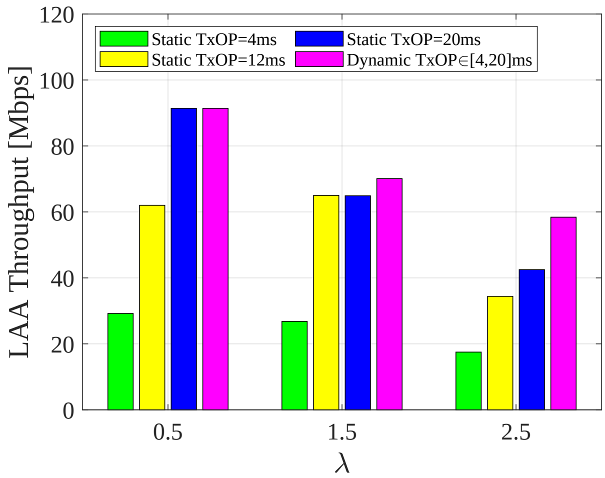

Fig. 5. Throughput performance of LAA operator for Wi-Fi/LAA coexistence scenario with 5 STAs/UEs per cell under different arrival rates using the static and dynamic TxOP methods.

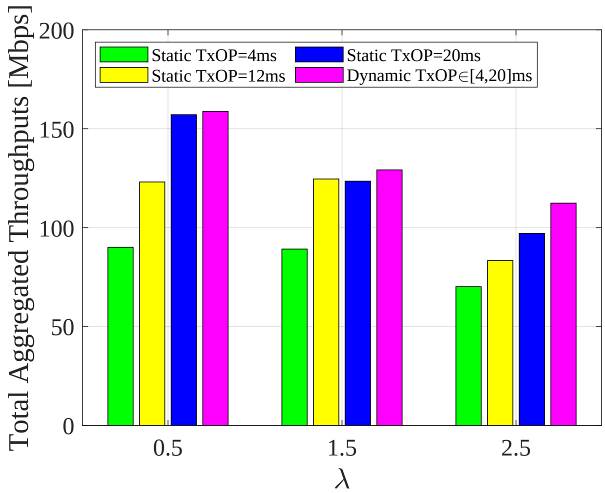

Fig. 6. Total aggregated throughputs of Wi-Fi and LAA operators for Wi-Fi/LAA coexistence scenario with 5 STAs/UEs per cell under different arrival rates using the static and dynamic TxOP methods.

proposed method, the number of the STAs/UEs per cell is increased to be 10 STAs/UEs per cell (40 in total). As it can be seen in Fig. 7, for $\lambda = 1.5$, the 3GPP fairness condition is met for some static TxOP periods (e.g., 4 ms and 12 ms) of the Cat 4 LBT method while it is not met for other static TxOP periods (e.g., 20 ms). On the other hand, the fairness condition is satisfied for the proposed dynamic TxOP period method by providing better throughput for the existing Wi-Fi network compared to the Wi-Fi throughput of the reference case. In addition, it can be seen that there is a trade-off between the Wi-Fi and LAA throughputs for all TxOP periods of the Cat 4 LBT method. Finally, it can be noticed that the proposed dynamic method achieves the best throughputs for the coexisting networks and the best total aggregated throughputs as well. Specifically, the performance improvement in the total aggregated throughputs for both networks using the dynamic TxOP method compared to the static TxOP period method of Cat 4 LBT method is 61.5%

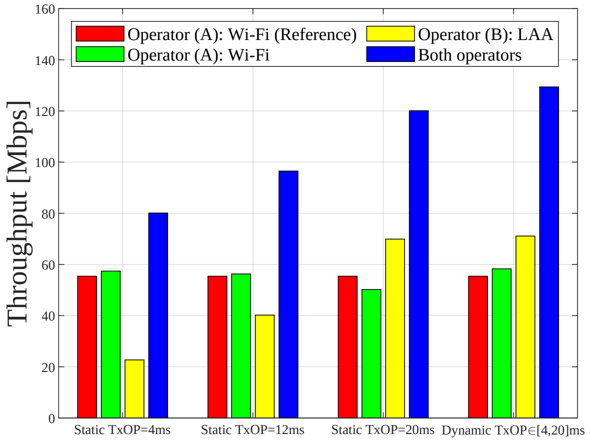

Fig. 7. Throughput performance of Wi-Fi and LAA operators with 10 STAs/UEs per cell under different arrival rates using the static and dynamic TxOP methods ($\lambda = 1.5$ packets/second).

(49.3 Mbps), 34.1% (32.9 Mbps) and 7.7% (9.3 Mbps) for static TxOP period of 4, 12 and 20 ms, respectively.

VI. Conclusion

The current 3GPP Cat 4 LBT algorithm implements a static scheme for the TxOP period for LAA to achieve fairness while coexisting with the Wi-Fi technology over the unlicensed bands. This algorithm does not meet the fairness condition under different traffic loads as defined by the 3GPP TR 36.889. However, the TxOP period plays a key role in this coexistence between LTE-LAA and Wi-Fi. Thus, a novel dynamic TxOP period method has been proposed to update the TxOP period in a dynamic manner based on the HARQ reports. The obtained results show that the proposed dynamic TxOP period method can enable a more fair coexistence than the static TxOP period method of the Cat 4 LBT algorithm. Moreover, it provides higher total aggregated throughputs for both coexisting networks.

Acknowledgment

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

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