Performance of Multi-Carrier LBT Mechanism for LTE-LAA

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***Abstract*—In Rel-13, Licensed-Assisted Access (LAA) to unlicensed spectrum has been approved as a new work item to meet the increasing traffic demands for operators. For LAA, the listen-before-talk (LBT) is an efficient way to ensure fair and friendly coexistence in unlicensed band with other operators and radio access technologies (RATs). To use more bandwidth, multiple unlicensed carriers could be aggregated and activated independently for LAA. However, the general LBT mechanism is unfeasible for multi-carrier operation due to the RF leakage at transmitter side, which would result in the saturation of the channel sensing in neighbouring carrier and thereby a low probability of simultaneous data transmission over multiple carriers. In this paper, we first analyze the coexistence mechanism for Wi-Fi and LAA. After that, we propose an effective LBT mechanism for LAA multi-carrier operation so as to provide better coexistence fairness with other technologies (e.g. Wi-Fi) and to increase bandwidth utilization. Furthermore, the simulation results show that the proposed solution could provide better fairness and performance in comparison with other solutions when LAA coexists with Wi-Fi.**

Keywords—Licensed-Assisted Access (LAA); Listen-Before-Talk (LBT); Carrier Aggregation (CA); Unlicensed Spectrum

I. INTRODUCTION

A conventional LTE deployment is in licensed band where the spectrum is exclusively reserved. This can ensure better Quality of Service (QoS) and more efficient spectrum utilization. However, the licensed spectrum for LTE system is quite limited; on the other hand, the amount of data traffic carried over cellular networks is expected to dramatically increase year by year. Striving to meet the increasing market demands, there has been increasing interest from operators in deploying some complementary access utilizing unlicensed spectrum to meet the traffic growth [1]. For this purposes, 3GPP LTE approved a new work item on Licensed-Assisted Access (LAA) to Unlicensed Spectrum in Rel-13 [2]. And thus, the use of LTE in unlicensed spectrum can serve as a useful additional tool by operators to maximize the value they can provide to users, while the core of the activity of the operators remains anchored to the licensed spectrum [1].

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Due to the non-exclusive use of unlicensed spectrum, the key challenge of LAA is to ensure fair and friendly co-existence in unlicensed band with other LAA operators or/and other radio access technologies (RATs), e.g. LTE operating in the Wi-Fi band results in a significant performance degradation of the coexisting Wi-Fi systems. This is because Wi-Fi moves to silence mode due to the carrier sense multiple access with collision avoidance (CSMA/CA) feature [3][4]. Some studies show that LAA performance is nearly unchanged in the presence of Wi-Fi use of the same band (less than 4% in most cases), while Wi-Fi performance degrades significantly in the presence of LTE (70% in sparse deployment and over 90% in dense deployment) [5]. So in some regions of the world, the unlicensed technologies need to abide to certain regulations, e.g. Listen-Before-Talk (LBT) is one of mechanisms to ensure fair coexistence between LTE and other technologies such as Wi-Fi as well as among LTE operators. Especially in European and Japanese, the regulations mandate the usage of LBT in the unlicensed bands [6][7][8]. Apart from regulatory requirements, carrier sensing via LBT is one way for fair sharing of the unlicensed spectrum and hence it is considered to be a vital feature in a single global solution framework for LAA [1].

In LTE, the maximum bandwidth supported by each carrier is 20MHz, and LTE can use more available bandwidth by aggregating multiple RF carriers as defined in the carrier aggregation framework [1]. In this case, multiple unlicensed carriers could be configured and activated independently for LAA, and the LBT operation of one carrier could be performed independently from other carriers. However, for multi-carriers within the same band or neighboring bands, it may not be feasible to perform LBT on one carrier if adjacent carriers are actively transmitting data. This is mainly due to the RF leakage as addressed in [9]. In this case, once a LAA node starts to transmit data on one unlicensed carrier after its LBT succeeds, the successful likelihood of LBT on other adjacent carriers is minimal due to the RF leakage. The RF leakage is very strong in the neighbour carrier at the transmitter side, which would saturate the channel sensing in LBT on this neighbour carrier. Therefore, the probability of simultaneous the success of LBT and afterwards data transmission over current and adjacent carriers is very low. This would clearly result in low channel access probabilities in the multi-carrier case. Thus, to avoid this RF leakage problem on LBT, the coordination among the LBT procedures on multiple carriers is required.

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In [9], a self-deferral based LBT mechanism is proposed to enable multi-carrier operation. Each carrier would independently perform LBT procedure, and if a LBT procedure finishes, it would wait additional clear channel assessment (CCA) slots until LBT synchronization boundary (LSB) to allow other carriers to complete their backoff counting down. More bandwidth can be hence utilized. Although this way could allow the eNB to synchronize transmission across multiple carriers and get the benefit from the increased bandwidth, it is at the cost of waiting and wasting additional CCA slots and at the risk of losing the carriers for which the eCCA countdown has already been completed. On the other hand, in the Wi-Fi system, each Wi-Fi node performs a single eCCA procedure only on the primary channel [4]. In the meantime on all the secondary channels, only a single CCA check is performed. Comparatively, the proposal of [9] requires each LAA node to complete both the eCCA countdown and the iCCA (Initial CCA) before transmission across multi-carriers. As a consequence, this method would put LAA at disadvantageous position when LAA coexists with Wi-Fi.

To provide better fairness for the coexistence of LAA with other nodes (e.g. Wi-Fi) and benefits from the increased bandwidth, a novel LBT mechanism is proposed in this paper based on the coordination among the LBT procedures on multiple carriers. In addition, the system performance is evaluated and analyzed for different LBT mechanisms to verify our proposal when LAA coexists with Wi-Fi system with multiple unlicensed carriers.

This paper is organized as follows. We first provide an overview of the existing LBT mechanism to ensure fair and friendly coexistence among different operations and RATs in Section II, and then present the proposed LBT mechanism to avoid the RF leakage for multi-carrier operation on unlicensed band in Section III. Numerical results and the corresponding observations are provided in Section IV. Finally, we conclude the paper in Section V.

II. Listen-Before-Talk Mechanism

As addressed that the use of LBT procedure is vital for fair and friendly coexistence of LAA with other operators and technologies operating in unlicensed spectrum. The LBT procedures on a node attempting to transmit on an unlicensed carrier require the node to perform a clear channel assessment to determine whether the channel is free to use. Regulatory requirements in some regions, e.g., in Europe, specify an energy detection threshold. If a node detects the signal energy greater than this threshold, the node assumes that the channel is not free. For LAA, the Category 4 LBT mechanism with random back-off and a contention window of variable size is agreed as the baseline at least for LAA DL transmission bursts containing PDSCH [1]. In this mechanism, an initial CCA (iCCA) check using “energy detection” should be performed before a transmission on an unlicensed channel. If the channel is idle, the equipment may occupy this channel immediately. If the channel is occupied or the equipment has made use of this channel for Maximum Channel Occupancy Time, the equipment shall perform an Extended CCA (eCCA) check which is based on a randomly generated backoff counter. When the backoff counter is reduced to zero, the channel is able to be occupied immediately by the LAA. Fig.1 depicts an example of Category 4 LBT, where the backoff number for eCCA is 5.

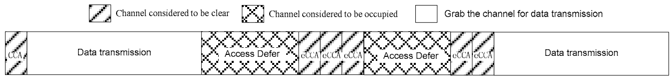

Fig.1: Illustration of Category 4 LBT Mechanism

According to the European regulation [6], the maximum Clear Channel Assessment Energy Detection (CCA-ED) threshold is given by

$$TL = -73\ \text{dBm} / \text{MHz} + (23\ \text{dBm} - PH) / (1\ \text{MHz}) \quad (1)$$

where PH is the maximum transmission power specified in dBm Effective Isotropic Radiated Power (EIRP). For 20 MHz operating bandwidth with 18 dBm maximum transmission power, the CCA-ED threshold is -55 dBm. For multi-carrier operation, the CCA-ED threshold could be increased since the maximum transmission power per carrier is reduced. For example, for 80 MHz operating bandwidth with equal power allocation over each carrier, the transmission power per carrier is reduced to 12 dBm and the CCA-ED could be increased to -49 dBm.

However, the transmitter unwanted emissions to the adjacent carriers would be larger than the CCA-ED threshold cross the whole band. In the presence of differing amounts of interference on each carrier, some carriers may first complete the eCCA countdown and start data transmission earlier than other carriers. In this case, the successful likelihood of LBT on the adjacent carriers is minimal due to the RF leakage and thus result low channel bandwidth utilization. According to ETSI requirements on out of band emissions in Europe, the transmit spectrum power mask outside the bandwidth of ten carriers for RLAN equipment within the frequency is about -47dB i.e. N > 10 as illustrated in Fig. 2 [1]. In this case of 80 MHz operating bandwidth with equal power allocation over each carrier, there is -35dBm emission even outside the bandwidth of ten carriers which would be greater than the CCA-ED threshold -49dBm.

Thus, to avoid the impact of RF leakage on LBT, the coordination among the LBT procedures of multiple carriers is required.

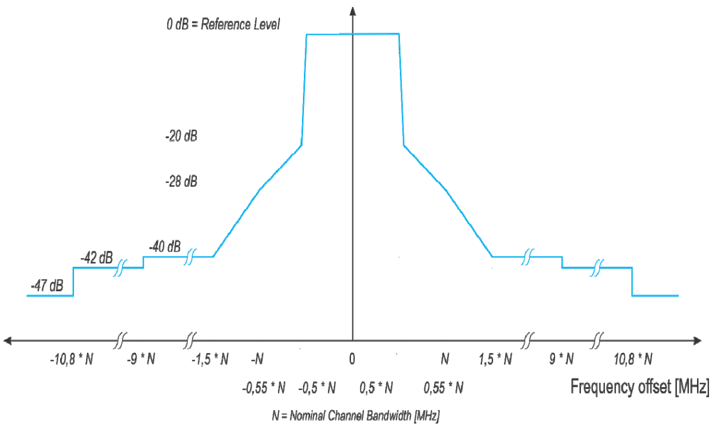

Fig.2: Transmit spectral power mask for RLAN equipment operating within the frequency bands 5150-5250 MHz; 5250-5350 MHz or 5470-5725 MHz

III. MULTI-CARRIER LBT OPERATION

A. Multi-carrier Channel Access of Wi-Fi

In this section, we discuss multi-carrier channel access for Wi-Fi. IEEE 802.11ac follows a hierarchical channel bonding scheme on 20 MHz channels to determine its transmission bandwidth for a PPDU frame, which could be 20 MHz, 40 MHz, 80 MHz, and 160 MHz with the combination of contiguous 20MHz sub-channels in a non-overlapping manner. The relationship between the sub-channels making up the wider channel is shown in Fig.3. One of the 20MHz channels is chosen as the primary 20MHz channel. 40 MHz bandwidth can be achieved if the transmitter occupies the 20 MHz primary channel and the 20 MHz secondary channel adjacent to the 20 MHz primary channel. This combination of 20 MHz primary channel and 20 MHz secondary channel is called the primary 40 MHz channel. 80 MHz bandwidth can be achieved if the transmitter can occupy the 40 MHz primary channel and the 40 MHz secondary channel adjacent to the 40 MHz primary channel. This combination of 40 MHz primary channel and 40 MHz secondary channel is called the primary 80 MHz channel. 160 MHz/ 80+80 MHz bandwidth can be achieved if the transmitter can occupy the 80 MHz primary channel and the 80 MHz secondary channel adjacent/ non-adjacent to the primary 80 MHz channel.[4].

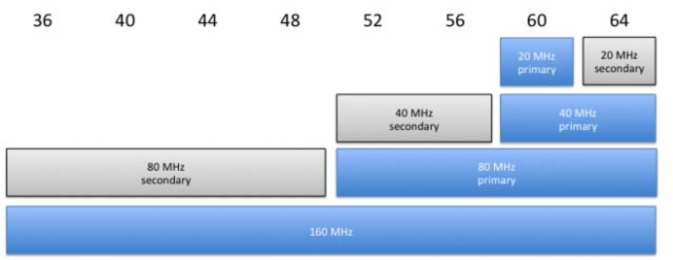

Fig.3 Relationship between primary and secondary carriers in Wi-Fi

For multi-carrier channel access, the Wi-Fi nodes perform the extended CCA procedure only on the primary 20MHz channel. On the secondary channels, only a quick CCA check for a PIFS duration (generally 25 μs) is performed before the potential start of transmission to determine whether the additional secondary channels are available for transmission. Based on the results of the secondary CCA check, transmission is performed on the larger bandwidth; otherwise transmission falls back to smaller bandwidth. The Wi-Fi primary channel is always included in all transmissions, i.e., transmission on secondary channels alone is not supported. The Wi-Fi AP in a Wi-Fi network can have different primary channel. The selection of primary 20MHz channel is important for Wi-Fi AP as all channel access timing for a node is based on the CCA of the primary 20MHz channel.

B. Proposed Multi-Carrier LBT Mechanism for LAA

To support wider bandwidth and provide a higher data rate, carrier aggregation (CA) is used by aggregating intra-band contiguous, intra-band non-contiguous and inter-band carriers in LTE. In particular, it can be cost-efficient to use single RF for intra-band CA case. Considering wide 5 GHz band from 5150 to 5925 MHz, the LAA device may not implement an individual RF for each carrier. As addressed in the Section II, the LAA device can't sense the channel on some carriers while it transmits transmission bursts on the other adjacent carriers. Therefore, the coordination is needed among the LBT procedures for multi-carrier transmission so as to avoid the negative impact of RF leakage on multi-carrier LBT operation. In this section, a novel mechanism is proposed for multi-carrier LBT operation in order to provide better coexistence fairness with other nodes and higher bandwidth utilization ratio than existing scheme.

The basic principle of the proposed solution is to allow simultaneous transmission on more than one carrier if a subset of those carriers has completed an integral eCCA procedure and other carriers are found to be idle before transmission with the duration of a quick CCA (e.g. iCCA). The detailed procedure is described as below:

- First, the LAA device need complete a full random backoff procedure for an aggregated bandwidth over a subset of carriers to synchronize the transmission with LBT on this subset of carriers.

  Herein, these carriers which perform a full random backoff procedure are termed as the synchronization carriers, and the position where the synchronization carriers complete the countdown of eCCA procedure is defined as the LBT synchronization boundary (LSB). For LAA, the device can autonomously decide which unlicensed carriers as the synchronization carriers so as to trade off the delay in channel access and coexistence fairness with other nodes, e.g. the LAA device can dynamically perform the independent full-fledged random backoff on all the carriers. The carrier which completes the random backoff first can be considered as the synchronization carrier so as to allow fast channel aggregation.

- For other carriers out of the subset, a quick CCA per carrier (e.g. iCCA with the duration of at least 25us), is required to determine the LBT outcome on each carrier. Herein, the quick CCA check is performed before the potential start point of transmission i.e. the LSB.

- Finally, the LAA device could start data transmission on both the synchronization carriers and other carriers with successful quick CCA check.

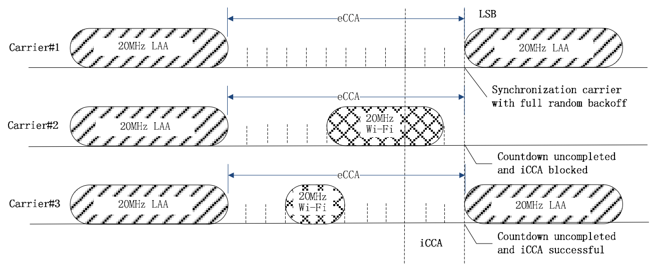

Fig.4: LBT procedure for LAA multi-carrier operation

An example is given in Fig.4 that the LAA device performs independently eCCA procedure on all the carriers and selects the carrier #1 which first completes the eCCA as the synchronization carrier. And the position where carrier #1 completes the countdown is defined as the LSB for multiple-carrier synchronization transmission. Other carriers need to perform an iCCA. It shows that the node starts the data transmission on carrier #3, but blocks the transmission on carrier #2.

For this approach, since the synchronization carrier does not need to wait for additional CCA slots to let other carriers complete the count down, it could enable fast channel access and avoid the risk of losing the carriers in which countdown has already been completed, and thus improve the bandwidth utilization ratio. As this solution is similar to Wi-Fi's mechanism, it could provide better coexistence fairness with Wi-Fi. Unlike Wi-Fi, each LAA carrier can be configured and activated independently, so the data transmission on any combination of the carriers is possible.

IV. Numerical Results

In this section, the system-level simulation performance are evaluated for three multi-carrier LBT mechanisms of LAA (i.e. general LBT solution without inter-carrier coordination, self-deferral based solution [9], proposed solution) when LAA coexists with Wi-Fi. For the solution in [9], it's provided that LAA node starts transmission only at the slot boundary of each subframe for carriers, which finish the full random backoff procedures and check the channel to be free before transmission. In addition, the performance of Wi-Fi/Wi-Fi coexistence is also evaluated to verify the impact of LAA on Wi-Fi after one of Wi-Fi nodes is replaced with LAA node in terms of different multi-carrier operation for LAA. Herein, the outdoor coexistence scenario is simulated where two operators deploy with 4 small cells per operator. The LBT algorithm used for LAA is based on the recommended Category 4 LBT algorithm in [1]. The primary channels in the Wi-Fi networks are not aligned, i.e., each of the 4 Wi-Fi APs adopts a different Primary channel. The detailed simulaiton assumption is shown in TABLE I. The additional simulaiton assumption is based on the agreed outdoor coexistence assumption in [1] .

TABLE I. Simulaiton Assumptions

Parameter	Wi-Fi	LAA
Layout	Based on SCE#2a; The number of small cells per operator:4, The number of unlicensed carriers: 4; 10 UEs per operator	
Carrier Frequency	5GHz	
System Bandwidth	20MHz per carrier	
MCOT	4ms	3ms
Traffic model	FTP Model 3; File Size: 0.5 Mbytes	
File arrival rate	2.0	
Antenna Configuration	2Tx2Rx in DL; Adaptive Stream	2Tx2Rx in DL; 2 Fixed Stream
CCA-ED	-62dBm	-62dBm
CCA slot	9us	9us
Defer Period	34us, i.e. the duration of iCCA	34us
Link Adaption	Minstrel Rate Control Algorithm	Idea

TABLE II illustrates the 5th percentile, 50th percentile, 95th percentile and average user perceived throughput (UPT) respectively for the outdoor deployment where FTP traffic is considered. In the Wi-Fi and LAA coexistence scenario, in the first step, Operator A and B both use Wi-Fi. In the second step, operator B and its corresponding UEs are replaced by an LAA operator and LAA UEs while operator A and its UEs remain unchanged. Moreover, the licensed PCell carrier is not used in the LAA network. It's observed that:

- Due to RF leakage, the general LBT solution has low bandwidth unitization for LAA node, and thus the LAA performance in this solution is worse than the replaced Wi-Fi performance in baseline.
- The LAA performance in the self-deferral based solution [9] is still worse than the replaced Wi-Fi performance in baseline, and even the LAA cell-edge UPT performance i.e. 5% UPT performance is lower than that in the general LBT solution. This can be explained by that the self-deferral based solution required both a full random backoff procedure and an iCCA, and thus the probability of simultaneous data transmission across multiple carriers for this solution is still very low. Furthermore, this solution has the risk of losing the carriers for which the random backoff procedure has already been completed due to waiting additional CCA slots until the slot boundary in a subframe. As a consequence, this solution would put LAA at a disadvantageous position when LAA coexists with Wi-Fi.
- In comparison with the solution in [9], the proposed solution only perform a full random backoff procedure on synchronization carrier and a quick CCA procedure on other carriers before transmission, and thus has more probability of simultaneous transmission across multiple carriers. In this case, the proposed solution has better LAA UPT performance than the self-deferral based solution. Since this solution is similar to Wi-Fi's mechanism, the LAA performance in the proposed solution is close to the Wi-Fi performance in the baseline. In addition, LAA with multi-carrier LBT mechanism does not impact Wi-Fi services more than an additional Wi-Fi network on the same carrier.

Therefore, the proposed solution could provide better fairness and performance in comparison with other solutions when LAA coexists with Wi-Fi.

TABLE II. Performance of LBT mechanisms for multi-carrier operation

Scenario	Solution	Operator A (Mbps/User)			
		5%	50%	95%	Mean
Wi-Fi/Wi-Fi	Baseline	51.8528	272.4320	633.3333	303.5481
Wi-Fi/LAA	General LBT solution	117.4323	283.5845	544.0476	307.6060
	Self-deferral based Solution	131.5220	429.0670	668.6639	419.0059
	Proposed Solution	133.5928	460.2814	654.7096	429.4574
		Operator B (Mbps/User)			
Wi-Fi/Wi-Fi	Baseline	53.2592	282.3457	570.3704	297.3487

Wi-Fi/LAA	General LBT solution	8.3346	36.1863	78.2679	40.7739
	Self-deferral based Solution	3.6397	39.1258	109.4831	49.0267
	Proposed Solution	78.2414	275.9463	455.0679	291.0655

V. CONCLUSIONS

In this paper, we provide an overview of LBT mechanism for LAA and Wi-Fi. For LAA, the general LBT mechanism is unfeasible to ensure simultaneous transmission across multiple carriers due to RF leakage. So, a new LBT mechanism is proposed to avoid the adverse impact of RF leakage on multi-carrier operations for LAA. It's observed that the proposed solution could provide better fairness and performance in comparison with other solutions when LAA coexists with Wi-Fi. Our further work could be the optimization of the proposed solution e.g. on how to determine the energy detection threshold of eCCA on channels where the full eCCA procedures are not performed.

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