Multi-Carrier Listen Before Talk with Power Leakage Awareness for LTE-LAA in Unlicensed Spectrum

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***Abstract*—Licensed-assisted access (LAA) is a new feature of 3GPP LTE that utilizes unlicensed spectrum as a means of providing additional bandwidth. For fair coexistence with other incumbent systems such as Wi-Fi, LAA runs a listen-before-talk (LBT) procedure before transmission, which is designed to support multi-carrier operation as well. However, inherent power leakage to adjacent carriers ruins multi-carrier LBT and deteriorates aggregation capacity considerably. To solve this power leakage problem, we propose a hybrid design of the two LBT types of the specification to have the advantages of both, which is realized by carrier grouping, and develop an algorithm that determines division of carriers into multiple groups with a guard band in between to avoid power leakage among groups and selects the primary carrier of each group so as to maximize LAA's carrier aggregation capacity. Through extensive simulation, we demonstrate that the proposed algorithm enhances system throughput considerably over conventional mechanisms while coexisting fairly with Wi-Fi systems. We also investigate the impact of the depth of group splitting and transmit power on performance.**

***Index Terms*—LTE-LAA, unlicensed spectrum, coexistence, listen before talk, carrier aggregation**

I. Introduction

The recent study of the 3rd generation partnership project (3GPP) has enabled the operation of LTE system in unlicensed spectrum, especially 5 GHz bands, from Release 13 [1]. This new feature named *licensed assisted access* (LAA) is equipped with the *listen-before-talk* mechanism (LBT) [2] which is of importance to address the coexistence of LTE and other wireless technologies such as Wi-Fi in shared unlicensed bands. Multi-carrier aggregation is the key to capacity increase in LAA as well. Two LBT options named *Type A and B* are designed for multi-carrier operation of LAA; Type A runs independent LBT (backoff) processes for individual carriers while Type B runs a backoff process in a single primary carrier only like Wi-Fi.

In LBT Type A, however, inherent *power leakage* to adjacent carriers [3] ruins LBT within a LAA base station (eNB), i.e., the eNB detects a busy carrier due to not only the activity of other systems in the carrier, but also the transmission of itself on other carriers (due to proximity of transceivers), and deteriorates aggregation capacity considerably. There is a known solution, called *self-deferral*, to alleviate the problem by aligning the transmission times of all carriers regardless of individual LBT processes' end time [4]. Another approach to solve the problem is to use LBT Type B which uses a single primary carrier to coordinate the transmission timing of multiple carriers.

However, when the total number of available carriers that a LAA eNB can aggregate for data transmission is large (e.g. 32 carriers), the efficiency of both LBT Type A and B is low (as evaluated in Section V). Unlicensed spectrum is shared by multiple radio access systems such as legacy single-band 802.11a/g and wide-band 802.11n/ac Wi-Fi systems; thus the availability of a carrier for transmission is not guaranteed at a specific time point and even different between carriers. For LBT Type A, the self-deferral method does not guarantee the availability of more carriers at the end of self-deferral. LBT Type B's decision on transmission timing is made based on the status of a single primary carrier only (the availability of other carriers is checked at the end of backoff for a short duration) and thus may not be able to utilize multiple carriers with heterogeneous conditions efficiently.

In this paper, we design a multi-carrier LBT mechanism and develop an associated algorithm for LTE-LAA that operate adaptively with various conditions of each carrier such as power leakage and channel load. Instead of aligning the transmission time of all carriers, the new LBT design lets an eNB divide them into multiple groups with consideration of power leakage between carriers. Then, in each group, LBT Type B is performed with one of the carriers in the group selected as the primary carrier. That is, the new design can be considered as a *hybrid* of LBT Type A and B to have the advantages of both with no need of any specification modification, thus still guaranteeing fair coexistence with Wi-Fi as the specification of LAA does.

The objective of the associated algorithm named **C***arrier-***G***rouping* **A***lgorithm* (CGA) is to determine a set of configuration parameters for the new LBT design such as the number

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of groups, a set of carriers belonging to each group and the primary carrier of each group, that satisfies (i) each group can operate simultaneously with no power leakage impact to the each other; (ii) the LAA system achieves the maximum carrier aggregation capacity. The target problem is considered as an optimization problem whose objective is to maximize the LAA system capacity while minimizing the resource waste of guard-band carriers between groups. In order to solve the problem, the algorithm applies binary splitting of a given set of carriers (into two groups) recursively until a further gain is achievable or a given depth of binary splitting is not reached. Once the backoff process on the primary carrier of a group gets to finish, the algorithm extends the set of secondary carriers beyond the group to exploit the whole unlicensed spectrum efficiently.

Our simulation study demonstrates that the proposal achieves a significant improvement of LAA system throughput, e.g. 2 to 7× in single-spot case (all nodes are placed on the same point) and more than 3× in the 3GPP indoor scenario, while letting coexisting Wi-Fi systems experience no performance degradation. The comparison with results of exhaustive search (in the single-spot case) shows that the proposed algorithm achieves close to the optimum in most cases even with a small depth of group splitting. We also investigate the impact of transmit power and RF leakage bandwidth on performance and show that the relationship of the two parameters is another important factor of multi-carrier LBT.

In summary, the main contribution of our work is detailed as follows:

- A new design of LBT for avoidance of the RF leakage problem in multi-carrier operation is proposed as a hybrid of existing LBT options, thus needing no modification of standards and preserving the coexistence nature of LAA with other incumbent systems in unlicensed spectrum.
- An algorithm of carrier grouping and primary carrier selection associated with the new LBT design is developed with an adjustable depth of search (binary grouping of carriers) such that it achieves high aggregation capacity by exploiting as many carriers as possible with consideration of individual carrier loads.
- Comprehensive simulation results are provided to show the performance gains over conventional mechanisms, optimality and coexistence characteristics with other systems of the proposal under consideration of various system and configuration parameters.

The rest of the paper is organized as follows. Section II presents background. In Section III, we introduce the relevant work on LTE-LAA and LBT mechanism, while in Section IV, we describe the details of the proposal. In Section V, we evaluate and compare the proposal with other multi-carrier LBT options via simulation. Finally, Section VI concludes the paper.

II. Background

In this section, we explain the channel access procedure of LAA for multi-carrier aggregation and the accompanied power leakage problem.

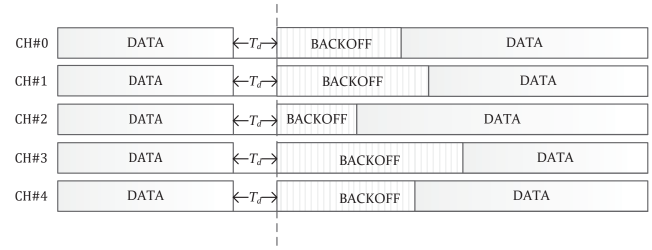


Figure 1. Multi-carrier LBT procedure: Type A (with no RF leakage)

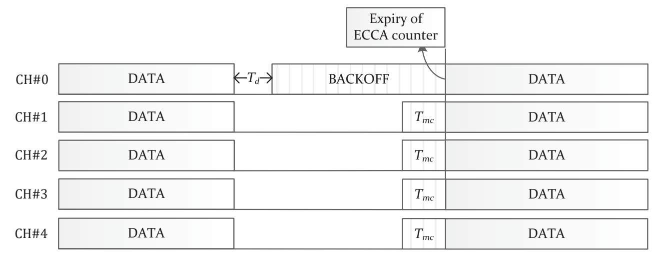


Figure 2. Multi-carrier LBT procedure: Type B

A. Multi-Carrier LBT Procedure

In LAA DL, there are two types of multi-carrier LBT: Type A and B [2]. The major difference between two types is the number of carriers for each of which an independent LBT procedure runs:

- Type A: an independent LBT process is run for each carrier;
- Type B: an LBT process is run for a single primary carrier.

In LBT Type A, as illustrated in Fig. 1, eNB runs an independent backoff process for each carrier, thus can exploit each adaptively to each's condition. After a carrier is sensed idle via clear channel assessment (CCA) for a defer duration of T_d, its backoff count starts to decrease every T_{sl}. When the backoff count of a carrier becomes zero, the eNB can start transmission in the carrier.

The other option, Type B, is designed similar with the wide-band channel access mechanism of Wi-Fi as illustrated in Fig. 2. In LBT Type B, eNB configures a primary carrier among all and runs a backoff process on this carrier only. On the other carriers called *secondary* carriers, a short CCA during T_{mc} is performed immediately before the backoff count of the primary carrier becomes zero. Then, transmission starts on the primary carrier as well as the secondary ones which are sensed idle for the short CCA; if a secondary carrier is sensed busy during this short CCA, it is not considered for transmission. Unlike Wi-Fi, no channel bonding rule is applied in LAA.

B. Power Leakage Problem

Fig. 3 shows the transmit spectral power mask of LTE-LAA for 20MHz carrier bandwidth in 5GHz unlicensed bands as specified in 3GPP TS36.104 [3]. When eNB transmits at the maximum allowable transmit power, i.e., 23dBm, in carrier i,

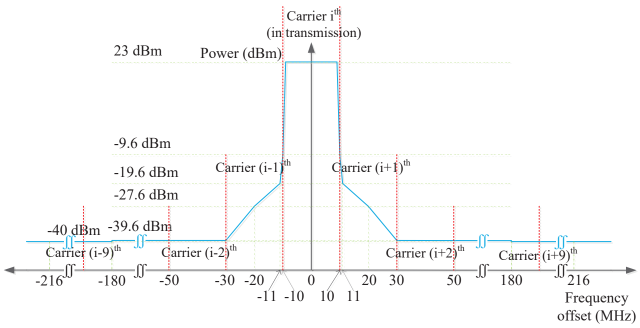
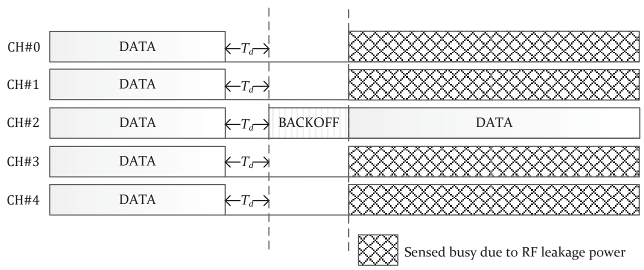
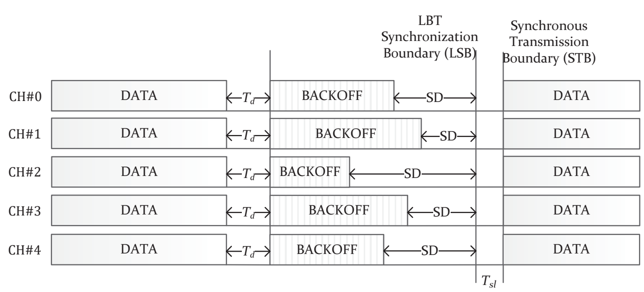


Figure 3. Spectral power mask requirement of LTE-LAA for 20MHz carrier bandwidth in 5GHz band



(a) LBT Type A with RF leakage



(b) LBT Type A with self-deferral (SD)

Figure 4. RF leakage problem of LBT Type A and self-deferral to solve it

the power leakage resulting from this transmission to adjacent carriers $i-1$ and $i+1$ will reach up to -27.6dBm at each's center frequency. Even for farther carriers ($i\pm2,\ldots,i\pm9$), the maximum possible power leakage is still as high as -40dBm.[1] We define *RF leakage bandwidth* as the adjacent bandwidth over which the power leakage of a carrier gets over the ED threshold of LAA. The RF leakage bandwidth of an LAA eNB will be reduced with its reduced transmit power, but probably at the expense of the degradation of each carrier's link capacity.

This power leakage problem makes eNB fail to use multiple carriers at the same time in LBT Type A as shown in Fig. 4(a). The energy detection (ED) threshold of CCA ranges from -82 to -62dBm in LAA (depending on the transmit power in the carrier). Therefore, if eNB is transmitting in a carrier (CH#2 in the figure), it may sense other carriers busy and freeze the backoff counts for them until the transmission in the first carrier finishes.

[1]The spectral mask of Fig. 3 is the minimum requirement. Actual power leakage will depend on manufacturers.

To combat the power leakage problem in LBT Type A, eNB can optionally set an *LBT synchronization boundary* (LSB) by which eNB defers transmission for all carriers (even for those with a zero backoff count) called *self-deferral* (SD) [4]. At LSB, eNB performs a short CCA for time interval T_{sl} on the carriers with zero backoff counts and starts transmission on those sensed idle. By self-deferral, transmissions of all carriers start at the same time, thus avoiding the power leakage problem. However, there is no guarantee to use a larger number of carriers at the same time (i.e., a larger number of carriers are sensed idle at LSB) than the case with no SD (Fig. 1) due to other interference sources such as Wi-Fi devices and other LAA eNBs/user equipments (UEs).

LBT Type B has no power leakage problem inherently. However, it may not be able to exploit each carrier more efficiently than Type A (as will be shown in Section V) since it monitors (i.e., runs a backoff process in) a single primary carrier only. Therefore, selection of the primary carrier has a high impact on performance in LBT Type B. If a selected one is busy, eNB does not exploit whole carriers well (even though secondary carriers are idle).

III. Related Work

Channel Access Procedure. There are two major approaches for LTE coexistence mechanisms: (i) *duty-cycle method* which requires a minimal modification to the current LTE protocol since it uses a discontinuous transmission pattern, known as LTE-U [5]–[19]; (ii) *listen-before-talk* (LBT) scheme which LTE-LAA is based on [13], [14], [18], [20]–[38]. While the duty-cycle method is mainly targeted for early deployment and applicable to USA, Korea and China markets, the LBT-based scheme is considered as a prominent candidate due to the regulatory requirements mandated in some regions (e.g. Europe, Japan) and thus suitable to the design target as a single global framework of LTE-LAA. Among those studies about the LBT-based scheme of LTE-LAA, there are a number of papers that investigated and proposed schemes for adjusting LBT's parameters such as a sensing period of LBT: [27] for a fixed duration as a fraction of time within a frame or one frame duration; [14], [21], [22], [26] for a fixed contention window; [14], [23], [28], [33], [36], [37] for a variable size of contention window, energy detection (ED) threshold in [14], [33], [37], channel occupancy time in [38]. A comprehensive network monitoring scheme for LAA network with multiple criteria such as interference, cell load and capacity was considered in [30].

Radio Resource Coordination. Other coexisting mechanisms in [19], [39]–[41] are based on resource coordination between LTE and Wi-Fi such as spectrum assignment, interference management, etc. For example, a cognitive coexistence scheme to achieve both spectral efficiency and fairness between LTE and Wi-Fi is shown in [19]; Sagari *et al.* [40] applied a logically centralized optimization framework that is used to exchange information as dynamic spectrum management and inter-network coordination between LAA and Wi-Fi systems; To combat uncontrollable interference from coexisting Wi-Fi networks which may cause a hidden terminal

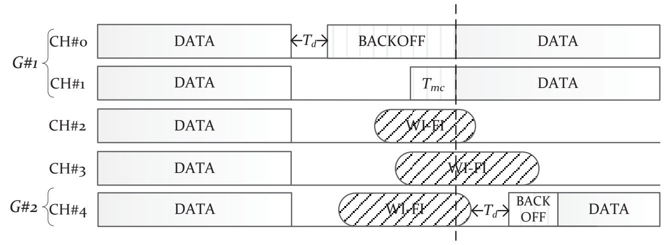


Figure 5. Illustration of carrier grouping with a 40MHz guard-band

problem, the authors in [41] developed a dynamic switch mechanism between scheduling-based and random access to optimize radio access for UL transmission of LAA.

Considering a joint resource allocation problem with licensed/unlicensed carrier aggregation of LAA was studied in [42], [43] while frequency reuse among neighboring cells of a LAA network in unlicensed spectrum was considered in [32], [44], [45]. A comprehensive survey of these three spectrum sharing technologies, i.e., LAA, LWA (LTE-WLAN aggregation) and LWIP (LTE-WLAN radio level integration with IPsec tunnel), was provided in [46].

Under the perspective of game theory, there are also a number of studies for coexistence and inter-operation between LTE and Wi-Fi as in [9], [16], [47]–[49] such as: A reinforcement learning based dynamic duty-cycle selection technique for LAA to facilitate Wi-Fi and LAA simultaneous operation in the unlicensed spectrum in [9]; Taking into account interference among cellular users of different operators and also unlicensed users in other networks, Zhang *et al.* [47] used a hierarchical game approach; The coexistence issues between Wi-Fi and LTE systems can also be modeled as the interactions between Wi-Fi and LTE users using suitable matching games [48].

Multi-Carrier Listen-Before-Talk Mechanism. Among the previous studies of LBT channel access schemes, most considered a single carrier only. For multi-carrier transmission of LTE-LAA, there are a few studies such as: for the duty-cycle method, Guan *et al.* [19] designed a scheme which jointly determines channel selection, carrier aggregation and fraction of spectrum access for LTE-U network. Several proposals for selection of the self-deferral period in LBT Type A are in [4], [50]. However, it is shown in [24] that fixed or sub-frame boundary-aligned self-deferral period is inefficient because it cannot adapt to changing network conditions. Liu *et al.* [51] proposed a mechanism for LBT Type B that a carrier which completes a backoff process first is selected as the primary carrier. Wang *et al.* [52] studied the performance of LBT Type B, then proposed a mechanism to switch on and off multi-carrier aggregation based on the traffic load. Zeng *et al.* [53] developed a mathematical model to analyze the coexistence fairness and proposed a weight-based carrier selection method that LAA eNB selects the ones less used by Wi-Fi systems to avoid contention with them. A coexistence study of multi-carrier LAA with and without a channel bonding rule was given in [54]. The study indicated that LAA without channel bonding still coexists fairly with Wi-Fi.

IV. Carrier Grouping-based Multi-Carrier LBT

In this section, we describe the details of the proposed LBT design and associated problem-solving algorithms.

A. Hybrid LBT Design

The proposed LBT design divides carriers into multiple groups such that there exists no power leakage problem between groups and thus groups access their member carriers independently from the others. To avoid the power leakage problem within each group, we apply LBT Type B within a group; a primary carrier is selected among those of a group and the other carriers of the group are aligned to the LBT procedure of the primary one. That is, the proposed design is a hybrid of LBT Type A and B, thus having the following advantages:

- It alleviates the power leakage problem of LBT Type A;
- It enables eNB to exploit carriers more adaptively to their conditions than LBT Type B,

both leading to the increase of carrier aggregation capacity.

Then, the proposed design faces two problems to solve:

- *P1*: How to group carriers?
- *P2*: How to select a primary carrier within each group?

We illustrate our solution approach to these problems in Figs. 5 and 6 where the power leakage of a carrier over the ED threshold reaches up to adjacent 40MHz bandwidth (two carriers). Carriers are grouped into $G\#1$ and $G\#2$ such that two groups have a 40MHz guard-band to avoid power leakage between them. The guard-band is configured as a set of consecutive carriers having highest loads so as to minimize the impact on eNB's throughput performance, which are $CH\#2$ and $CH\#3$ in the figures. Then, $G\#1$'s transmission does not produce any power leakage to $G\#2$ and vice versa. Thus they run independent LBT Type B procedures; $G\#1$'s primary carrier is set to $CH\#0$ and $G\#2$'s to $CH\#4$.

The proposed LBT design has two prerequisites for realization: (1) carrier load estimation; and (2) power leakage identification. Carrier load estimation can be implemented based on CCA results for each carrier as in [55]. To find a guard-band between groups, identifying how far power leakage over the ED threshold reaches is needed. Since this is determined by the RF filter of eNB, the information can already be known in a production stage. Alternative is to let eNB transmit in a carrier and listen in the rest in its initialization step.

In what follows, we describe the details of the proposed algorithms to solve the problems *P1* and *P2* (their pseudo codes are given in Algorithms 1 and 2, respectively).

B. Carrier Grouping Algorithm

The algorithm to solve *P1* is named **C***arrier*-**G***rouping* **A***lgorithm* (CGA). First, CGA determines two groups and guard-band carrier(s) in the target spectrum. Then, CGA divides each group again into two groups and guard-band carrier(s) if needed. This process is repeated in a recursive manner until a further gain of grouping is achievable or the depth of search (recursion) is not reached.

Suppose that the target unlicensed spectrum is a set of non-overlapping carriers $N = \{1, \cdots, n, \cdots, |N|\}$ where we index carriers in an ascending order of frequency, i.e., a carrier with a higher index has a higher center frequency. We assume that each carrier is 20MHz wide.

Let β_n be the probability that an LAA eNB transmits in carrier n in a random slot. Then, the link capacity that the eNB can achieve in carrier n is determined by

$$U_n = \beta_n \sum_{k \in M_n} C(b_k^n, SINR_k^n) \tag{1}$$

where M_n is the set of users assigned radio resource in carrier n and C is the achievable capacity of a user during transmission for given bandwidth b_k^n and signal-to-interference-plus-noise ratio ($SINR_k^n$) which can be expressed by Shannon's capacity theorem as

$$C(b_k^n, SINR_k^n) = b_k^n \log_2(1 + SINR_k^n). \tag{2}$$

An LAA eNB monitors the load of carrier n as p_n which is the probability that any energy is sensed over the ED threshold in a slot time. If β_n is expressed in terms of p_n, we can obtain β_n. Since LAA's LBT for a single carrier is designed same as the DCF procedure of Wi-Fi, β_n is obtained from p_n based on Bianchi's DCF model [56] as

$$\beta_n = \frac{2(1-2p_n)}{(1-2p_n)(CW_{\text{min}}+1) + p_n CW_{\text{min}}(1-(2p_n)^k)} \tag{3}$$

where CW_{min} is the minimum contention window size and k is the maximum backoff stage of the LAA eNB.

If eNB performs LBT Type B for N with primary carrier $i \in N$, the total aggregation capacity is given as

$$\begin{aligned} U_N^i = &\beta_i \sum_{k \in M_i} C(b_k^i, SINR_k^i) \\ &+ \sum_{j \in N \setminus \{i\}} \beta_i \beta_j^{sc} \sum_{k \in M_j} C(b_k^j, SINR_k^j) \end{aligned} \tag{4}$$

where the first term is the capacity of primary carrier i and the second term is the capacity sum of secondary ones; β_j^{sc} is defined as secondary carrier j's probability of transmission that is triggered when it is sensed idle in a short CCA during T_{mc} and thus obtained as $(1-p_j)^{\lceil T_{mc}/T_{sl} \rceil}$.

For a set of carriers N, CGA divides it into two groups G_1 and G_2 and a guard-band carrier set G_{guard}. Then, we have

$$N = G_1 + G_2 + G_{\text{guard}}. \tag{5}$$

For division, CGA finds G_{guard} first, then from the boundary carriers of G_{guard}, G_1 and G_2 are identified. Let us define $G_{\text{guard}} = \{r_s, \cdots, r_s + m - 1\}$ which contains m consecutive carriers with total bandwidth of $m \times BW$MHz; r_s is the start carrier of G_{guard}. Then, the carriers of G_1 and G_2 are defined as $G_1 = \{1, \cdots, r_s - 1\}$ and $G_2 = \{r_e + 1, \cdots, |N|\}$. The size m of G_{guard} is determined by identifying how far the power leakage of a carrier reaches based on a method mentioned in Section IV.A.

To minimize capacity degradation due to G_{guard}, CGA selects the carriers of G_{guard} as those having the minimum capacity. Thus r_s of G_{guard} is determined as

$$r_s = \arg \min_{1 < i < |N| - m} \sum_{i}^{i+m-1} U_i. \tag{6}$$

To make a final decision to divide N into two groups or not, CGA compares the total capacity with and without division, i.e., if $U_{G_1}^{i_1} + U_{G_2}^{i_2} > U_N^i$, the division is made ($i_1$ and i_2 are the primary carriers of G_1 and G_2, respectively); otherwise, CGA stops further division of N and the carrier grouping process is completed.

Algorithm 1 CGA Algorithm

N: Set of carriers for which grouping is to be made
m: Guard-band width in terms of the number of carriers
d: Remaining depth of search (recursion)
procedure RECURSIVECG(N, d)
    $r_s = \arg\min_{1<i<|N|-m} \sum_i^{i+m-1} U_i$
    $G_1 \leftarrow \{1, \cdots, r_s - 1\}$
    $G_2 \leftarrow \{r_s + m, \cdots, |N|\}$
    i = FINDPC(N)
    i_1 = FINDPC(G_1), i_2 = FINDPC(G_2)
    Calculate U_N^i, $U_{G_1}^{i_1}$ and $U_{G_2}^{i_2}$ in Eq. (4)
    if $U_{G_1}^{i_1} + U_{G_2}^{i_2} \geq U_N^i$ **then**
        Accept the grouping decision (take G_1 and G_1)
        if $d \geq 1$ **then**
            if $|G_1| \geq m + 2$ **then**
                RECURSIVECG($G_1, d-1$)
            end if
            if $|G_2| \geq m + 2$ **then**
                RECURSIVECG($G_2, d-1$)
            end if
        end if
    else
        Abort the grouping decision (take N)
    end if
end procedure

C. Dynamic Primary Carrier Selection within Each Group

To select a primary carrier in a group of carriers G, eNB finds a carrier which, if selected as a primary carrier, will result in the maximum total aggregation capacity given in Eq. (4). We assume that primary carrier selection is triggered periodically at a given rate.[2] When eNB picks a new backoff count for carrier n as bo_n, it estimates the transmission probability of the carrier as $\beta_n = (1-p_n)^{bo_n}$ for $\forall n \in G$. Based on Eq. (4), eNB estimates the total aggregation capacity U_G^n for all primary candidate carriers and selects one with which U_G^n is maximized.

D. Extension of Secondary Carriers

In the operation of Fig. 5, each group's transmission is triggered by the backoff process of a single primary carrier and does not span the guard-band carriers or other group's carriers.

[2]For fair coexistence with incumbent systems like Wi-Fi, eNB is allowed to select a primary carrier no more frequently than once every 1 second.

Algorithm 2 Dynamic Primary Carrier Selection

G: Group of carriers among which a primary carrier is to be selected
bo_n: Backoff counter value of eNB on carrier n
p_n: Transmission probability in a slot time on carrier n
c_{pc}: Primary carrier of G
procedure FINDPC(G)
  Initialize $U^* = 0$
  for all $n \in G$ **do**
    $\beta_n = (1 - p_n)^{bo_n}$
    Calculate U_G^n of Eq. (4)
    if $U^* < U_G^n$ **then**
      $c_{pc} \leftarrow n$
      $U^* \leftarrow U_G^n$
    end if
  end for
  Return c_{pc}
end procedure

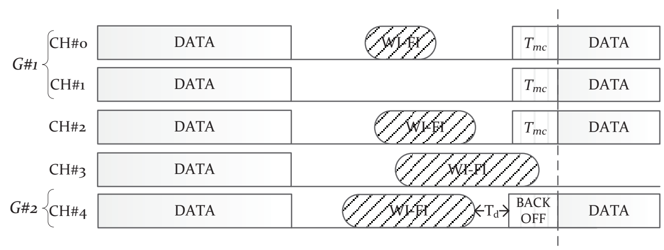


Figure 6. Illustration of carrier grouping with secondary carrier extension

To relax this limitation, the proposed LBT design extends the set of secondary carriers beyond a group as illustrated in Fig. 6 where $G\#2$'s secondary-carrier set is extended beyond the group to the rest of carriers and same for $G\#1$'s. When a group's backoff process is about to finish, a short CCA is performed not only for the secondary carriers of the group, but also for its extended secondary-carrier set, thus taking more transmission opportunities in carriers. This operation can be interpreted as configuring multiple primary carriers.

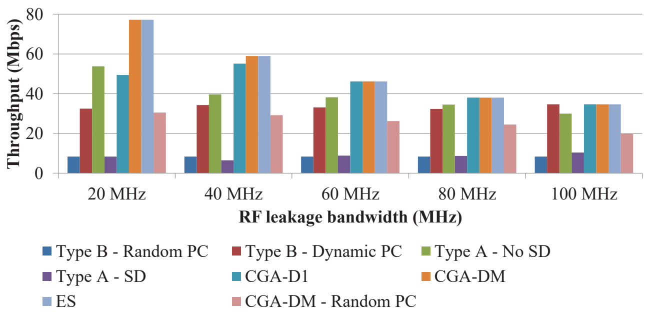
If secondary-carrier extension activates transmission in guard-band carriers, the bandwidth of the guard-band is utilized additionally, but the carriers of the adjacent group will experience RF power leakage. For example, suppose that eNB finishes backoff for $G\#1$ earlier than for $G\#2$ and transmits in some of guard-band carriers as well via secondary-carrier extension, but not in those of $G\#2$ since they are sensed busy due to the ongoing transmissions of Wi-Fi systems. If the Wi-Fi transmissions in the carriers of $G\#2$ end earlier than eNB's transmission in the guard-band carriers, eNB still senses the carriers of $G\#2$ busy due to the RF power leakage from the transmission in the guard-band carriers. Alternatively, we can allow secondary-carrier extension to groups' carriers only, thus always avoiding RF power leakage between groups. The gain from exploiting more carriers and the loss from RF power leakage are analyzed in the following evaluation section.

Table I
SIMULATION PARAMETERS

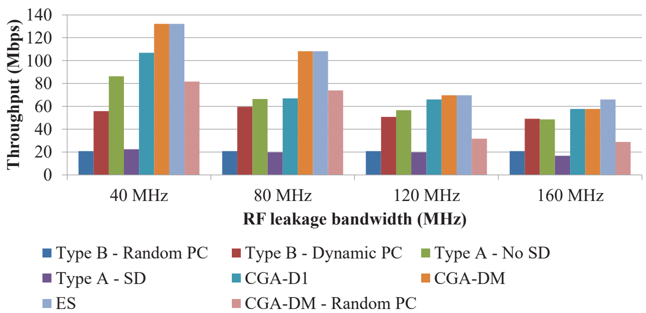
Parameter	LAA	Wi-Fi
Frequency	5GHz	
Carrier bandwidth	20MHz	
Tx power	18dBm for both eNB/AP and user devices	
Slot time T_{sl}	9μs	
Defer duration T_d (DIFS)	34μs	
T_{mc} (PIFS)	25μs	
$CW_{\min}$	16	
$CW_{\max}$	1024	
MCS	QPSK, 16QAM, 64QAM	802.11ac's MCSs except 256QAM
Number of carriers	8, 16, 32	4
Max channel occupancy time	3ms (DL + UL)	1ms (by each node)
Energy detection threshold	-72dBm	-62dBm
Preamble detection threshold	N/A	-82dBm
Duplexing	DL + UL	
Link adaptation	Channel state information based	
Antenna configuration	2×2 MIMO	

V. PERFORMANCE EVALUATION

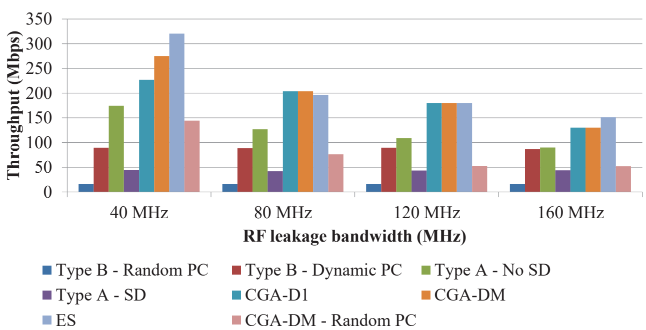
In this section, we evaluate the system performance of both LAA and Wi-Fi in coexistence scenarios with comparison of various LBT options and provide in-depth analyses. The proposed LBT design is represented as CGA-D1 (the search depth is one), CGA-DM (the maximum search depth is used) and ES (grouping is determined by the exhaustive search for the best one (maximum capacity) among all possible candidates). In order to study the impact of each of CGA's features, we consider the variants of CGA—with random primary-carrier (PC) selection, secondary-carrier extension to groups' carriers only, and without secondary-carrier extension—and also a variant of Type B as the one with our dynamic PC selection feature. Unless specified otherwise, CGA is equipped with dynamic PC selection and secondary-carrier extension to all carriers. The conventional LBT options of LAA for comparison are Type A with and without self-deferral (SD), and Type B with random primary carrier selection. For Type A with SD, the self-deferral period is fixed as 10 slot times. A wide range of RF leakage bandwidth is considered in simulation. Data traffic is generated by a full-buffer model in both LAA and Wi-Fi systems. The maximum channel occupancy time (MCOT) of LAA is set to 3ms which is composed of a duration up to 1ms for a reservation signal by eNB, 1ms for a downlink transmission by eNB and 1ms for the following uplink transmission by scheduled users. Wi-Fi's MCOT is set to 1ms since channel accesses of Wi-Fi are determined by individual nodes (either AP or station). The simulation parameters are listed in Table I. The considered deployment scenarios are single-spot (all nodes are placed on the same point, thus having no hidden nodes) and 3GPP indoor scenarios [20].



(a) 8 carriers

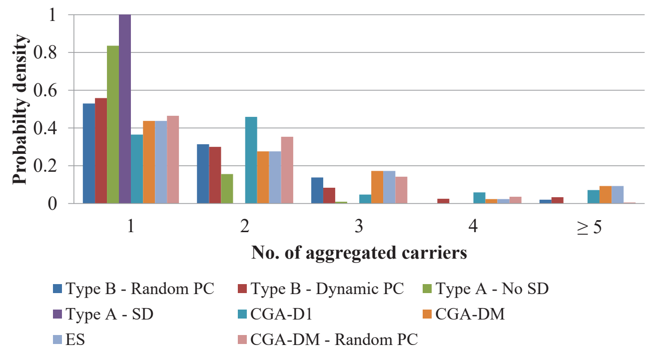


(b) 16 carriers

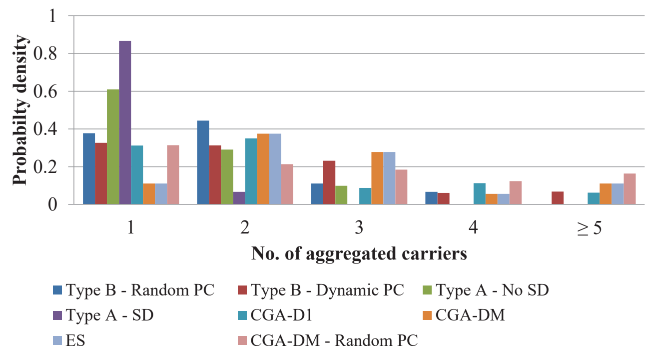


(c) 32 carriers

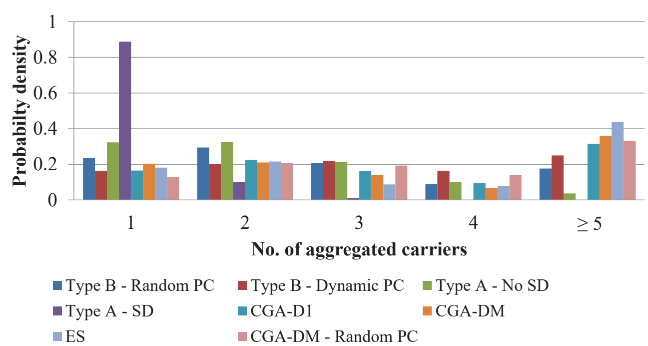
Figure 7. LAA downlink throughput in single-spot deployment scenario for a varying number of carriers; The search depths are (a) (3, 3, 2, 2, 2), (b) (3, 3, 3, 2) and (c) (4, 3, 2, 2) in the order of the considered RF leakage bandwidths.



(a) 8 carriers



(b) 16 carriers



(c) 32 carriers

Figure 8. Distribution of the number of aggregated carriers in LAA downlink transmission under power leakage over 40MHz; The search depths are (a) (3), (b) (3) and (c) (4).

A. Single-Spot Deployment Scenario

In this scenario, the LAA network contains an eNB and ten UEs connected to it and supports carrier aggregation; the Wi-Fi network has an AP and ten stations using single-band operation in each carrier.

Fig. 7 shows LAA downlink performance of different LBT options when the maximum number of aggregated carriers is varied from 8 to 32. It can be observed from the results that LAA eNB performing two conventional LBT options (Type B - Random PC and Type A - SD) gains the smallest LAA throughput performance among all considered LBT mechanisms in all cases, which indicates the inefficiency of this two options under a heavy traffic load condition. The main reason of the low performance of LAA eNB using Type B is the requirement that LAA eNB monitors a single primary carrier only, which limits transmission opportunities of LAA eNB even when the number of carriers is increased. For Type A - SD, LAA eNB with a fixed self-deferral period cannot adapt with changing channel conditions, especially in high traffic load conditions with many contending nodes. The results of Fig. 8 proves that most of LAA eNB's transmissions using Type A - SD occur in a single carrier only. Therefore, the gain of deferring for a self-deferral period to aggregate more carriers is significantly smaller than the loss of transmission opportunities on the carriers which have already finished a backoff process.

On the contrary, Type A - No SD, CGA-D1, CGA-DM and ES show a good adaptability for LAA network under a high load condition. In Type A - No SD, LAA eNB runs an independent backoff process for each carrier, thus can exploit each adaptively to each's condition, as a result yielding high LAA throughput when the maximum number

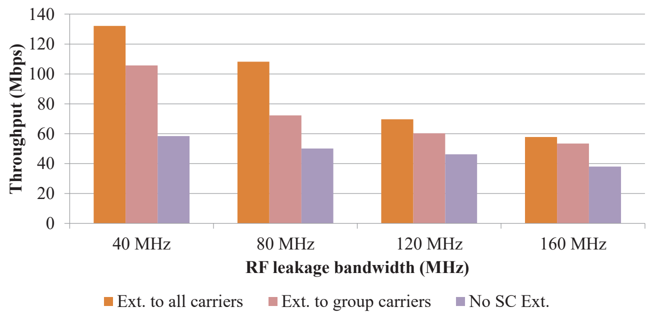


Figure 9. LAA downlink throughput of CGA with the variants of secondary-carrier extension: extension to all carriers, groups' carriers only, and no extension (16-carrier case).

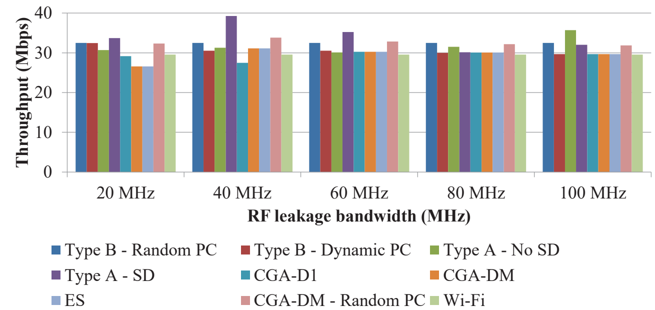


Figure 10. Wi-Fi system throughput with 8 total carriers (Wi-Fi's single-band operation); The search depths are (3, 3, 3, 2, 2) in the order of the considered RF leakage bandwidths.

of aggregated carriers is increased. CGA-D1 and CGA-DM achieve a significant improvement (5 to 7× with 8 carriers and power leakage over 20MHz) of LAA downlink throughput compared to Type B - Random PC and Type A - SD.

The results also show how much each feature of CGA contributes to the overall throughput gain. Comparing the results of CGA with dynamic and random PC selection, we see that the dynamic PC selection feature gives a significant improvement of throughput by over 50% in all cases. Comparison of Type B between random and dynamic PC selection cases also show the gain of dynamic PC selection; Type B with dynamic PC selection achieves up to 3× throughput (8 carriers and RF power leakage bandwidth of 20MHz). Fig. 9 shows the benefit of secondary-carrier extension by comparing three variants: extension to all carriers, groups' carriers only, and no extension. In the figure, extension to all carriers outperforms the other two and no extension case is the worst. This implies that the throughput gain from exploiting more carriers is higher than the loss from RF power leakage on average. However, there could still be some moments that only some guard-band carriers are activated by secondary-carrier extension and the adjacent group cannot proceed backoff for a short period. We leave an extended design of secondary-carrier extension to handle such moments dynamically as future work.

By allowing CGA to search a greater depth of group splitting, CGA-DM achieves better performance than CGA-D1 (the search depth is one) especially when the RF leakage bandwidth is small; for example, the gain of CGA-DM over CGA-D1 is as high as 40% when the RF leakage bandwidth is 20MHz with 8 carriers and 80MHz with 16 carriers. Such an improvement of CGA-DM, however, disappears when the RF leakage bandwidth gets larger; CGA-DM achieves almost same as CGA-D1 when the RF leakage bandwidth is 40MHz or larger with 8 carriers, 120MHz or larger with 16 carriers and 80MHz or larger with 8 carriers, 120MHz or larger with 16 carriers. This is because a small RF leakage bandwidth leads to a large number of carrier combinations for grouping; however, the number of carrier combinations for grouping is reduced for a large RF leakage bandwidth since CGA has to reserve more carriers for guard bands. It is also shown that CGA-DM achieves the same performance as ES's in most cases. However, due to the sub-optimality of CGA, ES is able to find a better solution of carrier grouping in some cases and achieves higher throughput.

CGA's performance is sensitive to the RF leakage bandwidth. In Fig. 7, as RF power leakage spans wider bandwidth, their LAA system throughput decreases. CGA reduces the number of carriers assigned to groups due to a wider guard band, which directly degrades the LAA performance of CGA. CGA is also impacted by the power leakage bandwidth since the effectiveness of dynamic PC selection highly depends on the number of candidate carriers and the carriers of guard bands are not considered as candidates.

CGA has another advantage that, when the total number of carriers is increased from 8 to 32 by four times, the LAA throughput also improves as the same rate, i.e., four times. In particular, when the power leakage bandwidth is 20MHz, the improvement of LAA throughput is from 50 to 200Mbps for CGA-D1 and from 70 to 280Mbps for CGA-DM. However, it is only 3× increase for Type A - No SD and just a small improvement for Type B and Type A - SD.

The results of Fig. 7 are better understood if the number of aggregated carriers for each transmission is observed together as given in Fig. 8. It is clearly shown that the proposed algorithms succeed to aggregate more carriers for a transmission than other LBT options. For example, transmission using Type B, Type A - SD and Type A - No SD mostly can aggregate one to two carriers while almost 50% of total transmissions for CGA use four and more carriers when the total number of carriers is 32.

The throughput of the Wi-Fi system (downlink) when it coexists with another Wi-Fi operator (Wi-Fi vs. Wi-Fi case) and a LAA operator (Wi-Fi vs. LAA case) with 8 total carriers is shown in Fig. 10. In the figure, the bars denoted as "Wi-Fi" correspond to the Wi-Fi system throughput of the Wi-Fi vs. Wi-Fi case; other bars are the Wi-Fi system throughput of the Wi-Fi vs. LAA case. If a bar for coexistence with a LAA's LBT option is taller than the "Wi-Fi" bar, it means that the Wi-Fi system achieves higher throughput when coexisting with the LAA system (using the corresponding LBT option) than with another Wi-Fi system and thus the LBT option coexists well with Wi-Fi system. As shown from the results, the Wi-Fi system achieves similar or even higher throughput performance when coexisting with the CGA-enabled LAA system compared with the performance with another Wi-Fi system.

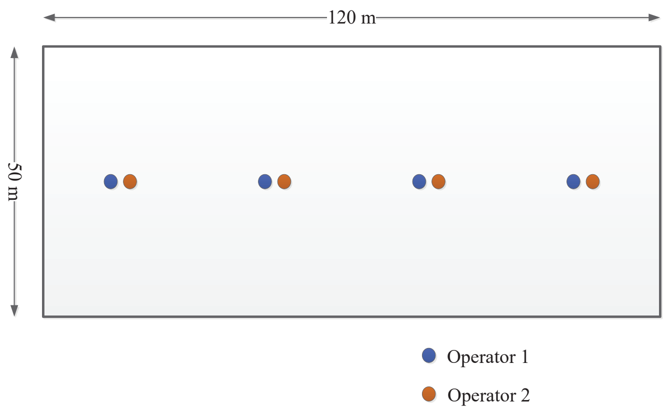


Figure 11. Indoor deployment scenario

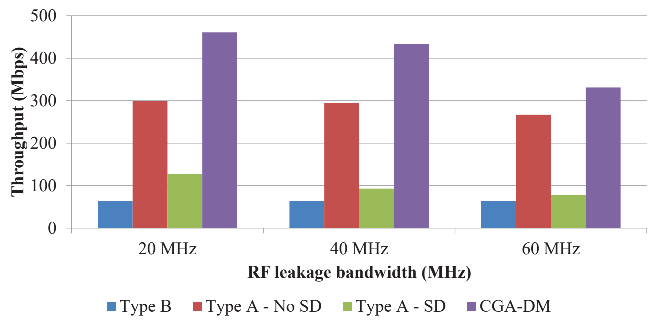


Figure 12. LAA downlink throughput in the indoor scenario; The search depths are (2, 2, 2) in the order of the considered RF leakage bandwidths

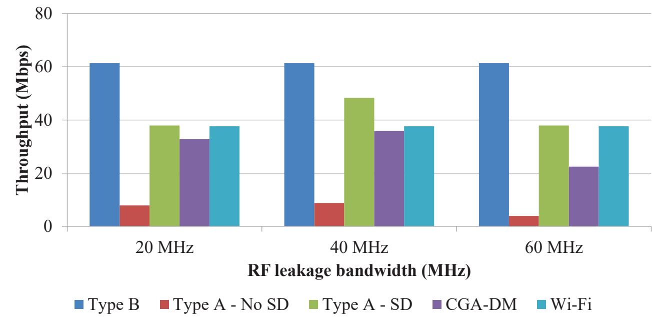
B. Indoor Deployment Scenario

Next, we run simulation for the indoor scenario as specified in 3GPP TR36.889 [20]. In this scenario, each of two operators deploys four small cells in a single-floor apartment as depicted in Fig. 11. Each cell has ten UEs which are randomly distributed around its serving eNB or AP. The number of available carriers is four. We consider CGA-DM (due to the small number of carriers, CGA-D1, CGA-DM and ES achieve similar results). The simulation parameters of Table I are still used.

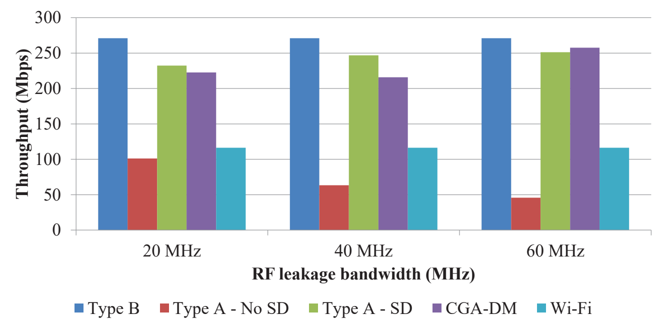
The system performance of LAA downlink (DL) is given in Fig. 12. Similar with the single-spot scenario, CGA achieves significantly improved throughput compared to the conventional LBT options; It achieves $4\times$ of Type A - SD's throughput and even higher over Type B's.

Fig. 13 shows the Wi-Fi downlink and uplink throughput for Wi-Fi vs. Wi-Fi and Wi-Fi vs. LAA operator cases. It is observed that except Type A - No SD which severely degrades the Wi-Fi performance, other conventional options and our proposals improve the Wi-Fi system throughput compared to the Wi-Fi vs. Wi-Fi case. Coexistence results are also presented as cumulative density function (CDF) graphs of Wi-Fi per-node throughput in Fig. 14. The figure demonstrates that CGA allows 50% of Wi-Fi nodes to achieve more than 5Mbps while only 25% are allowed in the Wi-Fi vs. Wi-Fi case.

Fig. 15 presents the CDF of LAA's per-node throughput. First of all, Type A - No SD has an improvement in terms



(a) Downlink



(b) Uplink

Figure 13. Wi-Fi system throughput with 4 carriers in a spectrum band in the indoor scenario (Wi-Fi's wide-band operation); The search depths are (2, 2, 2) in the order of the considered RF leakage bandwidths for both link directions.

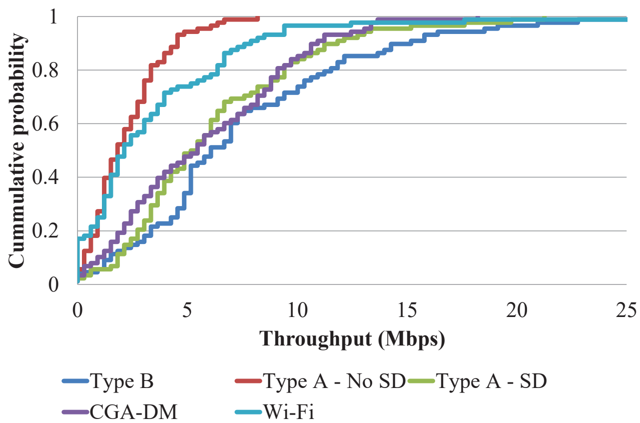
of the minimum throughput that a LAA node can achieve (at least 3Mbps) as a trade-off for a significant negative impact on Wi-Fi performance as shown in Fig. 14. The reason of this improvement of Type A - No SD is that it enables LAA eNB to access carriers independently by running a separate LBT process on each carrier, but makes Wi-Fi nodes to access the channels less at the same time. On the other hand, LAA eNB performing Type B, Type A - SD and our proposal have a number of UEs suffering a shortage of UL transmission opportunities due to different levels of ED thresholds between LAA and Wi-Fi as explained in [33].

C. Impact of Transmit Power

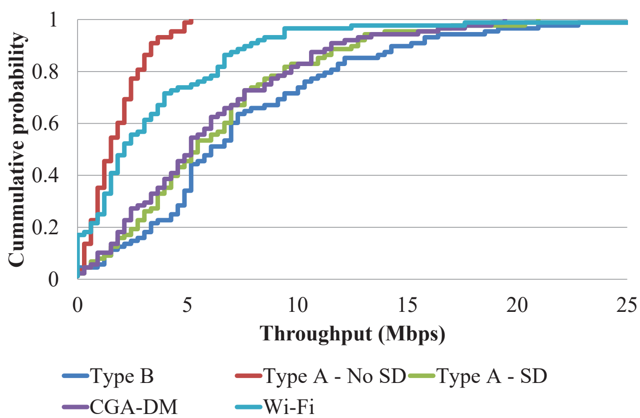
In this section, we investigate the impact of transmit power and its relationship with the RF leakage bandwidth on the LAA system throughput.

As we described in Section III.B, the RF leakage power depends on the transmit power of an LAA eNB on a carrier. That is, a higher transmit power is used for transmission in a carrier, a higher RF leakage power appears in its adjacent carriers. However, the transmit power also affects link capacity; reduction of transmit power results in reduced SINR and thus decreased link capacity (as can be seen in Eq. (2)). Therefore, there exists a tradeoff when an LAA eNB adjusts its transmit power.

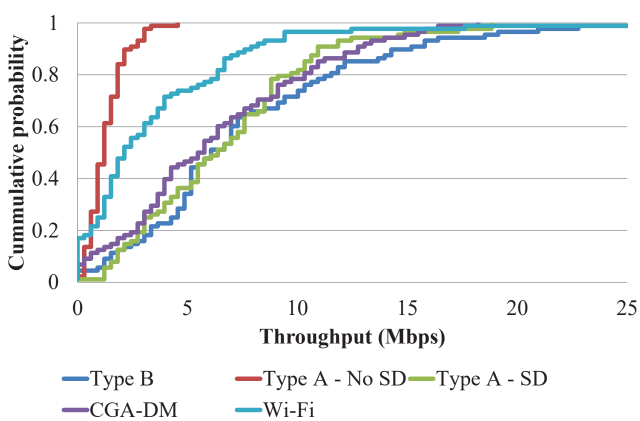
In order to investigate such a tradeoff, we consider a single LAA eNB in the previous indoor scenario, but still with Wi-Fi systems in carriers as in the single spot scenario, to limit the affecting factors on performance. We define ΔP as the amount



(a) RF leakage bandwidth: 20MHz

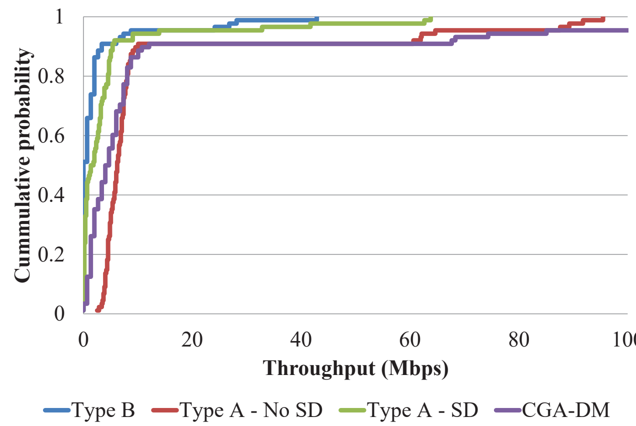


(b) RF leakage bandwidth: 40MHz

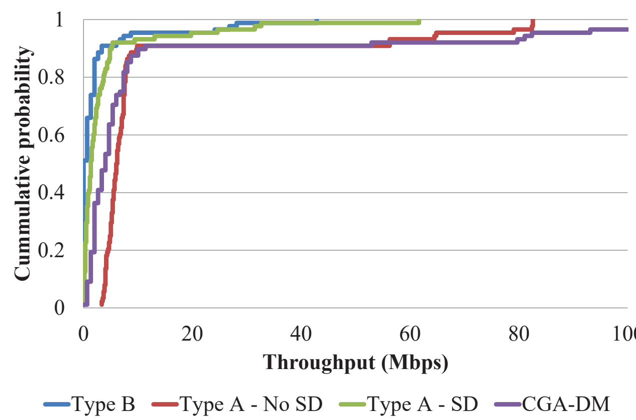


(c) RF leakage bandwidth: 60MHz

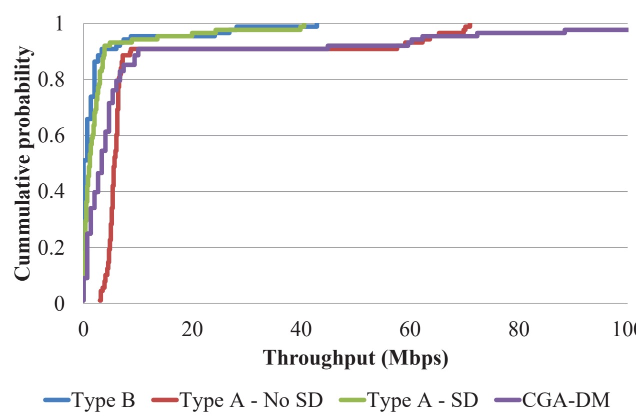
Figure 14. Wi-Fi node throughput with 4 carriers in a spectrum band in the indoor scenario (Wi-Fi's wide-band operation); The search depth is two.



(a) RF leakage bandwidth: 20MHz



(b) RF leakage bandwidth: 40MHz

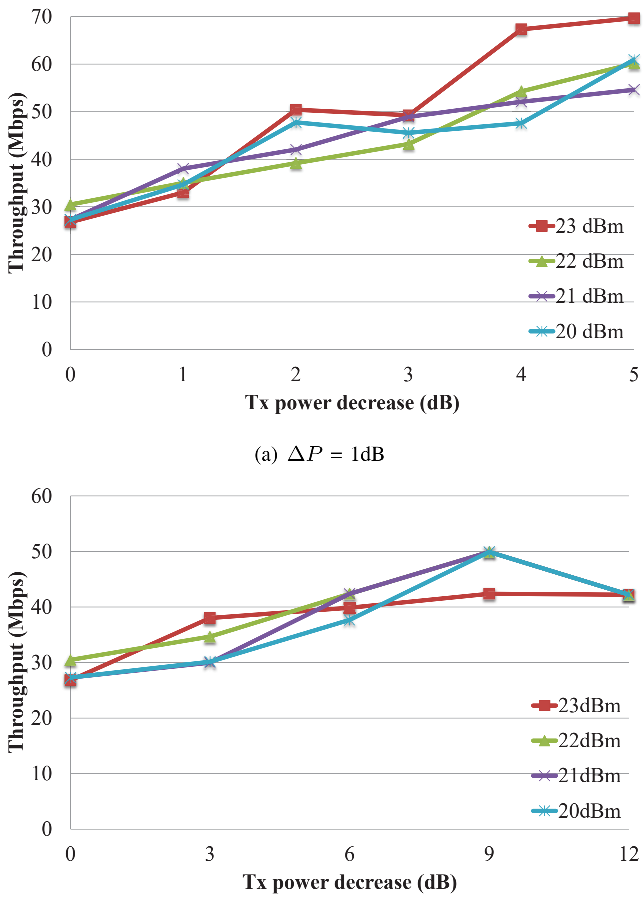


(c) RF leakage bandwidth: 60MHz

Figure 15. LAA node throughput with 4 carriers in a spectrum band in indoor scenario (Wi-Fi's wide-band operation); The search depth is two.

of transmit power decrease that is needed to reduce the RF leakage bandwidth by 20MHz. So, if the LAA eNB decreases its transmit power by $x\Delta P$ where x is a non-negative integer, the RF leakage bandwidth is decreased by $x\times$20MHz. In the simulation, the number of available carriers is eight and the transmit power of the LAA eNB is distributed evenly between carriers. The RF leakage bandwidth with no (zero) transmit power decrease is 100MHz.

Fig. 16 shows the impact of transmit power decrease on LAA system throughput when ΔP is varied from one to three dB. With ΔP = 1dB, the LAA system throughput gets better as the transmit power is reduced; the throughput increases from 30 to 60-70Mbps after transmit power decrease by 5dB. This is because the impact of RF leakage on throughput is higher than that of transmit power within the limited range of transmit power decrease; transmit power decrease by 5dB results in no RF leakage between all carriers and the resulting transmit power is still sufficient for serving UEs.



(a) ΔP = 1dB

(b) ΔP = 3dB

Figure 16. LAA downlink throughput (8 carriers) with varying transmit power and RF leakage bandwidth; The search depth of CGA is two.

However, with ΔP = 3dB in Fig. 16(c), the throughput increase of the LAA system for transmit power decrease gets smaller; the throughput increases up to 40-50Mbps only. This means that the expense of transmit power decrease for reducing RF leakage bandwidth is high compared to the benefit. Moreover, reducing transmit power does not always increase throughput, especially when the amount of transmit power decrease is too large, i.e., by 12dB; in this case, the throughput is decreased for the initial transmit power lower than 23dBm.

VI. Conclusion

In this paper, we proposed an enhanced multi-carrier LBT operation for LTE-LAA and associated algorithm for aggregation throughput improvement of the LAA system with better coexistence. To achieve this, we formulated the target problem as an optimization problem whose objective is the maximization of the aggregation capacity of the LAA system. Then, the problem solving algorithm was designed; the activities of incumbent systems (Wi-Fi) are measured in each carrier and power leakage-independent carrier groups are determined. The algorithm applies binary splitting of a given set of carriers recursively until a further gain is achievable or a given depth of binary splitting is not reached. In each group, eNB chooses a primary carrier such that the capacity of each group is maximized. Through extensive simulation, we demonstrated that our proposals enhance system throughput considerably over conventional ones while coexisting well with Wi-Fi systems. We also showed that the proposed algorithm achieves close to the solution of exhaustive search. Another investigation we made was on the impact of transmit power and RF leakage bandwidth; the relationship of the two parameters was shown important for multi-carrier LBT.

The following issues remain for future work. Resolving the RF power leakage to an adjacent group when guard-band carriers are used via secondary-carrier extension is needed. A coexistence study of CGA in the presence of Wi-Fi systems of the latest IEEE 802.11ax is another subject for future research.

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