Multi-Carrier LAA with Adaptive Energy Detection and Carrier Selection

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***Abstract*—Licensed-Assisted Access (LAA) is a promising technology to address the issues of ever-increasing traffic demands in cellular systems. However, the efficient coexistence of Wi-Fi and LAA in the same unlicensed spectrum raises many challenges. Most of the studies addressing this coexistence issue focus on a coexistent LAA and Wi-Fi network sharing a single carrier. In this paper, we investigate a coexistent network with multiple available carriers, which is the case for practical deployments. Specifically, we develop an efficient adaptive energy detection algorithm to avoid frequent collisions in coexistent Wi-Fi and LAA networks. moreover, a carrier selection algorithm, based on the LAA energy detection threshold, is proposed to further improve the coexistence performance. Simulation results validate the effectiveness of the proposed adaptive energy detection and carrier selection schemes.**

***Index Terms*—Licensed-assisted access, 802.11ac, multi-carrier listen-before-talk, adaptive energy detection, carrier selection**

I. Introduction

To alleviate the issue of scarce wireless spectrum and keep up with the ever growing traffic demands in cellular systems, the 3rd Generation Partnership Project (3GPP) standardization group has investigated and standardized Licensed-Assisted Access (LAA) in Long Term Evolution (LTE) Release 13 [2]. In particular, carriers in the unlicensed bands are used as secondary carrier frequencies which are anchored by licensed primary carrier frequencies within the LTE carrier aggregation framework. Recently, 3GPP Release 15 has itemized "new radio (NR) based unlicensed access" and "enhancements to LTE operation in unlicensed spectrum," where the evolution of LAA will be standardized to allow 5G to access the unlicensed spectrum [3]–[5].

Wi-Fi networks, which include IEEE 802.11a/n/ac, have had tremendous success operating in the 5 GHz unlicensed band; thus, one major focus of the LAA studies is to design access mechanisms for LTE to efficiently (and fairly) coexist with Wi-Fi to contend for access in the unlicensed band. In LTE Release 13, a Cat 4 Listen-Before-Talk (LBT) procedure is recommended for LAA to sense whether the carrier is idle or not before data transmissions. In parallel with the standardization effort, there have also been research activities within the academic community to study these coexistence issues. Based on the Cat 4 LBT, in [1], an adaptive energy detection algorithm is proposed to improve the coexistent performance of Wi-Fi and LAA networks by adjusting energy detection threshold to decrease the collision probability. In [6], user association and resource allocation are jointly optimized to improve the system throughput and fairness in coexistent Wi-Fi and LTE-U networks. In addition, a fair LBT scheme is proposed in [7], in which the total system throughput and fairness are jointly considered between LAA and Wi-Fi, to allocate appropriate idle periods to Wi-Fi.

To provide high-speed and low-latency communications, 802.11ac and LTE networks utilize channel bonding and carrier aggregation mechanisms, respectively, to aggregate multiple channels/carriers. For LAA systems, different options for multi-carrier LBT are proposed in [2] so that LAA can access multiple carriers effectively without adversely affecting the performance of the coexistent Wi-Fi systems. Among recent works, a coexistence solution based on carrier selection is proposed in [8], in which user (UE) measurements are used to optimize the network sum capacity. In [9], a new LBT mechanism is proposed to avoid the adverse impact of radio frequency (RF) leakage on multi-carrier operations for LAA. In [10], different carrier aggregation schemes are evaluated to show their effectiveness in improving throughput performance and end-user experience in a dense network with multiple carriers. Although these techniques improve the coexistence performance, they require additional feedback or significant modifications in the current multi-carrier LBT procedure.

The main goals of this paper are to investigate the performance of different multi-carrier LBT schemes and improve the performance of coexistent Wi-Fi and LAA networks. We first summarize two different options for multi-carrier LBT schemes. Then, we extend the adaptive energy detection algorithm proposed in [1] to the multi-carrier case. To further improve the coexistence performance, based on the adaptive energy detection algorithm, we propose a simple, but efficient, carrier-selection algorithm based on LAA energy detection (LAA-ED) thresholds. In particular, carriers with low energy detection thresholds may suffer from interference and, hence, are less likely to be aggregated. Simulation results validate the effectiveness of the proposed adaptive energy detection and carrier selection algorithms.

II. Multi-Carrier Transmissions for 802.11ac and LAA Networks

In this section, we discuss the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) and LBT operations at the Access Points (APs) and eNodeBs (eNBs), respectively, when there are multiple carriers available.

A. Multi-carrier access in 802.11ac

CSMA/CA is employed in IEEE 802.11 for Wi-Fi nodes, i.e., APs and Stations (STAs), to contend for access to the shared unlicensed medium. In the IEEE 802.11ac standard, channel bonding is employed for a node to switch transmission bandwidth dynamically on a frame-by-frame basis (i.e., 20 MHz, 40 MHz, 80 MHz, or 160 MHz). Also, *primary* and *secondary* channels[1] are introduced to facilitate transmissions over multiple channels. Particularly, channel bonding requires that: 1) a primary channel should always be included in each channel bandwidth; and 2) only adjacent channels in specific patterns can be combined to obtain a wider channel [11]. In addition, the entire CSMA procedure is only performed on the primary channel; on the associated secondary channel, only a quick Clear-Channel-Access (CCA) check, i.e., the duration of a point coordination function interframe space (PIFS), is performed before transmitting data.

B. Multi-carrier LBT operation for LAA

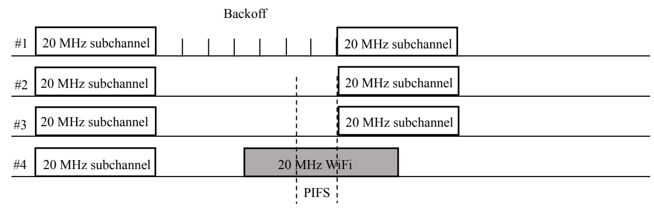
3GPP introduces the Cat 4 LBT procedure to facilitate the coexistence of LAA and Wi-Fi, as well as multiple LAA networks, in the same unlicensed spectrum [2]. The basic idea of Cat 4 LBT is similar to CSMA/CA: an LAA eNB is required to perform a CCA to check whether the carrier is idle or not before transmission [11]. To access multiple carriers in an LAA system, 3GPP proposes two main options:

- Option 1: Similar to Wi-Fi, only one full Cat 4 LBT procedure is completed on one selected carrier (primary carrier), and quick CCA checks (of duration PIFS) are performed on other carriers (secondary carriers) before data transmission.
- Option 2: Multiple Cat 4 LBT procedures are independently performed on different carriers, and the data transmissions over multiple carriers are aligned by introducing a self-deferral period.

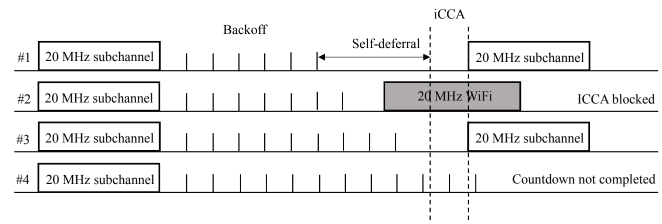
Fig. 1 presents examples of the two options with four candidate carriers, where each carrier has a bandwidth of 20 MHz. In Option 1, as shown in Fig. 1(a), the LAA eNB performs a full Cat 4 LBT procedure on the "primary" carrier (Carrier #1 in the example), and performs sensing for the duration of PIFS before transmitting data on all the "secondary" carriers. Different from the channel bonding approach adopted in a Wi-Fi system, LAA can aggregate any idle carriers[2], thus, LAA can transmit with a bandwidth of 60 MHz by aggregating

[1]To follow the terminology used by the IEEE 802.11 standard, "channel" is used here, which has the same meaning as "carrier" in the LTE standard.

[2]In a real LAA system, multiple candidate carriers could exist; the maximum number of carriers that can be aggregated depends on the system configurations and requirements.



(a) Multi-carrier LBT Option 1



(b) Multi-carrier LBT Option 2

Fig. 1: Two options for multi-carrier LBT in LAA systems: a single Cat 4 LBT procedure is performed on the "primary" carrier in Option 1, and Cat 4 LBT procedures are independently performed on all four carriers in Option 2.

Carrier #1, #2 and #3. In Option 2, as shown in Fig. 1(b), four LBT procedures are performed independently on all four carriers. Different carriers would finish their individual LBT procedures at different times. To synchronize transmissions across multiple carriers, a self-deferral period is added to the carrier that finishes its LBT procedure first. After the self-deferral period, the carriers who finish their Cat 4 LBT procedures will be selected for data transmission after a quick initial CAA (iCCA) check. In this example, Carrier #1 finishes its LBT procedure first. During the waiting time of the self-deferral period, Carrier #2 also finishes its LBT procedure but is unfortunately occupied by other Wi-Fi transmissions, and Carrier #4 is still in the back-off procedure. Thus, #1 and #3 are aggregated for data transmissions.

Between the two options, Option 1 is generally more aggressive and might be unfair to Wi-Fi, while Option 2 is an extension of the Cat 4 LBT for the single carrier case, and the performance depends on the self-deferral period. With a long self-deferral period, the idle carriers might be occupied by other systems; with a short self-deferral period, the system would only be able to transmit data on a few carriers, since the Cat 4 LBT procedures on other carriers might not have finished yet.

III. Multi-carrier LBT with Adaptive Energy Detection and Carrier Selection

In a coexistent network of Wi-Fi and LAA, due to the asymmetric detection thresholds adopted for APs and eNBs, frequent collisions may occur during data transmissions.

A. Review of Cat 4 LBT with Adaptive Energy Detection

To encourage simultaneous transmissions while reducing possible collisions, an extended Cat 4 LBT scheme is proposed in [1], which incorporates a distributed adaptive energy detection (AED) algorithm into the original Cat 4 LBT scheme to improve the coexistence performance of Wi-Fi and LAA. The basic idea of the distributed AED algorithm is that an eNB's LAA-ED threshold is decreased if this eNB encounters frequent collisions; otherwise, a high LAA-ED threshold is maintained to encourage concurrent transmissions. Note that, in a single-carrier network, a single unlicensed 20-MHz channel is assumed to be shared between LAA and Wi-Fi networks.

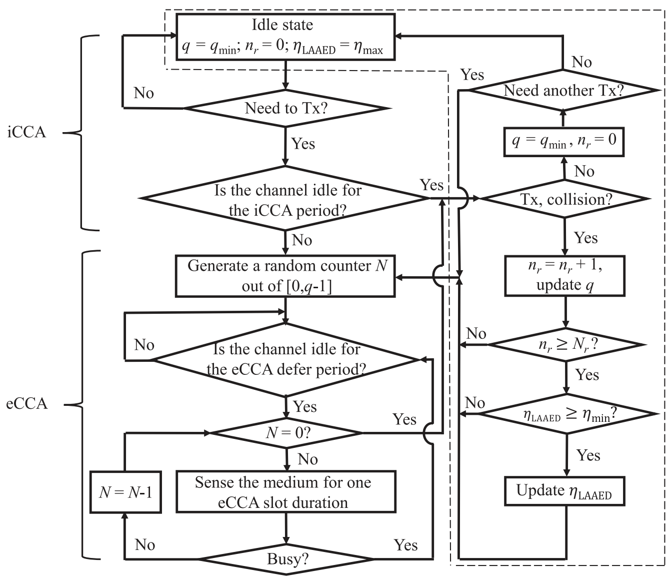


Fig. 2: The extended Cat 4 LBT with the AED algorithm, where the LAA-ED threshold is adaptively updated due to collisions [1].

The extended Cat 4 LBT with the AED algorithm is shown in Fig. 2, where $\eta_{\min}$ and $\eta_{\max}$ denote the predefined minimum and maximum LAA-ED thresholds, respectively. Variable n_r denotes the number of retransmissions for a specific packet, and is initialized to zero. Also, the contention window size q is set to its minimum value $q_{\min}$, and the LAA-ED threshold η_{LAAED} is initialized to $\eta_{\max}$. The AED algorithm can adaptively change the LAA-ED threshold per UE. Specifically, the updating rule is that, if a packet fails to be transmitted in N_r trials, η_{LAAED} is decremented by 1, i.e., $\eta_{\text{LAAED}} = \eta_{\text{LAAED}} - 1$. With the AED algorithm, an UE that is close to its associated eNB will have a higher LAA-ED threshold because the received signal power will still be strong enough compared to the interference from other ongoing transmissions. Then, eNBs refrain from transmissions by setting lower LAA-ED thresholds for the UEs who are far away from their associated eNBs. By having different LAA-ED thresholds for different UEs, the system can handle more concurrent transmissions without causing too many collisions. For further details, please refer to [1].

B. Multi-carrier Cat 4 LBT with the AED algorithm

In this subsection, Cat 4 LBT with AED, as described above, is extended to the case of multiple carriers. We also assume that each LAA eNB i can have a different threshold $\eta_{\text{LAAED}}(i, j)$ for its associated UE j.

Let $\mathcal{C}$ denote the set of available carriers in the coexistent LAA and Wi-Fi systems. We define $\mathcal{C}(i, j)$ to denote the candidate carriers for data transmission from eNB i to UE j, i.e., the carriers considered to be idle after performing the multi-carrier LBT procedure (either Option 1 or Option 2). Let $\mathcal{K}(i, j)$ denote the actual aggregated carriers for the data transmissions from eNB i to UE j. Since there might be a limit N on the maximum number of carriers that can aggregated for each transmission, let $|\mathcal{K}(i, j)| \leq N$, where $|\cdot|$ denotes the cardinality. We then have

$$\mathcal{K}(i, j) \subseteq \mathcal{C}(i, j) \subseteq \mathcal{C} \quad (1)$$

In addition, we define $\eta_{\text{LAAED}}(i, j, k)$ as the energy detection threshold from eNB i to UE j on carrier k, and $\eta_{\text{LAAED}}(i, j, k)$ is initialized to the maximum threshold $\eta_{\max}$ for $k \in \mathcal{C}(i, j)$. After performing multi-carrier LBT procedures, if collisions happen during data transmissions, we decrease $\eta_{\text{LAAED}}(i, j, k)$, $k \in \mathcal{K}(i, j)$, to avoid frequent collisions until either the packet is transmitted successfully, or $\eta_{\text{LAAED}}(i, j, k)$ reaches or falls below its minimum value ($\eta_{\min}$). Specifically, the updating rule for the LAA-ED threshold (η_{LAAED}) in Fig. 2 is

$$\eta_{\text{LAAED}}(i, j, k) = \eta_{\text{LAAED}}(i, j, k) - 1, \quad \text{for } k \in \mathcal{K}(i, j) \quad (2)$$

The updating rule for the AED algorithm is the same for both Option 1 and Option 2, i.e., even though Cat 4 LBT procedures are applied to one carrier (Option 1) or multiple carriers (Option 2), the LAA-ED thresholds are updated on all aggregated carriers if collisions occurred (leading to unsuccessful transmissions).

Here, we decrease the energy detection thresholds on all aggregated carriers k ($\forall k \in \mathcal{K}(i, j)$) after collisions for two reasons: 1) for an unsuccessful transmission over multiple carriers, we may have no information about which carrier suffers from severe interference; and 2) by decreasing the energy detection thresholds of all aggregated carriers rather than only specific carriers, the probability of aggregating multiple carriers is decreased, which could be beneficial to both LAA and Wi-Fi due to the power limitation in the unlicensed band. By aggregating fewer carriers, the LAA eNB can transmit with a relatively high power, which makes the LAA system more robust to interference in a dense network, and also gives Wi-Fi more transmission opportunities.

Note that, because different carriers may be aggregated during different transmissions, the LAA-ED thresholds of $\eta_{\text{LAAED}}(i, j, k)$ can be different from each other for $k \in \mathcal{C}(i, j)$. Also, if there is no more data to be transmitted from eNB i to UE j, the LAA eNBs will reset $\eta_{\text{LAAED}}(i, j, k)$ to $\eta_{\max}$ for all $k \in \mathcal{C}(i, j)$.

C. Multi-carrier Cat 4 LBT with carrier selection

With multiple carriers available, carrier selection can significantly improve the performance of coexistent Wi-Fi and LAA systems [8], in which carrier selection is fulfilled based on UE measurements. We propose a carrier selection algorithm based on the current LAA-ED thresholds of different carriers per UE, which requires no additional feedback from UEs.

To avoid potential collisions with Wi-Fi or other LAA transmissions, we follow two general rules in the carrier selection procedure:

1) Choose "clean" carriers to transmit data.
2) Choose carriers that are less likely to break the channel bonding patterns adopted in Wi-Fi.

For example, assume that we have four carriers: #1, #2, #3 and #4, and Wi-Fi's primary channel is #1. In this case, LAA would prefer to choose Carrier #3 or #4 rather than #2 or #1, which could be relatively "clean" and give Wi-Fi more opportunities to transmit with a higher bandwidth.

The key idea of the proposed carrier selection algorithm is that, for data transmissions from eNB i to UE j, eNB i will first aggregate the carriers with high LAA-ED thresholds. This is because a certain carrier k, shared by multiple systems, is more likely to have a low $\eta_{\text{LAAED}}(i, j, k)$ thresholds to avoid too many collisions according to the AED algorithm. Thus, aggregating carriers with high LAA-ED thresholds would make the LAA system to choose relatively "clean" carriers. In addition, we add another preference for the carrier aggregation in LAA systems: LAA eNBs follow the channel bonding patterns as adopted in the Wi-Fi system if there are multiple candidate carriers. With this preference, LAA can transmit with a large bandwidth as well as reduce the negative impact on the channel bonding scheme used by the Wi-Fi networks.

In summary, for Option 1, the "primary" carrier is predefined, and the aggregated "secondary" carriers are chosen to satisfy

$$\eta_{\text{LAAED}}(i, j, k) \geq \eta_{\text{LAAED}}(i, j, \bar{k}), \text{for } k \in \mathcal{K}(i, j), \quad \bar{k} \in \mathcal{C}(i, j) \backslash \mathcal{K}(i, j) \quad (3)$$

where $A \backslash B$ denotes the set of elements in set A but not in set B. For Option 2, there are no "primary" or "secondary" carriers, so all the aggregated carriers should satisfy Eq. (3). Moreover, for both Option 1 and Option 2, to fairly coexist with Wi-Fi, LAA's carrier aggregation scheme will try to follow the channel bonding approach in the Wi-Fi systems, if possible.

IV. Simulation Results

To evaluate the coexistence performance of Wi-Fi and LAA with adaptive energy detection and carrier selection, we adopt the indoor scenario specified by 3GPP [2]. Each operator (Operator A for 802.11ac, or Operator B for LAA) deploys four cells in a one-floor building. Each eNB/AP serves five UEs/STAs, and all UEs/STAs are randomly located within the coverage area of their associated eNBs/APs. The total transmit power of LAA eNBs, Wi-Fi APs, and STAs in the unlicensed spectrum is set to 23 dBm, 23 dBm, and 18 dBm, respectively. Traffic is modeled as an FTP download of a 0.5 MB file with a Poisson request rate of $\lambda = 2.5$. The self-deferral period of Option 2 is 10 slots (100 μs). LAA/Wi-Fi can aggregate/bond at most 4 carriers, and there are 8 unlicensed 20-MHz carriers in total to be shared by LAA and Wi-Fi networks. The energy detection thresholds scale up with increasing channel bandwidth due to the power limitation in the unlicensed 5-GHz band. Each simulation is executed for 500 seconds, and results are averaged over 50 runs. For the remaining simulation setting, please refer to [1].

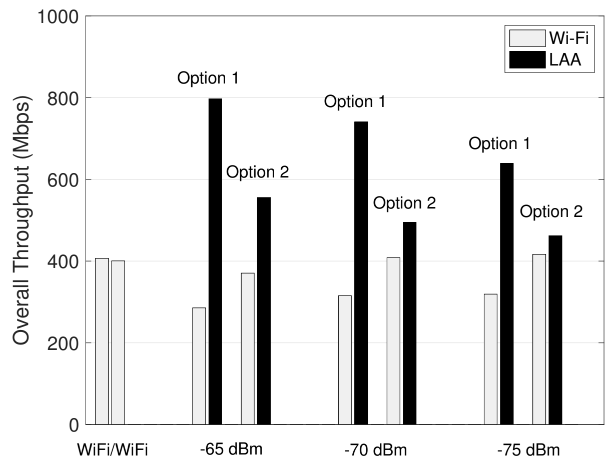


Fig. 3: Overall throughput performance of Wi-Fi and LAA systems with different LAA-ED thresholds for multi-carrier LBT Option 1 and Option 2.

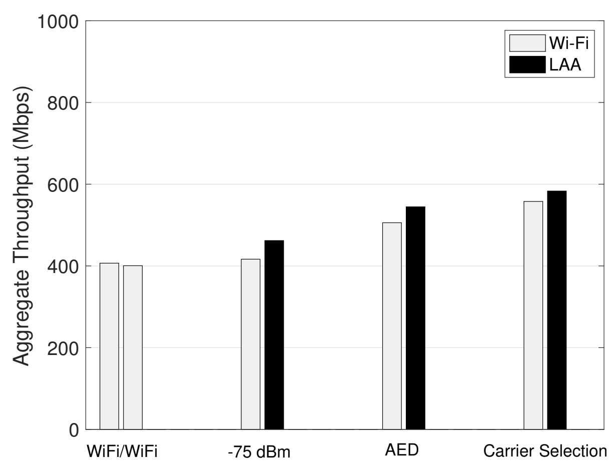


Fig. 4: Aggregate throughput performance of Wi-Fi and LAA for four cases: pure Wi-Fi, LAA with a fixed LAA-ED threshold of -75 dBm, LAA with adaptive energy detection, and LAA with adaptive energy detection and carrier selection.

In Fig. 3, the aggregate throughputs of the Wi-Fi and LAA networks are shown for different LAA-ED thresholds (-65 dB, -70 dB, and -75 dB), where all eNBs have the same LAA-ED threshold for all UEs. Here, after the multi-carrier LBT procedures, we assume that the actual aggregated carriers $\mathcal{K}(i, j)$ are randomly selected from the idle carriers $\mathcal{C}(i, j)$ for eNB i and UE j. For comparison purposes, the performance of a pure Wi-Fi network is also shown in Fig. 3, where both

Operator A and Operator B deploy Wi-Fi APs. Note that the throughput is measured by the number of successfully transmitted bits over the total transmission period, and the aggregate throughput is the sum of the individual throughputs of the eNBs/APs for one operator. It is observed that: 1) introducing an LAA operator can improve the overall throughput (the sum throughput of both Operator A and Operator B); 2) Wi-Fi systems may suffer from severe performance loss, especially for Option 1; 3) by setting a low LAA-ED threshold, LAA becomes less aggressive, which yields more transmission opportunities to Wi-Fi. In the following simulations, we focus on the simulation of multi-carrier LBT Option 2 since this option coexists better with Wi-Fi. Fig. 4 illustrates the aggregate throughput of the coexistent Wi-Fi and LAA network for four different cases. From left to right, 1) a pure Wi-Fi network that acts as our reference; 2) a Wi-Fi/LAA coexistent network, in which the LAA operator employs multi-carrier LBT Option 2, with a fixed LAA-ED threshold of -75 dBm and random carrier selection; 3) a Wi-Fi/LAA coexistent network, in which the LAA operator employs multi-carrier LBT Option 2 with the AED algorithm; and 4) a Wi-Fi/LAA coexistent network, in which the LAA operator employs multi-carrier LBT Option 2 with the AED algorithm and the proposed carrier selection algorithm. The sum throughputs of Operator A and Operator B are about 807 Mbps, 878 Mbps, 1050 Mbps and 1141 Mbps for the four cases, respectively. Particularly, for the last two cases, i.e., multi-carrier LBT with AED and multi-carrier LBT with AED and carrier selection, the aggregated throughput gains are about 20% and 30%, respectively, compared to the case of multi-carrier LBT with a fixed LAA-ED threshold. Moreover, it is observed that, by extending the AED algorithm in [1] to multi-carrier LBT and including carrier selection, not only does the system performance get further improved, but also can LAA coexist better with Wi-Fi in terms of fairness.

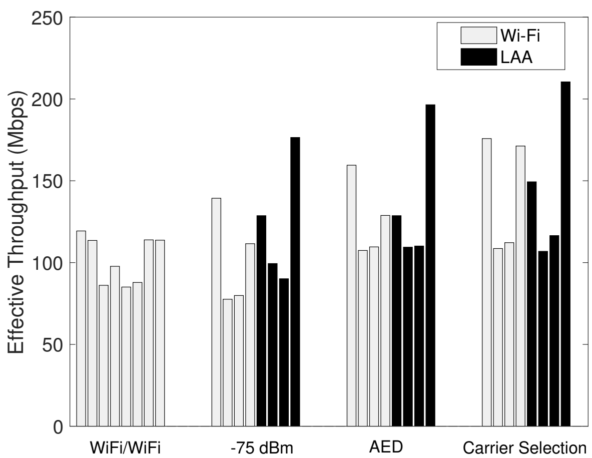


Fig. 5: Effective throughput performance for individual APs and eNBs for four cases: pure Wi-Fi, LAA with a fixed LAA-ED threshold of -75 dBm, LAA with AED, and LAA with AED and carrier selection.

In Fig. 5, the throughputs of individual APs and eNBs are shown for the previously described four cases. The light colored bars for each case represent the individual throughputs of WiFi #1, WiFi #3, WiFi #5, and WiFi #7. Similarly, the dark colored bars for each scheme denote the individual throughputs of LAA #2, LAA #4, LAA #6, and LAA #8, respectively. Due to the specific linear layout specified by 3GPP, the transmitters in the middle will be disadvantaged since they need to contend for access to the shared carrier with transmitters from both sides, while the transmitters at the edges only need to compete with the transmitters on one side.

V. Conclusions and Future Directions

In this paper, in a coexistent network of Wi-Fi and LAA with multiple available carriers, we studied and evaluated two different multi-carrier LBT schemes for LAA. We showed LAA with multi-carrier LBT Option 2 coexists better with Wi-Fi because it performs LBT procedures on all carriers and introduces a self-deferral period, which can give Wi-Fi more opportunities to transmit. Then, the previously proposed adaptive energy detection algorithm was extended to the multi-carrier case, to achieve a better coexistence performance. In addition, a new carrier selection algorithm was proposed, in which the carriers with high LAA energy detection thresholds are aggregated first; this was demonstrated to further improve the coexistence performance.

As future research directions, we plan to study Wi-Fi/LAA coexistence with IEEE 802.11ax, and deterministic backoff procedures with the distributed reservation proposed in [12].

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