Design and Evaluation of Licensed Assisted Access LTE in Unlicensed Spectrum

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Abstract

Licensed assisted access (LAA) is a new feature for 3GPP LTE systems to operate in the unlicensed spectrum. Under LAA, licensed carriers will be aggregated with unlicensed carriers in order to opportunistically enhance user throughput, while still offering seamless mobility and outdoor coverage. In order to coexist with other technologies in the unlicensed bands, several new functionalities for LAA LTE have been introduced, including long-term channel selection, short-term channel sensing based on listen-before-talk (LBT), and discontinuous transmission on a carrier with limited maximum transmission duration. In this article, we present research findings behind the designs for LAA systems. We discuss the impact of several parameters of the LAA LBT framework on the channel access opportunities of LAA, and its coexistence performance toward co-channel networks based on extensive system-level simulation results. The investigation covers both single-channel as well as multi-channel operation and coexistence scenarios. In addition to the finalized designs for downlink LAA operations in Release 13, our findings in this article further shed light on the uplink LAA operations to be introduced in Release 14.

Introduction

Using 5 GHz unlicensed spectrum in LTE networks is an attractive solution for operators to provide their LTE users high data rates and capacity in areas with concentrated traffic. Recently, Third Generation Partnership Project (3GPP) LTE Release 13 introduced a new feature, licensed assisted access (LAA), to utilize the 5 GHz unlicensed spectrum [1, 2]. Users can be served by at least one LTE carrier in licensed spectrum and one or more unlicensed band carriers at the same time under this LAA framework. The licensed band carrier will provide users with wide-area LTE services including mobility support and reliability, while the unlicensed band carrier can provide performance boost in terms of system capacity and user throughput in selected high traffic areas.

Unlike traditional cellular spectrum, the unlicensed spectrum is open to technologies and systems that fulfill the region-specific regulatory requirements. The IEEE 802.11 system, commonly referred to as Wi-Fi, is the most widely deployed technology using the 5 GHz unlicensed band. It is essential for LAA to coexist fairly with other unlicensed band technologies and particularly with Wi-Fi. This is the fundamental difference between LAA and LTE. In a licensed-carrier-based system such as LTE, there are no spectrum sharing mechanisms with other technologies needed. These are, however, crucial for operating in an unlicensed band [3]. For an early deployment in the unlicensed band, LTE can implement dynamic on/off transmission [4, 5]. However, this operates on a relatively slower scale without channel monitoring compared to Wi-Fi's Listen Before Talk (LBT) mechanism. When specifying LAA in LTE Release 13 for downlink-only operations, 3GPP included several tools to allow fair coexistence between LAA and other systems, and adapt more quickly to the situation on the medium. One important addition is the LBT mechanism, where an LAA device first measures the medium and verifies that the measured energy does not exceed a pre-defined threshold before transmission.

This article discusses the investigation leading to the 3GPP LAA LBT designs. In contrast to the existing 3GPP contributions (e.g., [6–11]), which provide details on specific aspects of LAA LBT, this article gives an overview of all aspects discussed in relation with LAA LBT and summarizes the different challenges faced to ensure fair coexistence between LAA and Wi-Fi. We explore the trade-offs in the different LBT parameters and procedures in terms of coexistence between LAA and Wi-Fi as well as LAA performance. We also discuss a robust fairness and coexistence evaluation framework between two systems that do not use the same technology and thus cannot have the same performance. To support the discussion, the article provides and analyzes performance results of two coexisting LAA and Wi-Fi networks using different settings of the LAA LBT mechanism and using a thoroughly described scenario and methodology. The uplink (UL) LAA operation is to be introduced in LTE Release 14. This article explains the performance limitations of a straightforward approach to include UL operations for LAA and proposes alternative LAA UL design options for optimizing the LAA UL performance while ensuring fair coexistence with other technologies.

The article is structured as follows. We first discuss the approach taken to evaluate the fair-

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ness of the coexistence between LAA and Wi-Fi. We also describe the evaluation scenario used throughout the article. We then discuss the LBT and energy detection threshold settings for single-channel operation in the first step, while we focus on LBT for multi-channel operation in the next step. UL LAA design options are presented before concluding.

Robust Coexistence Evaluation Framework

In contrast to a typical cellular network's performance evaluation in licensed spectrum, a different evaluation framework is required to verify the performance and coexistence between multiple networks deployed by different operators in the same unlicensed band. In the case where both coexisting operators deploy the same technology (e.g., both with LAA or with Wi-Fi), performance metrics evaluated for the coexisting operators using the same settings are expected to give the same outcomes. Thus, coexistence can be considered fair if the performance of both networks is similar.

In the other case, where the coexisting networks adopt different technologies, there is no reason for both networks to have identical performance. The coexistence evaluation methodology then consists of two steps. In the first step, performance metrics for two Wi-Fi networks are evaluated and recorded as a reference. In the second step, one of the Wi-Fi networks is replaced with an LAA network. A comparison of the performance metrics of the non-replaced Wi-Fi network between the two steps is used to evaluate the coexistence between LAA and Wi-Fi. When several LAA designs lead to fair coexistence between LAA and Wi-Fi, it appears natural to select the designs providing better LAA performance.

In the following, different key design features for DL and UL LAA are discussed and evaluated using the indoor scenario defined in 3GPP [1, 12]. The indoor scenario considers two operators running their networks in the same building without coordination. Each operator deploys four access points (APs) at randomized locations, which operate in 20 MHz frequency channels of the 5 GHz band. Twenty users per channel per operator are uniformly distributed in location, and each user can only associate with cells of its own network. The traffic is generated by repeated file downloads of 0.5 MB by users according to FTP model 3. Files for each user arrive according to a Poisson process the intensity (file arrivals per second) of which directly affects the level of offered traffic in the system.

To focus on the unlicensed band coexistence performance between Wi-Fi and LAA, the licensed carrier for LAA is not considered when serving LAA user equipments (UEs). Thus, both Wi-Fi and LAA transmissions are 20 MHz wide in the baseline single-channel case. The LBT algorithm adopted for 3GPP LAA is similar to the Wi-Fi procedure [1]. Except for the energy detection threshold, the basic LBT parameters such as the slot time duration, and maximum and minimum contention window sizes are exactly the same as in Wi-Fi (Table 1). In the following, we consider two key performance metrics: user data rate and served traffic per AP and operator. The user data rate is measured as the average file transfer rate, which is defined by the file size divided by total elapsed time to successfully transmit all its bits. The served traffic is calculated as the total number of bits that are successfully transmitted from all transmitters (both users and APs) of a network divided by simulation end time. Both the user data rate and system-wide served traffic depend on the offered traffic in the system, which in turn depends on the file arrival rate per user. By increasing the file arrival rate per user, a series of these performance metrics (user data rate and system-wide served traffic) is obtained and provided in the X and Y axes, respectively, in the figures of the following sections.

	Parameter	Value
Common parameters in Wi-Fi and LAA	Node transmit (Tx) power	18 dBm
	Antenna configuration	2Tx 2Rx, cross-polarized
	Fixed minimum sensing duration	34 μs
	LBT slot duration	9 μs
	Contention window range in DL	15–63 slots
	Contention window range in UL	15–1023 slots
	Maximum Tx duration	4 ms
	Maximum Tx duration	4 ms
	Scheduling for DL	Proportional fair
	Link adaptation	Feedback-based
Wi-Fi-specific parameters	MCS	802.11ac MCS table with 256-QAM
	Channel coding	LDPC
	Frame aggregation	Activated
	RTS/CTS	Deactivated
	CCA carrier sensing threshold	–82 dBm and preamble decoding
	CCA energy detection threshold	–62 dBm
	DL/UL duplexing	DL traffic only for the replaced Wi-Fi network, DL and UL for the non-replaced Wi-Fi network
	MCS	802.11ac MCS table with 256-QAM
LAA-specific parameters	MIMO loop scheme,	Open loop 2 × 2 MIMO
	MCS	QPSK, 16-QAM, 64-QAM, 256-QAM
	CCA ED threshold	–72 dBm unless otherwise stated

Table 1. Wi-Fi and LAA system evaluation parameters.

LBT and Energy Detection Threshold for LAA

LBT is an important functionality designed for LAA to achieve fair sharing of the unlicensed band with other systems operating on the same frequencies. The LBT mechanism enables a device to perform clear channel assessment (CCA) checks using energy detection (ED) before transmitting on the channel. Such a mechanism reduces inter-

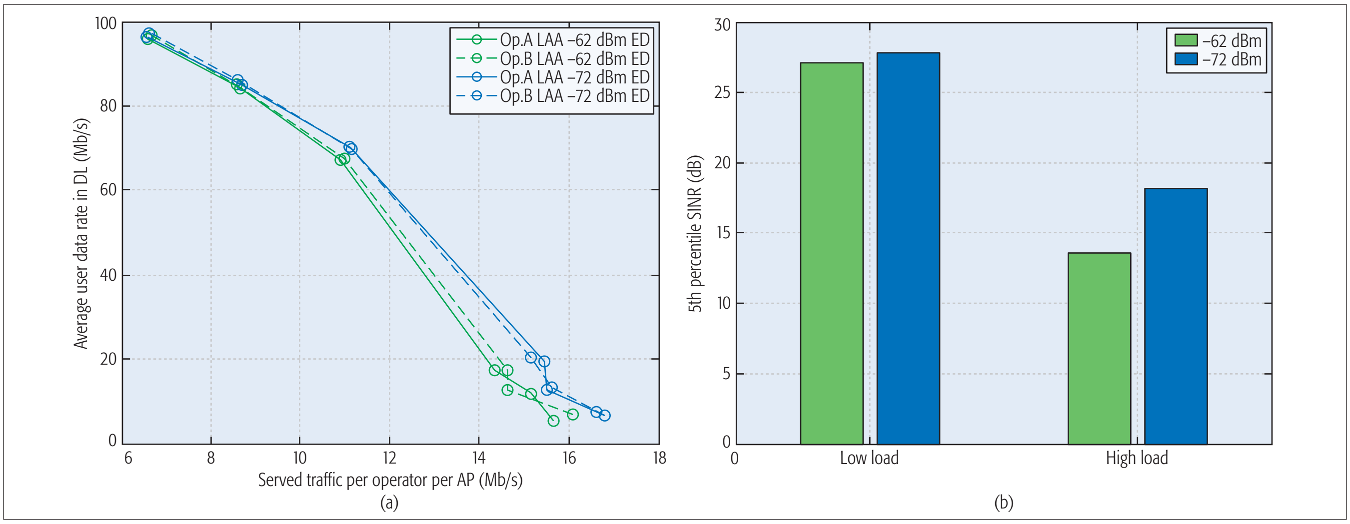

FIGURE 1. Coexistence between two LAA networks: a) downlink user data rate of each network over total served traffic per AP. Both operators have only DL traffic; b) 5th percentile SINR of operator A with two ED thresholds.

ference and increases probability of successful LAA transmissions when the energy in a CCA slot is measured to be below the ED threshold. Regulatory requirements in some regions (e.g.,, in Europe [13]) specify the maximum allowed ED threshold, thus setting a limit on the most aggressive behavior transmitters may have. Using ED thresholds gentler than regulatory requirements is possible and may be beneficial. In this section, we analyze different LBT designs in terms of the ED threshold and channel access delay.

LAA Energy Detection Threshold

In general, a higher ED threshold enables more spatial reuse, as contending nodes are less likely to refrain from transmitting. More simultaneous transmissions and higher interference can be expected in a given service area. This heightened interference can lead to a higher probability of erroneous packet reception if the system does not adapt to the channel conditions responsively. This trade-off between spatial reuse and interference levels makes the setting of optimal ED threshold dependent on the deployment specifics. Figure 1 shows the DL average user data rate vs. the served traffic for different traffic loads when two unsynchronized LAA networks, Op. A and Op. B, coexist in the indoor scenario. In general, the average user data rate drops when the served traffic increases due to higher interference, longer contention, and scheduling delays. At a given ED both LAA networks perform similarly despite asynchronous transmission between the two networks. Using a gentle ED threshold (e.g., −72 dBm), is shown to be more beneficial than −62 dBm at high load in this indoor scenario due to improved cell edge signal-to-interference-plus-noise ratio (SINR) (Fig. 1b). With a gentler ED threshold more nodes will refrain from transmitting, which decreases the overall interference in the building.

Unlike LAA LBT, which uses only a single threshold regardless of the neighboring network type, Wi-Fi uses a dual threshold approach. A Wi-Fi node backs off to another Wi-Fi node when the preamble is received at a received energy level of −82 dBm or higher, but backs off to any other non-Wi-Fi node only when the received energy exceeds a much higher threshold of −62 dBm. The behavior of Wi-Fi nodes is thus intrinsically aggressive toward any other technology operating on the same frequency. This unbalanced situation makes the design of LBT and the selection of a suitable ED threshold for LAA challenging.

The impact of different LAA ED thresholds on Wi-Fi-LAA coexistence performance is presented in Fig. 2a. The reference performance of two coexisting Wi-Fi networks is also included. When one of the networks is then replaced with LAA, the performance of the non-replaced Wi-Fi network improves with any of the LAA ED threshold settings. The performance of both networks is further improved if they both use LAA, as seen when comparing Fig. 1 and Fig. 2a. LAA indeed inherits LTE's more robust interference mitigation, error correction, and retransmission schemes. This results in greater efficiency in serving the traffic, thus providing more opportunities for coexisting systems to access the medium. However, the different ED thresholds have significant impact on the LAA performance (Fig. 2a). Having an ED threshold that is too low substantially reduces LAA channel access probability at medium and high loads. A higher LAA ED threshold leads to improved LAA performance, while the Wi-Fi performance remains higher than the reference case. This issue is caused by Wi-Fi's aggressive behavior against other technologies, as discussed above. To split fair channel access with Wi-Fi, LAA should use an ED threshold similar to that employed by Wi-Fi or adapt an ED threshold according to the scenario characteristics.

Readers interested in outdoor scenarios can find comprehensive results in [1, 6].

Freeze-Period-Based LBT

In the above investigation, we assumed that the LAA transmitters continuously sense the channel and react to the channel conditions. The LTE Release 13 specifications give the possibility of freezing the backoff counter of the LAA LBT procedure. An LAA transmitter can voluntarily "freeze" updating the backoff counter for a period of time. This freeze period (FP) is an additional tool to improve LAA coexistence capability with other

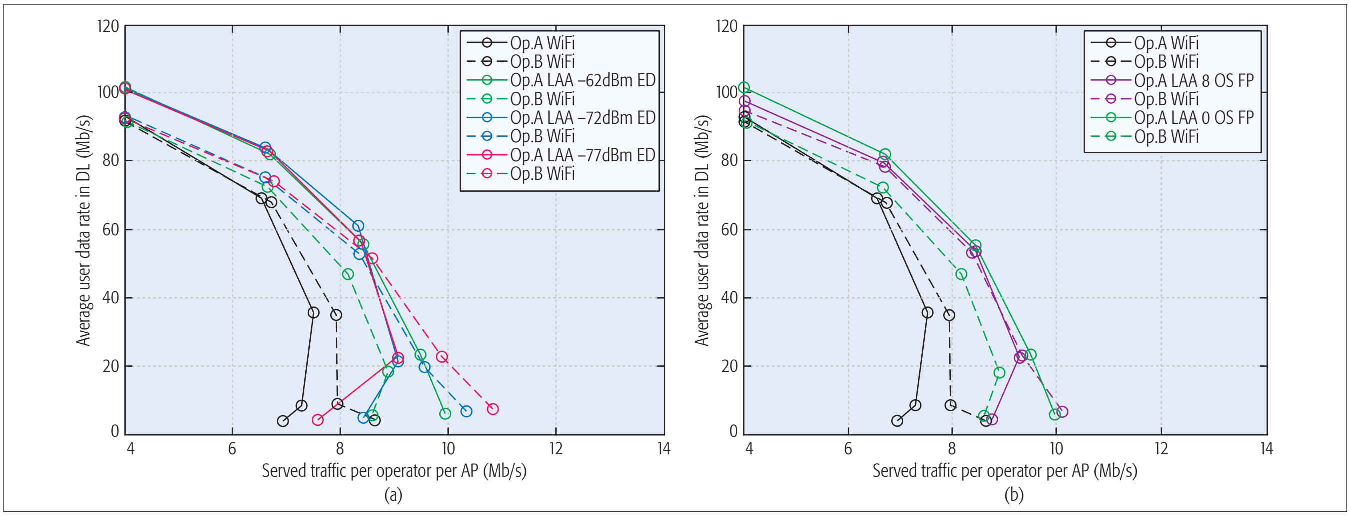

FIGURE 2. Coexistence between an LAA and a Wi-Fi network in a single-channel scenario. The non-replaced WiFi network, Op. B, has DL and UL traffic, while the replaced network, Op. A, has DL only traffic: a) average user rate when different ED thresholds are used in LAA but with 0 OS freeze period; b) the impact of different size of FP when using –62dBm ED threshold.

systems, as it increases the time in which other systems may access the channel and lowers the channel access opportunity of LAA systems. For instance, an LAA node may decide to freeze its backoff counter in the last 8 orthogonal frequency-division multiplexing (OFDM) symbols (OSs) of a 1 ms LAA subframe. During that time, the LAA node does not contend for the channel. This LBT scheme is referred to as 8 OS FP in the following.

Figure 2b compares two LAA LBT schemes: LBT with continuous sensing (i.e. 0 OS FP) and LBT with 8 OS FP when LAA uses –62 dBm as the LBT threshold. Here, we assume that the non-replaced Wi-Fi has both DL and UL traffic with 80/20 percentage split, whereas the replaced Wi-Fi or LAA network has only DL traffic in the unlicensed band carrier. The gentle LAA LBT with 8 OS FP leads to user throughput improvement for the neighboring Wi-Fi network compared to 0 OS FP LAA LBT. However, at high load, the use of a longer FP disadvantages LAA as it reduces channel access opportunities for LAA too much. This leads to less served traffic in the LAA network and more served traffic in the Wi-Fi network in the case of 8 OS FP. This indicates the need for an adaptive LAA LBT scheme that varies the length of the FP according to the load situation in the system.

LBT FOR MULTICARRIER LAA

In practice, several unlicensed carriers can be aggregated to serve an LAA UE. In this section we discuss several schemes to perform LBT in case of multicarrier transmissions. In IEEE 802.11ac, a hierarchical channel bonding scheme is followed. The transmission bandwidth of a Wi-Fi node could be 20 MHz (i.e., single channel), 40 MHz, 80 MHz, 160 MHz, or non-contiguous 80+80 MHz. One of the 20 MHz channels is chosen as the predefined primary 20 MHz channel, and only contiguous channels are bonded. Hence, this imposes constraints and dependencies between the primary channels and other secondary channels. Transmission on secondary channels is not performed if the primary channel is not idle. Full-fledged random back-off is done on the primary channel, and, shortly before the back-off of the primary channel is finished, a quick CCA check for a priority interframe space (PIFS) duration (25 μs) on the secondary channels is performed to determine if the additional secondary channels are available for transmission.

Several approaches for LAA DL multi-channel LBT have been considered to support LAA transmission bandwidth wider than 20 MHz.

Multi-channel LBT with channel bundling restriction (CBR): This first approach follows the same hierarchical channel bonding rules as Wi-Fi.

Independent multi-channel LBT (IML): This approach is a straightforward extension of the LAA single-channel LBT scheme. In contrast to the CBR scheme, IML does not include any hierarchy between carriers. A node performs independent full-fledged random backoff on each of the 20 MHz channels. Simultaneous transmission happens on the one or multiple carriers that finish random backoff first. At that point, the carriers that did not finish their random backoff will self-defer and resume the count down at a later time (i.e., when the ongoing transmission finishes). Due to hardware limitation, self-deferring is required since sensing cannot happen on carriers close to another transmitting carrier.

Dynamic multi-channel LBT (DML): This approach aims at combining the previous approaches [7, 8]. As a first step, a node starts independent full-fledged random backoff on all the channels, similar to IML. One periodically or randomly selected carrier needs to finish the full-fledged random backoff. As a second step, to determine if any additional channels are available for transmission, the other channels are checked to see if they were idle during the last 25 μs before the intended transmission. The second step is similar to how Wi-Fi examines secondary channels. Nevertheless, unlike Wi-Fi, the carrier aggregation framework allows transmission on non-contiguous channels, which makes it possible to transmit on any combination of the carriers (i.e., any 20 MHz, 40 MHz, 60 MHz, or 80 MHz).

System performance results with four 20 MHz channels are presented in Fig. 3a. As observed, the LAA-Wi-Fi scenario can serve higher traffic

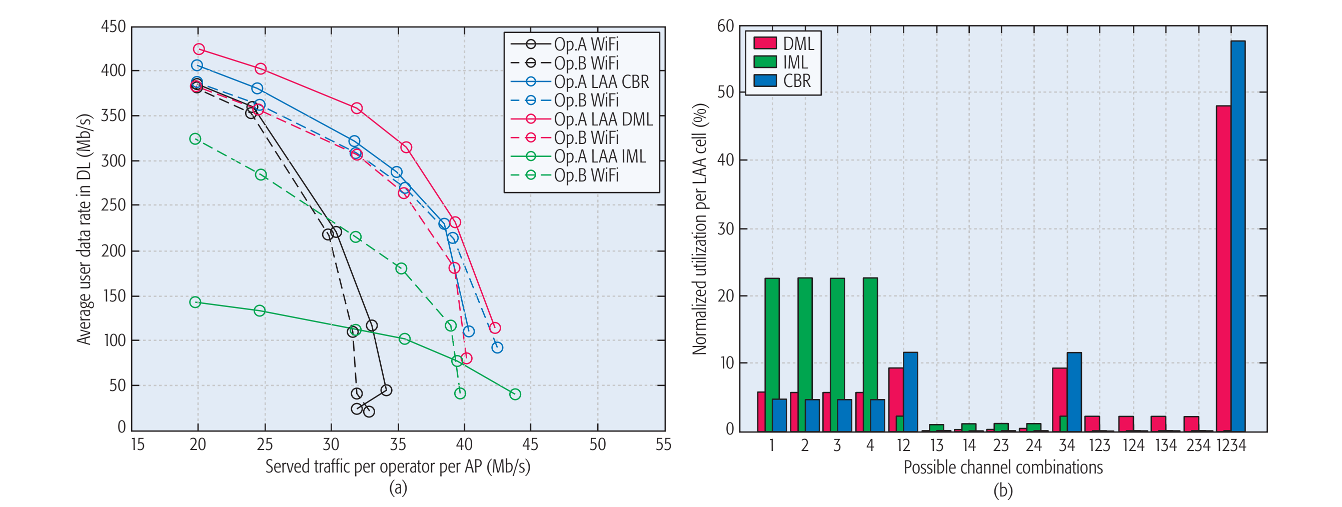

FIGURE 3. Coexistence between an LAA and a Wi-Fi network in a multi-channel scenario: a) average user throughput for different LBT multi-channel LBT; b) the normalized channel utilization of each multi-channel LBT for the replaced network (LAA) at medium load (50 percent buffer occupancy)

load compared to the reference Wi-Fi–Wi-Fi scenario. Wi-Fi must verify that the primary channel is free before attempting to transmit on any of the channels. This can result in frequent wasted opportunities on the secondary channels, which also induces higher latency.

From a coexistence point of view, both the CBR and DML algorithms perform well. Even though both multi-channel LBT schemes follow the CCA principles used in Wi-Fi, the performance of both networks is boosted when one of the networks is replaced by an LAA network. Nevertheless, LAA DML can be considered as the scheme that enables LAA with flexibility and agility for channel access, resulting in better LAA performance than when using CBR.

Figure 3b shows the normalized channel combination utilization used at medium load (50 percent buffer occupancy) for the replaced network. Denoting the four available channels by 1, 2, 3, and 4, Fig. 3b lists the probability that one combination (e.g., "13" for channel 1 together with channel 3) is used for transmission. Overall, DML and CBR enable higher probabilities of transmitting over multiple channels. However, due to the channel bonding restrictions, the channel utilization figures with CBR show that some combinations are never used (e.g., 13, 134). Even if three channels are found to be free, CBR needs to fall back to transmit on two contiguous channels only. Since the performance of an LAA network using DML is better than CBR at all load points, flexibility in the channel access is an important factor to adapt the utilized channels based on the given interference situation and to minimize wasted transmission opportunities.

The IML scheme performs substantially worse than the other two LAA solutions due to lack of coordination between the carriers of the LAA node. The eNB will effectively transmit on individual channels and seldom on multiple carriers due to the misalignment between the independent backoff counters and the self-defer problem. As expected, Fig. 3b shows that LAA nodes transmit using only one channel almost 80 percent of the time. LAA can end up utilizing the primary channel of neighboring Wi-Fi and thereby blocking Wi-Fi transmission on any carrier. In such cases, both LAA and Wi-Fi waste the opportunity to transmit on the secondary channels. Note that optimizations of IML are possible to increase the likelihood of transmission alignment among multiple carriers as discussed in [9, 10].

KEY ASPECTS OF LAA UPLINK DESIGN

Support for UL transmissions using LAA is currently under investigation and will be introduced in LTE Release 14. In contrast to Wi-Fi, which uses contention-based UL transmissions, LTE UL transmissions are scheduled by the eNB. While Wi-Fi UEs can contend for the medium as soon as UL data is in their buffer, LAA UEs must receive a UL grant from their serving eNB before performing their transmissions. Non-scheduled systems thus have a clear advantage at low load, when few UEs have data at the same time. However, when the traffic load increases, non-scheduled UL is not an efficient option, as many UEs often contend simultaneously for the medium and collide with each other. This leads to higher deferral time and higher collision probability than a scheduled system where the number of contending UEs is controlled. But scheduled systems also have drawbacks. In the legacy LTE grant procedure, a specific UL subframe is scheduled by a dedicated grant that is sent exactly 4 ms in advance. If the LAA UE is not able to access the medium in the scheduled subframe due to unsuccessful LBT, the scheduled UL transmission is simply aborted. It cannot be postponed, and the scheduling procedure for UL has to start over. This has negative consequences on user performance, as analyzed below. To counter this, the legacy grant procedure should be modified to allow more flexible subframe assignments. As seen in the previous sections, a well functioning LAA is beneficial to coexisting networks as it leaves more idle time for other systems. It is thus in the interest of achieving fair coexistence that LAA UL is designed efficiently.

Two possibilities exist to send the UL grant for an LAA transmission. In one case, cross-carrier scheduling can be applied where the grant for the LAA UL transmission occurs on the licensed

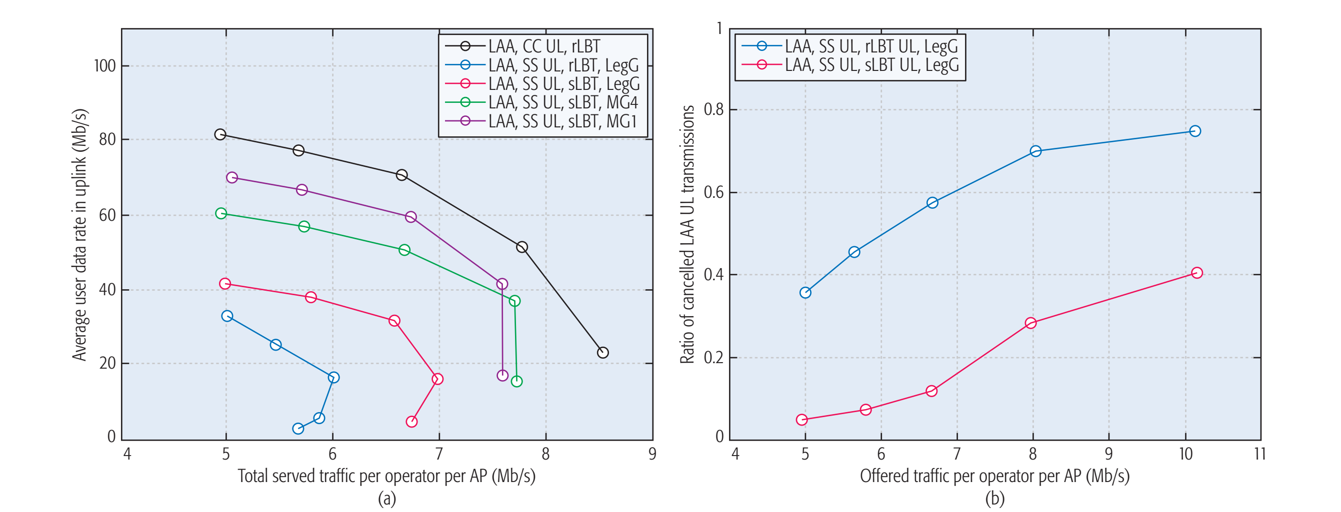

FIGURE 4. Uplink performance of the LAA operator, Op. A, when coexisting with a Wi-Fi network: a) average user throughput for different LAA UL designs; b) the ratio of aborted LAA UL transmissions.

carrier. Although attractive, this solution is limited by the control channel capacity of the licensed carrier, which may restrict the number of unlicensed channels that can be aggregated at the same time. A more scalable solution for LAA is self-scheduling, where the UL grant of an LAA transmission is sent by the eNB in the same unlicensed channel directly.

Figure 4a shows the performance of LAA UL in terms of user throughput in the unlicensed band for different variants of the UL LBT and UL grant transmission in a scenario where Wi-Fi and LAA networks coexist in one unlicensed channel, and 50 percent of the traffic in both networks is UL. The UL performance of LAA with self-scheduling and regular UL LBT (the line with "LAA, SS UL, rLBT, LegG") is much lower than the one with cross-carrier scheduling (the line "LAA, CC UL, rLBT"). With self-scheduling, two LBT procedures must succeed for an LAA UE to perform the scheduled transmission in the unlicensed channel: one LBT for the UL grant transmission by the eNB and the second one for data transmission by the UE. This is a disadvantage for LAA when competing with non-scheduled systems in the same channel. Figure 4b shows that a shorter sensing duration at the LAA UE (the line "LAA, SS UL, sLBT, LegG") significantly enhances the probability that a scheduled UL transmission is performed successfully. This improves the UL throughput, especially at medium to high load. The throughput at low load, however, remains limited by the signaling overhead of the legacy LTE grant. Using a DL subframe to send the grant for each scheduled UL data subframe leads to a 50 percent signaling overhead if there is no DL data with which to multiplex the UL grant (which is frequently the case at low load) [11]. This highlights the need for an alternative grant design to multiplex several UL grants in the same DL subframe and reduce the signaling overhead. By doing so, the UL performance is further improved as visible in the line "LAA, SS UL, sLBT, MG4" in Fig. 4a. But the legacy grant delay of 4 ms creates idle time between the subframe containing the grants and the first scheduled UL subframe. To further improve the UL performance, a reduced grant delay (e.g., of 1 ms) could be considered additionally (the line "LAA, SS UL, sLBT, MG1"). With both improvements, the performance of the Wi-Fi network coexisting with LAA improves compared to the initial situation of two coexisting Wi-Fi networks, as shown in Fig. 5.

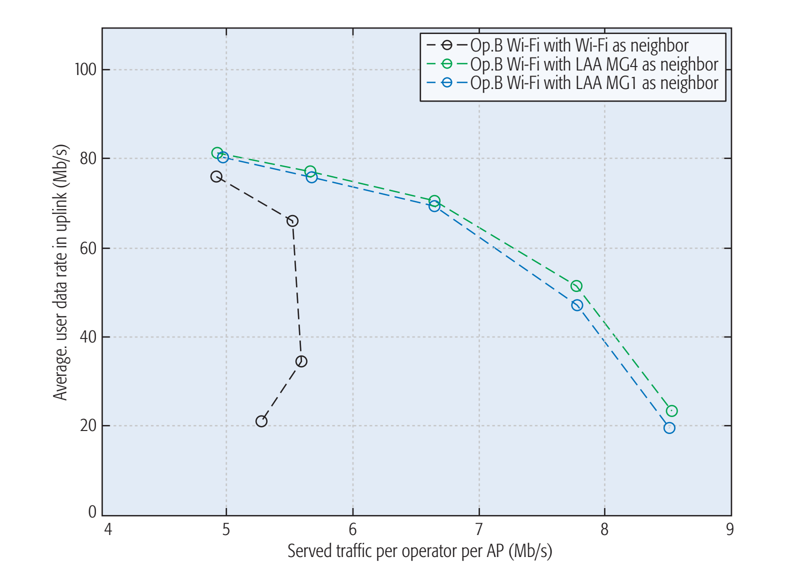

FIGURE 5. Uplink Wi-Fi performance when coexisting with networks of different technologies.

CONCLUSIONS

In this article we discuss key design aspects of LAA that directly influence the performance of LAA and its spectrum sharing capabilities with coexisting networks. Detailed system-level simulation results are provided to give insight on the performance impact of these aspects.

Within the generic LAA LBT framework defined in LTE Release 13, the energy detection threshold and freeze period of the LAA LBT procedure can be tuned to influence the channel access opportunities of LAA and its gentleness toward coexisting networks. Results highlight the importance of adapting these LBT parameters to

Future research could investigate further aspects of LAA UL, such as UL LBT optimization or the trade-off between scheduled and unscheduled LAA UL.

the scenario and load situation. The article further introduces possible extensions of the LBT procedure to support simultaneous LAA transmission over multiple unlicensed channels. An LBT procedure that includes some of the 802.11ac channel bonding rules but without the primary carrier restriction was found to be particularly beneficial in terms of LAA performance while ensuring fair spectrum sharing with other networks. Finally, the article gives insights about the uplink LAA challenges and desirable design for later LTE releases to ensure efficient LAA UL operation and fair coexistence with other networks. Future research could investigate further aspects of LAA UL, such as UL LBT optimization or the trade-off between scheduled and unscheduled LAA UL.

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