System Architecture and Coexistence Evaluation of Licensed-Assisted Access LTE with IEEE 802.11

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***Abstract*—Licensed-assisted access (LAA) is a new operation mode of Long-Term Evolution (LTE) in the unlicensed spectrum currently under study in the 3GPP standardization forum. In order to coexist with Wi-Fi, some of the new functionalities required of LAA LTE include a mechanism for clear channel assessment based on listen-before-talk (LBT), discontinuous transmission on a carrier with limited maximum transmission duration, and dynamic frequency selection (DFS) for radar avoidance in certain frequency bands. This paper presents a detailed overview of the impact of unlicensed spectrum operation on the LTE physical layer architecture, such as downlink physical channel design, scheduling, and radio resource management. System-level simulation results are then presented for indoor and outdoor scenarios, and show that fair coexistence between LAA and Wi-Fi can be achieved and that deployment of LAA can provide a boost in Wi-Fi performance.**

Keywords—Licensed-assisted access; LTE-Wi-Fi coexistence; listen-before-talk; carrier aggregation.

I. INTRODUCTION

The rapid uptake of Third-Generation Partnership Project (3GPP) Long-Term Evolution (LTE) in different regions of the world shows that both demand for wireless broadband data is increasing, and that LTE is an extremely successful platform to meet that demand. Existing and new spectrum licensed for use by IMT technologies will remain fundamental for providing seamless wide-area coverage, achieving the highest spectral efficiency, and ensuring the highest reliability of cellular networks. To meet ever increasing data traffic demand (e.g., video streaming) from users and, in particular, in concentrated high traffic buildings or hot spots, more mobile broadband bandwidth will be needed. Given the large amount of spectrum available in the unlicensed bands around the globe, unlicensed spectrum is more and more considered by cellular operators as a complementary tool to augment their service offering. As part of this evolution, a new initiative of LTE Release 13 is the on-going study on licensed-assisted access (LAA) operation in the unlicensed spectrum [1]. Based on the principle of carrier aggregation, LAA Secondary Cells (SCells) carry data transmissions in the unlicensed spectrum with assistance from a primary cell (PCell) in the licensed spectrum. The PCell retains the exchange of essential control messages and also provides always-available robust spectrum for real-time or high-value traffic. It enables operators to leverage the existing or planned universal seamless coverage in the LTE network with additional bandwidth and capacity. The 3GPP study prioritizes DL-only operation as the most relevant initial use case.

The usage of LTE in unlicensed spectrum creates numerous challenges since LTE physical channels have largely been designed on the basis of uninterrupted operation on licensed carriers (though Rel-12 LTE has added a new ON/OFF operations mode of SCells in the licensed bands). In addition, different geographical regions have distinct regulatory requirements for transmission in the unlicensed spectrum, e.g., [2]. Therefore for the 3GPP SI, it has been agreed to target a single global framework for LAA with functionalities to meet regulatory requirements in different regions and bands. Furthermore, LAA design should provide sufficient configurability to enable efficient operation in different geographical regions. A key objective of the LAA study item is that the LAA design should target a fairness coexistence mechanism with existing Wi-Fi networks so as to not impact Wi-Fi services more than another Wi-Fi network on the same carrier would, with respect to throughput and latency. The LAA design should further target fair coexistence among LAA networks deployed by different operators so that the LAA networks can achieve comparable performance.

Some of the new functionalities required of LAA from a coexistence perspective include a mechanism for clear channel assessment based on listen-before-talk (LBT), discontinuous transmission (DTX) on a carrier with limited maximum transmission duration, and dynamic frequency selection (DFS) for radar avoidance in certain bands. The DTX and LBT functionalities will have a major impact on various aspects of LTE ranging from downlink physical channel design, channel state information (CSI) estimation and reporting, hybrid ARQ (HARQ) operation, to radio resource management (RRM). The coexistence of LBT-based LTE and Wi-Fi has not been evaluated in detail in prior work such as [3]–[6], which have featured simplified models without LBT schemes.

This paper presents an overview of the impact of unlicensed spectrum operation on the LTE physical layer. A candidate LAA system architecture for downlink operation is proposed and described in detail, covering aspects such as carrier selection, DFS, LBT, physical channel design, and RRM. An enhanced LBT procedure is proposed for improving coexistence of LAA and Wi-Fi. Comprehensive system-level

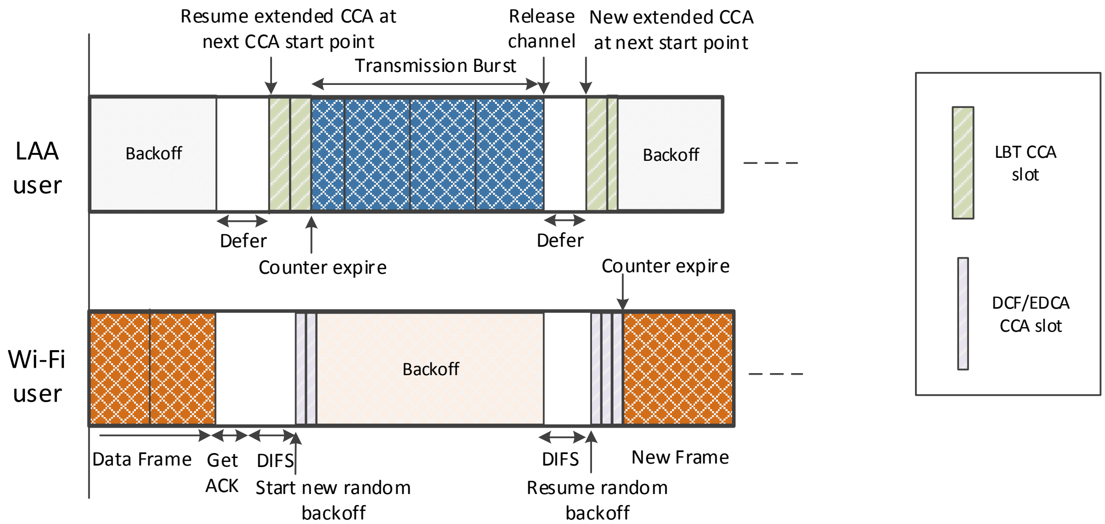

Fig. 1: General LBT principle with backoff defer period for LAA-Wi-Fi coexistence.

simulation results based on 3GPP evaluation assumptions are then presented to show that fair coexistence between LAA LTE and Wi-Fi can be achieved in both indoor and outdoor scenarios.

II. LAA System Architecture

A. Carrier Selection, DFS, and LBT

1) Carrier Selection: In Japan, Europe, and the US, between 455 MHz to 555 MHz of unlicensed spectrum is currently available for use in the 5 GHz band. Most regulations put limits on transmission powers in the unlicensed bands. For instance, for the lower 5 GHz band, the maximum transmission power in Europe is 23 dBm EIRP. As a result of the transmission power limits, LAA will generally be more suited for small cell deployments. Careful carrier selection is the first step for LAA nodes to achieve good co-existence with other unlicensed spectrum deployments. The objective of carrier selection is to select one or more 20 MHz channels for operation that would receive least interference for the node itself and, hence, would cause least interference to existing nodes. Therefore, carrier selection can be performed periodically in a semi-static manner since average interference levels may change in the long term due to varying numbers of neighboring nodes and traffic loads. These carriers are then configured and activated as SCells for the LAA user equipments (UEs). However, carrier selection can be implemented autonomously without any specification impact by an LAA eNB by computing average received interference power estimates on candidate carriers.

2) Dynamic frequency selection: DFS is a regulatory requirement for certain frequency bands in various regions, e.g., to detect interference from radar systems and to avoid co-channel operation with these systems by selecting a different carrier on a relatively slow time scale. The corresponding time scales for DFS are in the order of seconds and can therefore be considered to be at an even slower time scale than carrier selection. It has been agreed in 3GPP that this functionality is an implementation issue and will also not have an impact on the LTE specifications [1].

3) Listen-Before-Talk: The LBT procedure is defined as a mechanism by which an equipment applies a clear channel assessment (CCA) check prior to transmitting on the channel. It is therefore the counterpart of the distributed coordination function (DCF) and Enhanced distributed channel access (EDCA) MAC protocols in Wi-Fi. The CCA utilizes at least energy detection to determine the presence or absence of other signals on a channel in order to determine if a channel is occupied or clear, respectively. Japanese regulation and one of the harmonized standard cited by European regulation currently require the usage of LBT in the 5 GHz unlicensed bands. Apart from regulatory requirements, carrier sensing via LBT can be beneficial to sharing the unlicensed spectrum without co-channel deployments. Hence, it is considered to be a candidate feature for fair and friendly operation in the unlicensed spectrum under a single global framework.

An example of a generic LBT procedure is a load-based LBT protocol which can perform channel sensing with dynamic timing [2]. Specifically, in this LBT procedure an initial CCA of at least 20 μs is performed prior to a new transmission. If the equipment finds the channel to be clear, it may transmit immediately. On the other hand, if the medium is sensed to be already occupied, the transmission is deferred and an extended CCA (ECCA) is performed until the channel is deemed to be idle. In an ECCA check, the operating channel is observed for the duration of a random factor N multiplied by the CCA observation time. N defines the number of clear idle slots that need to be observed before initiation of the transmission. The value of N is randomly selected as $N \in [1,q]$ every time an extended CCA is required and the value stored in a counter. The value of q is selected by the manufacturer in the range of [4, 32]. The counter is decremented every time a CCA slot is deemed to be unoccupied. When the counter reaches zero, the equipment may transmit.

The load-based LBT procedure is similar to the physical carrier sensing in Wi-Fi, albeit with two major differences: no

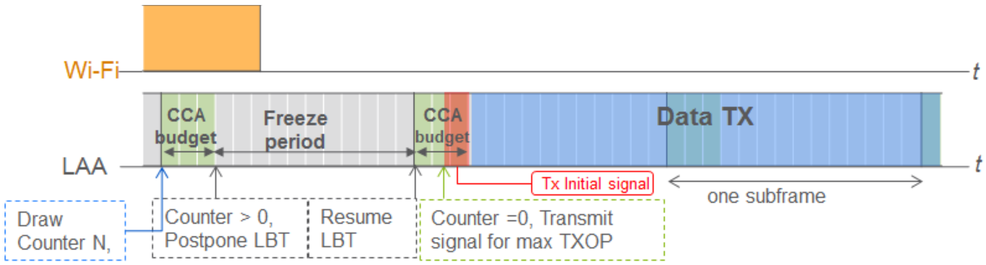

Fig. 2: Proposed LBT procedure with fixed CCA window at subframe boundaries and freeze periods where backoff and CCAs are suspended.

defer periods, and no exponential increase in the backoff contention window. Under the DCF, a Wi-Fi device defers the resumption of counting down the random backoff counter until the just-vacated channel is idle for 34 µs. The load-based LBT procedure lacks such a deferring mechanism after the channel is occupied. Therefore, directly reusing the load-based LBT procedure with the minimum required CCA durations may lead to undesirable coexistence behavior due to the lack of defer periods. For instance, the initial LAA CCA which substantially overlaps with the SIFS interval between a Wi-Fi frame transmission and its corresponding ACK may declare the channel to be idle. This could trigger an immediate LAA transmission which ends up colliding with the Wi-Fi ACK.

Therefore, in this paper an enhanced LBT procedure is used for LAA which incorporates a backoff defer period of at least 20 µs after a busy channel has just become free, as shown in Fig. 1. The impact of discontinuous transmission is also seen in Fig. 1 since LAA releases the channel after transmitting for four subframes, which corresponds to the maximum channel occupancy limitation of 4 ms in Japan. The effect of the additional deferral period is that the earliest time that LAA can transmit after the channel becomes idle is at least as large as Wi-Fi [7].

Additional transmission opportunities are provided to Wi-Fi by restricting the LAA CCA starting points to LTE subframe boundaries and enforcing "freeze periods" where the backoff procedure and CCA sensing is completely suspended, as shown in Fig. 2 for the downlink (DL) case. Configuring freeze periods at eNB during the LBT procedure reduces the overhead due to the possible transmission of any initial signals (which can contain reference symbols to assist the receivers), since it may not be feasible to immediately start LTE data transmission at an arbitrary time instance. Additionally, this feature increases the opportunities for other contending nodes in the medium to access the channel in an effective manner which can serve a purpose similar to the exponential backoff feature in Wi-Fi technology. The structure of the chosen LBT protocol has several implications for the design of the DL and UL physical channels, as described in the sequel. The performance of the proposed LBT protocol is evaluated numerically in Sec. III.

B. Downlink Design Considerations

1) Physical Channels and Reference Signals: In the proposed LBT scheme in Fig. 1, CCA starts at the beginning of a LAA subframe. The first three OFDM symbols (OS) at the beginning of a subframe could for example be set aside (punctured) to accommodate the possible range of CCA times when no interference is present. With this design, the data-bearing Physical Downlink Shared Channel (PDSCH) and Enhanced Physical Downlink Control Channel (EPDCCH) transmission will always start in the 4th OS in the first subframe of the transmission burst. If the CCA is completed before the 4th OS, additional control or reference signals can be transmitted to help the receiver prepare the reception parameters. The duration of the transmission burst depends upon regulatory restrictions on maximum channel occupancy, e.g., up to the end of the fourth subframe in Japan.

The PDSCH may occupy all 14 OS in the subframes except for the first one after the CCA stage. With this LBT design, there is no impact on UE-specific Demodulation Reference Signals (DMRS) and Channel State Information Reference Signals (CSI-RS) since they are located after the 5th OS within a subframe. This option is also more favorable to design the LAA carrier to rely on DMRS-based DL physical channels including both PDSCH transmission mode 10 (TM10) and EPDCCH. It is noted that Cell-specific RS (CRS)-based PDSCH TM4 may still be supported, though the functionality of the CRS here is more similar to DMRS (since CRS cannot be transmitted continuously).

2) Scheduling: In Rel-10 CA, a SCell may carry scheduling grants for UEs served on that same SCell (referred to as self-scheduling), or UEs on a particular SCell may be scheduled from the PCell or another SCell via cross-carrier scheduling configuration. To support self-scheduling on the LAA SCell, EPDCCH resources should be configured for the SCell. The EPDCCH should always start in OS #3 irrespective of where the subframe is located in a transmission burst as shown in Fig. 3. A new field may be needed in the DCI to indicate to the UE whether the subframe is a normal subframe (with PDSCH occupying all 14 OS) or a shortened subframe (with PDSCH starting at OS #3). This is because the UE does not have *a priori* knowledge of whether a particular subframe is the first subframe of a transmission burst. (Since the functions of PDCCH can be covered by EPDCCH, the first three OS of a subframe, where PDCCH is usually located, can be punctured and used for LBT.)

Following the LTE carrier aggregation framework, PUCCH carrying HARQ-ACK and CSI for all aggregated cells should be sent on the UL PCell. Since the PUCCH resources on the PCell are reserved and always available (unlike the LAA SCell), sending UCI on the PUCCH is one important advantage of LTE PHY layer over the Wi-Fi PHY layer. The LTE PUCCH is designed for coverage and reliability via very low rate coding, repetition, and frequency hopping.

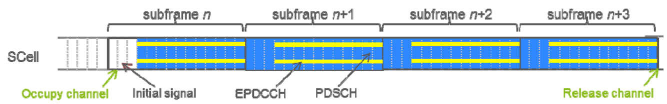

Fig. 3: Proposed data transmission mapping and control channel mapping for LAA SCell self-scheduling design.

Transmitting on the licensed PCell further allows the UE to transmit at higher powers and at lower carrier frequencies (with lower path losses). The Wi-Fi control channel for both UL and DL is based on BPSK rate 1/2 convolutional coding and the frame acknowledgement design requires substantially more bits than the LTE design. In all, the Wi-Fi control channel has been designed to provide coverage in localized areas such as indoor deployment and is not suitable for outdoor deployment. The LTE control channel design in comparison enables reliable outdoor deployment and a larger coverage area.

C. *Radio Resource Management and CSI Feedback*

The combination of the LBT and maximum transmission burst duration functionalities of LAA implies that LTE reference signals are not guaranteed to be transmitted with a fixed periodicity on LAA SCells. This can affect the methods by which RRM, CSI measurements and feedback, and time-frequency tracking are currently supported in LTE. Considering time and frequency tracking as an example, UEs require periodic opportunities to estimate time and frequency. A filtering/tracking operation is applied to these estimates to maintain time and frequency synchronization. A lack of such functionality to support this will severely impede data reception at UEs. Similarly, RRM measurements form the basis for cell selection and mobility management, and closed-loop link adaptation is not feasible without accurate CSI measurements and feedback.

Therefore, there is a need for alternate methods to support time and frequency tracking, RRM measurement and CSI acquisition for efficient operation of LAA SCells. In Rel-12, periodic transmission of primary/secondary synchronization sequences (PSS/SSS), CRS, and CSI-RS are generally used to achieve these objectives. Since periodic reference signal transmission is no longer feasible on LAA SCells, this raises the question if PCell reference signals can be utilized for at least coarse time-frequency synchronization and automatic gain control (AGC) adjustment on the SCells. While coarse timing synchronization may be possible using the PCell RS in a co-located scenario, AGC adjustment would not be feasible due to the PCell potentially operating on a carrier (e.g., 2 GHz) that has substantially different characteristics and path loss compared to the LAA SCells in the 5 GHz band. This difference in long-term channel properties also rules out using PCell RS for channel estimation filter adjustment on LAA SCells.

Based on the above discussion, our proposed solution is to transmit discovery reference signals (DRS) on the LAA SCells, potentially in conjunction with a LBT phase. The Rel-12 DRS comprising at least PSS/SSS/CRS that was designed for small cell PHY enhancements can serve as a starting point for RRM measurements for LAA. The mapping of signals and RS density within the DRS can potentially be changed for Rel-13 so as to avoid gaps in time during DRS transmission. Additional management and control information such as system information relevant to unlicensed bands can be embedded in the LAA DRS. Moreover; CSI-RS together with CSI-IM (or other known unused REs) can be used to derive CSI reports from the UE when they are available. Due to the unpredictable availability of the unlicensed carrier, the most practical approach would be to rely only on aperiodic CSI reports for the LAA SCell, as opposed to periodic CSI reports.

III. Coexistence Evaluation Results

This section presents detailed system-level throughput and buffer occupancy evaluations for both indoor and outdoor coexistence scenarios, based on the current 3GPP simulation assumptions. An important aspect to stress is that the evaluations are performed with *non-full buffer* evaluations, for a set of different load points. The evaluation considers FTP downloading of a 0.5 MB file with variable Poisson arrival rates [1]. VoIP service model is also considered. In the following results, large-scale fading effects are incorporated while fast fading is not modeled, and CSI estimation is assumed to be perfect for both LAA and Wi-Fi. Detailed simulation assumptions are given in [1].

The LAA LBT procedure performs or resumes CCAs at subframe boundaries with a fixed contention window size and freeze periods of 11 OS. The Wi-Fi networks operate in infrastructure mode with all communications passing through the APs. Both operators have access to a 10 MHz licensed carrier when deploying LAA. In the coexistence evaluations, the following methodology is followed for each UE and eNB/AP drop:

- Step 1: The performance metrics for two Wi-Fi networks coexisting in a given evaluation scenario are evaluated and recorded.

- Step 2: Wi-Fi is replaced with LAA for the group of eNBs and UEs served by one of the Wi-Fi operators. Performance metrics of the Wi-Fi network coexisting with the LAA network are evaluated and recorded.

A. *Coexistence of DL-only LAA with DL-only Wi-Fi*

We first consider DL-only traffic for both LAA and Wi-Fi networks in an outdoor hot-spot scenario [1]. Fig. 4 illustrates the mean (circular markers) and 5th-percentile (triangle markers) per-user data rates with four unlicensed 20 MHz carriers shared between two operators, each of which deploys four APs in each hot-spot. Note that the channel selected by each AP in Step 1 and Step 2 is the same. The performance of UEs associated with the macro layer is not considered. The key conclusion from the evaluation is that the proposed LAA coexistence solution enables the non-replaced Wi-Fi network to achieve better performance. In particular, the 5th-percentile throughput of the non-replaced Wi-Fi network improves from a few kbps to around 70 Mbps at moderate loads when the neighboring Wi-Fi network is replaced by LAA. The two co-existing LAA networks exhibit very similar performance. It can be concluded that LAA LTE is a good neighbor not just to Wi-Fi, but to other LAA networks as well.

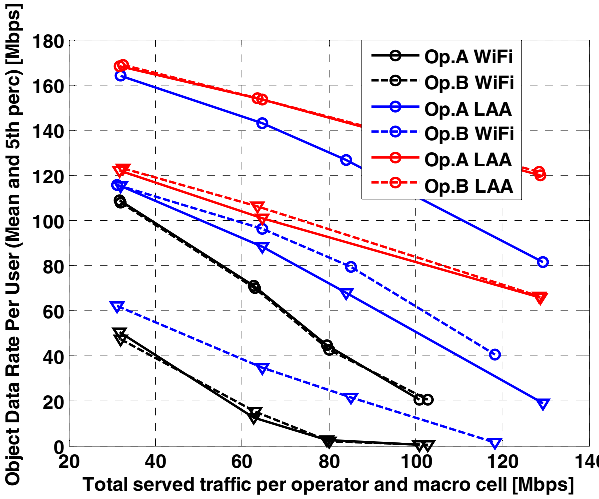

Fig. 4: Per-user data rates for outdoor scenario with four unlicensed 20 MHz carrier shared between two operators, LAA CCA ED threshold of -62 dBm.

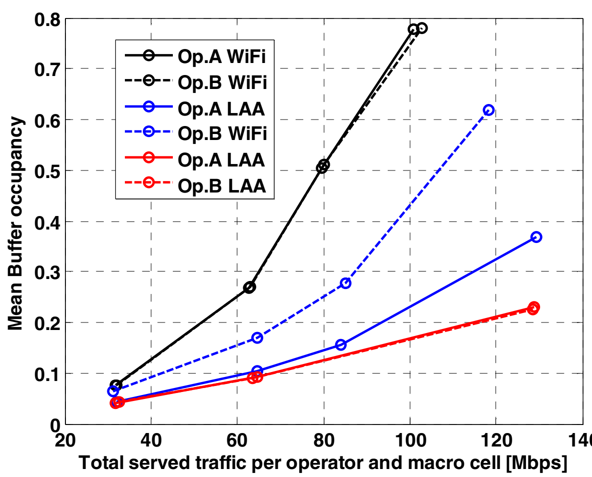

Fig. 5: Mean buffer occupancy for outdoor scenario with four unlicensed 20 MHz carrier shared between two operators.

The corresponding mean buffer occupancy for the outdoor scenario is shown in Fig. 5. When traffic is DL-only, the buffer occupancy of the i^{th} small cell (Wi-Fi and LAA) is defined as the sum of the period of time during which the i^{th} small cell has data to transmit including retransmissions (i.e., its queue is not empty) divided by the total simulation time [1]. The mean buffer occupancy is then the buffer occupancy averaged over all the small cells of the same operator, and serves as an indicator of traffic load and congestion levels. Coexisting Wi-Fi networks consistently exhibit higher mean buffer occupancy even with four unlicensed carriers being available, which implies that Wi-Fi nodes tend to back off more frequently to each other. This comes from the low sensing threshold used by a WiFi node towards another WiFi signal at -82dBm, compared to the one used against LAA at -62dBm. As a result, the presence of the LAA neighbors improves the frequency reuse characteristics of the Wi-Fi network. This can be observed in the slower scaling of mean buffer occupancy with the total served traffic when one or both networks employ LAA.

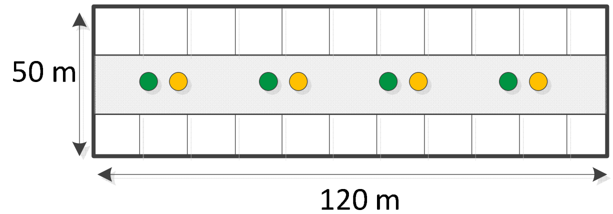

Fig. 6: Indoor topology with 4 LAA eNBs (green) and 4 Wi-Fi APs (orange).

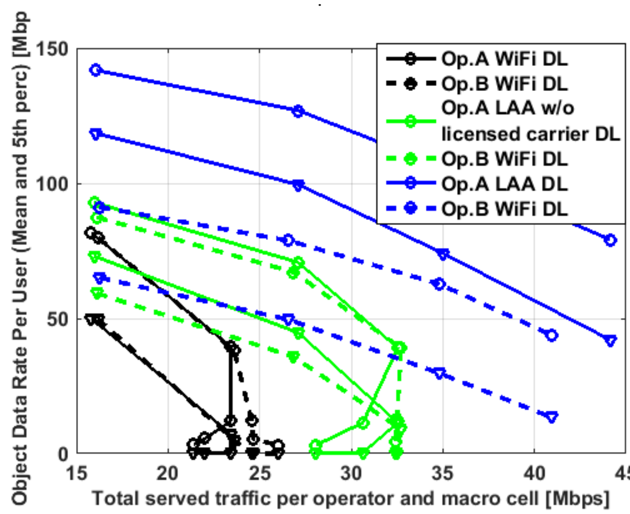

Fig. 7: Per-user DL data rates for indoor scenario with a single shared unlicensed 20 MHz carrier, LAA CCA ED threshold of -82 dBm.

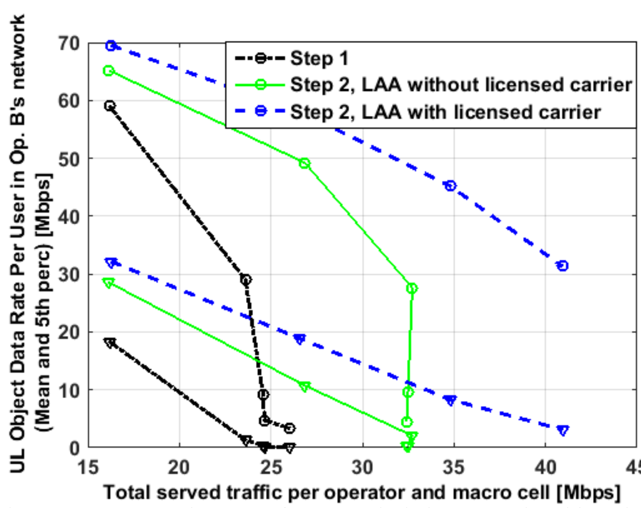

Fig. 8: Per-user UL data rates for Op. B in indoor scenario with a single shared unlicensed 20 MHz carrier, LAA CCA ED threshold of -82 dBm.

B. *Coexistence of DL-only LAA with DL+UL Wi-Fi*

We next consider an asymmetric indoor deployment where LAA continues to have DL-only traffic, whereas the non-replaced Wi-Fi network has traffic in both DL and UL directions. In the indoor scenario, two operators deploy 4 small cells each in the single-floor building, as shown in Fig. 6. The traffic split of Wi-Fi is set as 80% DL, 20% UL. The small cells of each operator are equally spaced and centered along the shorter dimension of the building. The distance between two closest nodes from two operators is random.

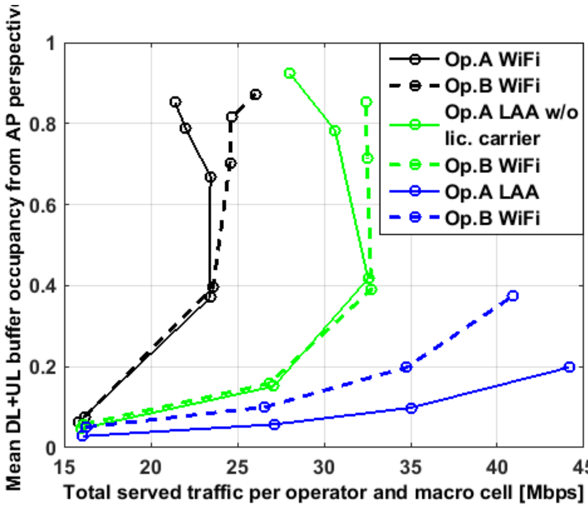

Fig. 9: Mean buffer occupancy versus served traffic for indoor scenario with a single shared unlicensed 20 MHz carrier.

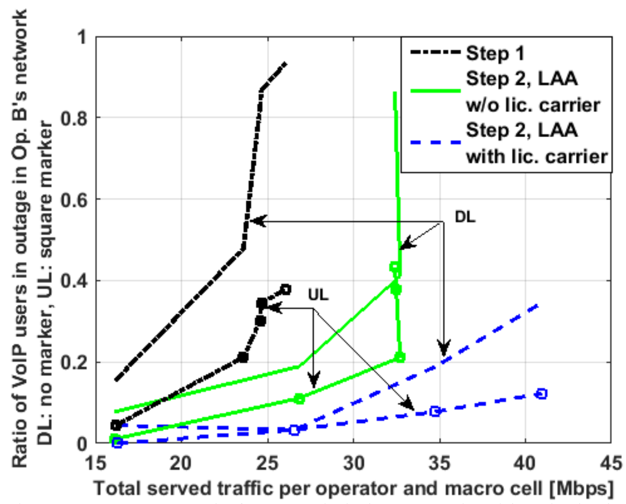

Fig. 10: VoIP outage ratio for Op. B in indoor scenario with a single shared unlicensed 20 MHz carrier, LAA CCA ED threshold of -82 dBm.

Consider a congested case with a single unlicensed 20 MHz carrier shared between LAA and Wi-Fi, 20 UEs per operator with FTP traffic, and 2 UEs per operator with delay-sensitive VoIP traffic. The mean (circular markers) and 5th-percentile (triangle markers) per-user data rates are shown in Fig. 7 for Step 1 (both operators are Wi-Fi) and Step 2 (operator A replaced with LAA). For the LAA network, the users are either served by both the licensed band LTE carrier and the unlicensed band LAA carrier (blue curves in Fig. 7), or by the unlicensed band carrier only (green curves in Fig. 7). The two key observations based on Step 2 is that LAA improves the coexisting Wi-Fi network performance as compared to another Wi-Fi network. The proposed LBT procedure provides more opportunities for Wi-Fi to obtain channel access, compared to the case where it competes with an identical MAC protocol of another Wi-Fi network. The associated UL data rate performance for the non-replaced Wi-Fi network of operator B is shown in Fig. 8, which exhibits similar trends as the DL results. As seen in Fig. 10, also the fraction of VoIP users in outage in either traffic direction improves in Step 2 compared to Step 1 for the same reasons as mentioned earlier. Note that a VoIP user is considered to be in outage if the 98 percentile delay of all its VoIP packets exceeds 50ms.

The mean overall buffer occupancy for the indoor scenario is shown in Fig 9. For the Wi-Fi network with both DL and UL traffic, the overall buffer occupancy from AP *i*'s perspective is defined as the sum of the period of time during which either the i^{th} small cell or at least one of its associated STAs has data to transmit including retransmissions, divided by the total simulation time. The mean buffer occupancy for an operator is defined as before. In Fig. 9, it is observed that the mean buffer occupancy is significantly lower when LAA and Wi-Fi are coexisting. This is partly because of the improvement of reuse characteristic discussed in the last section. Another reason is that LAA can serve its traffic and vacate the channel quicker compared to a Wi-Fi network, which then yields more transmission opportunities to the Wi-Fi network of the other operator. The performance of LAA is better than Wi-Fi both with and without use of the licensed carrier, due to its fast link adaptation and inherent robust designs to handle and recover from unexpected interference via the hybrid-ARQ protocols.

In the tested scenario, the non-replaced Wi-Fi network has up to 24 nodes (from the APs and the STAs) contending for channel access, which is substantially more than the 4 eNBs in the LAA network. As a result, it can be observed in the green curves in Fig. 7 that the Wi-Fi network retains high served traffic while that of the LAA network can be depressed by the more aggressive Wi-Fi network (shown by the 'bending back' portion of the curve in the figure).

IV. Conclusions

We presented an overview of a candidate DL physical-layer architecture for LTE with LAA operating in the unlicensed spectrum. It was shown how the introduction of new functionalities such as DTX and LBT necessitates numerous changes in the DL and UL physical channels, HARQ feedback procedures, scheduling, RRM mechanisms, and CSI acquisition. Detailed system-level simulation results were then presented to show that fair coexistence between LAA and Wi-Fi can be achieved in a range of indoor and outdoor scenarios. Furthermore, the fairness of the coexistence of LAA with other adjacent LAA networks was also verified via simulations.

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