A MAC Solution for Distributed Coordination of 5G LAA Operator Networks and Fair Coexistence with WLAN in Unlicensed Spectrum

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Abstract— **Acquiring more spectral resources is a key enabler for the envisioned high data rates of next generation mobile networks. Licensed-assisted access (LAA) to the vast and free-of-charge unlicensed spectrum has been therefore receiving tremendous interest, especially with the advancements in small cells and carrier aggregation. We propose a novel 5G MAC solution for fair and efficient coexistence with WLAN and other 5G operator networks in unlicensed spectrum (5G-U). A UE-centric joint association and channel selection algorithm maximizes the achievable long-term rates. Neighboring LPNs of the same 5G-U network opportunistically form per-channel disjoint radio access clusters (RACs). During an active sensing phase, RACs discover their potential interferers and 'contend-to-coordinate' their self-allocation of the unlicensed channel. A self-allocated RAC dynamically optimizes its coexistence frames with WLAN to achieve the estimated soft airtime share over the coordination frame. We generalize the simple sequential inhibition model, which has been shown to accurately model the carrier sense multiple access, to capture the impact of longer LAA bursts as well as the priority access mode in the downlink simulations. Results with single-LPN RACs show substantial coexistence throughput gains compared to two different models of LTE-LAA. Additional gains are realized with multi-LPN RACs in dense deployment and high channel occupancy scenarios.**

Keywords— Licensed Assisted Access (LAA), 5G-U, LTE-U, distributed inter-operator coordination, coexistence with WLAN, LAA LBT, LAA frequency reuse.

I. INTRODUCTION

While licensed spectrum remains the mobile broadband (MBB) operators' main reliable asset to deliver advanced services and improve users' experience, opportunistic use of the unlicensed spectrum has been attracting tremendous interest as a major performance boast to meet the continuously growing traffic demand. This is evident from the current 3GPP Rel-13 activities on licensed-assisted access (LTE-LAA) [1], which relies on the recent specifications for small cells and carrier aggregation (CA). In contrast to WiFi offloading through the 802.11 WLAN air interface (AI), LAA aims at porting the benefits of the carrier-type AI to the unlicensed spectrum in a user-transparent and revenue-generating manner. Among these benefits is the unified operation/management as well as the robust link adaptation and interference management schemes exploiting the infrastructure backhaul [2]. However, several technical challenges are faced on the way to achieve fair and efficient coexistence of multiple geographically overlapping LAA networks with WLAN; the most dominant occupant of the targeted 5 GHz spectrum. Compliance with different region-specific regulations further adds to these technical challenges.

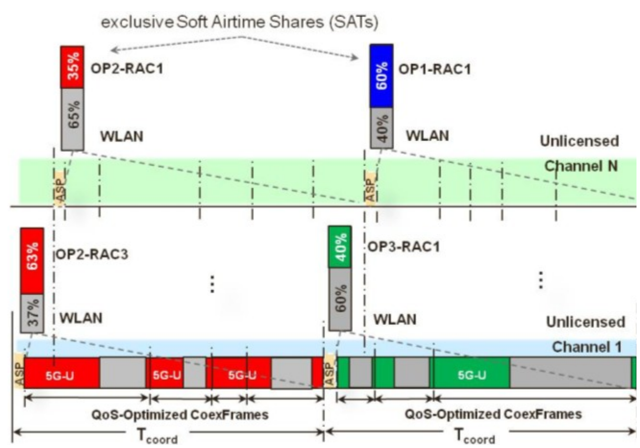

Figure 1: Neighboring LPNs of same 5G-U network periodically form disjoint RACs which contend-to-coordinate their self-allocations of the unlicensed frequency channel during the ASP window. A self-allocated RAC dynamically optimizes its coexistence frames with WLAN to achieve the estimated fair SAT over the coordination frame.

As such, LTE-LAA has so far considered the following main design targets [1]: Dynamic frequency selection, e.g., to avoid RADAR-occupied channels; transmit power control (TPC); channel selection to reduce the interference from/to other nodes in proximity; discontinuous transmission (DTX) to comply with the regulated maximum channel occupancy (MCO); and most importantly, energy detection (ED)-based listen-before-talk (LBT) as the medium access mechanism. It worth noting though that the robustness and successful coexistence of different WLAN networks featuring various 802.11 AIs lay mainly within the distributed coordination function (DCF) and its carrier sense multiple access/collision avoidance (CSMA/CA) LBT mechanism [3]. In addition to the AI-agnostic ED, CSMA/CA employs carrier sense (CS) to assess the channel and coordinate/reserve resources for its transmissions among those of coexisting WLAN nodes in a fully distributed manner. While LTE-LAA may use lower ED thresholds and longer defer periods to overcome the aggressiveness of ED-based LBT, one would expect that LTE-LAA's intra- and inter-operator coexistence will be inferior to that of WLAN; this is intuitive because of the tangible value of CS to WLAN. As for the intra-LAA coexistence, LTE-LAA specifications embark on LTE-Advanced interference management schemes and advise that the LBT design should allow 'neighboring' LPNs to synchronize their channel assessment and transmit bursts so that mutual blocking is avoided and the frequency reuse is retained [1]. However, no criterion was specified for defining such neighborhoods or forecasting the impact of synchronous access on coexisting WLAN. For the inter-LAA operator coexistence, no dedicated mechanism was specified as well, except for some proposals to introduce LAA reservation signals after LBT which would reduce the collisions but not the contention level per channel.

Since unpredictable resources are rendered by random access mechanisms anyway, it is intricate for a carrier-type AI to provision for periodic measurement, control, and synchronization signals or guarantee the QoS for data traffic, e.g., latency, without claiming access priority especially under high levels of contention. Interestingly, a pre-standardization non-LBT solution for LTE-Advanced in unlicensed spectrum (LTE-U) has been proposed in [4]. Although such a solution is applicable only in regions where LBT is not required by regulations, e.g., USA and China, simulation and experimental results have demonstrated that fair and efficient coexistence with WLAN still can be achieved through direct (~highest priority) access of LAA LPNs given that their duty cycle is fairly adapted based on estimated WLAN utilization through CS. However, the desired frequency reuse is not achieved since bursts of neighboring LPNs are time-multiplexed.

Furthermore, although selecting an unlicensed channel based on the total power sensed (either by the serving node or the terminal) attempts to avoid the interference as compared to random selection, e.g., [4,5], it might often lead to uninformed decisions as it ignores the spectrum access opportunities and overestimates the actual interference. For instance, a WLAN access point (AP) in close proximity of an LAA node would create an illusion of potentially strong interference despite its light loading. The reality, however, is that such an AP is very likely to be blocked by the LAA transmission by the virtue of its proximity, especially if a WLAN-like reservation signal precedes the LAA burst. Moreover, a greater airtime share can be utilized by these LAA bursts if the LAA node estimates the light load of the coexisting AP. This should be also seen in light of the fact that different serving LAA nodes might block different sets of WLAN nodes on a given channel. This is particularly important when dealing with the hidden node problem in which a UE experiences interference from a WLAN node outside the coverage (blocking footprint) of its serving LAA node. We note that, while WLAN handles the hidden node problem efficiently within itself through the fast two-way blocking mechanism request-to-send/clear-to-send (RTS/CTS) [3], the LAA supplementary downlink only (LAA-SDL) mode cannot employ a similar mechanism between the LPN and the UE. As such, we observe that the problems of UE association and channel selection should be handled jointly and more intelligently to improve the coexistence performance in next generation LAA networks.

Incorporating the lessons learnt from WLAN and the observations discussed earlier into our design sandbox, in the following we introduce a novel MAC solution for granting 5G networks fair and efficient access to the unlicensed spectrum (5G-U) yet with higher-level of QoS guarantees. As shown in Fig.1, this is achieved in the longer time scale through UE-centric joint association and channel selection and frequency-domain distributed coordination using a CSMA-like protocol among opportunistically grouped clusters of the 5G-U operator networks. In the shorter time scale, time-domain coexistence of the self-allocated clusters with WLAN can be optimized given a fair target soft airtime share (SAT).

Thanks to the decoupling of the inter-LAA and the LAA-WLAN coexistence problems, a self-allocated 5G-U RAC enjoys an exclusive SAT to coexist in time with WLAN on the channel without contention or interference from other 5G-U operator RACs in its vicinity for the duration of the coordination frame. Therefore, and given the long coordination time scale (100s msec), our SSI-based simulations focus on the multi-channel coexistence of already self-allocated RACs from one 5G-U operator with WLAN. Thus, we note that the performance of baseline LTE-LAA schemes can be seen as an upper bound as contention and interference from other LTE-LAA operators is not captured for a fair comparison. Our contribution in this paper can be summarized as follows:

- A novel 5G-U MAC solution for fair and efficient coexistence with incumbent WLANs and other 5G-U operator networks is proposed comprising five components:
    1. Passive carrier sensing at the LAA LPNs and UEs
    2. UE-centric joint association and channel selection
    3. Opportunistic grouping of LPNs into RACs
    4. Contend-to-coordinate (C2C): Inter-RAC active sensing and distributed frequency-domain coordination
    5. Time-domain QoS-optimized coexistence with WLAN
- We generalize the simple sequential inhibition model (SSI) used in [6], which accurately models the CSMA/CA [7], to capture the impact of longer LAA bursts as well as the priority access mode in the downlink simulations
- Results with single-LPN RACs show substantial coexistence throughput gains compared to two different models of LTE-LAA. Additional gains are realized with multi-LPN RACs in dense deployment and high channel occupancy scenarios.

In Section II, we introduce the system model followed by our proposed solution in Section III. Simulation results and conclusions are presented in Sections IV and V, respectively.

II. SYSTEM MODEL

We consider an existing WLAN network comprising a number of WiFi APs and stations (STAs) in a given geographical area where a number of MBB operators deploy their backhaul-connected LPNs in an independent and inevitably overlapping manner. The MBB networks typically operate in orthogonal licensed bands while a total number of N unlicensed channels is available for shared access with WiFi.

WiFi employs CSMA/CA in which the node perceives the channel idle during a clear channel assessment (CCA) slot if the total power received from all surrounding devices is less than the ED threshold, Th_{ED}^{W}, and no other WiFi transmission is detected through CS with a received power greater than the CS threshold, Th_{CS}^{W}. A random backoff counter is uniformly generated for an initial data transmission from a contention window $[0, CW_{min}]$ to defer the transmission for CW idle CCA slots after the channel has been idle for 34μsec; the common distributed inter-frame spacing (DIFS)[1]. The counter is frozen once the channel gets occupied within that window and its value is used in the following access attempt. The transmission happens if the counter reaches zero but if a collision is detected, i.e., the packet was not received, the CW_{min} is doubled according to the exponential backoff rule.

We compare three different scenarios for the MBB networks to exploit the unlicensed spectrum. The first is the reference coexistence scenario where the LPNs are typically WiFi APs as in WiFi offloading of LTE traffic to the UEs through their WiFi AI. The second is the baseline scenario in which LAA is used such that the LTE-LAA LPNs serve their associated UEs over m unlicensed channels through LTE-Advanced CA to the licensed primary component carrier (PCC). Unlike WiFi, the CCA of an LTE-LAA node does not CS a transmission by another LTE-LAA or WiFi node as it perceives the channel idle if only the total power received from all surrounding devices is less than an ED threshold, Th_{ED}^{L}. A backoff mechanism similar to that of WiFi is however assumed for LTE-LAA's LBT. Finally, the LPNs in the third scenario also use CA to serve the UEs over m unlicensed channels yet the LPNs possess the capabilities, and employ the MAC mechanisms, of our proposed 5G-U solution as follows.

III. PROPSED 5G-U SOLUTION

The operations of the proposed solution span different time scales: The observation frame (ObservFrame) which is in the order of minutes; the coordination frame (CoordFrame) which is in the order of 100s of msecs; and the coexistence frames (CoexFrames) in the order of a few msecs each. While the passive sensing is performed by indvidual LPNs, a logical central spectrum management controller (CSMC) hosted by a base station or a network entity physically connected to a set of LPNs collects the sensing reports, forms disjoint RACs per selected unlicensed channel, and handles the rest of the 5G-U operations for those RACs.

[1] This is the legacy DCF inter-frame spacing for data bursts. Shorter duration, i.e., PIFS, is used with priority frames such as beacons. Longer durations are used with best effort and background traffic under the EDCA function.

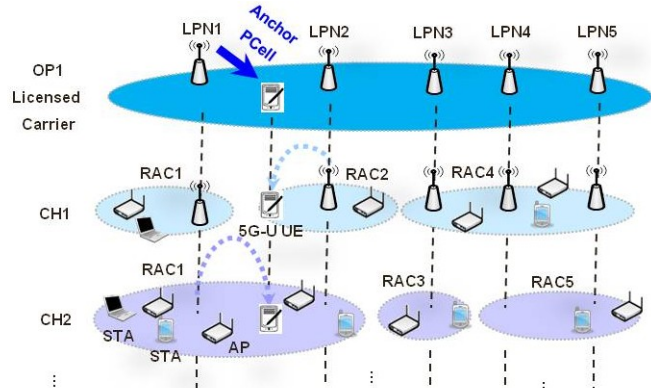

Figure 2: UE-centric joint association and channel selection. If a candidate LPN belongs to a multi-LPN RAC on the candidate channel, the union RAC footprint determines the UE's residual interference from WLAN.

A. Passive Carrier Sensing

LPN passive CS: This operation is performed by all LPNs, and the results influence the decisions of the coordination and coexistence mechanisms on both the ObservFrame and CoordFrame time scales. In line with [4], it is assumed that a 5G-U LPN can detect WiFi beacons and preambles at the CS threshold and thus identify the APs in its vicinity, their respective strength, as well as their served STAs/access categories (ACs) per unlicensed channel. In other words, the LPN senses the channel utilization by neighboring WLAN nodes and thus identifies the potentially blocked WiFi nodes and their channel usage, i.e., its 'footprint' on that unlicensed channel. This footprint information is updated every CoordFrame. Every ObservFrame, a passive sensing result is also used to avoid RADAR-occupied channels as well as to avoid extremely busy channels that are not good candidates for time-domain coexistence in this vicinity.

UE passive CS: This operation expands the existing capability of a UE to identify its surrounding APs and their respective signal strengths per unlicensed channel through CS. The 5G-U UE provides such a CS report every CoordFrame period to its primary serving cell (PCell) on a licensed PCC; the report is then forwarded to the CSMC. Otherwise, if uplink is enabled (LAA-CA mode) the report can be sent through a current serving unlicensed secondary cell (SCell).

B. UE-centric Joint Association & Channel Selection

The CSMC combines the per-channel CS reports from its set of backhaul-connected LPNs and the UEs every CoordFrame and triggers this operation with the objective of maximizing the UEs' long-term rates over the CoordFrame. The key idea is that, if the 5G-U LPN speaks the WLAN CS language, nodes within its footprint will be blocked, including the strong ones. This can be implemented by preceding the CoexFrames by a WiFi reservation signal to invoke its virtual CS or including a WiFi preamble in the burst to invoke its physical CS. Therefore, to maximize the long-term spectral efficiency of the DL transmission to the UE, the CSMC should select the best m pairs of a serving LPN and an unlicensed channel for which the long-term SINRs are maximized.

Since, in practice, this operation could be triggered for a UE during the CoordFrame due to asynchronous reporting of UEs or upon admitting a flow to the unlicensed spectrum, a candidate LPN could be already accessing/reserving the medium synchronously as part of a RAC on the candidate channel. In such case, the union footprint of the LPNs forming the RAC of this LPN on that channel is considered rather than its own footprint. The example in Fig. 2 therefore explains the operation in this generic form. While the inter-LAA interference is not a concern when calculating the long-term SINRs, thanks to the frequency-domain coordination mechanism, the potential intra-LAA interference from neighbor LPNs including those within the candidate RAC has to be considered. Such information can be available to the CSMC through: UL sounding on that channel (LAA-CA only); or UL sounding in the licensed spectrum; or from the UE's RSRP report. Proper adjustment can be applied with the latter two options to account for different carrier frequencies.

However, due to the time multiplexing with WLAN, the k^{th} UE's spectral efficiency on channel n will only apply during the estimated soft airtime share for LPN l, $SAT_{l,n}$, which will be common to all the synchronous LPNs of its RAC over the CoordFrame as explained in Subsection *C*. As such, the CSMC should rather select the best m pairs as follows,

$$[l_k^*, n_k^*] = arg \max_{l,n}\left\{SAT_{l,n}^{+k}.\, w_{l,k}^{+k}.\log_2\left(1+\bar{\gamma}_{l,n,k}\right)\right\}, \qquad (1)$$

where $w_{l,k}^{+k}$ is the long-term bandwidth share of the UE upon association with the LPN and is inversely proportional to the total number of the LPN's associations. While incorporating this factor provides a more accurate estimate of the long-term rate, it also imposes an implicit load balancing behavior. The long-term SINR per-tone, $\bar{\gamma}_{l,n,k}$, can be expressed as

$$\bar{\gamma}_{l,n,k} = \frac{P_{l,k}^{rx}}{\sum_{i\in RACs_n} I_{i,n,k}^{LAA} + \sum_{j\in J_{k,n}} I_{j,n,k}^{WiFi\_residual} + P_n}, \qquad (2)$$

where $P_{l,k}^{rx}$ and P_n denote the long-term received reference power and noise power, respectively. Whereas $I_{j,n,k}^{WiFi\_residual}$ is the long-term interference power from an unblocked (hidden) WiFi node j which is in the UE's CS report for channel n but outside the footprint of the LPN's RAC. The summation of the terms $I_{i,n,k}^{LAA}$ captures the worst case long-term intra-LAA interference from all the LPNs across the channel RACs. Note that $SAT_{l,n}^{+k}$ refers to the updated target SAT upon adding the load of UE k to the RAC's load. Extending the concept in [8], a fair target SAT can be computed for RAC l as follows,

$$SAT_{l,n}^{+k} = \frac{RACLoad_{l,n}^{+k}/m}{RACLoad_{l,n}^{+k}\ /m + CoexAdj * FootprintLoad_{l,n}}, \qquad (3)$$

where $RACLoad_{l,n}^{+k}$ captures the sum of average rates required by the served UEs, and the division by m captures the fact that a UE can be scheduled on m channels. The $CoexAdj$ is a positive tuning parameter for the operator to emphasize/de-emphasize the weight of the 5G-U traffic w.r.t. the affected WiFi $FootprintLoad_{l,n}$ which can be deduced from the beacon ACs. Note that the results of this operation lead only to configuration of UEs and LPNs if triggered for an upcoming CoordFrame. This is because transmissions will commence on a channel after RACs are formed and self-scheduled through the C2C mechanism. Intermediate triggering however leads to direct activation of the selected SCells.

C. *Opportunistic Grouping of LPNs (RAC Merging)*

By the end of the CoordFrame, the CSMC dissolves all present RACs and runs the association and channel selection algorithm using the available reports perceiving each LPN a 'single-LPN RAC.' Based on such results, the CSMC runs the RAC Merging algorithm per selected channel to examine, in a pair-wise manner, the opportunities in synchronous access of the merged RACs' LPNs such that a common airtime share is used, i.e., merging into a bigger RAC. The intuition is that 'neighboring' LPNs might have overlapping footprints on a given channel; this is particularly important in scenarios of dense LPN deployment and/or high channel occupancy, e.g., 802.11ac. As such, the overlap of LPNs' footprints very well defines the merging neighborhood and meanwhile enforces coexistence fairness with WLAN. This is because the asynchronous access of such LPNs would result in the commonly blocked WiFi nodes not receiving any of the airtime shares individually estimated by these LPNs.

The merging algorithm can therefore use a max-min approach to implement this criterion by iteratively attempting to merge the RAC with least target SAT (visitor RAC) with other RACs down the sorted list (host RACs) keeping track of the best merge that results in the greatest relative improvement w.r.t. the host RAC, i.e., $best\_merge \leftarrow current\_merge$ if

$$\frac{SAT_{current\_merge}}{SAT_{current\_host}} > \frac{SAT_{best\_merge}}{SAT_{best\_host}}. \qquad (4)$$

The final best merge, if any, for that visitor RAC is executed, the visitor RAC is eliminated, and the merged RAC thus moves down the sorted list due to increased SAT, keeping its host ID. In fact, an increased SAT implies serving a bigger set of UEs with relatively minimal expansion of the footprint. In addition to enforcing the coexistence fairness while achieving the desired frequency reuse, this grouping mechanism reduces mutual blocking of LBT LPNs, increases their fair SAT, and eliminates more interference caused by hidden WiFi nodes to the UEs due to the union footprint.

D. *Contend-To-Coordinate (C2C)Mechanism*

In the design of this mechanism, we embark on the success of the DCF of WLAN by employing a CSMA-like protocol yet for inter-LAA frequency-domain coordination. Using C2C, rather than contending continuously on a selected channel to transmit data bursts at unpredictable instants, 5G-U RACs contend only during a short active sensing phase (ASP) at the beginning of the CoordFrame to transmit coordination beacons (CBs) for discovery and exchange of scheduling information. Self-allocated RACs can thereafter share the channel with WLAN exclusively in their vicinity without contention/interference from other 5G-U operators. The C2C protocol works like CSMA, as described in Section II, but it is different in the following aspects: 1) CCA is performed

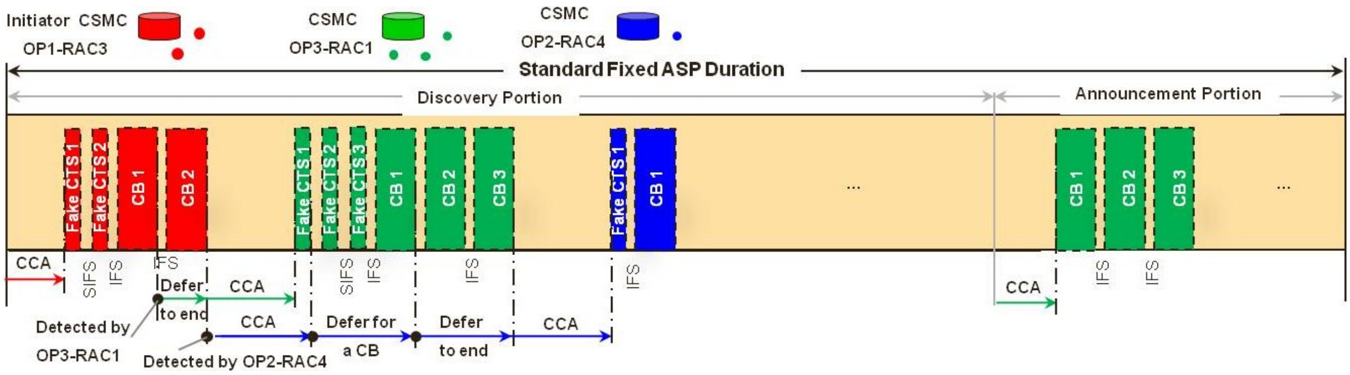

Figure 3: 5G-U Contend-To-Coordinate (C2C) mechanism for inter-LAA frequency-domain coordination during the ASP using a CSMA-like protocol

synchronously by the RAC LPNs using a shorter *defer period* (>20μsec and < PIFS = 25μsec) for priority access; 2) A short fixed CW_{min} is used by the CSMC to generate for each RAC a random backoff counter common to its LPNs. 3) As shown in Fig. 3, when medium is perceived idle for a RAC, comprising LPNs sequentially [2] transmit a WiFi reservation signal to protect the ASP from WiFi access, e.g., CTS-To-Self, and follow with sequential CBs using an IFS ≤ SIFS =16μsec.

If a CSMC has been contending on the channel in a previous CoordFrame, the beginning of the ASP is already defined in reference to the previous ASP. Otherwise, a starting CSMC searches for the CBs to identify the ASP to contend on. However, if no CBs were detected within the CoordFrame period, the CSMC initiates the ASP on the channel by instructing its current RACs to run the C2C protocol to poll the neighboring RACs. CBs are transmitted at the maximum allowed TPC power level using the most reliable MCS and mainly carry information such as the 5G-U operator/CSMC ID, RAC ID, CB order in sequence, remaining time of the ASP, in addition to the standard *scheduling parameters*.

When a RAC receives the response CBs during the fixed *discovery portion* of the ASP, its neighbor RACS are identified by the CSMC and their corresponding scheduling metrics are computed. The receiving RAC runs C2C to respond if it did not respond earlier. Hence, for each *contention set* of a channel RAC and its identified inter-/intra-operator neighbor RACs, $S_{l,n}^{C}$, CSMC C applies the standard scheduling rule to decide whether its RAC has scored the greatest metric and thus can be self-allocated. If so, the self-allocated RAC announces such a result to its neighbor RACs through C2C immediately after the *discovery portion* elapses, i.e., in the *announcement portion* of the ASP; otherwise, the unallocated RAC waits for the maximum contention period (*defer period* + CW_{min}) expecting to hear an announcement from a neighbor RAC with a greater metric. If no announcement is heard, the CSMC instructs its RAC with the greatest metric within the *contention set* to claim the channel through C2C. Due to the advanced interference management of the carrier-type AI, same operator RACs in the *contention set* of the self-allocated RAC can claim the channel as well since other operator RACs have already retreated. However, the CSMC will optimize the transmissions of such RACs individually, i.e., bursts are not necessarily synchronous. This further mitigates the intra-LAA interference. We also recall that a UE served by an LPN of a channel RAC should not experience relatively high interference from the RAC LPNs due to the joint association and channel selection mechanism.

The overall spectrum utilization and inter-LAA fairness are determined by the computed standard *scheduling metric*. A key parameter is the CSMC's moving average of total allocated airtime over the unlicensed spectrum, $\overline{T}_C$. Using a metric such as $1/\overline{T}_C$ achieves blind equal fairness among CSMCs in terms of average total allocated airtime. Analogous to proportional fair scheduling of UEs, a metric such as $SAT_{l,n}^{C}/\overline{T}_C$ achieves an efficient tradeoff between spectrum utilization and inter-LAA fairness by incorporating the achievable SAT of the CSMC's channel RAC. Note that such scheduling parameters are broadcasted in CBs and can be easily monitored and compared by regulatory bodies to actual airtime to verify/detect a malicious activity.

E. Time-domain QoS-optimized Coexistence with WLAN

After the ASP has elapsed on a given channel, a self-allocated RAC seeks to achieve its estimated fair SAT in absence of inter-LAA contention/interference. In non-LBT regions such as USA and China, the RAC can directly reserve/transmit its bursts while abiding to the allowable MCO and applying its fair SAT as physical duty cycle for each CoexFrame similar to the individual LTE-LAA LPNs in [4]. In LBT regions such as Europe, a load based equipment may access the medium using either the combination of ED-based LBT and MCO that is proportional to CW_{min}; or the CCA mechanism of WLAN [8]. Similar to WLAN transmission of priority frames, and given the CS capability of 5G-U LPNs, the combination of priority access and estimated fair SAT can be achieved using the CSMA-like CCA of C2C to reserve DL/UL burst durations instead of the ASP. However, since the RAC grabs the channel faster than WLAN to implement the fair SAT through reservations, collisions with WLAN are not a concern. Meanwhile, intra-LAA interference from LPNs of the same or other channel RACs is managed by the 5G AI. This is of course in the absence of inter-LAA contention. Therefore, increasing the CW_{min} to recover from and avoid further collisions, e.g., exponential backoff, is not required.

[2] If supported, joint transmission of the CB as well as the CTS-To-Self is also possible to further shorten the standard duration of the ASP.

Nevertheless, we observe that there is a degree of freedom 5G-U can exploit to improve QoS in the unlicensed spectrum by optimizing the CoexFrames based on the UEs' QoS requirements, e.g., delay budgets, and provisioning as well for periodic synchronization and control signals at their due instants. This is in contrast to most WLAN coexistence literature [9,10]. Furthermore, the information about WLAN ACs could also be used to ensure that the 'OFF' portion of CoexFrame i, $\lambda(i)T_{Coex}(i)$ is adequate for successful WLAN transmit opportunities (TXOPs). However, the OFF duration will add to the packet's delay if it is not served within the maximum effective 'ON' burst, i.e., $MCO - T_{res}$, where T_{res} is the duration of the RAC reservation signals (CTSs+SIFSs) preceding the ON burst. Hence, the following constraint could be imposed on $\lambda(i)$ to aim for in-time delivery of packets with the least delay budget, $D_{p^*}(i)$, in the next CoexFrame $i+1$,

$$D_{p^*}(i) > 2\,T_{res} + w_{p^*}(i) + \lambda(i)T_{Coex}(i),\ \ 0 \leq \lambda(i) < 1. \qquad (5)$$

$w_{p^*}(i)$ is the packet's expected service delay given the UE's queue size and expected service rate at the serving LPN. Since, $\lambda(i)$ can vary from the target $\lambda_o = 1 - SAT_{l,n}$ due to this best-effort frame-by-frame optimization, an equalization step can be employed for $\lambda(i+1)$ to account for the actual OFF durations realized in previous CoexFrames, $T_{WLAN}(j)$,

$$\lambda(i+1)T_{Coex}(i+1) + \sum_{j=0}^{i} T_{WLAN}(j) = \lambda_o \sum_{j=0}^{i+1} T_{Coex}(j). \qquad (6)$$

In the following section, we use the SSI model to accurately capture the behavior of CSMA/CA and ED-based LBT transmitting a TXOP burst using uniform random CWs [7]. In each iteration, access attempts are treated as a sequence of events executed in the order of their random weights such that previous events may inhibit forthcoming ones based on CCA. However, as shown in Fig. 4, a generalization has been carried on to capture the priority access of 5G-U RACs as well as the impact of longer LTE-LAA bursts, i.e., multiple contiguous TXOPs spanning as many consecutive iterations. Similarly, dynamically optimized CoexFrames of a RAC are modeled as bursts of random numbers of TXOPs satisfying the overall estimated SAT. This is implemented using independent Bernoulli processes with the probabilities $p_{l,n} = SAT_{l,n}\ \forall\ l,n$.

IV. Simulation Results

In reference to our system model in Section II, in the first set of outdoor DL simulations, 10 UEs+10 STAs and 30 Picos+30 APs, are uniformally dropped in the geographical area of 21 Macro cells. 10 unlicensed 20 MHz channels are considered with 30 dBm maximum transmit power for APs and Picos. Legacy WiFi APs and LTE-LAA Picos employ random channel selection and maximum-received-power based association. The WiFi AP Round-Robin schedule their legacy STAs across SSI iterations on a single a channel.

As shown in Fig. 5, WiFi 1+WiFi 2 is the reference scenario. APs and STAs of WiFi 2 are replaced by Picos and UEs to assess the performance of both LTE-LAA and 5G-U. We first analyze the performance with single-LPN RACs. Two scenarios are also considered for LTE-LAA. In Scenario I, similar to 5G-U, LTE-LAA protects its bursts by allowing

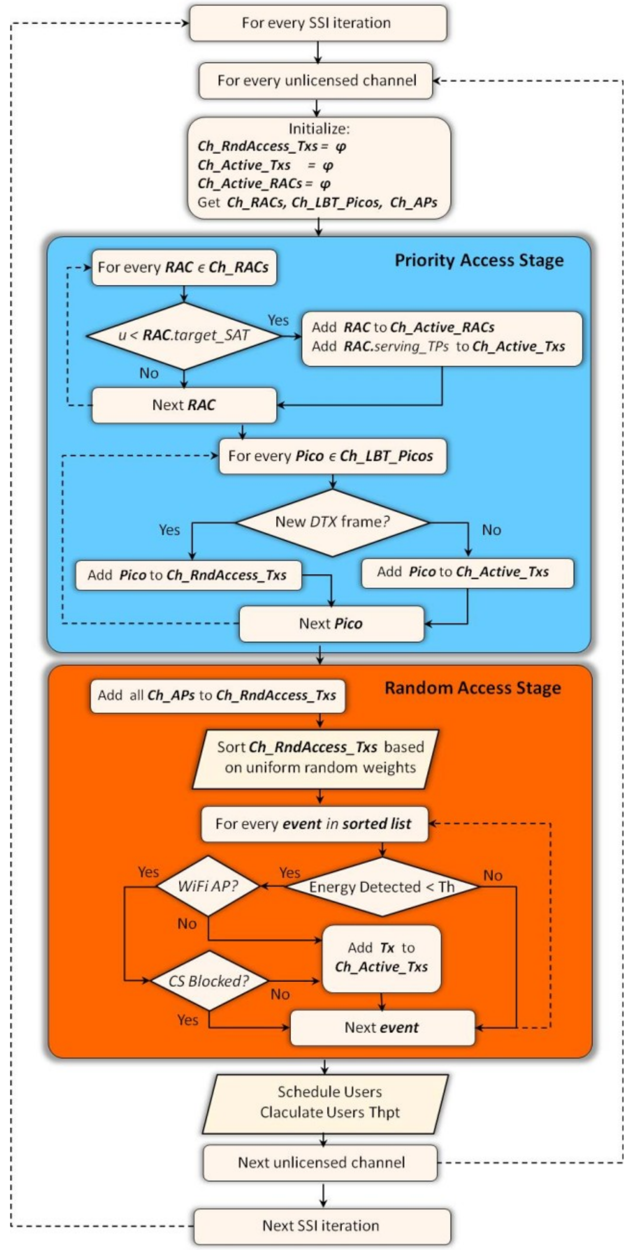

Figure 4: Flowchart of our generalized simple sequential inhibition model

WiFi to CS them at Th_{CS}^{W} = -82 dBm. Whereas, in Scenario II, LTE-LAA bursts are hidden from the WiFi nodes unless they contribute to a total energy exceeding Th_{ED}^{W} = -62 dBm. Consequently, WiFi nodes are invited to access the medium more often yet with much higher chances of collisions and increasing backoff delays. Looking at the results of Scenario I, it is observed that setting LTE-LAA DTX duration to a single WiFi TXOP and using the same ED threshold as of WiFi, LTE-LAA Picos access the medium more often than WiFi APs since both ED and CS conditions have to be met based on WiFi's CCA. As such, WiFi APs are often blocked without collision. LTE-LAA can further reduce its ED threshold, Th_{ED}^{L}, to be less aggressive but not as low as -82 dBm. However, this results in a major loss in LTE-LAA throughput. More aggressiveness is observed when increasing the number of channels LTE-LAA Picos contend on. Therein, substantially lower Th_{ED}^{L} is needed to maintain reasonable coexistence fairness. In contrast, 5G-U operating point can be tuned using the $CoexAdj$ (0.1:2) to yield the channel more often to WiFi rendering same or superior WiFi performance w.r.t. the reference scenario while achieving substantial throughput gains ranging from 79% to 98% for its UEs as compared to the LTE-LAA baseline with the least Th_{ED}^{L}. This comes along with a WiFi throughput gain of 12% to 46%. The value of the joint association and channel selection mechanism can be specifically seen in the 1Ch/10 cases where 5G-U achieves better coexistence with WiFi than both the baseline and reference scenarios, even at the most aggressive point (0.1).

In Scenario II, a reduction in LTE-LAA throughput can be observed using the same Th_{ED}^{L} and number of channels. This is due to the increase in WiFi access being incapable of CS-ing LTE-LAA. This can be seen from the improvement in WiFi throughput on this simulation platform which captures only the interference due to collisions but not the exponential backoff due to potential packet loss. Considering the practical threshold of -72 dBm [1] and comparing the 5G-U points of same WiFi performance with such optimistic points, throughput gains of 58.4%, 63%, and 53.9% are realized using 1, 2, and 4 channels, respectively.

Applying the RAC Merging while imposing more channel utilization through increasing the load (15UEs+15STAs /cell), an almost uniform throughput improvement across various $CoexAdj$ values is realized as follows: 7%, 20%, and 45.5% using 1, 2, and 4 channels, respectively. This implies that RAC Merging becomes essential with network densification, higher numbers of users, and/or higher utilization of unlicensed channels. Such an improvement comes along with an insignificant impact on WiFi throughput as the algorithm aims at serving more UEs with relatively minimal expansion of the footprint. As shown in Fig. 6, compared to LTE-LAA Scenario II, 5G-U with RAC Merging achieves significant throughput gains ranging from 42% to 118%. This comes along with a relative WiFi throughput gain of 4% to 61%. Using the ED threshold of -72dBm, and given the same WiFi performance, the coexistence throughput gains using 1, 2, and 4 channels are 60%, 61%, and 53%, respectively.

V. CONCLUSIONS

We propose a novel MAC solution for fair and efficient coexistence with incumbent WLANs and other 5G-U operator networks. Combining the carrier sensing results of surrounding WLAN activities from 5G-U LPNs and UEs, a joint UE association and channel selection algorithm maximizes the achievable long-term rates. Neighboring LPNs of the same 5G-U network opportunistically form per-channel disjoint RACs. During an active sensing phase, RACs discover their potential interferers and 'contend-to-coordinate' their self-allocation of the unlicensed channel. A self-allocated RAC dynamically optimizes its coexistence frames with WLAN to achieve the estimated soft airtime share over the coordination frame. We generalize the SSI model to accurately capture both the random and priority access modes

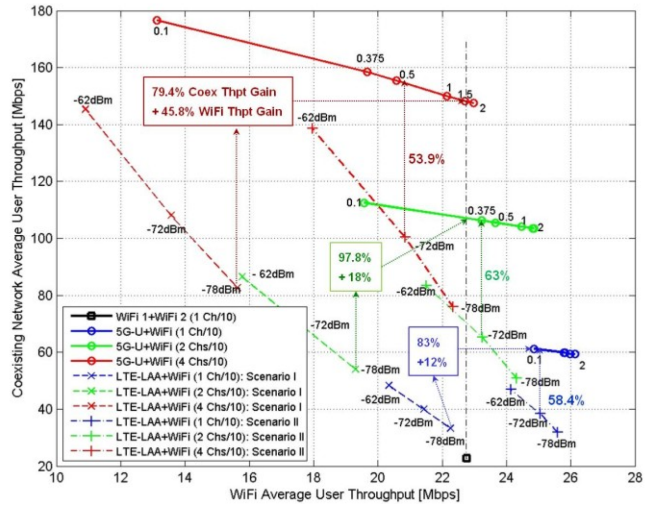

Figure 5: Results for LTE-U scenario I and II vs. Single-LPN 5G-U RACs

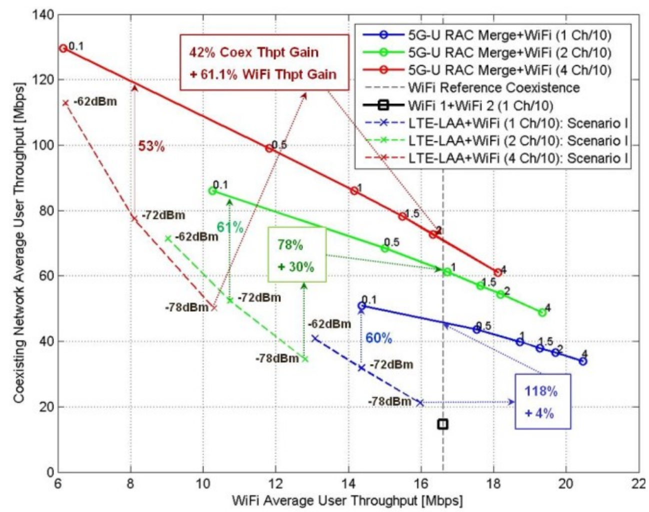

Figure 6: Results for LTE-U scenario II vs. Multi-LPN 5G-U RACs

in the downlink simulations. Results with single-LPN RACs show substantial coexistence throughput gains compared to two different models of LTE-LAA. Additional gains are realized with multi-LPN RACs in dense deployment and high channel occupancy scenarios.

REFERENCES

[1] 3GPP TR 36.889, "Study on Licensed-Assisted Access to Unlicensed Spectrum," May 29th, 2015.

[2] Wan Lei, Huawei, "LTE-based Unlicensed Carrier Offloading, Workshop on LTE-U," Paris, France, Jan 21st, 2014.

[3] P. Eldad, Next Generation Wireless LANs, Cambridge Univ. Press, 2014.

[4] Qualcomm Research, "LTE in Unlicensed Spectrum: Harmonious Coexistence with Wi-Fi," June 2014.

[5] A. Al-Dulaimi, et al, "Pursuit of More Capacity Triggers LTE in Unlicensed Band," IEEE Vehicular Technology Magazine, March 2015.

[6] A. Bhorkar, et al, "Performance Analysis of LTE and Wi-Fi in Unlicensed Band Using Stochastic Geometry," IEEE PIMRC 2014.

[7] A. Busson, et al, "Capacity and interference modeling of CSMA/CA networks using SSI point processes," Springer Telecom. Sys., July 2013.

[8] ETSI 301893 "Harmonized EN covering the essential requirements of article 3.2 of the R&TTE Directive," July 2011.

[9] M. Siddique, et al, "Spectrum sharing between IEEE 802.16 and IEEE 802.11 based wireless networks," IEEE WoWMoM, 14-17 June 2010.

[10] L. Berlemann, et al, "Coexistence and Interworking of IEEE 802.16 and IEEE 802.11(e)," IEEE VTC 2006-Spring, 7-10 May 2006.