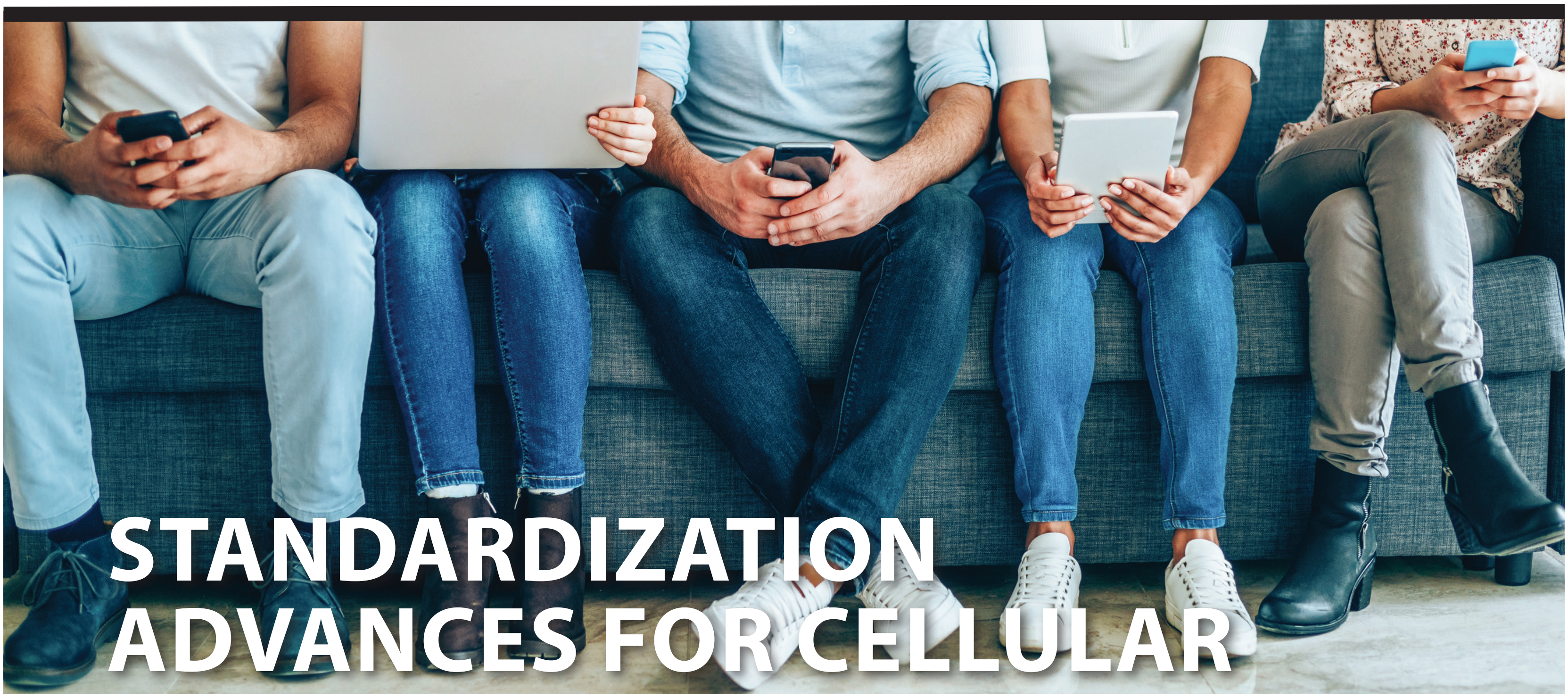
Vanlin Sathya *University of Chicago* **Srikant Manas Kala** *Osaka University*
Muhammad Iqbal Rochman and Monisha Ghosh *University of Chicago*
Sumit Roy *University of Washington*

Editors: Michelle X. Gong and Shiwen Mao



STANDARDIZATION ADVANCES FOR CELLULAR AND WI-FI COEXISTENCE in the Unlicensed 5 and 6 GHz Bands

Small-cell LTE and Wi-Fi networks are both currently deployed in the unlicensed 5 GHz bands globally, leading to the need for new coexistence regulations between two very different access technologies. 3GPP standardized LTE Licensed Assisted Access (LTE-LAA) addresses the above coexistence challenge with Wi-Fi through incorporation of similar sensing and back-off features. The success of LAA's fair and efficient coexistence with Wi-Fi can be considered a benchmark for collaborative cellular operation in unlicensed bands.

However, with ever increasing peak data rates demanded by the growth of new applications (Augmented/Virtual Reality, autonomous vehicles, etc.) as well as the continuing expansion of dense heterogeneous network deployments (Internet of Things), 5G networks in (new) unlicensed bands—such as 6 GHz—will encounter similar challenges. To that end, standardization bodies have created new study and working groups to investigate the anticipated challenges to 5G New Radio-Unlicensed (NR-U) and Wi-Fi coexistence. In this article, we present an integrated overview of the latest advances in the standardization of LTE- LAA/Wi-Fi (5 GHz) and 5G NR-U/Wi-Fi 6 (6 GHz) coexistence. We analyze the challenges in fair NR-U and Wi-Fi coexistence in the 6 GHz spectrum, with a futuristic vision for seamless coexistence in all subsequent spectrum that may be allocated for unlicensed operation.

The growing penetration of high-end consumer devices (smartphones, tablets, etc.) running bandwidth-hungry applications (e.g., mobile multimedia streaming) has led to a commensurate surge in demand for mobile data (pegged to soar up to 77 exabytes by 2022). An anticipated second wave will result from the emerging Augmented/Virtual Reality (AR/VR) industry and more broadly, the Internet-of-Things that will connect an unprecedented number of intelligent devices to next-generation (5G and beyond) mobile networks. These must therefore greatly expand their aggregate network capacity to meet this challenge. This is being achieved by a combination of approaches, including use of multi-input, multi-output (MIMO) techniques, network densification (i.e., deploying small cells) and more efficient traffic management and radio resource allocation.

Since licensed spectrum is a limited and expensive resource, its optimal utilization may require spectrum sharing between multiple network operators/providers of different types – increasingly licensed-unlicensed sharing is being contemplated to enhance network spectral efficiency, beyond the more traditional unlicensed-unlicensed sharing. As the most common unlicensed incumbent, Wi-Fi is now broadly deployed in the unlicensed 5 GHz band in North America where approximately 500 MHz of bandwidth is available. However, these 5 GHz unlicensed bands are also seeing increasing deployment of cellular services such as LTE Licensed Assisted Access (LTE-LAA). Recently, the Federal Communications Commission (FCC) sought to open up 1.2 GHz of additional spectrum for unlicensed operation in the 6 GHz band through a Notice of Proposed Rule Making (NPRM) [1]. This allocation of spectrum for unlicensed operation will thus only accelerate the need for further coexistence solutions among heterogeneous systems.

However, the benefits of spectrum sharing are not devoid of challenges, the foremost being the search for *effective* coexistence solutions between cellular (LTE and 5G) and Wi-Fi networks, whose medium access control (MAC) protocols are very different. While cellular systems employ a Time Division Multiple Access (TDMA)/ Frequency Division Multiple Access (FDMA) scheduling mechanism, Wi-Fi depends on the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) mechanism. As a consequence there have been multiple standardization efforts to facilitate LTE/Wi-Fi coexistence – notably LTE-U [2] and LTE-LAA [3]. The former was developed by an industry group, the LTE-U Forum, while 3GPP developed the LTE-LAA standard. Both standards facilitate LTE Wi-Fi coexistence, albeit through different mechanisms. The LTE-LAA standard employs a Listen Before Talk (LBT) mechanism quite similar to the CSMA/CA of Wi-Fi. In contrast, LTE-U relies on an adaptive duty cycling approach – termed as Carrier Sense Adaptive Transmission (CSAT) – based on its estimate of Wi-Fi activity through carrier sensing. In numerous circumstances, LTE-U/Wi-Fi coexistence has been shown to perform poorly [4]. The reasons are manifold but two are prominent: a) LTE-U's duty-cycle mechanism often initiates LTE transmissions during active Wi-Fi transmissions, causing co-channel interference, which in turn lowers data-rates and increases transmission errors, and b) the carrier sense mechanisms of LTE-U and Wi-Fi are inherently asymmetric [2]. Moreover, LBT for systems in the unlicensed bands, while not mandatory in the US, is required in most of the rest of the world. As a result, adoption of LTE-U by cellular carriers has been very limited to date, and 3GPP-standardized LTE-LAA is the predominant coexistence mechanism in practice, and will be our sole focus in this article.

The coexistence of Wi-Fi and LTE-LAA leads to many research challenges such as optimizing the energy detection threshold of LTE-LAA, dynamic adjustment of contention window size for fair sharing, resource allocation, and interference management. A fundamental aspect of coexistence among *dissimilar* networks such as Wi-Fi and LTE-LAA is whether the sharing is *fair* in any acceptable sense. Clearly, there are several well-accepted notions of sharing among networks – among which min-max and proportional fairness [5, 6] are well-recognized. The 3GPP definition [7] states *"LAA design should target fair coexistence with existing Wi-Fi networks to not impact Wi-Fi services more than an additional Wi-Fi network on the same carrier, with respect to throughput and latency."* In other words, the definition merely imposes a *insensitivity* requirement on Wi-Fi performance and is oblivious to actual LTE-LAA network throughput achieved in such sharing scenarios. A detailed analysis in [3] shows that the above definition does not lead to "fair sharing" under well-accepted fairness notions under many circumstances. There are *numerous* factors on *both* sides that impact any reasonable approach to fairness, and an adequate definition is needed that recognizes this complexity and seeks to balance the rights of two rather dissimilar networks. This 3GPP definition, which is quite different from traditional notions of fairness, has led to considerable dissonance among the industrial research community. Given a fairness definition consecrated in the standard, it automatically becomes a target to be met; however the inherent definitional shortcomings like those noted above are an impediment to actually achieving any accepted notions of fairness.

In this article, we describe the advances in the standardization activities of LTE-LAA/Wi-Fi (5 GHz) and propose a vision for 5G New Radio-Unlicensed (NR-U)/ Wi-Fi 6 (6 GHz) coexistence. Our primary contributions are elucidated below.

- We summarize the existing results on LAA/WiFi coexistence and discuss the evolution of standardization of the LAA/ Wi-Fi coexistence paradigm with respect to the further enhanced LAA (FeLAA) transmission procedures and the current status of real-time LAA deployments in the Chicago area.
- We summarize the FCC 6 GHz NPRM and take stock of the challenges in future NR-U/Wi-Fi operations and suggest a thematic vision on aspects such as channel access procedures and deployment methodologies.
- Finally, we discuss the respective interests of industry players and standardization working groups in the context of achieving fair NR-U/Wi-Fi coexistence. We analyze the prominent proposed solutions that are being debated, such as a common detection threshold, and common preamble and discuss the simulation (using system simulation packages such as ns-3) and experimental needs of the research community to enable future coexistence research.

LTE-LAA WI-FI COEXISTENCE: OVERVIEW

3GPP Release 13 (completed December 2015) defined LTE-LAA and catalyzed an industry-led exploration of LTE/Wi-Fi coexistence [7] in 5 GHz unlicensed band. Due to the very different underlying PHY/ MAC design philosophies of the two systems, particularly vis-a-vis channel access, it was anticipated that co-location of LTE-LAA and Wi-Fi would likely impact performance of the two constituent systems unequally.

The coexistence fairness is impacted by multiple factors viz., the contention parameters for channel access, the sensing threshold, and the transmission duration [8] explored the relative issue of differing channelization's (*i.e.*, channel bandwidth asymmetry) between LTE and Wi-Fi. Their results demonstrate that smaller bandwidth LTE-LAA transmission (e.g., 1.25 or 5 MHz) have a noticeable impact on Wi-Fi performance. Thus the latter is dependent on the location of the LTE-LAA frequency band relative to the Wi-Fi 20 MHz channel. In [9], Rochman et al. explored the effect of energy detect (ED) threshold on Wi-Fi and LTE-LAA via extensive simulations and demonstrated that if both Wi-Fi and LTE employed a sensing threshold of -82 dBm to detect the other, overall throughput of both coexisting systems improved, leading to fair coexistence.

On the other hand, Qualcomm [10] investigated the coexistence of Wi-Fi with LTE-LAA and LTE-U through simulation and showed that significant throughput gain can be achieved by aggregating LTE across licensed and unlicensed spectrum. More importantly, this throughput improvement does not come at the expense of degraded Wi-Fi performance and both technologies can fairly share the unlicensed spectrum. Ericsson in [11] explored aspects of LTE-LAA system downlink operation such as dynamic frequency selection (DFS), physical channel design, and radio resource management (RRM). An enhanced LBT approach was proposed for improving coexistence of LTE-LAA and Wi-Fi and results from a system-level simulation for 3GPP evaluation scenarios showed that fair coexistence can be achieved in both indoor and outdoor scenarios.

In summary, industry-driven research has produced mixed results. Some studies predict largely negative consequences for Wi-Fi with the proposed LTE-LAA coexistence mechanisms, and others claim that fair coexistence is feasible with necessary tweaks or enhancements. It is imperative that these conflicting inferences and conclusions are reconciled and attributed specifically to the scenarios to which they apply. Meaningful progress on this front requires a careful and transparent approach inclusive of *i.e.*, publishing results in the public based on model-based analysis of the problem coupled with experimentation and/or simulations using open source components.

While much of the coexistence effort from industry is driven by fair sharing as defined by 3GPP, academic research has explored coexistence fairness issues from a broader perspective. We next summarize some recent prior art that has contributed to this issue, including our own [12, 3]. [13] explores design aspects of LBT schemes for LTE-LAA as a means of providing equal opportunity channel access in the presence of Wi-Fi. Similarly [14] proposed an enhanced LBT algorithm with contention window size adaptation for LTE-LAA in order to achieve fair channel access as well as Quality of Service (QoS) fairness. In [15], Cano and Leith derive the proportional fair rate allocation 3 for Wi-Fi/LTE-LAA (as well as Wi-Fi/LTE-U) coexistence. Also in [16], fairness in coexistence of Wi-Fi/LTE-LAA LBT based on the 3GPP criteria is investigated through a custom-built event-based system simulator. Their results suggest that LBT (and correct choice of LBT parameters) is essential to achieving proportional fairness. In our work, we bootstrapped on the analytical model developed in [12] and enhanced it to include the impact of different sensing duration of Wi-Fi and LTE-LAA on respective system throughput during coexistence. The proposed new analytical model results were further validated via a National Instrument (NI) test-bed [12, 3]. Then, we explored the issue of fair coexistence by comparing results (coexistence system operating points) from the 3GPP definition [3] to a scheme that enforces proportional fairness whereby each node in either network achieves the same fraction-of-time access. The results conclusively show that proportional fairness is a much better notion than 3GPP fairness and produces equitable results for both networks in a larger variety of scenarios.

THE LESSONS LEARNED FROM 5 GHZ COEXISTENCE SHOULD INFORM THE DEVELOPMENT OF NEW STANDARDS FOR 6 GHZ, WHICH IS GREENFIELD FOR ALL PLAYERS: WI- FI, CELLULAR AND POTENTIAL NEW ENTRANTS

NEW STANDARDIZATION EFFORTS IN 5 GHZ: LAA UPLINK TRANSMISSIONS

LTE-LAA as specified by 3GPP in Release 13 adopted the LBT approach [3] for coexistence with Wi-Fi and supported only downlink (DL) transmissions in the unlicensed band: a secondary cell (sCell) aggregated with a licensed primary cell (pCell). Enhanced LAA (eLAA) as specified in Release 14 supports uplink (UL) operation as well in the unlicensed band as shown in Fig. 1(a). However the legacy LTE UL scheduling continued to be used in eLAA [17], thus increasing the processing delay in scheduling grants due to LBT procedures. Hence, in April 2017, the "further eLAA" (FeLAA) working group (in Release 15) was started with the objective of improving LAA DL and UL performance through an enhanced support for autonomous UL transmissions [18]. In the proposed FeLAA, a UL transmission ought to receive a grant from the eNB prior to the transmission, which solves the constraint imposed by the legacy eLAA.

FeLAA: eNB to UE Transmission Opportunity Time (TXOP) Sharing [18]

Consider a particular base station (eNB) which acquires a DL TXOP using LBT with random backoff with variable size contention window, i.e., CAT 4 LBT. Later, the eNB can share the TXOP with another UE for its UL without scheduling another grant request. The only caveat is that the total shared TXOP should not exceed the Maximum TXOP (MTXOP) limit assigned for the particular priority class [3]. In doing so, the sharing mechanism facilitates a relaxation for the UL transmission, which otherwise necessitates that a user equipment (UE) must schedule a grant before being permitted to transmit. Key players in the industry also proposed to incorporate this mechanism for Autonomous UL (AUL), especially since it does not suffer from the characteristic shortcomings of the eLAA UL. Thus, when an eNB obtains a TXOP and transmits on the DL without consuming the TXOP in entirety, it can convey this information to UEs through the Physical Downlink Control Channel (PDCCH). The UEs will then be able to transmit on the AUL with just 25μs LBT in the configured period.

FeLAA: UE to eNB TXOP Sharing [18]
As discussed earlier, the TXOP sharing mechanism was designed to aid LAA UL transmissions. When the modified regulations allowed it, it presented an opportunity for reverse TXOP sharing (from the UE to the eNB). This led several industry players to propose to 3GPP that if a TXOP obtained by a UE for AUL transmission is not fully exhausted, the UE should be permitted to share it with the eNB. The eNB then can use it to transmit control information or data to any UE with a pause and just 25 µs LBT.

DEPLOYMENT STUDIES OF LTE-LAA/WI-FI COEXISTENCE IN 5 GHZ

LTE-LAA as standardized by 3GPP developed a suite of features to enable coexistence with Wi-Fi while improving throughput of the cellular link. Most of these features have not been fully tested in the field before deployment. As LTE-LAA deployments are being rolled out in major cities in the US, they offer an opportunity for real world testing. In this section we first describe the main 3GPP coexistence features and then present some preliminary results on ongoing field testing of LTE-LAA deployments in the Chicago area.

A. 3GPP Coexistence Features

Table I describes the LAA coexistence features as proposed by 3GPP, the features implemented in the system simulation software ns-3 and those actually being deployed by carriers currently.

Multi Carrier LBT (3GPP TS 36.213): Multi-carrier aggregation is still pivotal to enhancing network capacity in the unlicensed spectrum. Therefore, LBT of LAA offers inbuilt support to multi-carrier operations through two options viz., Type A and Type B. LBT Type A offers an independent LBT (back-off) process to each individual unlicensed carrier while Type B runs only a single back-off process for a primary unlicensed carrier similar to the wide-band operation in Wi-Fi. Thus, LBT Type A ascertains the access timing of individual carriers separately depending on their specific channel conditions. In contrast, LBT Type B determines a common access timing for all carriers solely based on the condition of the primary carrier. It is therefore evident that LBT Type A is better suited to leverage multiple carriers and support carrier aggregation than Type B [19].

Transmission Mode (3GPP TR 36.889): Different kinds of transmission mode have been proposed by 3GPP for coexistence deployment: (a) DL only LAA coexisting with DL only Wi-Fi, (b) DL only LAA coexisting with DL + UL Wi-Fi, (c) DL + UL LAA coexisting with DL + UL Wi-Fi.

Carrier Aggregation (3GPP TR 36.889): LTE-LAA uses carrier aggregation in the DL to combine LTE in unlicensed spectrum (i.e., at 5 GHz for now) with LTE in licensed bands. The additional capacity provides faster data rates and improves the quality of experience for the end-user.

Antenna Configuration and Modulation Scheme: LTE- LAA offers 4 × 4 MIMO antenna configuration support and the maximum modulation coding scheme of 256 QAM.

B. 3GPP 5GHz Coexistence Deployment Scenarios (TR 36.889 V13)

LAA considers deployment scenarios with: a) macro coverage and without it, b) outdoor and indoor small cells, c) co-location and

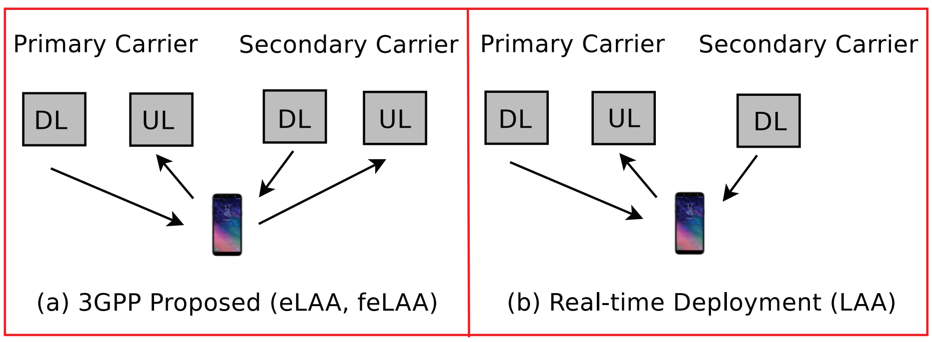


FIGURE 1. LTE-LAA Transmission Mode.

TABLE 1. LTE-LAA Coexistence Features: 3GPP Vs S/W Implementation Vs Carrier Deployment

Coexistence Features	3GPP Proposed	S/W (ns-3) Implementation	Current Carrier Deployment
LAA Architecture	Stand-alone and Non stand-alone	Non stand-alone	Non stand-alone
Transmission Mode	DL (LAA), UL + DL (eLAA, fe-LAA)	DL (LAA) is deployed and UL in licensed spectrum	DL (LAA) is deployed and UL in licensed spectrum
Multi-Carrier LBT	Type A and Type B LBT channel access procedure	Type A LBT implementation is deployed	Type A LBT implementation is deployed
Carrier Aggregation	Both licensed and unlicensed spectrum	Implemented in LTE but not in LAA	Both licensed and unlicensed spectrum
Antenna Configuration	4x4 MIMO	4x4 MIMO	4x4 MIMO
Modulation Scheme	256 QAM	256 QAM	256 QAM
Deployment Environment	Indoor and Outdoor	Indoor and Outdoor	Indoor and Outdoor

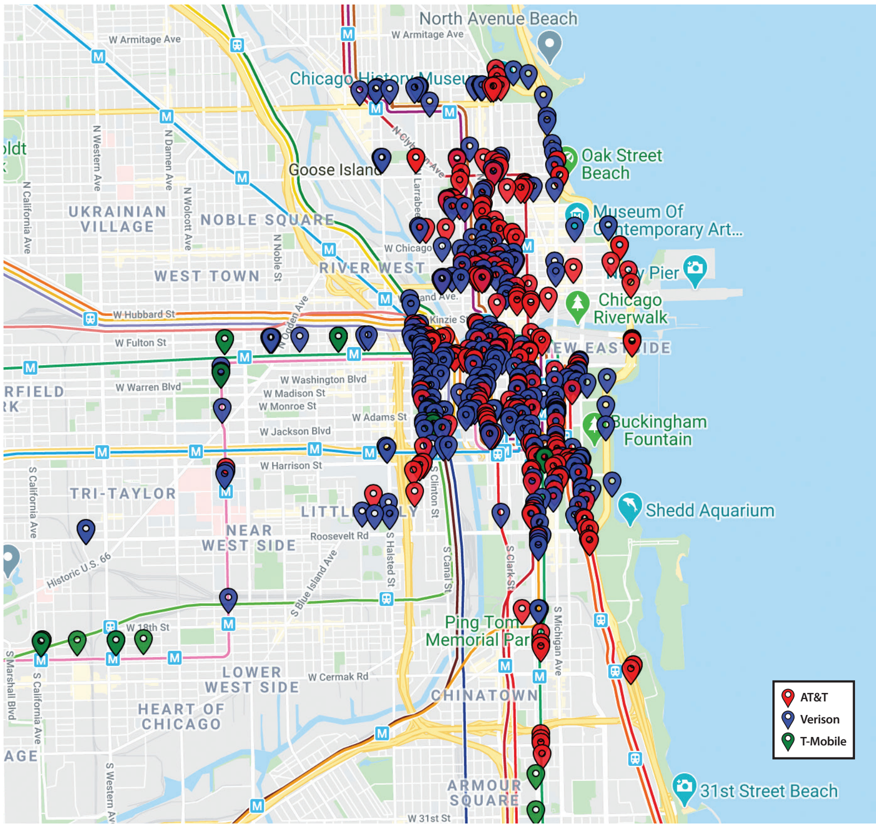


FIGURE 2. Chicago Downtown (Jan. 2020): LTE LAA Deployment by Verizon, T-Mobile and AT&T operators.

non co-location of licensed and unlicensed carriers. Depending upon the number of macro licensed carriers (F1), small-cell licensed carriers (F2) and unlicensed carriers (F3), four LAA deployment scenarios are possible.

- **Scenario 1:** Carrier aggregation between licensed macro cell (F1) and unlicensed small cell (F3).
- **Scenario 2:** Carrier aggregation between licensed small cell (F2) and unlicensed small cell (F3) without macro cell coverage.
- **Scenario 3:** Licensed macro cell and small cell (F1), with carrier aggregation between licensed small cell (F1) and unlicensed small cell (F3).
- **Scenario 4:** Aggregation between licensed macro cell (F1), licensed small cell (F2), and unlicensed small cell (F3).

If an ideal backhaul exists between the macro cell and all of small cells, then there is a possibility of carrier aggregation between these cells. Otherwise the licensed small cell and the unlicensed small cell must be connected in its own small cell cluster using an ideal backhaul. In addition, dual connectivity can be established between the macro cell and the small cell, if it is enabled.

C. Real-time Coexistence Deployments and Scenarios in 5 GHz as observed in Chicago

LTE-LAA deployments have begun in the US by the four major operators viz., AT&T, Verizon, Sprint, and T-Mobile in the following regions [20, 21] Chicago, Los Angeles, San Francisco, Indianapolis, Austin, Dallas, Houston, San Antonio, California, Florida, Alabama, Boston, etc. LAA capable mobile devices currently available are Samsung Galaxy S9, Samsung Galaxy S9+, Samsung Galaxy S10, Samsung Galaxy S10+, Samsung Galaxy S10e, Samsung Galaxy S10 5G, Apple 10S, Apple 10S max, Google Pixel 3, Google Pixel 4, LG G8 ThinQ, LG G8X ThinQ, OnePlus 7T, 7 Pro, etc.

We have just begun performing a careful measurement campaign of the LAA deployments by cellular operators, such as AT&T, Verizon, and T-Mobile in downtown Chicago and several residential areas as shown in Fig. 2. AT&T sites are marked in red, Verizon in blue, while the sites labeled in green are operated by T-Mobile. These measurements are being made using a Google Pixel 3 phone running the Network Signal Guru application [22] that enables measurement of key cellular metrics, such as signal strength, transmission parameters, channels used, etc. In this sub-section we present some preliminary observations from these measurements.

The LTE-LAA/Wi-Fi coexistence scenarios observed in Chicago are:

- Coexistence of Operator A (T-Mobile) and Operator B (Verizon) LAA with Wi-Fi in 5 GHz.
- Coexistence of one Operator (T-Mobile/Verizon) LAA with Wi-Fi in 5 GHz.

The radio predominantly used in LAA deployments was the Ericsson's micro Radio 2205 [23] which operates in the unlicensed 5 GHz band. The deployments in Chicago were generally observed to be outdoor or semi-outdoor, in spots such as street lamps, and operate on LAA channels, which are equivalent to Wi-Fi channels 36, 40, 44, 149, 153, 157, 161, 165 of the 5 GHz band. A plausible reason for outdoor deployments is that the LAA PHY/MAC derives several features from legacy LTE such as a long (71 µs) symbol duration and a limited number of starting/ending positions in a subframe. Such features reduce its suitability for indoor hotspot deployments. However, outdoor deployments may pose greater coexistence challenges than indoor deployments. If both Wi-Fi and LAA are deployed outdoors, the adverse effect of interference will be perceived fully, compared to indoor environments where walls and other obstructions may reduce interference.

Observations: The deployed LAA networks we observed have the capability of 2 × 2 MIMO transmissions with the maximum modulation coding scheme of 256 QAM. All three operators make use of a maximum of 3 unlicensed 20 MHz channels aggregated with a 20 MHz licensed carrier. We observe the performance metrics of LAA in terms of transfer speed for a 10 GB file (using the configuration listed in Table 2). The average download speed observed in T-Mobile, AT&T, and Verizon networks is 70, 53, and 47 Mbps, respectively. Similarly, the maximum download speed observed in T-Mobile, AT&T, and Verizon networks is 505, 302, and 210 Mbps, respectively. These metrics are captured in different regions (and with different load) in downtown and other residential areas of Chicago. The number of deployed Wi-Fi APs and the number of clients associated varied from one location to another. The Verizon and AT&T average and maximum data rates were observed in the downtown Chicago area where there are dense deployments of both Wi-Fi APs and LAA cells: hence the observed throughputs were lower than that of T-Mobile since the T-Mobile data rates were recorded in the residential area near the Guaranteed Rate Field stadium in Chicago and during the measurement campaign there were no games being played in the stadium and hence no Wi-Fi APs were active in the T-Mobile LAA channels. We continue to make more measurements to observe how these throughput numbers change as deployments of both Wi-Fi and LAA evolve.

We also observe that whether the secondary unlicensed component carriers get enabled or not depends upon the nature of the traffic (e.g., data, video, live streaming, etc.) and the availability of the small cell (Femto/LAA) coverage. For example, we observe that the operator does not enable the LAA unlicensed carrier for real-time live video traffic to ensure quality of service (QoS) to the connected users.

Further, we observe that the channel selection in LAA is almost static. This is in contrast to Wi-Fi channel selection which varies dynamically based on load and interference. Through several experiments we observed that there is very little LAA usage today in downtown Chicago, possibly because only a few phones today are LAA-capable and these tend to be more expensive. In many cases, ours was the only LAA phone in the cell, since all available resource blocks were allocated to our device (as reported by the Network Signal Guru app). This allowed us to perform a controlled experiment as follows. First, we turn LAA ON (i.e., the Google Pixel 3 phone is connected to the unlicensed component carrier of LAA) and requested full-buffer transmission. In this case, we observe fewer number of Wi-Fi APs on the same channel. Next, we observe a Wi-Fi/Wi-Fi coexistence scenario without LAA (i.e., no LAA unlicensed component carrier is turned ON), and requested the same full-buffer transmission using Wi-Fi. In this case, we observe a larger number of Wi-Fi APs coexisting on the same channel. From this, we conclude that the static channel allocation of LAA accommodates fewer Wi-Fi APs compared to the Wi-Fi/Wi-Fi coexistence scenario. Hence, the current deployment may pose a serious problem with respect to the static channel selection on LAA. As LAA resource allocation in a static channel increased, it adversely impacts coexisting Wi-Fi transmissions.

In most initial releases, LAA overlooked several critical points due to inadequate time, and limited knowledge and experience on the issues of coexistence in real-world scenarios as described above [24]. Such lessons learned from the 5 GHz coexistence are vital for fair and efficient coexistence deployments in 6 GHz and all future bands. We continue our measurement and experimentation campaign in Chicago to expand our understanding of coexistence in the real world.

6 GHZ BAND PROPOSED AND ADOPTED RULES

On Oct. 23, 2018, the FCC issued a NPRM with proposed rules for unlicensed systems to coexist with existing incumbents in the 6 GHz band (5925-7125 MHz) band [1, 25], followed by a Report and Order that was adopted on April 23, 2020 [26]. Similarly, the European Commission also plans to open 500 MHz in the 6 GHz band (5925-6725 MHz) for unlicensed access [27]. Hence it is clear that regulatory authorities worldwide are paying close attention to the 6 GHz band as the next spectrum band that will continue to enhance unlicensed services across the world. However, it is also clear that this band, like the 5 GHz band, will see both Wi-Fi and cellular systems being deployed, and hence the coexistence issues played out in the 5 GHz band will repeat in this new frequency as well. In recognition of this, the two principal stakeholder standardization entities, IEEE and 3GPP, held a coexistence workshop in July 2019 [28] to discuss methods to address this prior to the next generation of standards being specified. In this section, we discuss the recent activities on FCC's 6 GHz NPRM and IEEE & 3GPP efforts towards coexistence in the 6 GHz band.

TABLE 2. LAA Carrier Configuration Parameters

Parameter	Value
LAA Operating Band	46 (i.e., 5 GHz)
LAA Bandwidth per Channel	20 MHz
Maximum number of Channels	3
Number of Resource Blocks	300 RB
Transmission Power	18 dBm
Transmission Mode	Downlink
Mobility	Human walk
UE Traffic	Full Buffer

A. FCC 6 GHz NPRM

The FCC NPRM proposes to partition the 6 GHz band as shown in Fig. 3 into four new Unlicensed National Information Infrastructure (U-NII) bands with the following preliminary rules:

1) Proposed 4 U-NII bands: FCC NPRM [1] summarizes the proposed U-NII band rules for the 6 GHz band. Access points (APs) using standard power (1 W) can use 850 MHz bandwidth on U-NII-5 and U-NII-7 and low-power (250 mW) APs can use 350 MHz bandwidth on U-NII-6 and U-NII-8. There will be no operation of APs in moving vehicles such as cars, aircraft, UAVs (no clients either).

2) Proposed transmission powers: (a) *U-NII-5 and U-NII- 7 Standard-Power Access Points*: The maximum conducted output power is 1 watt and maximum power spectral density is 17 dBm in any 1 megahertz band. (b) *U-NII-6 and U-NII- 8 band Low-Power Access Points*: The maximum conducted output power is 250 milliwatts and maximum power spectral density is 11 dBm in any 1 megahertz band. (c) *Client Devices*: The maximum conducted output power is 63 milliwatts and maximum power spectral density is 5 dBm in any 1 megahertz band. For all the three cases, if a transmitting antenna with directional gain greater than 6 dBi is used, the maximum power and power spectral density shall be reduced by the amount in dBi that the directional gain is greater than 6 dBi.

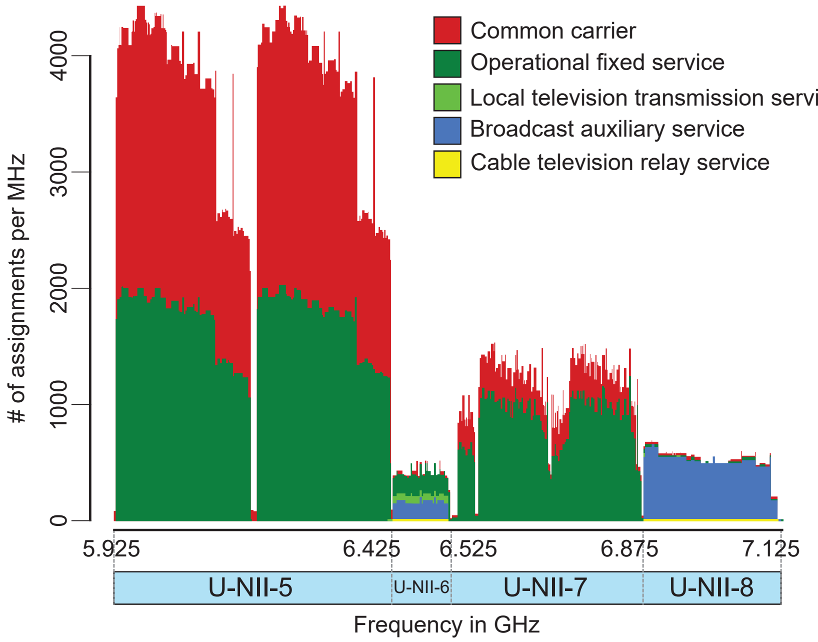


FIGURE 3. Bandwidth Allocation on 6 GHz Spectrum. [1]

3) Indoor Vs. Outdoor categories: The U-NII-5 and U- NII-7 APs need to consult a frequency database using automated frequency control (AFC) mechanism that protects the incumbent services in this spectrum from harmful interference. U-NII-6 and U-NII-8 operation is limited to indoor operation with low power access points which do not need access to a frequency database prior to transmission.

4) Existing Incumbents: The U-NII-5 and U-NII-7 sub-bands are predominantly used by fixed point-to-point microwave links and by the Fixed Satellite Service (FSS) for Earth-to-space transmissions. To protect the microwave links from harmful interference, the proposed rules would require that the standard-power access point obtains a list of frequencies upon which they may transmit from an AFC system. Similarly, the U-NII-6 and U-NII-8 bands are used for mobile stations in the Broadcast Auxiliary Service and the Cable Television Relay Service as well as fixed point-to-point microwave links.

The above rules intend to protect the fixed incumbents via a database and mobile incumbent users via low power and indoor operation only. However, there are still many open issues that need to be addressed such as determination of available frequencies, device registration, security mechanisms, what propagation models should be used to determine incumbent coverage, location accuracy requirements, aggregate interference at satellite receivers, interference to UWB devices, etc., that the FCC is seeking answers to from the research community: both academic and industry.

B. Comments on the FCC NPRM

The open comment period for the FCC NPRM produced a large number of responses from the three primary stakeholder communities: the incumbents, cellular operators and Wi-Fi proponents, with each proposing rule changes to protect their interests. In this section, we provide a short summary of some of the key points put forth by each community.

1) Comments from Incumbent Users: The incumbents urged the FCC to safeguard the incumbent 6 GHz licensed services by the creation of a reliable AFC database with the information of AP ID, position location, and power level, which is updated daily and can authenticate devices prior to activation [29]. They also propose that the AFC systems require interference protection analyses from transmissions on the neighboring and second-adjacent channels as well as co-channel interference in order to prevent interference from unlicensed devices. The National Public Safety Telecommunications Council (NPSTC) [30] recommends that both outdoor and indoor access points be required to connect to the AFC system since indoor APs could still interfere with licensed 6 GHz facilities, especially if the AP/client devices are on the high floor of a multi-storey building. The NPSTC recommends the Commission implements trial testing requirements to demonstrate that the AFC, and representative sample APs and client devices operate correctly according to the protocols and algorithms adopted. Such testing should include trial operations in a variety of environments, including urban, suburban and rural. Regular deployment of 6 GHz APs and client devices should await affirmative results of such testing.

2) Comments from the Cellular Industry: The success of LTE-LAA demonstrates the advantages of a technology-neutral approach in 5 GHz spectrum band. LAA is driving better in indoor/outdoor mobility, a reduction in call drops, and the enhancement of existing WiFi APs. Verizon recommends [31] the Commission builds on these successes and extends technology-neutral principles to unlicensed deployments in the 6 GHz band, ensuring continued innovation and enabling new and transformative technologies to emerge. While cellular operators desire to deploy 5G in the unlicensed bands, they also urged the FCC to facilitate greater mid-band spectrum availability for licensed cellular use as well, to encourage innovation, which in turn will attract the investment required for the proliferation of 5G and next generation wireless technologies.

3) Comments from the Wi-Fi Industry: The tremendous growth in the proliferation of Wi-Fi devices indoors continues to pose a challenge. The Wi-Fi industry would like the FCC to allow low-power usage in the U-NII 5 and U-NII 7 bands as well without the use of AFC, but restricted to indoor usage, with the claim that low-power combined with indoor usage will be sufficient to protect the incumbents in those bands too without the use of AFC. They claim that allocating only two, smaller sub-bands for Wi-Fi indoor operation without the use of AFC will not suffice to meet the bandwidth or channel size required to satisfy end-user data demand. Several reasons have been cited by Wi-Fi Alliance [32] to ensure that the low power transmissions will not adversely impact active transmissions of incumbent users with the claim that the high-interference scenarios described by some studies are extremely rare cases that are unlikely to be of consequence in reality.

The above interests and viewpoints from the various parties need further research and study to ensure that indeed the proposed changes will lead to fair coexistence and adequate protection of incumbents in an efficient and cost-effective manner. The implementation of databases for incumbent protection is usually a long drawn out process, e.g. in the TV White Spaces and 3.5 GHz proceedings, and hence it is understandable that the Wi-Fi industry would be against it: however more research is needed to ensure that doing so will not expose the incumbents to harmful interference.

C. Report and Order (R&O) and Further Notice of Proposed Rulemaking (FNPRM)

The FCC adopted a R&O and FNPRM on April 23, 2020 [26], taking into account the comments submitted into the record by all parties. The rules are summarized in Table 3. There were three major changes: (i) the rules will allow indoor, low-power access across the entire 1.2 GHz band (ii) while the allowed EIRP will remain at 30 dBm, the power spectral density (PSD) maximum has been reduced to 5 dBm/MHz, with the maximum 30 dBm being permitted across 320 MHz bandwidth and (iii) unlicensed devices will be required to implement a contention based protocol (similar to CSMA/CA used by Wi-Fi) that will limit the duty cycle used by unlicensed devices.

Since 6 GHz unlicensed devices (not access points) could be outdoors, the rules specified 6 dBm lower power for devices. Another change from the proposed rules is that instead of specifying a conducted power and antenna gain separately, the rules specify total Effective Isotropic Radiated Power (EIRP): this allows device manufacturers greater flexibility. The rules as adopted create operational scenarios that are markedly different from existing 5 GHz rules, which allowed for the maximum 30 dBm of transmitted power over 20 MHz bandwidth. 6 GHz unlicensed access points, on the other hand, will only be permitted 18 dBm, 21 dBm, 24 dBm, 27 dBm, and 30 dBm respectively over 20 MHz, 40 MHz, 80 MHz, 160n MHz and 320 MHz bandwidths respectively, with unlicensed devices permitted 6 dBm lower EIRPs.

The rules for standard-power outdoor access points remained essentially unchanged: these will require the use of an AFC, and devices will also be allowed 6 dBm lower power than access points.

The FNPRM posed two additional questions that will be considered: (i) should the PSD for low-power indoor devices be raised to 8 dBm/MHz and (ii) what is an appropriate power level for very lower devices to use outdoors, without an AFC, without causing interference to incumbents. The former will allow wider coverage per access point and the latter will enable high-bandwidth portable devices like AR/VR glasses.

6 GHZ COEXISTENCE: DEPLOYMENT SCENARIOS AND CHANNEL ACCESS

Although several industry entities were not in favor of a reevaluation, IEEE recommended that coexistence evaluations for NR-U should include 802.11ac (in 5 GHz), 802.11ax (in 6 GHz), and 802.11ad (in 60 GHz). For the sub-7 GHz bands, coexistence evaluations will be technology neutral (e.g., channel access mechanism) and will be performed in random carrier frequencies in the 5 GHz band. These evaluations also necessitate devising suitable 11ac/ax coexistence topologies with significant number of links below -72 dBm.

A. NR-U: Deployment Scenarios

Table 4 shows the standardization updates on 5 and 6 GHz spectrum band. The NR-U work item recently approved by 3GPP supports not only the existing unlicensed 5 GHz band but also the new unlicensed "*greenfield*" 6 GHz band. Industry players such as Qualcomm expect that in future releases other unlicensed and shared spectrum bands including mmWave will be added to this list. To investigate the functionalities needed beyond the specifications for operation in unlicensed spectrum, the following deployment scenarios will be studied [18].

- *Carrier aggregation* between licensed band NR (PCell) and NR-U (SCell): (a) NR-U SCell with both DL and UL. (b) NR-U SCell with DL-only.
- *Dual connectivity* between licensed band LTE (PCell) and NR-U (PSCell).
- *Stand-alone* NR-U.
- An NR cell with DL in unlicensed band and UL in licensed band.
- *Dual connectivity* between licensed band NR (PCell) and NR-U (PSCell).

The Legacy cellular operators oppose the NR-U stand-alone scenario and want 3GPP to drop it. They fear a stiff competition from

TABLE 3. Unlicensed 6 GHz Report and Order [26]

Device Class	Operating Bands	Maximum Power	Maximum Power Spectral Density/MHz
Low-Power Access Point (indoor only)	U-NII-5 (5.925-6.425 GHz) U-NII-6 (6.425-6.525 GHz) U-NII-7 (6.525-6.875 GHz) U-NII-8 (6.875-7.125 GHz)	Proposed: 30 dBm (1 W) Granted: 30 dBm (1 W)	Proposed: 17 dBm (50 mW) Granted: 5 dBm (3.16 mW)
Client Connected to Low-Power Access Point		Proposed: 24 dBm (250 mW) Granted: 24 dBm (250 mW)	Proposed: 11 dBm (12.5 mW) Granted: -1 dBm (0.8 mW)
Standard-Power Access Point (AFC Controlled)	U-NII-5 (5.925-6.425 GHz) U-NII-7 (6.525-6.875 GHz)	Proposed: 36 dBm (4 W) Granted: 36 dBm (4 W)	Proposed: 23 dBm (200 mW) Granted: 23 dBm (200 mW)
Client Connected to Standard-Power Access Point		Proposed: 24 dBm (250 mW) Granted: 30 dBm (1 W)	Proposed: 11 dBm (12.5 mW) Granted: 17 dBm (50 mW)

TABLE 4. 3GPP Standardization Updates on 5 GHz and 6 GHz Spectrum Band

3GPP Releases	LAA Wi-Fi Coexistence on 5 GHz Band							NR-U Wi-Fi Coexistence on 6 GHz Band					
	DL	UL	Autonomous UL	LBT	CA	Indoor	Outdoor	DL	UL	LBT	CA	Indoor	Outdoor
Release 13	✓	x	x	✓	✓	✓	✓	-	-	-	-	-	-
Release 14	✓	✓	x	✓	✓	✓	✓	-	-	-	-	-	-
Release 15	✓	✓	✓	-	✓	✓	✓	✓	✓	✓	✓	✓	✓
Release 16	-	-	-	-	✓	✓	✓	✓	✓	✓	✓	✓	✓

new players who can use NR-U standalone for limited cellular operation. NR-U is likely to be a more potent competitor to 802.11 than LAA as it will have a more flexible and efficient PHY/MAC marked by a shorter symbol duration, shorter HARQ Round Trip Time (RTT), etc. Further, NR-U can be deployed in every configuration where 802.11 is currently operational if both, standalone and dual connection, are approved. In addition, unlike 802.11, NR-U will be capable of deploying the same PHY/MAC with flexible configurations across all current and future unlicensed bands.

B. Narrowband vs. Wideband LBT in 6 GHz

The LBT mechanism is used by a device to avoid collisions by ensuring that no other transmissions are concurrently active in the channel. LTE-LAA follows CAT 4 LBT for most of its transmissions, while CAT 2 LBT is used for about 5% of DL transmissions [33]. NR-U is likely to adopt a mechanism similar to the LAA LBT. NR-U Release 16, like its predecessor, the NR Release 15, supports component carrier up to the maximum limit of 100 MHz bandwidth. In addition, it supports aggregation of several inter and intra band component carriers [34]. Multi-carrier LBT channel access as defined in 5 GHz is assumed, i.e., the Type A LBT in 3GPP TS37.213, where each channel performs its own independent LBT procedure. Consequently, there is bound to be high complexity when the operation bandwidth is wide. The alternative Type B LBT in 3GPP TS37.213 can reduce this complexity by performing single LBT on multiple channels. The wideband LBT could simplify the implementation of wideband operation when it can be guaranteed that the channel is free of narrow band interference, i.e., limiting usage of narrow band signal (20 MHz) on certain sub-bands or by long/short term measurements and LBT bandwidth adaption. Hence, wideband LBT is beneficial for systems operating with wide bandwidth as it simplifies LBT implementation.

NS-3 IMPLEMENTATION OF WI-FI AND LAA COEXISTENCE

In order to evaluate the performance of current and future Wi-Fi and cellular coexistence in realistic environments, academic and industry researchers are using a combination of analysis, simulation and real-world experimentation. Each of these methods are important in arriving at a complete understanding of the complicated coexistence scenarios enabled by the new technologies under development. One particularly important effort on the software simulation aspect is the implementation of coexistence scenarios in a widely used network simulator frame-work, ns-3. ns-3 consists of a wide range of simulation modules which includes wired and wireless networks, including Wi-Fi and LTE modules. At present, ns-3 has only implemented Wi-Fi up to 802.11ac and licensed spectrum LTE, while the work on 802.11ax and NR is currently still in progress. Therefore, this section will focus only on the 5 GHz coexistence framework that has been released.

In ns-3, modules are implemented independently of each other, therefore both Wi-Fi and LAA implementations are different even though they are contained within the same simulation framework. Hence, the "LAA-WiFi-Coexistence" module is designed to serve as a framework that unifies Wi-Fi and LAA implementations under ns-3 [35]. The LAA implementation is based on Release 13 and contains all of the indoor and outdoor scenarios defined in the 3GPP TR36.889 [7]. It modified the Wi-Fi and LTE modules to enable coexistence. For Wi-Fi, a spectrum channel model similar to LTE model is implemented, thus enabling the Wi-Fi module to sense the channel spectrum in response to LAA transmissions. The LTE module is also modified to handle LBT and TXOP procedures. An AdHoc Wi-Fi component is created in monitor mode (only to sense the channel) and tied to the LAA's procedure. This enables the reuse of Wi-Fi's CSMA procedure to enable LBT and to sense Wi-Fi transmissions.

Currently, the LAA implementation in ns-3 only supports non-standalone procedures. This implies that LAA is only deployed in downlink, while the uplink transmissions are done over the licensed spectrum. Further, it can be configured to a maximum of 4×4 MIMO and 256-QAM modulation. The current LAA simulation is also limited to one Wi-Fi channel (channel 36) with 20 MHz bandwidth. In the future, we intend to increase the number of channels that can be deployed. The full implementation of Release 16 is also planned, which will include interoperability between 802.11ax and NR-U specifications. The implementation of common preamble is also being considered.

INDUSTRY PROPOSED SOLUTIONS FOR 6 GHZ COEXISTENCE

Several ideas to improve coexistence in 6 GHz were put forth by several industry and some academic participants at the Coexistence Workshop in July 2019 [28]. In this section, we present the two that appeared to have the most consensus viz., a common Energy Detect (ED) threshold and common preamble with preamble detection (PD), as shown in Fig. 4. Although these have not yet been standardized by 3GPP or IEEE, they provide the best path forward for improving coexistence in 6 GHz.

A. Common Detection Mechanism and Thresholds

Past work by various researchers [9, 36] has amply demonstrated that the inherent asymmetry in the ED thresholds used by LTE-LAA and Wi-Fi is one of the root causes for poor coexistence between LTE and Wi-Fi in 5 GHz. Since Wi-Fi was already widely deployed in 5 GHz, it would have been difficult, if not impossible, to modify thresholds of the installed base of Wi-Fi APs and devices. However, since no such installed base exists in 6 GHz, revaluation of the protection thresholds used by NR-U and Wi-Fi 6 should be the preferred approach. The optimum ED threshold is one that not only maximizes throughput of each system individually, but also improves coexistence performance. Ongoing research on the best common threshold, - 62 dBm, - 72 dBm or - 82 dBm, will inform the standards bodies on the best way forward. Too low a threshold will lead to false “busy” detects and too high will exacerbate hidden node problems. From an implementation point of view a common ED threshold is simpler to enforce than other coexistence methods and can benefit both 802.11ax and NR-U, by facilitating additional spatial reuse gain [18].

B. Common Preamble Solution

While relying on energy detection for protection is easy to implement and does not require either system to “recognize” the other, it also has problems, the most serious being inefficient medium usage due to false detects, especially if the ED threshold is too low (e.g. - 82dBm). One solution, that does not involve explicit common preambles, is to use existing features in Wi-Fi (e.g. known training sequences in the preamble) and LTE/NR (e.g synchronization channels, OFDM symbol length) to reliably detect each other using correlation [37] and/or learning techniques [38]. However, these methods may not work reliably in all channel conditions and at low SNR. A common preamble as proposed in [39] that is used at the start of all transmissions from either system will enable robust coexistence by enabling each system to detect the presence of the other, reliably, at a low threshold of -82 dBm. In essence, this is how Wi-Fi coexists with itself and this approach has been proven to be successful. Expanding the fundamental idea to coexistence of dissimilar systems should be the preferred methodology, especially in 6 GHz, which is greenfield for both NR-U and Wi-Fi 6. While this basic idea has acceptance from both IEEE and 3GPP, it remains to be seen whether the details and a design that is acceptable to both parties can be standardized. A well-designed common preamble can also enable coexistence in scenarios where one or more systems is using directional transmissions and/or different bandwidths: an open problem even for 5 GHz. Furthermore, a long term benefit of a common preamble is that future systems, beyond IEEE and 3GPP, that wish to use the unlicensed 6 GHz spectrum may adopt the same preamble thus leading to improved spectral use for all coexisting systems, present and future.

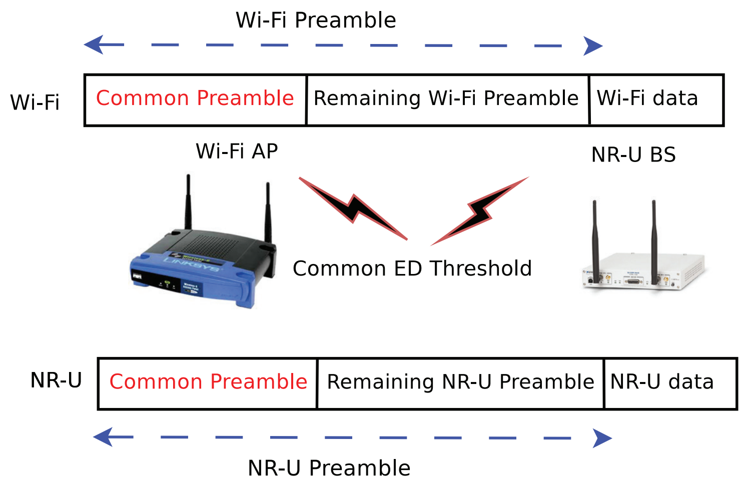


FIGURE 4. Common Preamble and ED for better NR-U Wi-Fi Coexistence in 6 GHz Spectrum.

CONCLUSION

We have presented a comprehensive overview of the standardization and beginning deployments of LTE-LAA in 5 GHz followed by a description of the proposed rules, challenges and standardization efforts in 6 GHz. The lessons learned from 5 GHz coexistence should inform the development of new standards for 6 GHz, which is greenfield for *all* players: Wi-Fi, cellular and potential new entrants. There is an opportunity to reevaluate and design all specifications to naturally coexist with any dissimilar system that may coexist in the same spectrum, for it is clear, as evidenced by recent FCC actions, that future spectrum allocations will more heavily lean towards spectrum sharing and coexistence rather than dedicated licensed spectrum. However, this will require cooperation between standardization groups, informed by the investigations and results from the broader research community, to develop coexistence methodologies (of which the common preamble is an example) that will truly address the coexistence problem from the ground up rather than after the fact. ■

Vanlin Sathya received his PhD in computer science and engineering from IIT Hyderabad, India, in 2016. He is a Postdoctoral Researcher with the University of Chicago, where he is involved in issues with 5G real time coexistence test-bed when LTE-unlicensed and Wi-Fi tried to coexist on the same channel. His primary research interests include interference management, handover in heterogeneous LTE networks, D2D in cellular networks, cloud base station, and LTE in unlicensed.

Srikant Manas Kala is a doctoral researcher at the Mobile Computing Lab, Osaka University, Japan. He received his MTech degree in computer science and engineering from IIT Hyderabad, India. He has been awarded the IIT-H Research Excellence Award in 2016 and 2017, Employee Excellence Award by Infosys in 2012, and best-paper awards in ICACCI-2015 and ICACCI-2018. His research interests lie in the domains of mobile computing and wireless networks.

Muhammad Iqbal Rochman received his BE in informatics engineering and his MS degree in computer science from Sepuluh Nopember Institute of Technology, Indonesia in 2012, and National Taiwan University of Science and Technology, Taiwan in 2016, respectively. He is currently a PhD student in computer science at the University of Chicago, USA, where he is studying the coexistence fairness between LTE and Wi-Fi in terms of throughput and spectrum access, both in real-time test-bed and simulation framework.

Monisha Ghosh (Fellow, IEEE) received her BTech from IIT Kharagpur, India, in 1986, and PhD in electrical engineering from the University of Southern California in 1991. She is currently the Chief Technology Officer (CTO) for the Federal Communications Commission (FCC). She is also a Research Professor with the University of Chicago, with a joint appointment with ArgonneNational Laboratories, where she conducts research in wireless technologies for the IoT, 5G cellular, next generation Wi-Fi systems, and spectrum coexistence.

Sumit Roy (Fellow, IEEE) received his BTech degree in electrical engineering from IIT Kanpur, in 1983, his MS and PhD in electrical engineering, and MA in statistics and applied probability from the University of California, Santa Barbara, in 1985, 1988, and 1988, respectively. He is currently an Integrated Systems Professor of electrical engineering with the University of Washington. His interests include fundamental analysis/design of wireless communication and sensor network systems spanning a diversity of technologies, and system application area, such as next-gen wireless LANs and 5G cellular networks.

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