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5 GHz Band LTE-LAA Signal Selection for Use as the Unintended Signal in ANSI C63.27 Wireless Coexistence Testing

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Abstract

This article details the experimental work conducted at the Electromagnetic Compatibility and Wireless Laboratory, U.S. Food and Drug Administration, to investigate the use of LAA signals for wireless coexistence testing. A software defined radio platform was deployed to generate realistic LAA signals and measure the wireless coexistence impact on the LAA communication link. The equipment under test (EUT) used IEEE 802.11ac as an example incumbent technology in the 5 GHz band. The standardized radiated anechoic chamber method was used for testing. Results highlight the mutual coexistence impact of LAA in the 5 GHz band and suggest that selecting an LAA signal with the maximum possible channel time occupancy and the highest possible modulation and coding scheme (MCS) yields the most impactful coexistence situation on both the EUT and the LAA system. Additionally, an analysis of the internal LAA system states during coexistence testing is presented to document the inverse relationship between LAA transmit and wait times during coexistence and the adverse impact of challenging coexistence scenarios on successful channel access. Finally, the risk management process of wireless coexistence for medical devices is summarized and associated with coexistence testing.

Keywords

Wireless coexistence; Wi-Fi; LTE; LAA; wireless medical device

I. Introduction

Wireless technology is a significant enabler of an increasing number of applications. Among other functions, medical devices use wireless technology to facilitate data retrieval by patients and care-givers, integrate mobility in the healthcare environment, and allow non-invasive communication with implanted devices. Although dedicated radio spectrum bands have been allocated by the Federal Communications Commission (FCC) in the United States and other overseas spectrum management agencies solely for medical devices[1], the use

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[1]E.g., Wireless Medical Telemetry Service (WMTS) and Medical Device Radiocommunications Service (MedRadio).

of unlicensed spectrum bands—through technologies like Wi-Fi and Bluetooth—continues to increase driven by the abundance of low-cost hardware, ease of integration, and user accessibility. The 2.4 GHz industrial, scientific, and medical (ISM) band has been a host of the majority of these applications. However, wireless medical applications are expanding to the 5 GHz band[2] and an increasing number of device submissions to the U.S. Food and Drug Administration (FDA) embed wireless functions in the 5 GHz band including radiography systems, infusion pumps, patient monitors, and others. According to the Cisco Visual Networking Index [1], the global mobile data traffic[3] will increase sevenfold between 2016 and 2021. This rapid increase in demand can be partly addressed by leveraging unlicensed spectrum bands to extend the capacity of mobile networks. Long Term Evolution (LTE) cellular system—traditionally based in licensed spectrum—is a newcomer to the 5 GHz unlicensed spectrum, which aims to fairly coexist with incumbent Wi-Fi systems (i.e., IEEE 802.11a/n/ac). In this context, fairness is often specified as not impacting Wi-Fi services more than an additional Wi-Fi network on the same carrier, with respect to throughput and latency [2]. In addition to reducing the traffic congestion on licensed bands used by mobile network operators, using LTE in the unlicensed spectrum could allow universal network management, increased system capacity benefiting from the new spectrum, and enhanced user experience. Similar design concepts and objectives are being considered in the development of the 5th generation (5G) New Radio (NR) specifications that use the unlicensed spectrum. However, operating in unlicensed bands is characterized by an inherited susceptibility to interference [3], which raises concerns for wireless coexistence.

The FDA recommends that medical device manufacturers address wireless coexistence, defined as *the ability of one wireless system to perform a task in a given shared environment where other systems (in that environment) have an ability to perform their tasks and might or might not be using the same set of rules*, in their premarket submissions [4]. Wherever unlicensed LTE systems are deployed, wireless medical devices operating in the 5 GHz band —using incumbent Wi-Fi—will have to share the wireless channel resources with users of the new technology. Additionally, novel devices may embed unlicensed LTE in their designs. Therefore, work was initiated to revise and update the American National Standards Institute (ANSI) C63.27 standard for evaluation of wireless coexistence [5], to address testing with unintended LTE-Licensed Assisted Access (LAA) signals. At the time of writing this article, the revision process is complete and the final draft will go through balloting by the ANSI Accredited Standards Committee (ASC) C63 Subcommittee 7 Spectrum Etiquette. The revised version of the ANSI C63.27 standard should equip device manufacturers and the FDA with tools to assess wireless coexistence in the 5 GHz band where devices share the spectrum resources using heterogeneous technologies (i.e., Wi-Fi and LTE-LAA).

A. Contribution

In this article, we detail the experiments conducted at the FDA's Electromagnetic Compatibility and Wireless Laboratory to investigate the use of LTE-LAA unintended signals for wireless coexistence testing. The work relied on a software defined radio

[2]Refers to U-NII bands in the 5150-5925 MHz range.
[3]mobile data and Internet traffic generated by handsets, notebook cards, and mobile broadband gateways

platform commercially available from National Instruments (NI) [6]. The platform was used to generate realistic LTE-LAA signals and establish an over-the-air communication link, over which User Datagram Protocol (UDP) packets were transmitted and the link quality metrics recorded. The ANSI C63.27 radiated anechoic chamber test method[4] was used to evaluate the wireless coexistence of an example IEEE 802.11ac equipment under test (EUT) with the LAA unintended signal. Accordingly, LAA signal temporal characteristics and modulation and coding scheme (MCS) were inspected, and the mutual LAA/EUT coexistence effects reported. The results of this investigation were contributed to the first revision of the ANSI C63.27 standard. To reduce the number of test vectors while stressing the EUT to reveal potential failures, an LAA test signal using the highest possible MCS and occupying 10 transmission subframes was recommended. Results indicate that this choice can create a state where systems operating in a shared wireless channel are most affected. This can be observed and reported in an iterative process that aims to determine the practical limits of EUT coexistence. In this study, we consider the decrease in achieved EUT link throughput as an indicator of coexistence impact.

This article goes beyond what was presented in [7] to provide further details on LAA/Wi-Fi coexistence and the observed behavior of the LAA system during testing. Specifically, throughput of the coexisting systems is recorded during testing and presented in a time series to highlight the instantaneous interactions of the two systems as a result of their heterogenous channel access mechanisms. The internal states of the LAA listen-before-talk (LBT) algorithm are logged and plotted in a probability density format to uncover how the LAA system allocated transmission and wait times relative to the programmed LAA maximum channel occupancy time and the varying channel utilization in the environment during coexistence. Evaluating wireless enabled medical devices for coexistence is a process that stems from the risk management of the device. Accordingly, we detail the risk management process of wireless coexistence in medical devices, which spans two interconnected standardized processes (i.e., for risk assessment and coexistence testing), and provide a framework for embedding the findings of this work into a realistic device development cycle. Hence, the structure of developing test-informed user recommendations is outlined and an example method is described.

The balance of this article is organized as follows. Section II provides a high-level technical background about the various solutions for enabling LTE in unlicensed spectrum bands. Section III presents the experimental work for evaluating the coexistence of wireless medical devices in the 5 GHz band. A discussion of the experimental results is provided in Section IV. The risk management process of wireless coexistence in medical devices is summarized and mapped to the coexistence testing specifications of ANSI C63.27 in Section V. Section VI concludes the article.

II. Background

When used in an unlicensed spectrum band without modification, LTE transmits continuously and does not release the radio channel, causing severe interference to Wi-

[4]Detailed in Annex D of ANSI C63.27.

Fi users [8]. This is because of the inherent design of the LTE system to operate in exclusive access, licensed spectrum bands. Consequently, to establish fair coexistence with incumbent users, unlicensed LTE needed technical modifications to facilitate spectrum sharing. Accordingly, development efforts led to the introduction of system specifications for LTE-Unlicensed (LTE-U) and LTE-LAA technologies, each meeting a unique set of regulatory constraints and design goals. Both systems are primarily intended for downlink communication (i.e., from the basestation to the user equipment [UE]), while uplink communication is carried exclusively through the mobile operator's licensed band. Designs for LTE uplink unlicensed operation are provided in enhanced-LAA (eLAA, Release 14 of the LTE specifications [9]) and MulteFire [10].

LAA was introduced in the 3rd Generation Partnership Project (3GPP) Release 13 specifications and satisfies global regulatory requirements for unlicensed spectrum access [2]. The specifications define LAA operation based on time division duplexing (TDD) in band 46 (i.e., 5150-5925 MHz). Regulations for unlicensed spectrum access vary across international regulatory bodies. For example, the use of LBT channel access strategy is not required by unlicensed bands regulations in the United States (see [3]). The case is similar in China, India, and South Korea. However, the European Union (EU) and Japan require the use of LBT for unlicensed spectrum access in addition to other requirements such as the maximum allowable channel access time. To address the variety of regulatory constraints regarding the use of LBT, LAA implements LBT in a way similar to the Wi-Fi distributed coordination function (DCF, based on carrier sense multiple access with collision avoidance [CSMA/CA]). LAA operates on a downlink secondary cell in the 5 GHz unlicensed band, while signaling between the basestation and the user equipment (UE) is maintained in the primary cell through licensed spectrum. LAA offers best effort throughput, while the primary cell offers guaranteed uplink quality of service (QoS) and reliable signaling. A new LTE frame type (i.e., Frame Structure Type 3) was introduced to facilitate unlicensed spectrum operation consisting of 10 subframes of length 1 ms as illustrated in Fig. 1. When data is available in the LAA transmission queue, the basestation employs energy detection to sense the wireless channel and determine whether it is busy or idle. The frame transmission is executed if the channel is deemed idle, otherwise the basestation backs off and waits for the channel to become available for use [11].

LTE-U is the result of an industry effort led by the *LTE-U Forum*, established in 2014 by several mobile phone manufacturers and network operators. LTE-U requires few modifications to LTE R10/11/12 physical and medium access control layers as it relies on the legacy LTE frame structures. This is facilitated because LTE-U does not implement LBT. Alternatively, a duty-cycle based *Carrier Sense Adaptive Transmission (CSAT)* algorithm is used. When transmission is active, LTE-U occupies the wireless channel regardless of other ongoing communications. When LTE-U transmission is inactive, CSAT monitors the contending nodes and adjusts the ratio of ON/OFF periods.

Alternative methods for exploiting unlicensed bands by cellular carriers include LTE/Wi-Fi link aggregation (LWA), where existing Wi-Fi networks are used to carry downlink traffic through coordination with the mobile operator. Uplink traffic remains exclusively on licensed bands. LWA does not change the landscape of used technologies from the user perspective—merely a convenient coordination between present technologies—thus coexistence concerns for Wi-Fi could be addressed by applicable standards and evaluation methods [5], [12].

Compared to other technologies, LAA stands out as one that went through several cycles of standardization in 3GPP specifications (i.e., R13 and R14), and is being used as a basis for novel standards such as MulteFire and 5G NR-Unlicensed [13], [14]. Accordingly, the focus of the C63.27 working group was directed to LAA for inclusion in the revised version of the standard. However, few experimental evaluations of unlicensed LTE technologies are published. These include trials by hardware manufacturers such as Qualcomm Inc. [15], Ericsson Inc. [16], and NI [6]. The majority of published evaluations were performed using simulation and analytical models (see [17], [18] for a survey and discussion). Other studies attempted to describe the consequences of Wi-Fi and unlicensed LTE coexistence quantitatively and qualitatively to conclude which system has an advantage over the other, the apparent effect of system parameters on coexistence, and identify potential coexistence issues. Early contributions used legacy (i.e., R10) LTE signals for the coexistence evaluation [19], resulting in severe impact on Wi-Fi nodes due to the lack of LBT mechanism for spectrum sharing. Others used realistic LAA signals like [20], where a software defined radio (SDR) system—similar to the one used in this article—was deployed to investigate the effects of diverging time synchronization on LBT time-slot accuracy. A modified LBT algorithm was proposed to alleviate synchronization errors and enhance the system throughput. Another experimental use of LAA was reported in [21] to validate an analytical model of the LAA LBT algorithm.

Coexistence evaluation plans were published by the Wi-Fi Alliance [22] and 3GPP [23] for LTE-U and LAA, respectively. Details and a comparison of these plans with the C63.27 test methods are provided in [24]. Both plans focus on specific technical capabilities of their respective technologies (e.g., the dynamic adaptation of LTE-U channel utilization (CU) with varying Wi-Fi traffic). The C63.27 standard recommends the use of specific test signals to evaluate the functional wireless performance (FWP) of an EUT for wireless coexistence. FWP is *the subset of the total functionality that both uses the wireless capabilities of the EUT and would result in unacceptable consequences if degraded or disrupted*. This is relevant in the case of wireless medical devices where the degradation of FWP may cause unacceptable risks to the patient or caregiver. The work presented in this article based on our previous conference proceeding paper [7] is novel as no other attempts were reported in the literature to identify an LAA test signal suitable for use in wireless coexistence testing or to investigate the LAA LBT systems states during coexistence. Accordingly. we detail the implementation of the ANSI C63.27 radiated anechoic chamber method for this study, and report the impact observed on LAA and Wi-Fi nodes during coexistence scenarios. Additionally, we incorporate the wireless coexistence testing performed into the overall risk management process of medical devices.

III. Experimental Work

Several coexistence test methods are detailed in the ANSI C63.27 standard [5]. Based on the medium used for electromagnetic waves propagation, test methods could be either conducted or radiated, and can accommodate a variety of scenarios (i.e., availability of test infrastructure, desired repeatability and reproducibility of test results [25], [26]…etc). Interested readers are referred to [27] for a summary of test methods. In this article we use the radiated anechoic chamber method, in which the quiet environment contributes to the repeatability of the test results. The test nodes included the EUT, the EUT companion device (cEUT), the source of the unintended signal, and the monitoring equipment (ME). Test nodes were placed in a fully anechoic chamber on non-conductive tables with 1 m height in a layout detailed in Fig. 2. All nodes were controlled remotely using cable connections. The following subsections detail the implementation of the EUT, LAA source of unintended signal, and the ME.

A. EUT

We realize a hypothetical EUT and cEUT nodes using Mikrotik RouterBOARD RB953GS-5HnT-RP boards, each equipped with R11e-5HacD radio card. The EUT was operating IEEE 802.11ac at $f_c = 5220$ MHz in station mode (STA). The cEUT operated the same wireless protocol in access point (AP) mode. To facilitate signal measurements, the transmission power of EUT and cEUT was fixed during testing and automatic power control was disabled.

The EUT was programmed to send a stream of UDP packets at a constant rate to cEUT. This is similar to several wireless medical device applications that provide regular reports to a central station (e.g., patient vital sign monitoring systems, glucose monitors, electrocardiogram, and others) or video streaming of surgical procedures in the operating room. Each test was repeated for three EUT throughput values (denoted by θ_{EUT}) to emulate multiple realistic medical device requirements for network throughput: 1) Low, 1 Mbps; 2) Medium, 15 Mbps; and 3) High, 60 Mbps (i.e., close to the maximum achievable throughput on IEEE 802.11ac network using a single transmission chain).

B. LAA source

The source of the LAA unintended signal was NI Universal Software Radio Peripheral (USRP) 2943R platform controlled through LabVIEW Communications System Design Suite and LTE Application Framework [6]. Both the LAA transmitter (Tx) and receiver (Rx) were embedded on the same unit with an internal loop-back connection for error calculation and reporting. The 3GPP R13 specifications [11] define the LAA LBT algorithm in addition to four channel access priority classes based on the type of traffic a device is communicating. Accordingly, channel access parameters are assigned according to the priority class (e.g., the minimum contention window size, the maximum channel occupancy time [MCOT, denoted by T_{MCOT}], and others). Following the design of the LAA frame structure [see Fig. 1], T_{MCOT} is set to 10 ms if the absence of any other technology sharing the channel can be guaranteed on a long term basis, otherwise 8 ms. Wireless coexistence becomes challenging the longer a transmitting node occupies the channel, resulting in increased CU and probability of collision with other channel users. Consequently, the chance for other nodes to access the channel decreases, resulting in reduced throughput and higher delays. In the frequency domain, the LAA signal occupied 20 MHz bandwidth centered at 5220 MHz (i.e., co-channel to the EUT). We used a custom platform [28] to characterize the observed CU exhibited by the LAA source when the EUT was off. The LAA source was iteratively programmed to use $T_{MCOT} \in [1; 5; 10]$ ms (i.e., 1, 5, and 10 subframes) for each transmission opportunity. The results are depicted in Fig. 3, where the x-axis refers to the programmed LAA MCS ranging from MCS 0 (corresponding to QPSK modulation) to MCS 28 (64QAM modulation). Each data point represents an error bar for which the center is the mean of 60 samples of CU values, each estimated over 1 s integration time. The length of the error bar represents two standard deviations of the CU estimate. Notably, the observed CU remained constant for varying MCS values, indicating that the change in MCS has little to no effect on CU and the main contributor to CU being T_{MCOT}. The maximum CU≈ 96% was observed when LAA operated at $T_{MCOT} = 10$ ms, which is comparable to the maximum CU exhibited by 802.11n and 802.11ac [29].

C. ME

In ANSI C63.27, identifying the EUT failure characteristics is an iterative process in which the parameters of the unintended signal are controlled to uncover the limits suitable for EUT successful operation. These include the CU, the intended-to-unintended signal (I/U) ratio of the EUT signal to the unintended signal, and the frequency allocation of both coexisting signals. The ME was a spectrum analyzer used to determine the I/U ratio, observed at the EUT and cEUT, respectively. As illustrated in Fig. 2, the ME was placed 1 m away from the EUT and $\sqrt{1 + 3.5^2} \approx 3.64$ m away from the LAA source. The intended signal was first measured when the LAA source was off. Max hold detector with 500 sweeps was used to measure the observed EUT intended signal P_O over 20 MHz bandwidth centered on f_c = 5220 MHz. Given that the testing was done in an anechoic chamber, Friis free space propagation formula was used to estimate the intended power level at the location of interest

$$P = P_O - FSPL(d) \tag{1}$$

where FSPL is the free space path loss at distance d [m]: $FSPL = 20 \log_{10} f_c + 20 \log_{10} d - 27.5$ [dB]. f_c is the center frequency [MHz]. Afterwards, the EUT was turned off, the LAA source was enabled, and a similar power measurement performed. Eq. 1 was then used twice (i.e., calculating the FSPL between ME and LAA source and then between LAA source and EUT) to determine the unintended signal level at the EUT P_U. In this study, the spatial arrangement of the test nodes (detailed in Fig. 2, which slightly deviates from that specified by ANSI C63.27) and their programmed transmission power levels were calibrated to reach an almost equal I/U ratio of 11.5 dB at the cEUT and LAA Rx antennae. This aims at establishing a fair comparison for the EUT and the LAA systems, where both have enough signal power to achieve their maximum performance in the absence of interference and an equal level of interference during coexistence. The I/U for cEUT refers to an intended EUT signal and unintended LAA signal. The opposite is true for I/U at the LAA Rx.

Unlike Wi-Fi Rx nodes that send an acknowledgement shortly after receiving a frame, LAA Rx in this setup does not emit any signals. Given that LAA Rx is passive and error reporting is done through a loop-back connection internal to the LAA platform, the deviation in test node placement from that recommended in ANSI C63.27 does not impact the outcome of

EUT performance. Notably, all the nodes are within the effective reception range of each other, i.e., the transmission by one node should successfully be detected by other nodes that are monitoring the channel during the LBT process.

Each test vector was operated for two minutes in the following sequence: 1) at $t = 0$ s: start the LAA source using a given programmed MCS and T_{MCOT} values; 2) at $t = 20$ s: start the EUT at a given programmed θ_{EUT}; 3) at $t = 80$ s: stop the EUT while leaving the LAA source running until time $t = 120$ s. 4) at $t = 120$ s: stop the LAA source. RouterOS[5] scripts were developed to automate the EUT operation and monitoring functions, which include establishing Wi-Fi AP/STA connection, initiating a UDP stream at the programmed data rate, and logging achieved throughput values for the lifetime of the connection. LAA throughput was monitored and reported using the physical downlink shared channel (PDSCH) received data that was received successfully (i.e., passed cyclic redundancy check [CRC] with OK status). The NI LabView software that implements LAA was extended to allow for throughput monitoring and other relevant data collection. Fig. 4 plots a throughput time series representation of one test vector where the EUT was set to operate at 15 Mbps and the LAA source used MCS 14 and $T_{MCOT} = 10$ ms. We note the clear impact of simultaneous operation of the EUT and LAA systems in the shared wireless channel. This impact is absent before and after the test period. In this example, the LAA link decreased in throughput while the EUT was able to maintain the desired communication function. Baseline and achieved throughput for Wi-Fi and LAA are aggregated and presented in Fig. 5 and Fig. 6.

IV. Discussion

In this section, we investigate the mutual impact between the EUT and the coexisting LAA link, with the objective of determining the LAA unintended signal that uncovers the maximum impact on Wi-Fi and LAA systems operating simultaneously in the shared environment. To do so, we fix the frequency allocation of the test nodes (i.e., co-channel) and the I/U ratio by maintaining a fixed spatial setup and constant transmission power values. The channel temporal occupancy is controlled by changing the throughout levels of the EUT and LAA T_{MCOT}. Note that the LAA implementation in the used platform always attempts to transmit and maintain an active link regardless whether data traffic was supplied or not. Additionally, the spectral efficiency of the LAA link is controlled by varying the programmed MCS modes. Accordingly, a total of 135 test vectors were evaluated—covering $\theta_{EUT} \in [1, 15, 60]$ Mbps, $T_{MCOT} \in [1, 5, 10]$ ms, and MCS taking every other value between 0 and 28.

Fig. 5 illustrates the behavior of the EUT during coexistence with LAA signals for three cases: 1) $\theta_{EUT} = 1$ Mbps (dotted red lines); 2) $\theta_{EUT} = 15$ Mbps (dashed green lines); and 3) $\theta_{EUT} = 60$ Mbps (solid blue lines). Both the baseline and the achieved EUT throughput are plotted on the y-axis with varying MCS levels on the x-axis. For the low and medium programmed θ_{EUT}, the achieved throughput closely matched the baseline, indicating little to no effect of the coexisting LAA signal—the effect of the EUT communication on

[5] https://wiki.mikrotik.com/wiki/Manual:RouterOS_features

LAA is illustrated in Fig. 6 and will be discussed later in this section. Lower throughput requirements indicate fewer attempts to access the wireless channel by the EUT, and an increased flexibility in choosing a suitable MCS to successfully achieve the desired throughput. Consequently, fewer collisions are expected with other wireless systems sharing the channel. When collisions occur, the ability to use lower MCS levels permits successful demodulation of the signal when I/U (i.e., analogous to the signal to interference ratio [SIR]) is low. When the EUT throughput requirements are high (i.e., programmed θ_{EUT} = 60 Mbps), the achieved throughput was significantly lower than the desired level. The high probability of collision, lower chance of channel access because of LAA CU, and the need for a high I/U ratio to demodulate higher MCS levels are among the contributing factors. Note that for θ_{EUT} = 60 Mbps, higher LAA T_{MCOT} resulted in greater impact indicated by the lower achieved EUT throughput. This can be explained by the correlation between the CU exhibited by the LAA system and the programmed T_{MCOT} (see Fig. 3).

Fig. 6 details the LAA throughput (i.e., PDSCH CRC OK) by comparing the achieved throughput during coexistence testing with the baseline when LAA T_{MCOT} was 1 ms (red curves), 5 ms (green curves), and 10 ms (blue curves), respectively. Notably, when θ_{EUT} was set to 1 Mbps, the achieved LAA throughput was close to the baseline for all three T_{MCOT} cases, indicating a low coexistence impact between the two systems, although LAA continuously attempted to access the channel. Conversely, EUT only transmitted when there was a data frame ready in the transmission queue. The coexistence impact became increasingly evident when θ_{EUT} was at the medium and high levels. It is clear in Fig. 6 that using a higher LAA MCS exhibited an elevated coexistence impact on the LAA link where the LAA throughput diminished close to zero. Operating the LAA link with a high T_{MCOT} would permit elevated throughput performance at high MCS values—if LAA had exclusive channel access. This is evident in the green and blue solid lines depicting the LAA baseline performance for $T_{MCOT} \in [5, 10]$ ms. However, wireless coexistence is negatively affected the longer a system occupies the channel resources, which increases the likelihood of collisions when other nodes attempt to transmit. Moreover, the collision rate increases with the demand for channel access. For example, when Wi-Fi is operating at elevated throughput leading to data continuously populating the transmission queue and prompting over-the-air frame transmissions. Upon collision, if the I/U ratio is adequate for demodulating the signal per the used MCS, the reception is successful. Otherwise, the receiver would not have enough received power to successfully demodulate the signal. The combination of the two events (i.e., I/U being adequate for a given MCS reception and collisions occurring at a rate relative to the channel access demand) can explain the reduction of LAA throughput at the low end of MCS values and the severe drop of LAA throughput at the high end of MCS values. This outcome highlights the importance of understanding the technical capabilities of a given wireless technology (e.g., expected link throughput) using a set of configuration parameters and the impact of the chosen configuration on the EUT's ability to coexist and achieve a specified function in an intended environment. Further discussion on wireless coexistence considerations relative to the EUT specified functionality is provided in Section V.

To gain further insight into the LAA system performance during coexistence, we plot the internal LAA system LBT states on Fig. 7. On the x-axis, we distinguish between the following states: startup, transmit, initial clear channel assessment (iCCA), and extended clear channel assessment (eCCA). Readers are referred to [6] for a detailed description of the LAA LBT algorithm and its implementation in the used hardware platform. The y-axis refers to the ratio of the corresponding state in the set of all observed states during coexistence (i.e., between seconds 20 and 80 of the coexistence test—see Fig. 4). We note the inversely proportional relationship between the time the LAA system spent transmitting and that spent deferring and waiting to gain channel access (i.e., in iCCA and eCCA), and how the transmission time decreased with the increase in θ_{EUT}. When comparing the case of T_{MCOT} = 1 ms [Fig. 7(a)] with that of T_{MCOT} = 5 ms [Fig. 7(b)] and T_{MCOT} = 10 ms [Fig. 7(c)], we note that the decrease in transmission time—counterbalanced by the increase in waiting time—became less evident when T_{MCOT} increased. When the LAA system acquired the channel following a successful LBT operation, it transmitted for the programmed T_{MCOT} time. Higher T_{MCOT} resulted in a long on-air time, which increased the possibility of collisions with other coexisting systems thus affecting the performance of all nodes, as depicted in Fig. 5 and Fig. 6. The opposite is true for low T_{MCOT}.

Wireless coexistence depends on sharing the wireless channel resources in time and frequency relative to the separation distance/transmission power of the systems sharing the channel. The time aspect is captured in wireless coexistence testing by the channel utilization of the unintended signal. The ANSI C63.27 standard allows the use of signal generators or real wireless networks as sources of unintended signals. However, using real networks facilitates the detection of mutual coexistence impact between the EUT and the source of unintended signals as opposed to being able to only observe the coexistence impact on the EUT if a signal generator was used. The higher the CU of the source of unintended signals, the more challenging coexistence becomes for the EUT as a result of the decreased transmission opportunity and increased probability of collision. When a single Tx/Rx pair is capable of generating a high CU, there is little room for increasing the CU value by replacing the single pair by multiple Tx/Rx pairs. This is evident in the case of LAA, 802.11n, and 802.11ac where the maximum observed CU by a single pair is greater than 90% (see Fig. 3 and [29]). Increasing the number of competing links would decrease the time share each transmitter acquires thus reducing the achievable throughput of each link [30]. However, this is only associated with a small change in the maximum observed CU [29]. For this and to maintain the test feasibility by only selecting a subset of the possible test vectors, a single source of unintended signals is typically specified in ANSI C63.27 in many cases as detailed in Annex A of the standard.

Based on the observations of increased LAA CU for higher T_{MCOT} illustrated in Fig. 3, and the results in Fig. 5 and Fig. 6, we note that an LAA test signal configured with the highest possible T_{MCOT} and MCS facilitates the detection of the strongest coexistence impact on both systems. A subset of the test vectors were repeated for an EUT using IEEE 802.11n for communication and consistent findings were observed. Accordingly, the ANSI C63.27 working group considered expanding Annex A of the standard, which details specific recommendations for testing common wireless technologies like Wi-Fi and Bluetooth, to specify that unintended LTE-LAA signals operate at the highest MCS and the maximum channel utilization. These CU and modulation characteristics are applicable to all three tiers of testing that are determined based on the criticality of FWP failure with decreasing thoroughness of testing from Tier 1 to Tier 3. For wireless medical devices, determining the adequate wireless coexistence evaluation tier is done following a risk assessment process as detailed in Section V. Tier 3 simulates EUT operation in a shared environment with enough available bandwidth to use separate channels. In this case, EUT is tested with a single LTE-LAA signal on either the lower or upper adjacent-channel. Tier 2 increases the test complexity by replacing the adjacent-channel signal with another on the co-channel of the EUT. This scenario replicates what commonly occurs in realistic deployments of local networks in unlicensed spectrum where two independent and uncoordinated networks use the same channel either by accident or because of the lack of free channels. To simulate an environment with high density of co-located network deployments, Tier 1 aggregates the recommendations of Tier 2 and Tier 3 to recommend that the EUT be simultaneously tested with LAA unintended signals on both the co-channel and adjacent-channel.

V. Risk Assessment

Including the use of wireless technology in a medical device introduces new considerations that may affect the safe and effective use of that medical device. These concerns are described in detail in the FDA guidance document referenced in [4]. Degradation or complete loss of wireless communication in a medical device could be a significant risk to the patient or user. For example, the loss of physiological monitoring of a patient in intensive care could be life-threatening. These risks can be mitigated through the careful consideration of the wireless environment and through wireless coexistence testing. The Association for the Advancement of Medical Instrumentation (AAMI) technical information report (TIR) 69 [31] addresses the risk management—referenced to the ISO 14971 standard for medical device risk management [32]—of radio frequency wireless coexistence for medical devices and systems. In principle, high risk devices call for more thorough testing, while low risk devices—wherein wireless functions have negligible impact on the safety of the patient or user—could be addressed without any testing. The AAMI TIR69 specifies four categories of risk:

- Major: could result in death or serious injury
- Moderate: could result in injury or impairment requiring professional medical intervention
- Minor: could result in temporary injury or impairment not requiring professional medical intervention
- Negligible: could result, as a maximum, in inconvenience or temporary discomfort

If a risk assessment accompanied the hypothetical EUT scenario presented in this article, it would fall into one of the above four categories of risk, which would specify the recommended level of testing from ANSI C63.27. A major category of risk should be tested to the highest tier of testing from ANSI C63.27 (Tier 1). A moderate category of risk should be tested to ANSI C63.27 Tier 2. A minor category of risk should be tested to the lowest tier of testing from ANSI C63.27 (Tier 3). For medical devices that belong to the lowest category of risk (Negligible) no testing is warranted. Presuming that our example did not belong to the Negligible category, pass/fail criteria would be specified to reflect the EUT needs to fulfill certain functions that are specified in the device FWP. This criteria could be very specific to the medical device function (e.g., all alarms should be communicated within 10 seconds) or could be specific to the wireless communication (e.g., a throughput of greater than 2 Mbps is necessary).

The outcomes of the coexistence test could be used to inform the risk management process through integrating appropriate mitigation strategies. A mitigation is often given in terms of separation distances since they are typically understandable and under control of the user. Once the I/U ratio for which the EUT is deemed to pass the test is determined, it can be coupled with a signal propagation and path loss model as appropriate for the intended use environment (e.g., free space, log-distance [33]) to extrapolate the test spatial arrangement, transmission power values, and test findings. The received signal strength at a receiver's antenna is inversely proportional to the separation distance from a transmitter. Therefore, radiated coexistence testing methods leverage a combination of modifying the transmission power of test nodes and tweaking separation distances to determine I/U. Accordingly, a simplified approach—assuming perfect propagation conditions and no multipath, shadowing, or fading—could be to linearly extrapolate $d(x)$, where x and d are the separation distances used during the coexistence test between EUT → cEUT and EUT → source of unintended signal, respectively. In addition to the origin, the point specified by the measured I/U and test arrangement can define the extrapolation line. As a result, measurement-driven user recommended practices can be established for the separation distance between the EUT and cEUT and to the nearest source of unintended signals in the environment. Accordingly, if the EUT was brought close to an interferer, the user would have an estimate of the accompanying decrease in the distance to the cEUT that should be implemented to maintain an established I/U ratio for safe operation. More sophisticated methods to develop test-driven user recommendations and further interpret wireless coexistence test results are the subject of open research and have yet to be addressed in ANSI C63.27. Test results are also helpful in the device design phase to understand the wireless coexistence challenges, plan the device functionality, and to inform the device design by optimizing its FWP upon deployment. For example, the configured packet size can be modified to achieve a desired functionality in a coexistence scenario [34].

VI. Conclusion

Medical devices benefit from unlicensed spectrum wireless technologies (e.g., Wi-Fi, Bluetooth, etc.) to offer unprecedented services to patients and caregivers. LTE-LAA is a newcomer to the 5 GHz unlicensed band. Novel medical devices might integrate LAA in their designs. These, other medical devices that use incumbent Wi-Fi technologies, and other coexisting users must share the spectrum resources. In this article, experimental work was presented to evaluate the wireless coexistence of Wi-Fi and LAA devices. The mutual coexistence impact on Wi-Fi and LTE-LAA systems sharing the same wireless channel has been identified and presented in terms of throughput time-series, probability density of LAA LBT states during coexistence, and Wi-Fi/LAA throughput trends as a function of LAA MCS and T_{MCOT}. Results indicate that an LAA test signal configured with the highest possible T_{MCOT} and MCS facilitates the detection of the strongest coexistence impact on the coexisting systems. If the EUT is a wireless medical device, a risk assessment of the EUT functions can help specify pass/fail criteria of the coexistence test. If the test results indicated an EUT failure, an iterative process begins to identify the coexistence limits of the EUT, which can be incorporated in developing user recommendations to safely operate the wireless medical device. This work is part of the revision effort of the ANSI C63.27 standard to address wireless coexistence of EUTs operating in the 5 GHz band with LTE-LAA unintended signals.

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Biography

Mohamad Omar Al Kalaa received the Bachelor’s degree in electronics and telecommunication engineering from Damascus University, Damascus, Syria, in 2008, the M.E. degree in advanced telecommunication from the École nationale supérieure des télécommunications de Bretagne, Brest, France, in 2012, and the M.Sc. and Ph.D. degrees in electrical and computer engineering from the University of Oklahoma, Norman, OK, USA, in 2014 and 2016, respectively. He is a Staff Fellow Electrical Engineer with the Center for Devices and Radiological Health (CDRH), U.S. Food and Drug Administration (FDA). His research interests include healthcare applications enabled by wireless technology, wireless coexistence of technologies in unlicensed bands, coexistence testing methodologies, cognitive radio, PHY and MAC design, and the application of machine learning in wireless communication. Dr. Al Kalaa currently serves as working group secretary of the ANSI C63.27 standard for evaluation of wireless coexistence.

Seth J. Seidman is a Research Electrical Engineer and EMC Program Advisor with more than 15 years experience with the Center for Devices and Radiological Health (CDRH) at the U.S. Food and Drug Administration (FDA). As the EMC Program Advisor he is responsible for the implementation of EMC policy matters within CDRH. He performs regulatory reviews, research, and has authored papers in the areas of medical device EMC and wireless coexistence. He is a U.S. representative to several working groups within International Standards Organization (ISO) Technical Committee 150, Subcommittee

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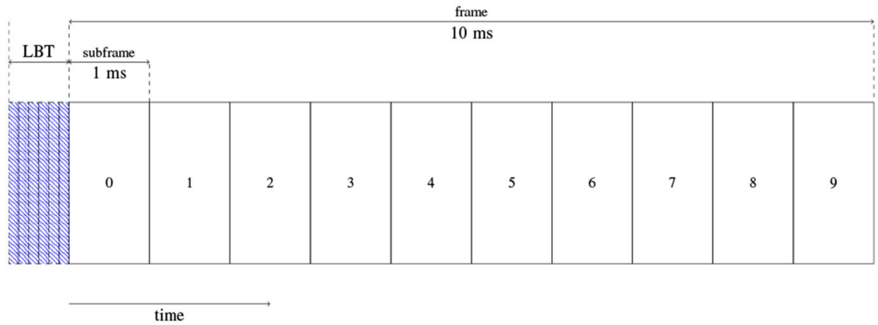

Fig. 1:
Frame Structure Type 3 used for LAA

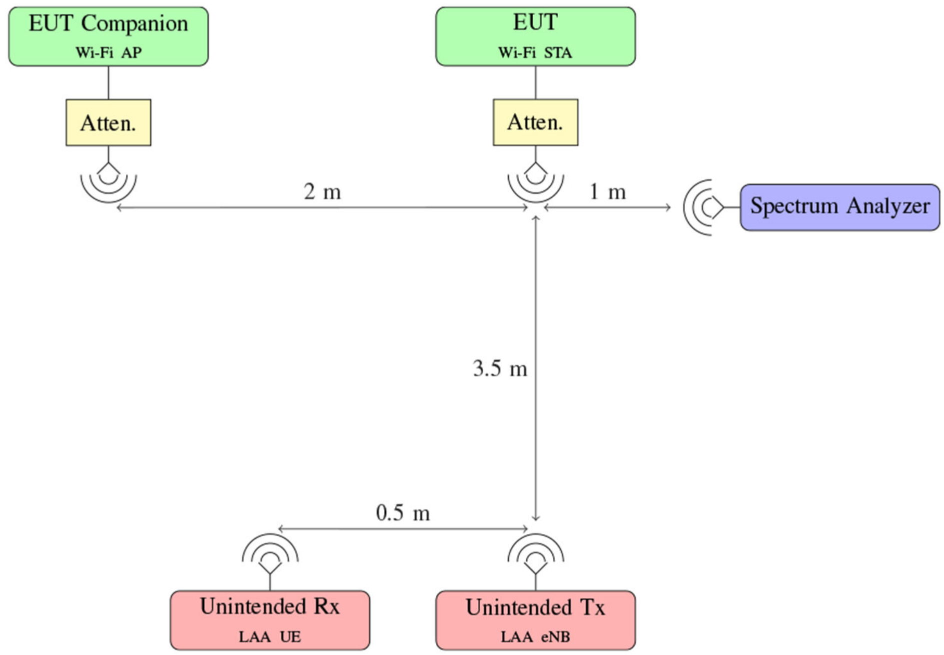

Fig. 2:

Experimental wireless coexistence test setup based on the ANSI C63.27 radiated anechoic chamber test method.

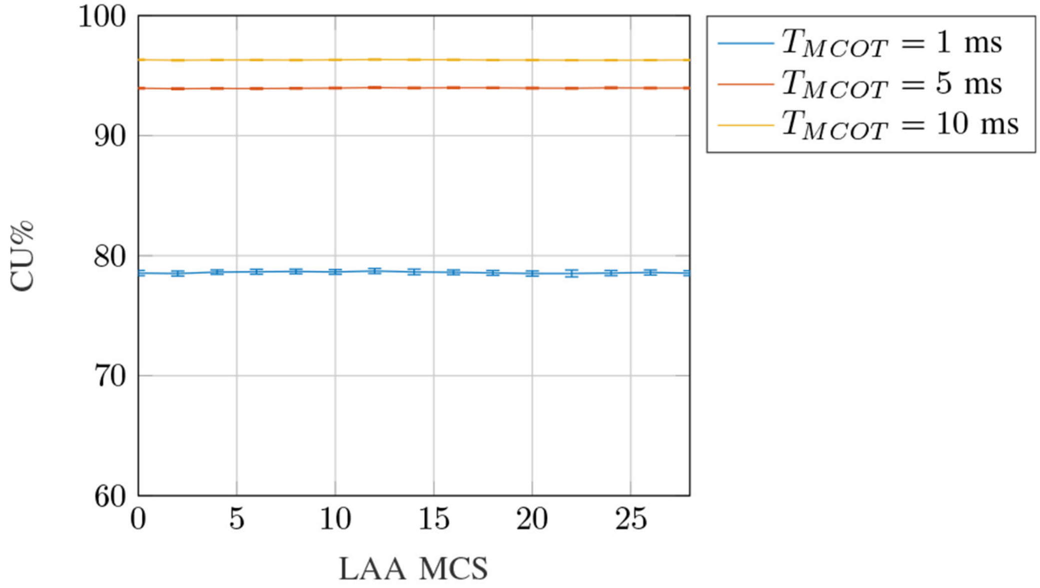

Fig. 3:
When the EUT was off, the observed CU increased when LAA used longer transmission periods. As the CU correlates to T_{MCOT}, CU does not vary with the used LAA MCS.

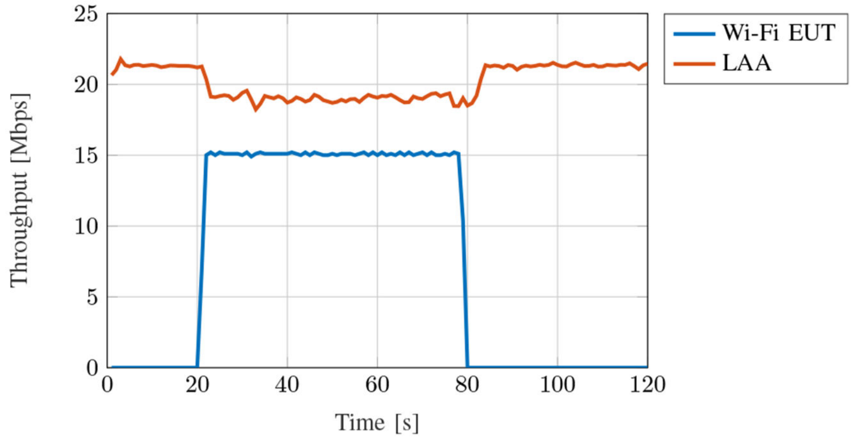

Fig. 4:
Time series of Wi-Fi EUT and LAA throughput during wireless coexistence test. In this case, θ_{EUT} = 15 Mbps, LAA source used MCS 14 and T_{MCOT} = 10 ms.

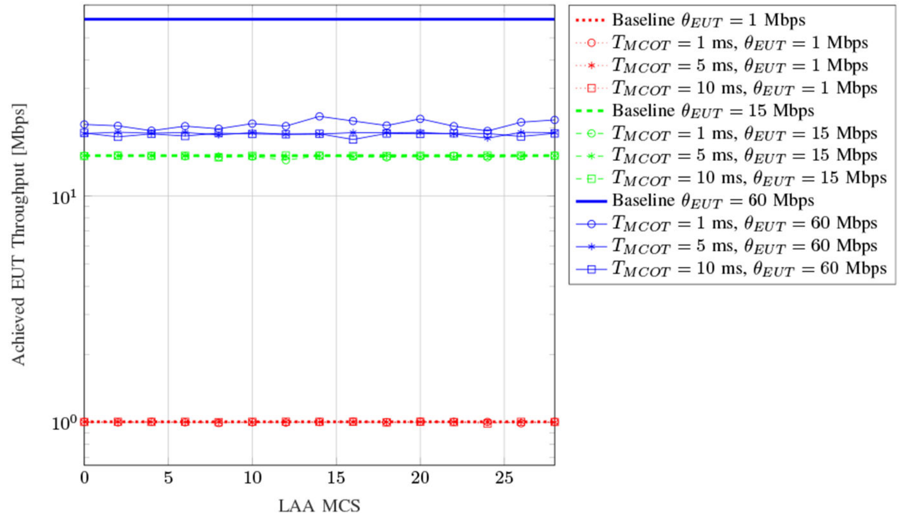

Fig. 5:

Achieved EUT throughput during coexistence with LAA. Three cases of θ_{EUT} are illustrated: Low (1 Mbps), Medium (15 Mbps), and High (60 Mbps).

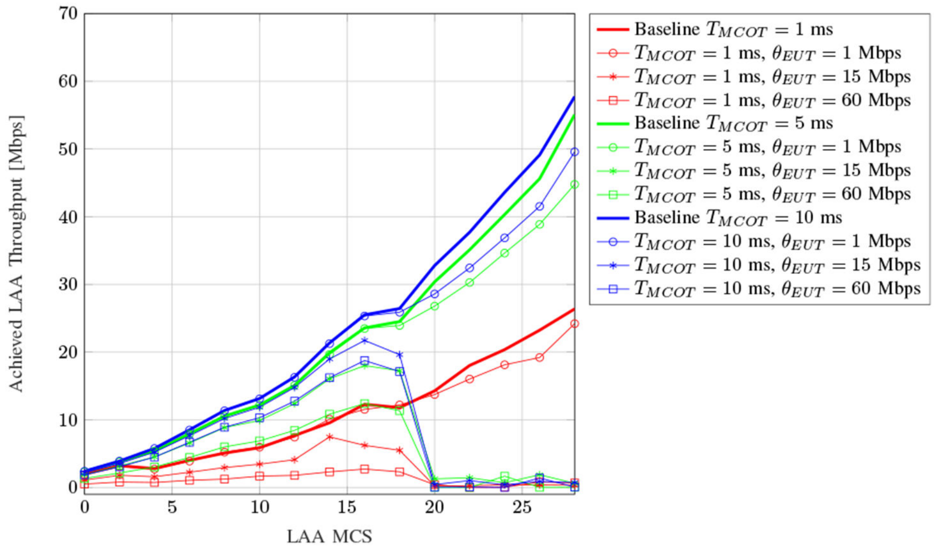

Fig. 6:

Achieved LAA throughput during coexistence with Wi-Fi EUT. LAA throughput is based on PDSCH data that successfully passed CRC check. Three cases of LAA T_{MCOT} are presented: 1 ms, 5 ms, and 10 ms.

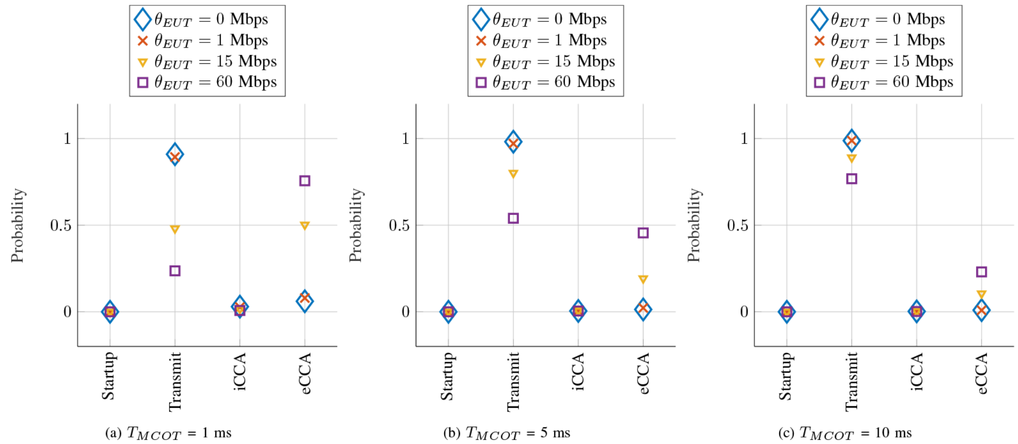

Fig. 7:

Example of LAA LBT states during coexistence testing. A baseline of the LAA communication is compared to three cases of coexistence scenarios where the EUT programmed throughput was 1 Mbps, 15 Mbps, 60 Mbps. The used LAA MCS in this example is MCS 28.