Before the
FEDERAL COMMUNICATIONS COMMISSION
Washington, D.C. 20554

Office of Engineering and Technology and Wireless Telecommunications Bureau Seek Information on Current Trends in LTE-U and LAA Technology	ET Docket No. 15-105

REPLY COMMENTS OF QUALCOMM INCORPORATED

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SUMMARY

The overwhelming majority of commenters wisely encourage the Commission to maintain its very successful technology neutral path, which has enabled the deployment of highly useful wireless technologies and will enable the timely development and deployment of LTE-U, LAA and MuLTEfire™ technology (collectively referred to as "LTE Unlicensed"). The record demonstrates that LTE Unlicensed will provide consumers with a vastly improved user experience and fairly share spectrum with Wi-Fi and other uses without any adverse impact. Many wireless industry stakeholders, including Qualcomm, have a strong vested interest in this result as they rely heavily on the continued success and evolution of Wi-Fi.

Qualcomm and many other unlicensed and licensed wireless industry stakeholders have worked together and through a number of industry organizations and associations (*e.g.*, 3GPP, ATIS, IEEE 802, the LTE-U Forum, and the Wi-Fi Alliance ("WFA")), to develop and explain LTE Unlicensed specifications that ensure successful spectrum sharing with Wi-Fi and other unlicensed users. The specifications include these coexistence techniques: (i) the identification and use of a vacant unlicensed channel or the "least crowded" channel; (ii) for LTE-U, developed through the LTE-U Forum, the use of a listen-before-talk technique called Carrier Sensing Adaptive Transmission ("CSAT"), which enables LTE-U operations to take turns with other nearby unlicensed users, or for LAA, being developed through 3GPP, the use of specific energy-based Listen-Before-Talk specification using Clear Channel Assessment, and (iii) adaptive channel occupancy based on detection of other nearby unlicensed nodes, be they Wi-Fi, LTE-U, LAA or MuLTEfire, and vacating the channel when it is not needed.

Qualcomm demonstrated LTE Unlicensed using these coexistence techniques at the Consumer Electronics Show and Mobile World Congress. We have shown numerous demonstrations to key Wi-Fi equipment vendors and service providers in our labs and over the

air on our San Diego campus in hyper-dense settings showing LTE Unlicensed successfully coexisting with Wi-Fi. Qualcomm's demonstrations have proven that adding a neighboring LTE Unlicensed node does not impact an existing Wi-Fi node any more than would adding another Wi-Fi node. In fact, in many cases, replacing a Wi-Fi node with an LTE-U node improves throughput for nearby Wi-Fi users.

In response to some commenters claiming that LTE-U will interfere with Wi-Fi unless LTE-U operates with an energy detection level that is 20 dB more sensitive than the level that Wi-Fi itself uses to decide whether a channel is available for use, Qualcomm recently ran additional tests that are detailed in the Appendix to these reply comments. These additional tests confirmed that LTE-U successfully shares spectrum with Wi-Fi when realistic parameters are used. These tests likewise confirmed that LTE-U actually improves Wi-Fi performance. In other words, LTE-U protects Wi-Fi to a greater degree than Wi-Fi protects itself. In short, the arguments put forth by opponents of LTE Unlicensed lack technical merit.

Qualcomm explains in detail in the technical appendix to these comments why LTE-U is such a friendly neighbor to Wi-Fi. LTE-U uses a Time Division Multiplexed spectrum access protocol that leaves the unlicensed channel available for use by other unlicensed users and scales very well with node density since each LTE-U node deterministically clears the channel after using a fair share of the channel resources. In this way, LTE-U is an improvement over current Wi-Fi implementations that use a random access scheme known as CSMA, which does not guarantee fair sharing of the channel resources and thus does not scale well with node density.

There is absolutely no basis for any new FCC regulation with respect to LTE Unlicensed. The development and deployment of LTE Unlicensed are the type of innovations that the FCC seeks to foster through its highly successful policies for unlicensed spectrum. LTE Unlicensed offers significant benefits for consumers by using many of the advanced technical innovations of 4G LTE and incorporating them into small cells that will use licensed and unlicensed spectrum to provide greater capacity for smartphones and tablets. Also, LTE Unlicensed brings into the unlicensed realm certain attributes from cellular that are crucial for successful wide scale deployments, including uniformity of base station and device implementations, rigorous performance and conformance specifications, and certification procedures.

As this filing details once again, and as others explained in their opening comments, LTE Unlicensed, in all of its forms, has been designed to fairly share spectrum with Wi-Fi. Mobile consumers and wireless providers heavily rely upon Wi-Fi and 3G/4G technologies, and virtually all smartphones sold today support Wi-Fi and 4G LTE; therefore, the industry at large has every incentive to ensure that Wi-Fi operations do not suffer harmful interference from LTE Unlicensed and both unlicensed technologies continue to perform well. No commenter can dispute this fundamental fact. As LTE Unlicensed technology is developed and deployed, Wi-Fi will be enhanced in response, and vice versa. Indeed, Qualcomm and the wireless industry are working to ensure that both Wi-Fi and LTE Unlicensed continue to improve, support increased capacity, and provide a great user experience.

LTE Unlicensed is one of many innovations that the wireless industry is developing to enhance consumers' user experience through using each sliver of spectrum in the most efficient manner possible. The FCC's technology neutral policy has worked exceedingly well for the nation and made these innovations possible. The FCC should continue this successful policy, and Qualcomm applauds the FCC's strong ongoing commitment to this policy. The FCC can be assured that LTE Unlicensed, in all its forms, will share spectrum with Wi-Fi and other unlicensed uses in an equitable manner because it is in everyone's interest to do so.

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REPLY COMMENTS OF QUALCOMM INCORPORATED

QUALCOMM Incorporated ("Qualcomm") respectfully submits these reply comments in response to the Office of Engineering and Technology and Wireless Telecommunications Bureau Public Notice seeking information on current trends in LTE Unlicensed technology.[1]

Many commenting parties appropriately recognize that the FCC's technology neutral policy has enabled countless unlicensed technologies to be developed and provided to consumers and should similarly allow the innovative LTE Unlicensed technology to be provided to consumers without delay. These commenters applaud the FCC's acknowledgment that it "has historically adopted rules that are technologically neutral and [that it] remains committed to this policy."[2] Like Qualcomm, many commenters are very excited by the significant user experience enhancements that LTE Unlicensed offers. As one of the developers of the technology, Qualcomm plans to incorporate it into the wireless chips, software, and firmware that we provide for small cells, smartphones, tablets, and other devices.

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[1] *See* Office of Engineering and Technology and Wireless Telecommunications Bureau Seek Information on Current Trends in LTE-U and LAA Technology, FCC Public Notice, DA 15-516 (rel. Oct. 5, 2015) ("Public Notice").

[2] *See, e.g.*, AT&T Comments at 6 (citing Public Notice at 2); Telecommunications Industry Association ("TIA") Comments at 1 (same).

INTRODUCTION

The comments filed in response to the Public Notice show that there is a high level of excitement among a wide array of wireless industry stakeholders about the much-improved user experience that LTE Unlicensed will provide to mobile consumers in terms of increased throughput, better coverage, and low latency broadband connectivity. Indeed, LTE Unlicensed is a critically important new wireless technology given that mobile broadband data demands are continuing to skyrocket and service providers need to use all of the available licensed and unlicensed spectrum resources to service consumers' needs.

As Qualcomm and others demonstrated in their opening comments, LTE Unlicensed does not cause harmful interference to Wi-Fi operations in the 5 GHz band. And, not only does LTE Unlicensed provide improved performance when compared to Wi-Fi, but LTE Unlicensed is at least as good a neighbor to Wi-Fi as well-behaving Wi-Fi is to itself. Given the important role that Wi-Fi and other 5 GHz unlicensed technologies play in today's wireless ecosystem, it is in the interest of every wireless industry stakeholder to ensure that LTE Unlicensed successfully shares spectrum with Wi-Fi and other highly useful unlicensed uses.

The record details that wireless companies, trade associations, and standards groups have been working together for many months to ensure that LTE Unlicensed, in all of its forms, coexists successfully with all other uses of unlicensed spectrum. There have been numerous bilateral and multilateral technical meetings between and among companies developing LTE Unlicensed technology and those who develop and deploy Wi-Fi technology. This important work will continue as LTE Unlicensed is refined and ultimately deployed. The opening comments explain that many companies developing LTE Unlicensed technology also develop and/or deploy Wi-Fi technology, so it is critically important that the newer technology successfully share spectrum with Wi-Fi and all other unlicensed uses.

The FCC's light-touch, technology-neutral regulatory regime — which typically sets emission bandwidths, maximum in-band transmit power and out-of-band emissions limits, and allows any technology that meets those requirements to be deployed — has worked well for countless unlicensed spectrum bands. Those parties opposed to LTE Unlicensed provide no valid reason why the Commission should deviate from this policy. The FCC should maintain its current pro-consumer, pro-innovation, technology-neutral policy so LTE Unlicensed and any future useful unlicensed technology that successfully shares spectrum with other unlicensed users can be freely developed and experienced by consumers as soon as possible.

DISCUSSION

I. Many Commenting Parties Agree That LTE Unlicensed Technology Will Provide Mobile Consumers With A Greatly Improved User Experience

Numerous commenters recognize that LTE Unlicensed will provide mobile consumers with a greatly improved user experience through enabling much higher data download and upload speeds, lower latency data connections, better coverage, and much smoother transitions between licensed and unlicensed spectrum bands.[3] To serve the ever-increasing demands of today's wireless consumers, these parties explain that the wireless industry is constantly researching and developing technologies to improve capacity and enhance the service provided to consumers, and LTE Unlicensed is such a technology.

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[3] *See* Alcatel-Lucent Comments at 2; Alliance for Telecommunications Industry Solutions ("ATIS") Comments at 1, 3; AT&T Comments at 2; Competitive Carriers Association ("CCA") Comments at 2, 8-9; CTIA Comments at 3; Ericsson Comments at 1-2; Huawei Comments at 10; Nokia Comments at 3, 12; Qualcomm Comments at ii, 3-4; T-Mobile Comments at 5; Verizon Comments at 1, 5-6.

LTE Unlicensed will be particularly useful in high traffic areas that need to support increased data throughput and highly reliable broadband connectivity. At the same time, the offloading to Wi-Fi that often occurs today in order to ease congestion on mobile networks will not change. Accordingly, service providers will continue to have a strong vested interest in ensuring that LTE Unlicensed shares spectrum equitably with Wi-Fi and that Wi-Fi does not suffer harmful interference.

II. Numerous Commenters Detail The Extensive Work That The Wireless Industry Has Done To Ensure That LTE Unlicensed Does Not Interfere With Wi-Fi

Broadband service providers and equipment suppliers explain how LTE Unlicensed has been carefully designed to successfully share spectrum with Wi-Fi operations, which is critically important because Wi-Fi technology supports a significant portion of wireless Internet traffic and plays an important role in providing mobile broadband service to consumers.[4] In fact, today's mobile consumers make use of licensed and unlicensed spectrum each and every day through their use of smartphones, tablets, and other mobile devices that support a variety of wireless technologies and spectrum bands. Thus, LTE Unlicensed must not only successfully share spectrum with Wi-Fi but also with other unlicensed spectrum uses.[5]

LTE Unlicensed has undergone extensive testing in the laboratory and in the field, using the latest version of 5 GHz Wi-Fi, *i.e.*, 802.11ac, running on a wide variety of top-selling 5 GHz Wi-Fi equipment. These tests showed that LTE Unlicensed has no adverse impact on Wi-Fi and

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4 *See* Alcatel-Lucent Comments at 4; ATIS Comments at 4; CTIA Comments at 11; Ericsson Comments at 1, 13; Qualcomm Comments; Verizon Comments at 2.

5 *See* Alcatel-Lucent Comments at 7-8; ATIS Comments at 4; AT&T Comments at 6; CCA Comments at 2, 9; Consumer Electronics Association (CEA) Comments at 5-7; CTIA Comments at 7; Ericsson Comments at 2, 7-13; Nokia Comments at 11-14; Qualcomm Comments; T-Mobile Comments at 1; Verizon Comments at 4-5.

that adding an LTE Unlicensed node provides a much improved user experience while introducing no more interference to a Wi-Fi node when compared to adding another Wi-Fi node. Notably, testing conducted separately by Qualcomm and Ericsson shows that replacing a Wi-Fi node with an LTE Unlicensed node improves the throughput for adjacent Wi-Fi users.[6] And, Qualcomm's tests of LTE-U in conjunction with latency-sensitive Wi-Fi uplink operations, such as VoIP calling over Wi-Fi, or latency-sensitive Wi-Fi downlink operations, such as watching a YouTube video over Wi-Fi, showed no degradation of any kind to Wi-Fi.[7]

A. All Three Versions Of LTE Unlicensed — LTE-U, LAA and MuLTEfire — Will Successfully Share Spectrum With Wi-Fi

LTE-U, the first version of LTE Unlicensed that uses a channel anchored in a licensed spectrum band, works with existing 3GPP Releases 10/11/12 and was developed by the LTE-U Forum. LTE-U uses several mechanisms to avoid interfering with Wi-Fi:

i. a listen-before-talk technique in which the small cell senses the spectrum to identify and begin operating in a vacant channel, and if there is no vacant channel, to begin operating in the least used channel using Carrier Sense Adaptive Transmission ("CSAT") as explained below;

ii. CSAT, an adaptive duty cycle technique in which LTE-U takes turns with other users and never uses the channel for longer than its proportionate share; for example, LTE-U never transmits for more than 50 milliseconds continuously, and when it does transmit, it has periods of off-time on the order of at least 1 millisecond, so Wi-Fi signals can support latency-sensitive applications, such as Voice over Internet Protocol ("VoIP") calls and the connection setup; and

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6 *See* Ericsson Comments at 10-11; Qualcomm Comments at 6-7, 17-19.

7 *See* Qualcomm Comments, App. A at Slide 25.

iii. an "on/off" switch, so the unlicensed band is used only when needed and vacated quickly when it is not needed to allow others complete access to use it.[8]

In its opening comments, leading Wi-Fi technology provider, Cisco, expressed appreciation for the variety of mechanisms that the LTE-U technology developers established to enable the new technology to coexist fairly with Wi-Fi.[9]

Licensed Assisted Access ("LAA"), the second version of LTE Unlicensed that uses a licensed anchor channel, is being standardized in the upcoming 3GPP Release 13. LAA will incorporate certain bandwidth constraints required by the ETSI spec and a specific Listen-Before-Talk protocol required in Europe and Japan. LAA will implement coexistence mechanisms that allow it to fairly coexist with Wi-Fi. Like LTE-U, LAA will use frequency selection to operate in the least used channel, and it will vacate the spectrum when it is not needed. Late last month, the 3GPP Release 13 LAA study item was successfully completed in the 3GPP RAN 1 group.[10]

Earlier this month, after the filing of initial comments in this proceeding, the 3GPP Release 13 LAA work item was formally approved for downlink operations, and technical parameters were included so that uplink operations can be added to a future 3GPP release without modifying the downlink-only design. This was a significant milestone for LAA, and it reflects a global consensus throughout the wireless industry that LAA will coexist successfully

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8 The LTE-U Forum, which demonstrated that LTE-U can coexist with Wi-Fi, has released specifications for both mobiles and base stations, and a technical report demonstrating successful LTE-U and Wi-Fi coexistence. *See* Alcatel-Lucent Comments at 7-8; CTIA Comments at 14; Ericsson Comments at 9-11; Nokia Comments at 11-12; Qualcomm Comments at 17-18; T-Mobile Comments at 11; Verizon Comments at 4-5.

9 *See* Cisco Comments at 8.

10 The Technical Report associated with this Study Item is available on the 3GPP website, *accessible here*: http://www.3gpp.org/DynaReport/36889.htm.

with Wi-Fi. LAA will continue to be developed through the 3GPP standards process to enable uplink and downlink operations and support successful coexistence with Wi-Fi.[11]

The third version of LTE Unlicensed, a standalone mode called MuLTEfire that will operate in unlicensed spectrum exclusively, will use similar spectrum sharing mechanisms to fairly share the spectrum with Wi-Fi. As Qualcomm explained in its Comments, while MuLTEfire will lack the benefits of an anchor channel in licensed spectrum, it still will provide improved performance when compared to other currently available technologies that use unlicensed spectrum.[12]

All versions of LTE Unlicensed will comply with the FCC's Part 15 rules for mobile operations in the 5 GHz band and Part 96 rules for mobile operations in the 3.5 GHz band.

B. Qualcomm And The Wireless Industry Are Continuing To Improve Wi-Fi Technology As LTE Unlicensed Is Being Developed And Deployed

While Qualcomm and its wireless industry partners are developing and refining the three versions of LTE Unlicensed detailed above, the industry is working just as hard to improve the capabilities of Wi-Fi. Most Qualcomm cellular (3G and LTE) chips include support for 802.11ac, and, over the coming years, Wi-Fi and LTE operations in unlicensed bands will continue to improve, support increased capacity, and enhance the user experience. In fact, Qualcomm recently announced improvements to its 802.11ac multi-user MIMO Wi-Fi chipsets, including support of 160 MHz-wide channels in the 5 GHz band to provide a much-improved consumer experience.[13] Qualcomm is combining 5 GHz 802.11ac Wi-Fi with 60 GHz

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11 *See* Alcatel-Lucent Comments at 8; AT&T Comments at 4; CEA Comments at 7; CTIA Comments at 14; Ericsson Comments at 12-13; Huawei Comments at 6, 9; Nokia Comments at 12-13; Qualcomm Comments at 17-18; T-Mobile Comments at 8.

12 *See* Qualcomm Comments at 6, 20.

13 *See* Qualcomm Comments at 7, n.6.

unlicensed spectrum where 802.11ad will be used to provide ultra-fast broadband connectivity throughout a home or office and high-capacity zones in living rooms, conference rooms, and classrooms.[14]

Qualcomm also is a key contributor to the IEEE 802.11ax standardization process. This interface under development will eventually become the successor to 802.11ac. Qualcomm plans to fully support Wi-Fi and LTE Unlicensed technologies well into the future and thus will ensure that both technologies coexist successfully in bands where they will operate on the same channel.

III. Many Parties Note That The Wireless Industry Has Been Working Together For Months To Ensure That LTE Unlicensed Successfully Coexists With Unlicensed Users

Many commenting parties also point out that the wireless industry has been working together via bilateral and multilateral technical discussions and face-to-face meetings to ensure successful spectrum sharing among LTE Unlicensed, Wi-Fi, and other unlicensed technology uses.[15] There have been extensive communications for many months on LTE-U between LTE-U Forum members and the WFA and its member companies, as the WFA itself acknowledges,[16] and between 3GPP and IEEE 802 on LAA. Many of the same companies are members of 3GPP, IEEE, and the WFA, and thus have internal experts on both Wi-Fi and LTE technologies.

The LAA standardization efforts in 3GPP involve numerous member companies that design, develop, manufacture, and deploy both cellular and Wi-Fi technologies. Also, most of

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14 *See also* Qualcomm OnQ Blog, "Capacity is King" (June 1, 2015) *accessible at* https://www.qualcomm.com/news/onq/2015/06/01/capacity-king.

15 *See* Alcatel-Lucent Comments at 6-7; ATIS Comments at 1, 5; CEA Comments at 7; CTIA Comments at 2; Ericsson Comments at 10-13; Nokia Comments at 10-11; Qualcomm Comments at 8; T-Mobile Comments at 4-5, 8-9.

16 *See* Wi-Fi Alliance Comments at 10.

the key LTE-U Forum participants develop and/or deploy Wi-Fi products and services, and LTE-U Forum members are participants in the WFA coexistence evaluation group. Qualcomm and others provided a detailed list of the interactions in the opening comments.[17]

Since the filing of opening comments, 3GPP announced that it will hold a technical workshop on LAA in Beijing on August 29, 2015. 3GPP invited representatives from the IEEE, WFA, WBA, ETSI, ETSI BRAN, GSMA, CCSA, FCC, and OFCOM. The meeting invitation is accessible here: RP-151095. Also, LTE-U Forum members will deliver a presentation on LTE-U at next month's IEEE 802 Plenary Session.

There is no question that bilateral and multilateral technical discussions among interested stakeholders are the best way to work through technical issues, and these efforts will continue among the companies working on LTE Unlicensed and companies developing and deploying Wi-Fi technology. Thus, we agree with Cisco that "industry standards forums are the best place to resolve co-existence problems between unlicensed technologies that will use the shared resource of radio spectrum."[18]

IV. Virtually All Commenting Parties Agree That The Commission Needs To Firmly Remain On Its Highly Successful Technology Neutral Path To Spectrum Regulation

An overwhelming majority of commenters agree that the FCC should reaffirm that as long as an unlicensed technology satisfies the minimal technical requirements, there is no need

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17 *See* Alcatel-Lucent Comments at 6-7; Ericsson Comments at 10, 12-13; Qualcomm Comments at 15-17.

18 Cisco Comments at 5 ("For LTE-U/LAA, we want to engage in the technical debates and understand the consequences both as a Wi-Fi manufacturer and a manufacturer of LTE technology").

for further regulatory involvement beyond ensuring compliance with those requirements.[19] Commenters also agree that the FCC's longstanding technology neutral approach towards spectrum regulation — for both unlicensed and licensed spectrum bands — has enabled the introduction of many useful technologies that have delivered tremendous benefits to consumers.[20] LTE Unlicensed is the latest innovative technology that significantly increases the efficiency of unlicensed spectrum use and dramatically improves consumers' mobile broadband experience.

The FCC's technology neutral approach to both licensed and unlicensed spectrum regulation has supported perpetual innovation in wireless by the entire industry. The FCC should continue its successful technology neutral policy to existing and future spectrum bands, and Qualcomm applauds the Commission's strong statement in the Public Notice that it "remains committed to this policy."[21] With regard to the development and deployment of LTE Unlicensed, the FCC record firmly establishes that this new technology will share spectrum with Wi-Fi and other unlicensed users in an equitable manner. Indeed, the companies developing and deploying LTE Unlicensed rely heavily upon reliable access to Wi-Fi — and they will continue to do so for many years into the future — so it is in their interest to ensure that there is successful spectrum sharing between the two unlicensed technologies.

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19 *See* AT&T Comments at 2, 6; Ericsson Comments at 6; CCA Comments at 10-11; CEA Comments at 1-2; CTIA Comments at 2-3, 7; Nokia Comments at 5, 14; Qualcomm Comments at i, 9 ; TIA Comments at 2; T-Mobile at 3.

20 *See* ATIS Comments at 6; AT&T Comments at 2, 7; CCA Comments at 10-11; CTIA Comments at 2; Ericsson Comments at 5; Nokia Comments at 4; Qualcomm Comments at v, 9; TIA at 1-2; T-Mobile at 3; Verizon at 8.

21 Public Notice at 2. Technology-specific regulation slows innovation. *See, e.g.*, AT&T Comments at 8; CEA Comments at 7-9; CTIA Comments at 1-2, 11; and TIA Comments at 3.

V. Parties Opposed To LTE Unlicensed Misstate The Factual Record And Demand FCC Intervention To Impose Harmful And Unnecessary Technology-Specific Regulations

A handful of misinformed parties have raised issues that are meritless and others that lack any basis in reality. These parties also ask the FCC to impose requirements on LTE Unlicensed that would deter continued innovation in the unlicensed bands and would unquestionably harm the public interest.

A. Claims That LTE Unlicensed Will Harm Wi-Fi Are Plain Wrong

The record before the Commission establishes that LTE Unlicensed can be and will be deployed in a manner that ensures successful sharing with Wi-Fi. Claims that LTE-U and LAA will undermine competition in the wireless market and harm consumers by degrading Wi-Fi, Bluetooth, and Zigbee[22] are way off the mark for at least several reasons. *First*, LTE Unlicensed is invigorating competition in the unlicensed device marketplace, for it is encouraging Wi-Fi technology developers to improve the capabilities of Wi-Fi more quickly than they otherwise would in order to better compete with LTE Unlicensed.[23] By way of example, the next version of Wi-Fi, called 802.11ax, will incorporate many of techniques that LTE uses to provide enhanced spectral efficiency, including the use of the OFDMA modulation scheme, synchronized operations, improved frequency reuse, and less overhead transmissions.

Second, LTE Unlicensed cannot possibly degrade Bluetooth and Zigbee because those technologies do not operate in the 5 GHz U-NII bands (and are not expected to operate in the recently authorized 3.5 GHz band) where LTE Unlicensed will operate. *Third*, as Qualcomm

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[22] *See* Cablevision Comments at 13; NCTA Comments at 27-28; *see also* Google Comments at 9.

[23] *See, e.g.*, Qualcomm Comments at 7 (noting the improvements being made to Wi-Fi technology).

and others have explained, those developing and deploying LTE Unlicensed have every incentive to ensure that the new technology successfully shares spectrum with Wi-Fi because Wi-Fi technology is used by millions of Americans every day, and it is embedded into smartphones, tablets, and other mobile devices that equipment suppliers and service providers sell to consumers.[24] The last thing these companies would do is enable a new technology that causes harmful interference to an existing technology that their customers heavily rely upon.

The LTE-U Forum. Some commenters complain that the LTE-U version of LTE Unlicensed is pre-standard or proprietary, and thus can easily be modified to monopolize the unlicensed band and create coexistence issues with Wi-Fi.[25] As Qualcomm explained in its opening comments, LTE-U is not pre-standard or proprietary. The LTE-U Forum specifications are publicly available, and any technology company can build LTE-U equipment. LTE-U uses the standard LTE PHY/MAC waveform from 3GPP Releases 10/11/12 along with the band definition, coexistence techniques, and test specifications detailed in the publicly available LTE-U Forum documentation.

The LTE-U Forum specifications, like other specifications, do not set specific parameters for the various coexistence techniques by design. Instead, they provide a high-level description and leave the implementation details to equipment providers to allow for vendor differentiation. Wi-Fi specifications similarly allow for vendor differentiation for some important channel access parameters, and the 3GPP standardization process follows a very similar approach, particularly

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[24] Thus, any and all claims that operators will undo coexistence algorithms to undermine Wi-Fi, *see* Cablevision Comments at 3, 9-10, NCTA Comments at 14, 23, are completely false.

[25] *See* Aruba Comments at 1; Broadcom Comments at 1; Dynamic Spectrum Alliance (DSA) Comments at 3; IEEE 802 Comments at 1; Ruckus Wireless Comments at 1, 3; ViaSat Comments at 3; WFA Comments at 5; xG Technology Comments at 1.

in the upper layers.[26] For example, the Wi-Fi rate control algorithm is not specified by the IEEE; it is left to the equipment supplier to allow for vendor differentiation. Even Google notes that there is a "wide variety" of vendor implementations of the rate control algorithm.[27] There also are different CSMA parameters used for different Wi-Fi implementations that operators can alter during operation.

Qualcomm also explained that coexistence techniques described in the LTE-U Forum documentation are an integral part of LTE-U, and it is not possible for an entity deploying the technology to disable them. The typical Operations, Administration, and Maintenance ("OA&M") parameters that an equipment manufacturer allows an operator to modify are very minimal in order to limit operational variation and streamline the deployment process.[28]

Use of a Licensed Anchor Channel. Some parties oppose the versions of LTE Unlicensed that rely upon a licensed anchor channel, claiming that it somehow gives those with licensed spectrum unfair access to unlicensed spectrum.[29] As Qualcomm and others explained, the use of a licensed anchor channel to support LTE Unlicensed improves the user experience and actually limits the amount of time that the unlicensed channel is used.[30] Both versions of LTE Unlicensed that use a licensed anchor, *i.e.*, LTE-U and LAA, use the licensed spectrum to support control signaling and other essential communications link signaling, such as acquisition,

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26 *See* Qualcomm Comments at 14, 21.

27 *See* Google Comments, Att. A at 9, n.13 ("Rate control is a very vendor-specific aspect of Wi-Fi, and a wide variety of algorithms are seen. Some algorithms automatically reduce the rate of the subsequent frame whenever a frame error occurs, while others reduce rate only after multiple errors are observed within some time window.").

28 *See id.* at 13.

29 *See, e.g.*, WISPA Comments at 4.

30 *See* Alcatel Lucent Comments at 8; Qualcomm Comments.

access, registration, paging, and mobility. Their use of the unlicensed spectrum band is thus minimized, and the use of the licensed anchor ensures that when the unlicensed band is used, consumers enjoy the best possible mobile broadband experience. Furthermore, one of the core benefits of LTE-U/LAA is the use of a single unified LTE core network that supports both licensed and unlicensed channels to enable the most efficient use of spectrum and best user experience possible.

B. Filings from Cable Interests Seeking to Delay LTE Unlicensed Are Incorrect

Cablevision and NCTA allege that the wireless carriers have opposed the development of a standalone version of LTE Unlicensed to prevent unlicensed competitors, such as cable companies, from utilizing the technology.[31] This is incorrect. Qualcomm announced that it is actively developing MuLTEfire, a standalone version of LTE Unlicensed that can be deployed by small businesses, enterprises, venue owners, Internet service providers, cable companies, and mobile operators.[32]

Cablevision and NCTA claim that LTE-U and LAA lack effective sharing mechanisms, and others claim that there is insufficient information about how LTE-U and LAA will manage coexistence with Wi-Fi and other unlicensed users.[33] These parties should review the detailed documentation on the LTE-U Forum website[34] as well as the detailed technical information

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31 *See* Cablevision Comments at 18; NCTA Comments at 33-34.

32 *See* Qualcomm onQ Blog, "Introducing MuLTEfire: LTE-like performance with Wi-Fi-like simplicity" (Jun 11, 2015); *see generally* Qualcomm Comments.

33 *See* Cablevision Comments at 1, 17; NCTA Comments at 7-13, 15, 18-22, 26-28; *and see* WFA Comments at ii; Wireless Internet Service Providers Association (WISPA) Comments at 1; Microsoft Comments at 1; Ruckus Wireless Comments at 2

34 *See* LTE-U Forum Documents *accessible at* http://lteuforum.org/documents.html.

provided in the comments filed by the LTE-U Forum member companies.[35] They also should review the detailed work done in 3GPP.[36] Finally, Appendix A to this filing contains yet additional technical information and test results. It's simply not fair to say that the extensive technical information provided is insufficient.

From the outset, both LTE-U and LAA have been designed to ensure that they will coexist very well with Wi-Fi and other unlicensed technologies. In developing LTE-U and LAA, the criterion for this coexistence has been that LTE-U or LAA will not have any adverse impact on a given Wi-Fi node, *i.e.*, that an LTE-U or LAA will node not negatively impact a Wi-Fi neighbor any more than another Wi-Fi node would impact a Wi-Fi neighbor. The extensive test results submitted into the record, which used the latest version of Wi-Fi, *i.e.*, 802.11ac, all verified that LTE-U does not have any adverse impact on Wi-Fi and, in fact, showed that LTE-U is a good neighbor to Wi-Fi, even in a very dense environment.[37] While Qualcomm found that LTE-U is as good a neighbor to Wi-Fi as well-behaving Wi-Fi is to itself, there are some poor Wi-Fi implementations that are bad neighbors to Wi-Fi. This result is not surprising given that the WFA does not test for coexistence between two unaffiliated Wi-Fi nodes; it only tests for interoperability between Wi-Fi Access Points and client devices.

NCTA also makes statements that are just incorrect, despite the extensive information, briefings, and demonstrations about LTE-U that Qualcomm has provided to NCTA, CableLabs, and others in the cable industry. According to NCTA, LTE was not designed to deal with

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35 *See generally* Alcatel-Lucent Comments; Ericsson Comments; Qualcomm Comments; and Verizon Comments.

36 *See generally* Alcatel-Lucent Comments; Qualcomm Comments.

37 Thus, claims that LTE-U coexistence testing used outdated versions of Wi-Fi and failed to represent real-world interference conditions, *see* NCTA Comments at 13-15; ViaSat Comments at 1-2, are completely false.

interference from other unlicensed users "because it operates in licensed spectrum that is totally controlled by a single operator and guaranteed to be interference free."[38] But, as NCTA should know, LTE Unlicensed technology has been designed to operate in unlicensed spectrum that is shared by all users in compliance with the FCC's regulations. NCTA next complains that the Qualcomm demo that NCTA saw at the Consumer Electronics Show included "only eight network nodes" while the average home contains eleven devices. Here, NCTA is incorrectly equating access points with user devices. The average home has one wireless router and the stress test demonstration that Qualcomm presented at CES used eight routers all sharing the same channel — a far greater number of routers and much more intensive spectrum use scenario than what is seen in typical installations. Qualcomm's demo showed that as the number of nodes (*i.e.*, Access Points) in a confined location changed from Wi-Fi to LTE-U, the LTE-U nodes produced substantial throughput gains, and the throughput of the remaining Wi-Fi nodes increased, thus showing that LTE-U will substantially improve the mobile broadband consumer experience.

C. Coexistence Specifications and Further Conformance Testing Confirms LTE Unlicensed Is As Good A Neighbor To Wi-Fi As Well-Behaving Wi-Fi

Qualcomm carried out additional testing to examine certain scenarios identified by parties opposed to LTE Unlicensed.[39] These tests, which are detailed in the Appendix to these reply comments, confirm that LTE Unlicensed successfully coexists with Wi-Fi and that adding a neighboring LTE Unlicensed node does not impact an existing Wi-Fi node any more than would adding another Wi-Fi node. The testing shows that replacing a Wi-Fi node with an LTE-

[38] NCTA Comments at 16.

[39] *See, e.g.*, Google Comments, Att. A.

U node improves the average throughput for nearby Wi-Fi users, just as Qualcomm's prior testing showed.

It is totally improper to compare the coexistence test results of LTE-U/LAA and Wi-Fi to single-link, interference-free Wi-Fi throughput, like the parties opposed to LTE Unlicensed did, and to use this "test data" to declare poor LTE-U to Wi-Fi coexistence where Wi-Fi throughput drops below 50% of the interference-free Wi-Fi throughput rate. The test results detailed in the Appendix to these reply comments show that when two neighboring Wi-Fi Access Points share a single channel, the Wi-Fi throughput drops below 50% of the single-link Wi-Fi throughput. Moreover, commercial Wi-Fi Access Points today often display unequal sharing behavior with each other, both in terms of throughput and medium utilization time, as Qualcomm and others have noted. And, more importantly, the Wi-Fi throughput when sharing a channel with another Wi-Fi communications session is often lower than the Wi-Fi throughput when it shares the same channel with an LTE-U session.

These tests replicated the scenarios presented in the opposing comments and collectively showed that LTE-U coexists very well with Wi-Fi when LTE-U is operating either above or below Wi-Fi's Energy Detect ("ED") level. LTE-U exhibited no adverse impact on Wi-Fi whether Wi-Fi is operating in downlink or uplink, and, in nearly all cases, LTE-U was a better neighbor to Wi-Fi than another Wi-Fi node was. As explained in the Appendix to these reply comments, the testing the opposing parties conducted for LTE-U/Wi-Fi coexistence below the ED level utilized extremely pessimistic and impractical technical assumptions. Using a far more realistic setup, Qualcomm's testing demonstrated that, contrary to what these parties claim, LTE-U improved Wi-Fi performance, and that while LTE-U fairly shares airtime with other unlicensed users, many existing Wi-Fi nodes do not share the medium fairly when operating near other Wi-Fi nodes.

In the case of co-channel coexistence below ED level, the current Wi-Fi specification does not protect other unlicensed technologies, including LTE-U or LAA. Wi-Fi nodes back off from each other using CSMA if both of their primary channels are aligned. Comparing the CSMA requirement (at -82 dBm) to the ED level (-62 dBm), Wi-Fi is 100 times more aggressive to non-Wi-Fi technology than to another Wi-Fi node. Also, in practical implementations, Wi-Fi nodes do not protect each other below the ED level on the secondary channel if the primary channels are not aligned. If a Wi-Fi node has secondary channels overlapping with neighboring Wi-Fi but does not sense neighbors on the primary channel, our test results demonstrate that commercial APs do not back off to each other, which leads to poor coexistence.

Other technical arguments made about potential harms to Wi-Fi also are mistaken as described in the Appendix to these reply comments. Further tests confirm that LTE-U has a negligible impact on Wi-Fi beacon delivery or latency sensitive Wi-Fi applications, such as VoIP. The LTE-Forum's coexistence specifications also mandate coexistence with Wi-Fi uplink and downlink traffic, and require LTE-U nodes to disable transmission into the unlicensed band when there is no need for it in order to prevent unnecessary interference. Thus, LTE-U will improve Wi-Fi performance when compared to adding an unaffiliated Wi-Fi node.

D. <u>The Design Of LTE Unlicensed Ensures Successful Sharing With Wi-Fi</u>

While the Carrier Sense Adaptive Transmission ("CSAT") technique used in LTE-U and the Carrier Sense Multiple Access (CSMA) technique used in Wi-Fi are based on carrier sensing and share the same objective of fair coexistence, they use fundamentally different approaches built on different sharing concepts.

While CSMA focuses on fair access to the medium, it does not guarantee fair sharing of the spectrum resources among Wi-Fi access points, much less between Wi-Fi access points and nodes using other technologies. This is because a Wi-Fi node using longer transmission duration compared to other nodes in the network will end up using more air time. Such a greedy Wi-Fi node that transmits for more than the maximum allowed time will have higher throughput because all other Wi-Fi nodes will back off until the greedy node finishes transmitting. And, as the density of Wi-Fi nodes increases, the ability of random access to enable time division multiplexing ("TDM") drops precipitously because of collisions between Wi-Fi nodes, making the CSMA scheme sub-optimal.

CSAT, on the other hand, is a pure TDM scheme across LTE-U nodes where the transmission time of an LTE-U node is proportional to the long-term medium utilization statistics of the neighboring Wi-Fi nodes. CSAT meets the objective of TDM across nodes in a manner proportional to their traffic loads, and this scales well with node density since each node deterministically clears the channel after using its fair share of the channel resources. When implemented properly, TDM relinquishes the medium in a manner that does not impact latency sensitive applications.

Because of these characteristics, CSAT does not need to use the same initial deferral or exponential backoff mechanisms as Wi-Fi. Further, LTE-U nodes from the same operator will be quasi-synchronized and can align the beginning of their transmission times. After they occupy the channel (and fair share of resources) based on surrounding medium activity, all LTE-U nodes will deterministically clear the channel. Thus, they will use the channel efficiently and ensure that there is equitable availability for other unlicensed users.

E. FCC Regulation Of LTE Unlicensed Would Deter Continued Unlicensed Spectrum Innovation And Harm The Public Interest

The parties opposed to the deployment of LTE Unlicensed that have asked the FCC to impose specific coexistence restrictions on the technology want the agency to hurtle down a very dangerous path.[40] Any such restrictions would set a troubling precedent and harm the public interest because they would deter continued innovation in the unlicensed spectrum bands.

The FCC should continue its policy of technology neutrality in the unlicensed bands for it has produced substantial economic growth by encouraging the introduction of many useful unlicensed technologies that consumers heavily rely upon today.

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40 *See, e.g.*, Aruba Comments at 3; WISPA Comments at 4.

CONCLUSION

As the record before the Commission demonstrates, there is no reason for the FCC to take any action that would slow the ongoing development of LTE Unlicensed. The wireless industry is working hard to ensure that this new technology is introduced as soon as possible so that consumers can experience its benefits. The record shows that all facets of the wireless industry are working together to ensure that LTE Unlicensed successfully coexists with other unlicensed users and that service providers deploy the technology in an open and transparent manner. The FCC's technology neutral approach to spectrum regulation has worked exceedingly well for decades, for both unlicensed and licensed spectrum bands, spurring innovation and improving the services provided to many millions of consumers.

Respectfully submitted,

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APPENDIX A – Technical Response to Parties Opposed to LTE Unlicensed

Contents

1. Introduction

This appendix responds to technical concerns raised in the recent filings with the FCC concerning the ability of LTE Unlicensed technology, including both LTE-U and LAA, to fairly coexist with other radio access technologies in unlicensed spectrum.

At the outset, before addressing the specific concerns raised in certain FCC filings, we explain a few key technical concepts that fundamentally illustrate why LTE-U shares spectrum equitably with Wi-Fi and other unlicensed users and why not all Wi-Fi nodes share spectrum equitably.

2. LTE-U Fundamental Technical Concepts

2.1 LTE-U Forum Specified Spectrum and Bandwidth

While LTE-U technology can, in theory, be used in any unlicensed spectrum, the LTE-U Forum has only specified the UNII-1 and UNII-3 bands of operation for LTE-U, and for downlink only operations in those bands [1]. That is the sole focus for LTE-U, as explained in Qualcomm's initial comments to the FCC.

Following the channel raster definitions for UNII-1 and UNII-3 in the U.S., the maximum number of non-overlapping 20 MHz Wi-Fi channels available is 10. Assuming Wi-Fi operates with a system channel bandwidth of 80 MHz (which is the worst case scenario from the perspective of LTE-U interfering with Wi-Fi) there are four possible Wi-Fi links; one 20 MHz Wi-Fi link on (Ch.32) and one 80 MHz Wi-Fi link (in UNII-1); one 20 MHz Wi-Fi link on (Ch.165) and one 80 MHz Wi-Fi link (in UNII-3). In this case, LTE-U needs to choose a channel that minimizes interference to the four links. That is, LTE-U has four channel options to choose from, and LTE-U channel selection will avoid the first, second, and third strongest interferers which improves SINR on the LTE-U link and the Wi-Fi link on the chosen channel. It also is important to note that 160 MHz bandwidth operation would require clearing CSMA over 8 Wi-Fi channels, and this is not a practical in very dense indoor/outdoor hotspot deployments where LTE-U is envisioned to operate.

From the above, it is apparent that LTE-U will have at least four channels to choose for its operation. It is also worth noting that the LTE-U Forum specifies only 20MHz and 40MHz contiguous spectrum blocks as valid channel bandwidths of operation for LTE-U.

2.2 CSAT and CSMA: Key Differences

While Carrier Sense Adaptive Transmission (CSAT) used in LTE-U and Carrier Sense Multiple Access (CSMA) used in Wi-Fi are based on carrier sensing and share the same objective of fair coexistence, they are fundamentally different in their approaches, *i.e.*, they are built on different theoretical concepts. CSMA is a random access scheme that intends to orthogonalize different interfering nodes on the same channel in a distributed manner. In essence, as long as the random access does not lead to collisions between nodes (for example, when using the same random number or hidden nodes), CSMA allows multiple transmitters to have equal probability of accessing the channel if the same CSMA parameters are used. Each node can then use the channel access opportunity to transmit proportional to its traffic load with a cap on the maximum occupancy per access instance (according to the 802.11 specifications [2]). The channel access at any point in time is a function of the instantaneous activity of other nodes within the sensing range.

Two main observations can be made here:

1. CSMA focuses only on fair access to the medium, and it does not guarantee fair sharing of the resources among Wi-Fi access points, much less between Wi-Fi access points and unlicensed devices using other technologties. This is because a Wi-Fi node using a longer transmission duration compared to other nodes in the network will occupy more air time. Furthermore, a greedy node that violates the rules of the game and takes longer than the allowed maximum time achieves greater throughput because all other nodes back off until the greedy node finishes its transmission.
2. As the density of Wi-Fi nodes increases, the ability of random access to enable time division multiplexing (TDM) drops because of collisions between Wi-Fi nodes. This makes CSMA sub-optimal (Refs.[3],[4]).

CSAT, on the other hand, is a pure TDM scheme across LTE-U nodes [5]. With CSAT, the transmission time of an LTE-U node is proportional to the long-term medium utilization statistics of its neighbor nodes. CSAT meets the objective of TDM across nodes in a manner proportional to their traffic loads. In addition, unlike CSMA, CSAT scales well with node density since each node deterministically clears the channel after using its fair share of the channel resources.

Because of the aforementioned characteristics, CSAT does not need to use the initial deferral or exponential backoff mechanisms that Wi-Fi uses. Moreover, LTE-U nodes from the same operator are synchronized and will align the beginning of their transmission time. After occupying the channel for their fair share of resources (which is determined based on surrounding medium activity), all LTE-U nodes deterministically clear the channel.

One important aspect here is that specifications preclude the maximum contiguous LTE-U On duration from being very long in order to avoid impairing latency sensitive applications/services of the neighbor nodes. This aspect was addressed in the LTE-U Forum specifications where requirements were adopted to ensure conformance of every LTE-U node [1].

3. Concerns on LTE-U Coexistence Design and Responses

Several filings to the FCC raised concerns regarding the effectiveness of LTE-U coexistence algorithms in protecting other technologies operating in the unlicensed band (Refs.[6]-[17]).

In this section, we address these concerns in sequence. Our response consists of lab tests, simulations, and theoretical analysis, as applicable. All lab tests specified in this document were conducted in an over-the-air (OTA) environment inside an RF isolation chamber. The CSAT On/Off waveform used in these tests is 40 ms On/40 ms Off (without any puncturing gaps) despite the fact that LTE-U deployments will use such puncturing gaps. These tests were specifically designed to replicate (to the fullest extent possible) the test scenarios cited in Google's FCC filing, in particular [6].

3.1 LTE-U/Wi-Fi Coexistence Below CCA-ED

One concern expressed by various commenters refers to the claimed lack of protection for Wi-Fi nodes operating below the Clear Channel Assessment - Energy Detection level (CCA-ED or ED hereafter). At the outset, we note that the IEEE 802.11 specifications do not have any coexistence mechanisms defined for non-Wi-Fi technologies below CCA-ED or ED [2]. In other words, the Wi-Fi specification does not require or even address detection of any other technology below the ED level. As a result, Wi-Fi nodes will not offer any protection to LTE-U nodes operating below CCA-ED.

Similarly, other regulatory bodies in Europe and Japan, which enforce a mandatory Listen Before Talk requirement, also do not have any coexistence requirement for operations in unlicensed spectrum below CCA-ED [18]. In other words, the LTE-U forum approach to coexistence below CCA-ED is no different from the IEEE 802.11 or other regulatory requirements world-wide.

In this section, we demonstrate that Wi-Fi itself does not protect other Wi-Fi nodes operating below CCA-ED when the primary channel of one Wi-Fi node overlaps with a secondary channel of another. While there are means in the 802.11 specifications [2] to detect such mid-packet collisions, they are rarely implemented in commercial products.

To illustrate the lack of protection beyond CCA-ED on the secondary channel, we present the following Wi-Fi only test scenario using two APs: AP1 and AP2. AP1 is configured to operate in 40 MHz mode while AP2 is configured to operate in 20 MHz mode. The channel configuration is such that the primary channel of AP2 is overlapping with the secondary channel of AP1. Both APs run full buffer UDP DL traffic to their respective clients. Figure 1 and Figure 2 below show the results of this experiment.

Figure 1 shows the duty cycle or fraction of air time occupied and Figure 2 shows the downlink throughput obtained by each AP in two scenarios: (a) isolated link scenario and (b) AP-AP scenario.

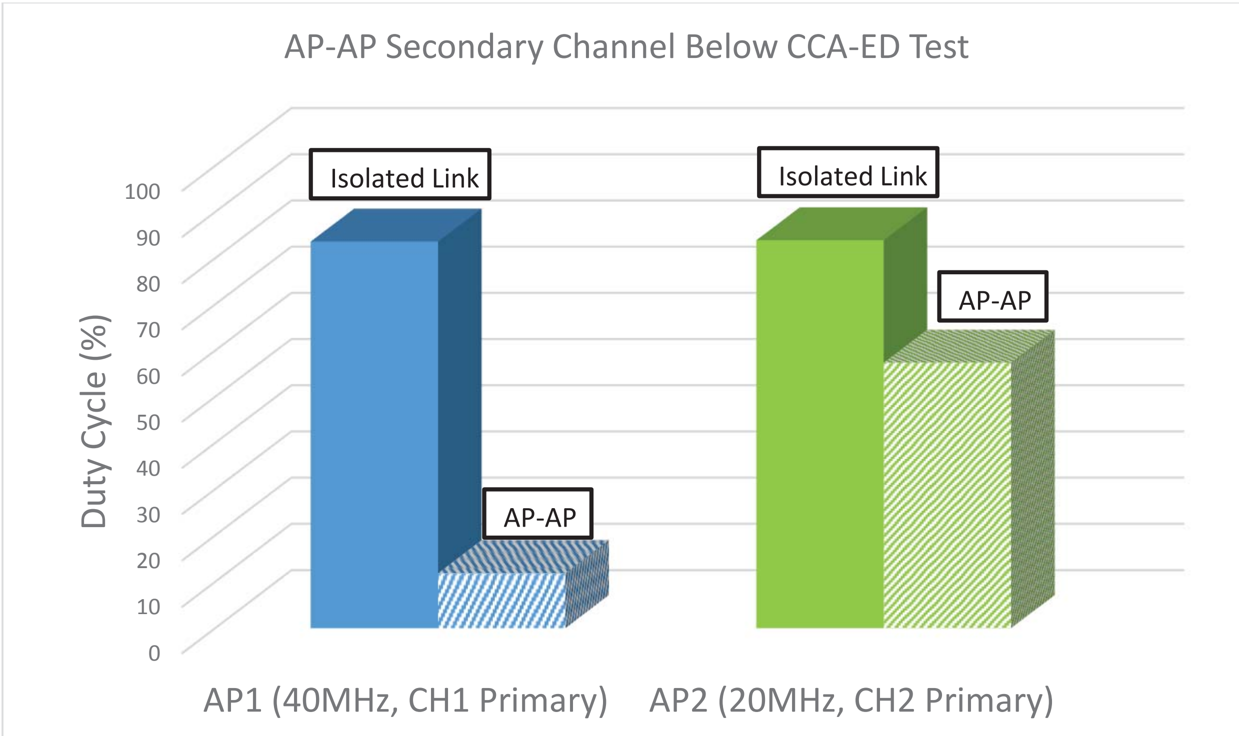


Figure 1. Duty Cycle Stats for AP-AP Secondary Channel Below CCA-ED Tests

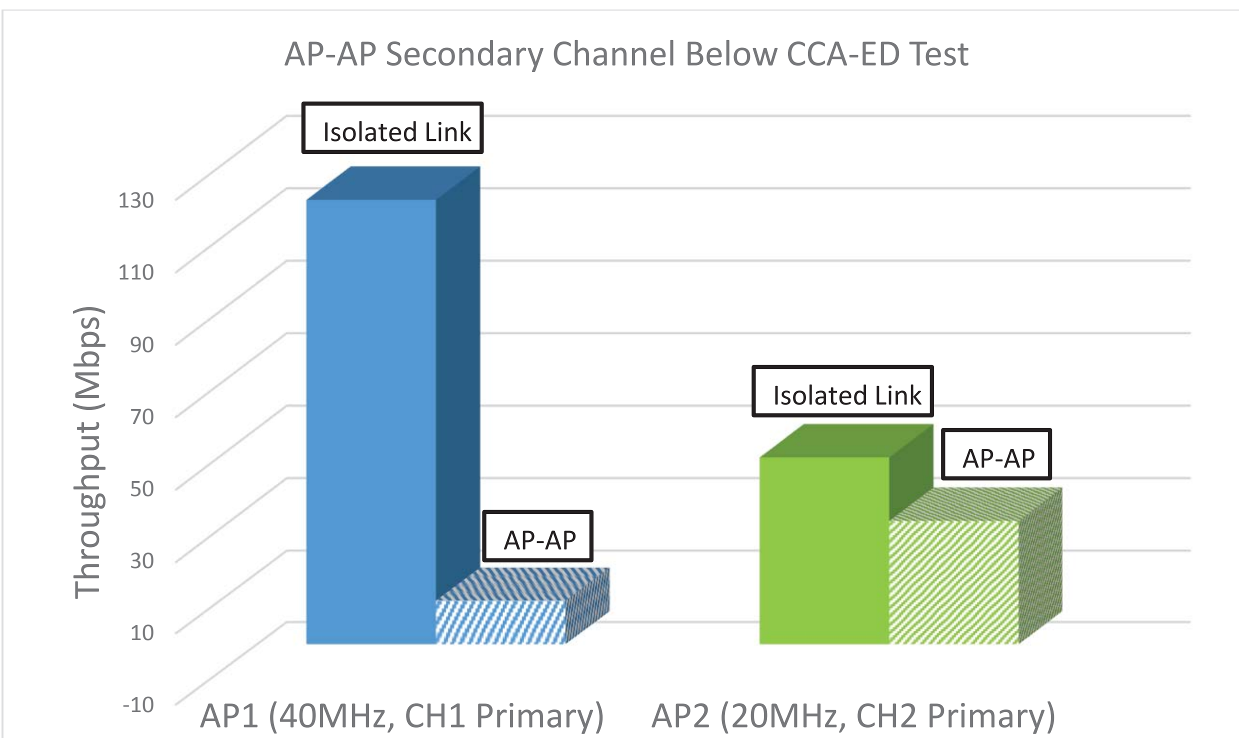


Figure 2. Throughput Stats for AP-AP Secondary Channel Below CCA-ED Tests

Figure 1 shows that the duty cycle of AP1 is hit severely when AP2 is introduced in the secondary channel below the CCA-ED threshold (set at -62 dBm in 20MHz). This is because AP1 transmits blindly without deferring to AP2 and experiences a lot of packet collisions. In this case, several Request to Send (RTS) packets from AP1 collide (at STA1) with concurrent transmissions from AP2 to STA2. As a result, STA1 doesn't respond with a Clear to Send (CTS) causing the overall medium utilization of AP1 to drop. This is best illustrated by the packet trace shown below in Figure 3. Figure 2 shows the corresponding huge hit in AP1's throughput because of overlapping with another Wi-Fi node on the secondary channel below CCA-ED.

AP2 defers to the 40 MHz preambles sent by AP1 and sees only a small degradation in duty cycle and throughput as a result of sharing the secondary channel.

Packet	Source Physical	Dest. Physical	BSSID	Band	Size	Protocol	Relative Time	Type/Subtype
5512	[redacted]:6f	[redacted]:b2	[redacted]	802.11a	1584	UDP	1.165809000	QoS Data
5513	[redacted]:6f	[redacted]:b2	[redacted]	802.11a	1584	UDP	1.165894000	QoS Data
5514	[redacted]:6f	[redacted]:b2	[redacted]	802.11a	1584	UDP	1.165971000	QoS Data
5515	[redacted]:6f	[redacted]:b2	[redacted]	802.11a	1584	UDP	1.166168000	QoS Data
5516	[redacted]:b2	[redacted]:6f		802.11a	75	802.11	1.166202000	802.11 Block Ack
5517	[redacted]:6f	[redacted]:b2		802.11a	63	802.11	1.270340000	Request-to-send
5518	[redacted]:6f	[redacted]:b2		802.11a	63	802.11	1.270390000	Request-to-send
5519	[redacted]:6f	[redacted]:b2		802.11a	63	802.11	1.282932000	Request-to-send
5520	[redacted]:6f	[redacted]:b2		802.11a	63	802.11	1.283002000	Request-to-send
5521	[redacted]:6f	[redacted]:b2		802.11a	63	802.11	1.295608000	Request-to-send
5522	[redacted]:6f	[redacted]:b2		802.11a	63	802.11	1.298636000	Request-to-send
5523	[redacted]:6f	[redacted]:b2		802.11a	63	802.11	1.298752000	Request-to-send
5524	[redacted]:6f	[redacted]:b2		802.11a	63	802.11	1.298854000	Request-to-send
5525	[redacted]:6f	[redacted]:b2		802.11a	63	802.11	1.302283000	Request-to-send
5526	[redacted]:6f	[redacted]:b2		802.11a	63	802.11	1.302328000	Request-to-send
5527	[redacted]:6f	[redacted]:b2		802.11a	63	802.11	1.302501000	Request-to-send
5528	[redacted]:6f	[redacted]:b2		802.11a	63	802.11	1.302647000	Request-to-send
5529	[redacted]:6f	[redacted]:b2		802.11a	63	802.11	1.302941000	Request-to-send
5530	[redacted]:6f	[redacted]:b2		802.11a	63	802.11	1.303121000	Request-to-send
5531	[redacted]:6f	[redacted]:b2		802.11a	63	802.11	1.303217000	Request-to-send
5532	[redacted]:6f	[redacted]:b2		802.11a	63	802.11	1.303394000	Request-to-send
5533	[redacted]:6f	[redacted]:b2		802.11a	63	802.11	1.303540000	Request-to-send
5534	[redacted]:6f	[redacted]:b2		802.11a	63	802.11	1.303705000	Request-to-send
5535	[redacted]:6f	[redacted]:b2		802.11a	63	802.11	1.303796000	Request-to-send
5536	[redacted]:6f	[redacted]:b2		802.11a	63	802.11	1.303976000	Request-to-send
5537	[redacted]:6f	[redacted]:b2		802.11a	63	802.11	1.304125000	Request-to-send
5538	[redacted]:6f	[redacted]:b2		802.11a	63	802.11	1.304307000	Request-to-send
5539	[redacted]:6f	[redacted]:b2		802.11a	63	802.11	1.304410000	Request-to-send
5540	[redacted]:6f	[redacted]:b2		802.11a	63	802.11	1.304658000	Request-to-send
5541	[redacted]:6f	[redacted]:b2		802.11a	63	802.11	1.304704000	Request-to-send
5542	[redacted]:6f	[redacted]:b2		802.11a	63	802.11	1.304886000	Request-to-send
5543	[redacted]:6f	[redacted]:b2		802.11a	63	802.11	1.305023000	Request-to-send
5544	[redacted]:6f	[redacted]:b2		802.11a	63	802.11	1.305205000	Request-to-send
5545	[redacted]:6f	[redacted]:b2		802.11a	63	802.11	1.305342000	Request-to-send
5546	[redacted]:6f	[redacted]:b2		802.11a	63	802.11	1.305541000	Request-to-send
5547	[redacted]:6f	[redacted]:b2		802.11a	63	802.11	1.305670000	Request-to-send
5548	[redacted]:6f	[redacted]:b2		802.11a	63	802.11	1.305850000	Request-to-send
5549	[redacted]:6f	[redacted]:b2		802.11a	63	802.11	1.305936000	Request-to-send
5550	[redacted]:6f	[redacted]:b2		802.11a	63	802.11	1.306118000	Request-to-send
5551	[redacted]:6f	[redacted]:b2		802.11a	63	802.11	1.306256000	Request-to-send
5552	[redacted]:6f	[redacted]:b2		802.11a	63	802.11	1.306435000	Request-to-send
5553	[redacted]:6f	[redacted]:b2		802.11a	63	802.11	1.306614000	Request-to-send

Figure 3. Wireshark packet trace showing RTS retransmissions from AP1 because of collisions caused by concurrent transmission from AP2

Despite the test results shown above, there is nothing in the LTE-U Forum specifications that precludes an operator from protecting Wi-Fi below CCA-ED, just as there is nothing in the IEEE 802 specifications that preclude Wi-Fi equipment from protecting LTE-U below CCA-ED. In the

LTE-U Forum specifications, this is left to implementation, and we believe that good LTE-U designs will do so.

3.2 Concern 1: Effectiveness of LTE-U Duty Cycle Approach in Protecting Wi-Fi Above CCA-ED

The concern raised here is the ability of LTE-U to coexist with Wi-Fi above CCA-ED since at the first transmission of LTE-U there may be a Wi-Fi node packet over the air that causes a packet loss. While there is an agreement that Wi-Fi should limit the collision's impact by stopping further transmissions once this packet loss occurs, Google [6] claims that such packet loss can cause Wi-Fi rate control to lead to a low throughput for Wi-Fi. This concern also was mentioned in other filings (Refs.[7]&[11]).

We note initially that the Wi-Fi rate control algorithm is a proprietary design by the Wi-Fi equipment vendor, and thus there is no benchmark algorithm for which to design LTE-U. Also, any reasonable implementation of rate control would avoid such degradation due to the limited boundary condition collisions. With the 30 ms/30 ms used in Google's filing [6] and assuming a typical 3 ms transmission opportunity (TXOP), the collision probability is about 10%, which should not impact any reasonable rate control design. Indeed, this is our experience as shown in the tests below.

3.2.1 Test 1: Downlink Full Buffer Traffic Tests Above CCA-ED

In this experiment we run full buffer UDP downlink (DL) traffic (*i.e.*, AP to client direction) for the following cases:

- An isolated Wi-Fi AP from vendor x;
- Two interfering links each with one AP connected to one STA, *i.e.*, the Station or Wi-Fi-enabled device that connects to the AP. Here the two APs are still from vendor x (and we denote this case AP-AP);
- One Wi-Fi AP from vendor x connected to one STA plus an interfering link with one LTE-U eNB connected to one UE (and we denote this case AP-LTE-U).

For this test (as well as subsequent tests in this document), we ran a CSAT cycle with 40 ms On/40ms Off configuration (50% duty cycle) with no puncturing gaps. Also, all tests are done OTA in an RF isolated chamber. The tests were repeated for 3 different AP vendors. The PHY rate used by the Wi-Fi transmissions as well as the average throughput are captured for each of the three cases listed above.

The test results are shown in Table 1. Note that, for the AP-AP scenario we show the PHY rate and throughput of the individual APs as well as the average. The results are also depicted in Figure 4, Figure 5, and Figure 6 below the table. They show that LTE-U has no adverse impact on Wi-Fi, contrary to Google's argument. The average throughput of a Wi-Fi node operating on the same channel as an LTE-U node is not worse, and is very similar, to the average throughput of a Wi-Fi node operating on the same channel as another Wi-Fi node, despite Google's boundary collision argument.

AP Vendor 1	Wi-Fi Isolated Link	AP-AP Baseline			Wi-Fi in AP-LTE-U
		AP1	AP2	Avg. AP	
DL Avg. PHY rate (Mbps)	86.63	72.08	71.83	71.96	84.29
DL Avg. Thpt (Mbps)	65.00	7.93	39.48	23.71	24.14

AP Vendor 2	Wi-Fi Isolated Link	AP-AP Baseline			Wi-Fi in AP-LTE-U
		AP1	AP2	Avg. AP	
DL Avg. PHY rate (Mbps)	80.81	80.03	77.25	78.64	78.66
DL Avg. Thpt (Mbps)	66.54	31.57	29.80	30.68	28.00

AP Vendor 3	Wi-Fi Isolated Link	AP-AP Baseline			Wi-Fi in AP-LTE-U
		AP1	AP2	Avg. AP	
DL Avg. PHY rate (Mbps)	76.45	75.68	71.36	73.52	72.48
DL Avg. Thpt (Mbps)	41.84	36.08	4.23	20.15	25.33

Table 1. DL traffic on 3 Wi-Fi AP models showing PHY rate and throughput for isolated, AP-AP, and AP-LTE-U scenarios

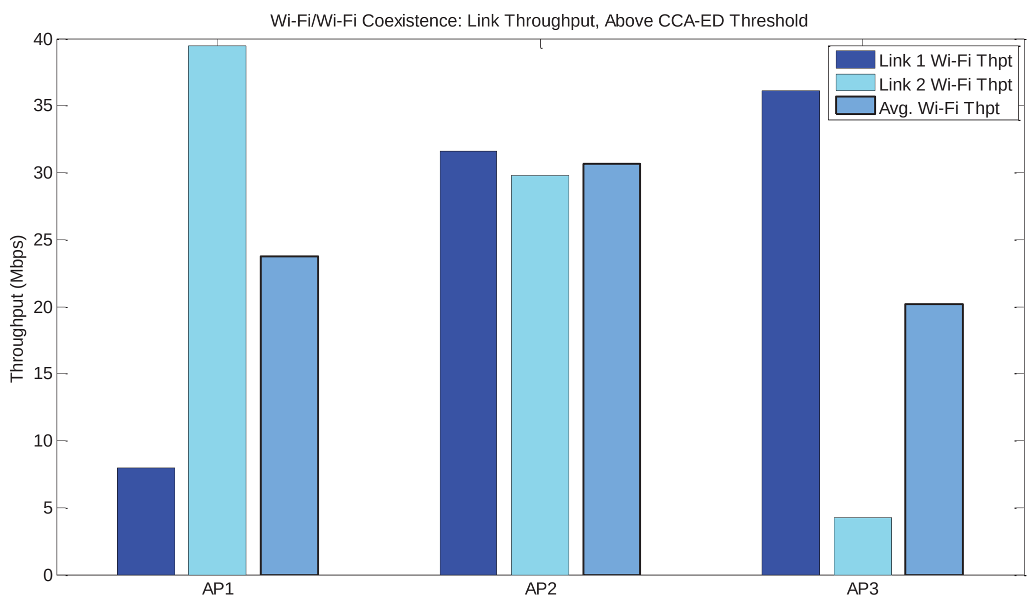


Figure 4. Wi-Fi/Wi-Fi Coexistence: Link Throughput, Above CCA-ED Threshold

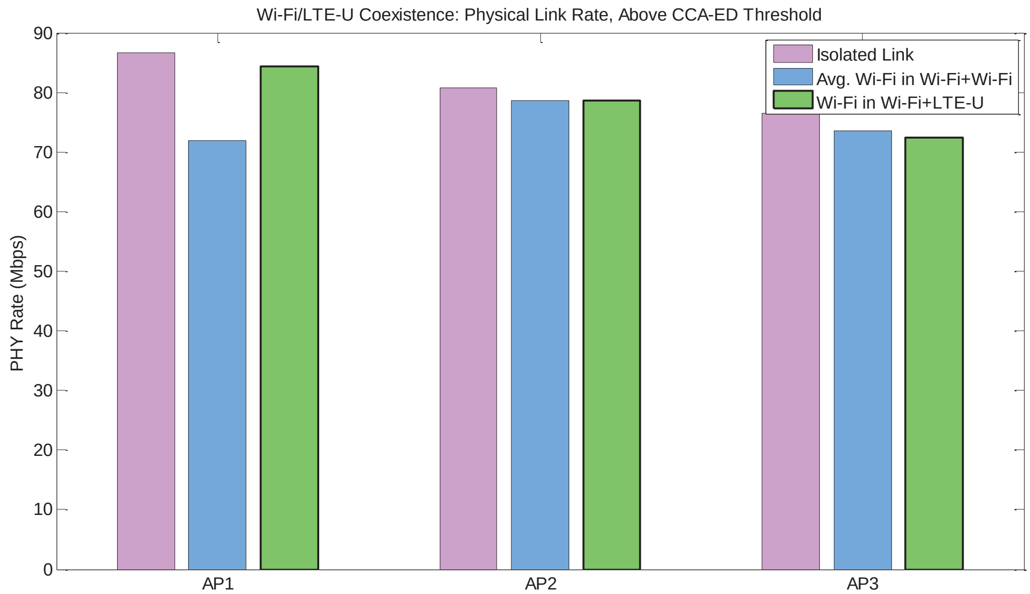


Figure 5. Wi-Fi/LTE-U Coexistence: Physical Link Rate, Above CCA-ED Threshold

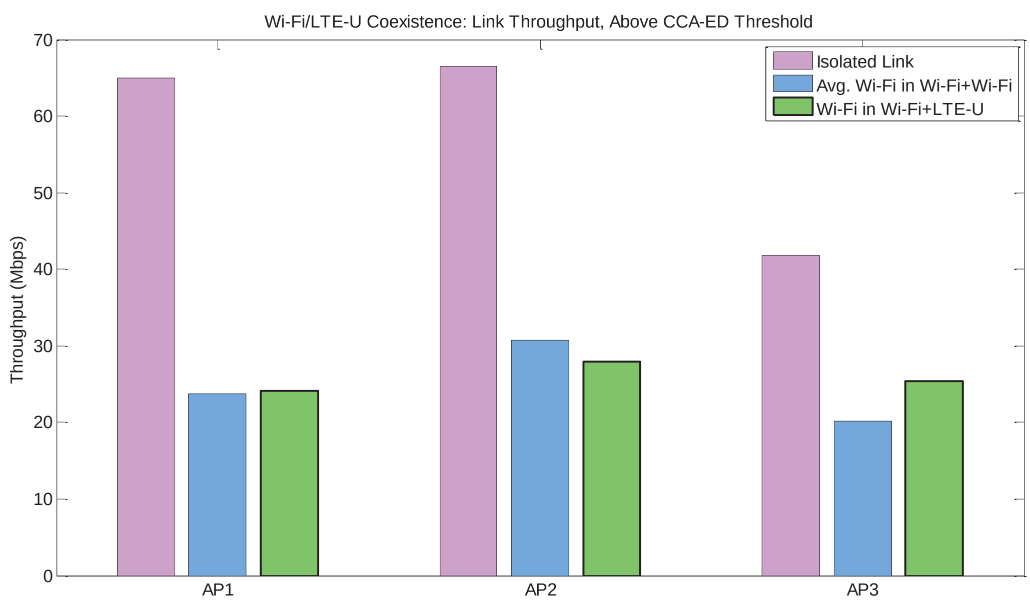


Figure 6. Wi-Fi/LTE-U Coexistence: Link Throughput, Above CCA-ED Threshold

The data in the Table and Figures above demonstrate that the performance of Wi-Fi PHY rate in AP-LTE-U is very similar to that of AP-AP, confirming the minimal impact of the boundary collision problem on Wi-Fi rate control loops raised by Google. Also, Figure 7 below shows a time trace of the DL PHY rate time trace of one of the APs, illustrating that Wi-Fi at almost all times maintains the maximum PHY rate except for a few very rare instances that do not impact the average value.

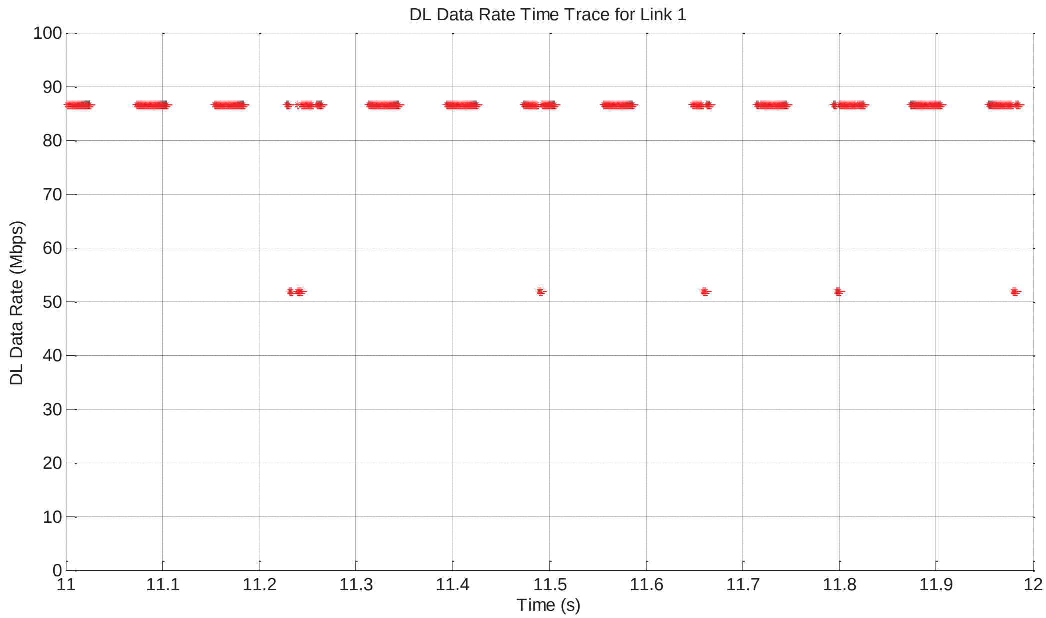


Figure 7. DL PHY Rate time trace showing no impact of rate control because of boundary collisions

The average throughput of Wi-Fi in AP-LTE-U is very similar to the average Wi-Fi throughput in the AP-AP case. In fact, in the case of AP model 3, there is 25% gain for Wi-Fi in the AP-LTE-U case attributed to medium access control (MAC) efficiency of LTE-U over Wi-Fi, *i.e.*, with CSMA the AP contends for the channel with another AP and backs off based on the random number of the contention window. And, it loses airtime because of exponential backoff if there are collisions. However, with LTE-U interference, the backoff is deterministic (CCA-ED is 1-persistent in CSMA) and the AP is able to make use of the medium during the Off time more efficiently than it did with another AP using CSMA because there is no one to yield to.

In the AP-AP testing, in many cases the two Wi-Fi APs experience very different average throughput numbers, which means they are not sharing the medium 50-50%. The discrepancy in AP model 1 and AP model 3 is such that one node gets around 5 to 9 times the throughput of the other one. Interestingly, this is the case between two nodes provided by the same vendor. This confirms the statement above in Section 2.2 that CSMA does not guarantee equal sharing of resources because the APs are occupying the medium for vastly different air times.

These tests prove that in many cases LTE-U protects Wi-Fi much better than Wi-Fi protects Wi-Fi.

3.2.2 Test 2: Uplink Full Buffer Traffic Tests Above CCA-ED

This test is similar to Test 1 except the traffic is in the uplink (UL) direction, *i.e.*, from client to AP. The same AP is used in all the test cases and 4 different client device vendors are sampled. Table 2 below shows the results of this experiment and they also are depicted in Figure 8 below the Table. Once again, the testing shows that LTE-U does not have any adverse impact on Wi-Fi, contrary to Google's argument.

Device vendor 1	Wi-Fi Isolated Link	STA-STA Baseline			Wi-Fi in STA-LTE-U
		STA1	STA2	Avg. STA	
UL Avg. PHY rate (Mbps)	78.16	86.44	78.18	82.31	73.35
DL Avg. Thpt (Mbps)	75.88	38.72	30.57	34.65	23.30

Device vendor 2	Wi-Fi Isolated Link	STA-STA Baseline			Wi-Fi in STA-LTE-U
		STA1	STA2	Avg. STA	
UL Avg. PHY rate (Mbps)	86.70	86.67	86.67	86.67	86.70
UL Avg. Thpt (Mbps)	75.46	33.09	36.55	34.82	33.49

Device Vendor 3	Wi-Fi Isolated Link	STA-STA Baseline			Wi-Fi in STA-LTE-U
		STA1	STA2	Avg. STA	
UL Avg. PHY rate (Mbps)	86.70	86.55	86.64	86.59	85.82
UL Avg. Thpt (Mbps)	79.20	40.68	37.68	39.18	37.19

Device Vendor 4	Wi-Fi Isolated Link	STA-STA Baseline			Wi-Fi in STA-LTE-U
		STA1	STA2	Avg. STA	
UL Avg. PHY rate (Mbps)	96.30	57.66	75.42	66.54	96.28
UL Avg. Thpt (Mbps)	76.28	22.90	18.29	20.59	36.75

Table 2. UL traffic on 4 Wi-Fi STAs showing PHY rate and throughput for isolated, and AP-LTE-U scenarios

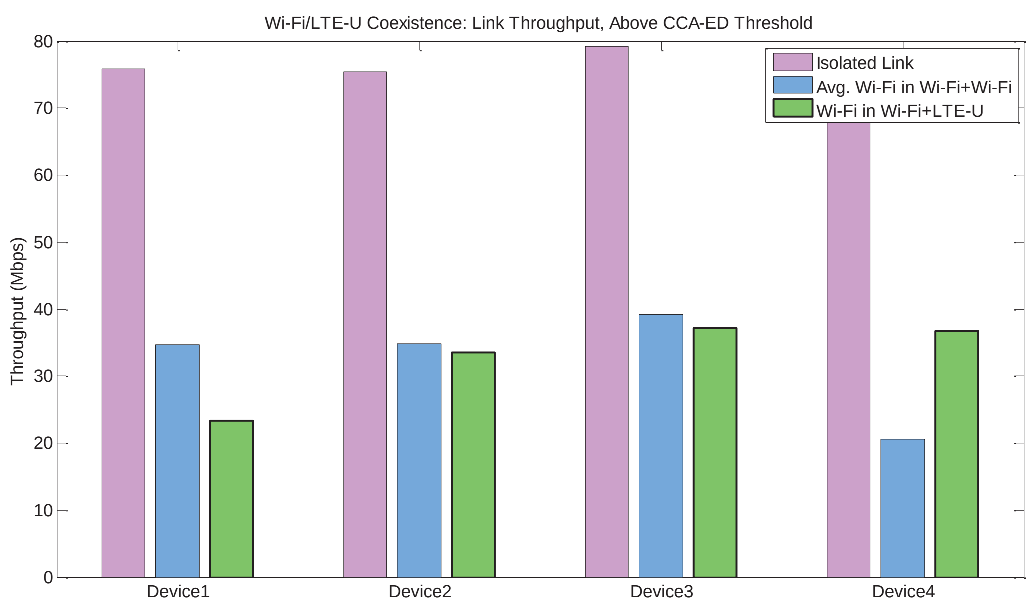


Figure 8. Wi-Fi/LTE-U Coexistence: Link Throughput, Above CCA-ED Threshold

The goal of Test 2 was to reproduce a scenario similar to the one reported in [6]. To be specific, this test corresponds to the 40 ms point on x-axis in the figure on page 11 of Google's filing. Three STAs based on this test are shown attaining an average throughput of 42%, 60% and 70% of the ideal baseline value. As shown above, we see similar behavior only for STA1, which was further studied in order to understand the cause.

Upon closer inspection of the Wi-Fi behavior of STA1, we found out that the TXOP used is 12 to 15 ms and is achieved through A-MPDU SIFS bursting. Hence, within 30 ms of LTE-U On time there is roughly only 3 packets, and one of them is hit on the boundary. That is, rate control is hit by a packet loss almost once every three TXOPs. This value of TxOP violates the 802.11 specifications, which limit the max TXOP to only 5.484 ms. Thus, the main reason for the poor throughput of STA1 is due to an implementation that violates the Wi-Fi spec. This also can happen if the STA does not back off at all to the energy from LTE-U even when it is above ED. That again can cause the same behavior of STA1 and also violates the Wi-Fi spec. LTE-U design assumes that such basic elements of the Wi-Fi spec (like observing ED threshold or TXOP size) will be respected. If a Wi-Fi node doesn't respect the specification, its performance will be impacted.

Hence, we believe that the poor results in Google's filing are caused by:

- Wi-Fi device not respecting 802.11 spec on TXOP limits and transmitting more than the spec compliant duration;
- Wi-Fi device not respecting 802.11 spec on the CCA-ED threshold and not backing off for energy; and
- Very poor rate control design.

Using the same setup assumptions in Google's filing, we demonstrated that LTE-U fairly shares the medium with Wi-Fi in DL and UL with multiple AP and STA vendors. The assumptions in Google's filing are very pessimistic to LTE-U, and coexistence typically will be better than what is shown in this report. *First*, the 30-40 ms On/Off duration pertains more to a Wi-Fi primary channel coexistence, which is something any reasonable implementation of LTE-U will try to avoid. *Second* and more importantly, the assumption used throughout Google's filing is that LTE-U interference will always come as an erasure to Wi-Fi, *i.e.*, interference is such that Wi-Fi cannot decode its minimum rate. In the next section, we address the validity of this assumption and show that it is overly pessimistic and impractical.

3.3 Concern 2: Effectiveness of LTE-U Duty Cycle Approach in Protecting Wi-Fi Below CCA-ED

This concern was mentioned by several filings, including Refs.[6],[7]&[11].

While the LTE-U Forum spec does not protect Wi-Fi below CCA-ED (again, just as the 802.11 spec does not protect LTE-U or other technologies below CCA-ED), the LTE-U Forum spec does not preclude such protection. Several FCC filings questioned the effectiveness of CSAT as a coexistence approach to dealing with other unlicensed technologies (Refs.[6],[7],[8]&[9]). Specifically, in Google's filing, a test was reported where even if CSAT is used below ED it can impact Wi-Fi performance adversely. The assertion is that since Wi-Fi does not back off to LTE-U below ED, Wi-Fi will suffer interference during the LTE-U On time and corrupt rate control in a way that impacts the performance even when LTE-U is Off, *i.e.*, the net outcome is that Wi-Fi performance will suffer. This point is similar to the same one made above ED except that collisions happen more often below ED.

We note first that we have concerns about the test setup that led to the results in [6] . The test clearly shows that if the LTE-U noise floor is 15 dB below Wi-Fi signal, *i.e.*, SINR=15 dB, Wi-Fi still attains zero throughput. The explanation there is that the Wi-Fi link is limited by UL ACK since typically there is a power mismatch between AP and STA. Going by the minimum performance allowed by 802.11a, this analysis effectively means that the AP is transmitting at least 11 dB higher power than STA. This high imbalance will create wide regions of hidden nodes that significantly impact performance. Notably, Qualcomm never encountered this configuration in all of its testing, that is, an AP is not able to get any useful throughput with 15 dB SINR. Google also stated that the lowest rate can be demodulated at -92 dBm, which is almost at SINR=4 dB. That can happen if the link is closed at both DL and UL at SINR=4 dB,[41] which does not align with the zero throughput argument at SINR=15 dB in [6].

Returning to the high interference assumption used by Google [6]: while some of the tests assume SNR sweep (which we question as discussed above), the major part is conducted assuming no Wi-Fi communications can happen while LTE-U is transmitting. That means, with LTE-U transmissions, that Wi-Fi SINR is below 4 dB (in fact the setup used by Google assumes 0 dB). We look closely at this assumption at this point.

The assumption of erasure interference to Wi-Fi pertains more to one channel, and not 10 channels as is the case here. Even if Wi-Fi uses the max channel BW, there are at least 4 channels available for LTE-U, as shown in the beginning of this report; one 20 MHz and one 80 MHz channel in each of U-NII-1 and U-NII-3. That means in the worst case scenario, channel selection will be able to peal out the first, second and third strongest jammer. The probability that the fourth strongest jammer hits Wi-Fi causing less than 4 dB SINR is very low, let alone that most implementations of Wi-Fi devices do much better than that. To illustrate this point, we highlight two simulation studies at reasonably high node density taken directly from the LTE-U Forum technical report [19].

In the first study, an outdoor deployment model is considered. Here there are 8 Wi-Fi nodes for Operator 1 and 8 LTE-U nodes for Operator 2 over 4 channels. That is, after channel selection, we have, on average, 4 nodes per channel. Figure 9 below shows the average SINR distribution of Wi-Fi nodes under the impact of interference from other nodes, which mainly are LTE-U here. The lowest 5th percentile user avg. SINR is more than 12 dB, and there is no significant degradation (< 1 dB) on the average Wi-Fi user SINR (with LTE-U interferer) compared to the average Wi-Fi user SINR (with Wi-Fi interferer).

[41] Unless the 4 dB SINR discussion in [6] was on the conceptual level not part of the conducted tests, there is a clear conflict in assumptions. Even if not, the point of not closing the link at 15 dB in an isolated RF chamber is very unrealistic.

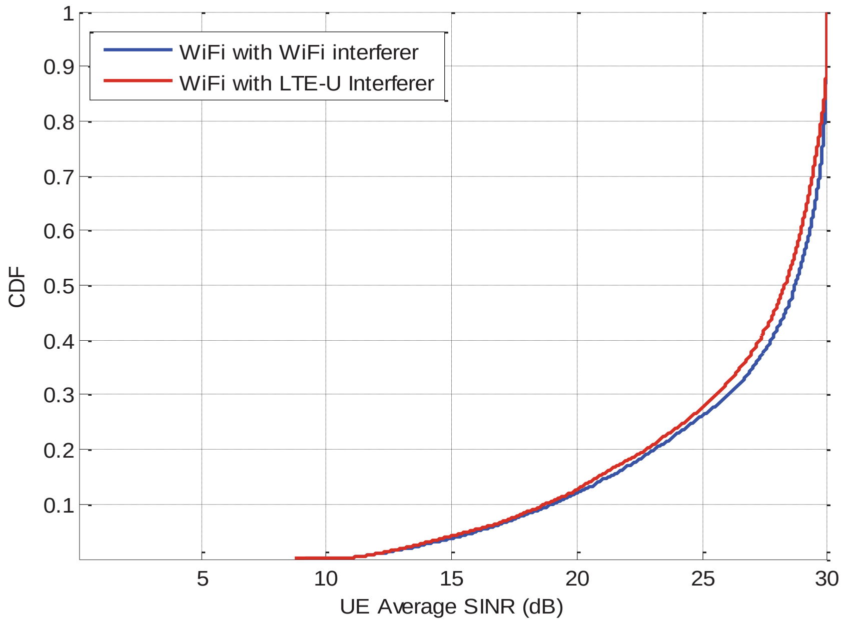


Figure 9. Average SINR Distribution for Outdoor Study With an Average Density of 4 Nodes per Channel [Ref.19]

Figure 10 below illustrates the impact of LTE-U on the tail SINR (5th percentile) distribution across users. The tail-tail SINR *i.e.*, the 5% worst SINR over all packets of the worst 5% user among all users is around 5 dB. This SINR would allow Wi-Fi to decode the lowest rate of 6 Mbps.

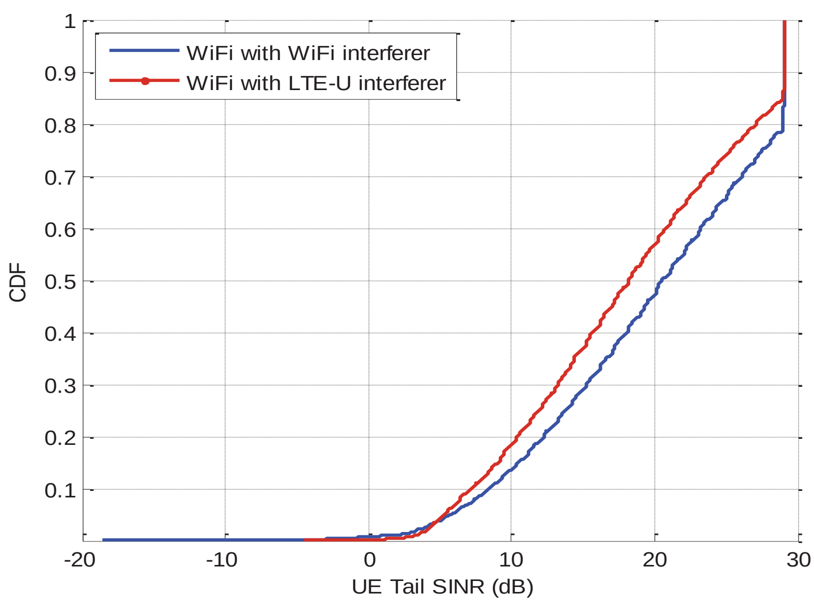


Figure 10. Tail SINR Distribution for Outdoor Study With an Average Density of 4 Nodes per Channel [Ref.19]

In the second study in [Ref.19], an indoor deployment model is considered. Here there are 4 channels available and 4 Wi-Fi nodes of Operator 1, 4 LTE-U nodes of operator 2, and 16 Wi-Fi independent nodes that are dropped randomly without any coordination in channel selection. In this setup, after channel selection, on average you have 6 nodes on one channel. Figure 11 below shows the SINR distribution of Wi-Fi nodes under the impact of interference from other nodes which mainly are LTE-U here. The lowest 5th percentile average SINR is more than 25 dB.

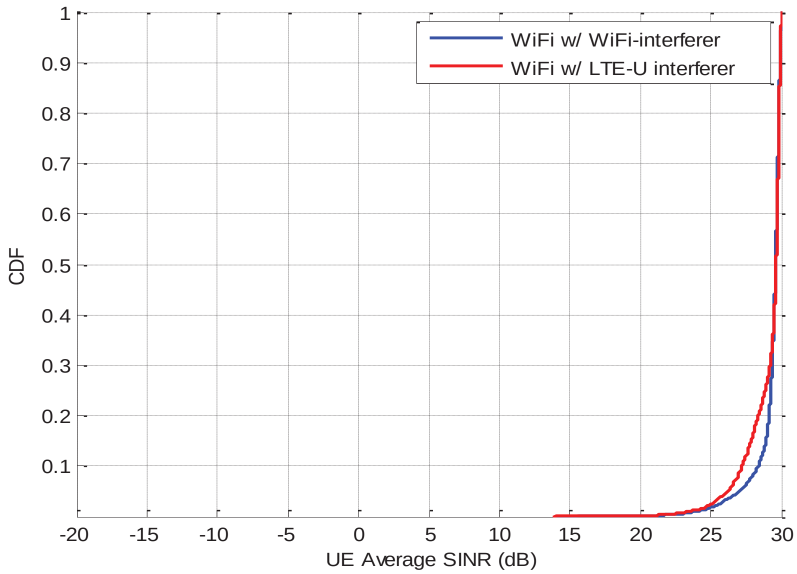


Figure 11. User Average SINR distribution for indoor study with an average density of 4 nodes per channel

Based on the above results, Google's assumption of 0 dB SINR is exceedingly pessimistic and impractical. In the next section, we show an experiment of LTE-U-Wi-Fi coexistence below ED with much less interference as a result. In fact, our testing below shows that in the most relevant scenarios, using LTE-U actually improves Wi-Fi performance, *i.e.,* that LTE-U protects Wi-Fi better than Wi-Fi protects itself.

3.3.1 Test 3: Downlink Full Buffer Traffic Tests Below CCA-ED

This test setup was very similar to that used for Test 1 in Section 3.2.1 except for:

- LTE-U energy is received at the Wi-Fi AP below ED threshold
- LTE-U interference during On time drops SINR at STA from peak to 10 dB

In Table 3 below, we show the peak rate and average throughput results for isolated AP, AP-AP, and AP-LTE-U. The results are depicted as bar charts in the figures below the table (see Figure 12, Figure 13, and Figure 14).

AP Model 1	Wi-Fi Isolated Link	AP-AP Baseline			Wi-Fi in AP-LTE-U
		AP1	AP2	Avg. AP	
DL Duty cycle (%)	88.30	27.70	56.99	42.35	77.82
iperf DL Avg. Thpt (Mbps)	70.00	20.25	40.2	30.23	48.00

AP Model 2	Wi-Fi Isolated Link	AP-AP Baseline			Wi-Fi in AP-LTE-U
		AP1	AP2	Avg. AP	
DL Duty cycle (%)	95.83	40.98	37.28	39.13	88.62
iperf DL Avg. Thpt (Mbps)	76.00	36.15	32.75	34.45	52.60

AP Model 3	Wi-Fi Isolated Link	AP-AP Baseline			Wi-Fi in AP-LTE-U
		AP1	AP2	Avg. AP	
DL Duty cycle (%)	91.92	49.77	43.59	46.68	85.22
iperf DL Avg. Thpt (Mbps)	63.60	31.67	28.37	30.02	37.90

Table 3. DL traffic on 3 Wi-Fi APs showing PHY rate and throughput for isolated, AP-AP, and AP-LTE-U scenarios. All results are above ED.

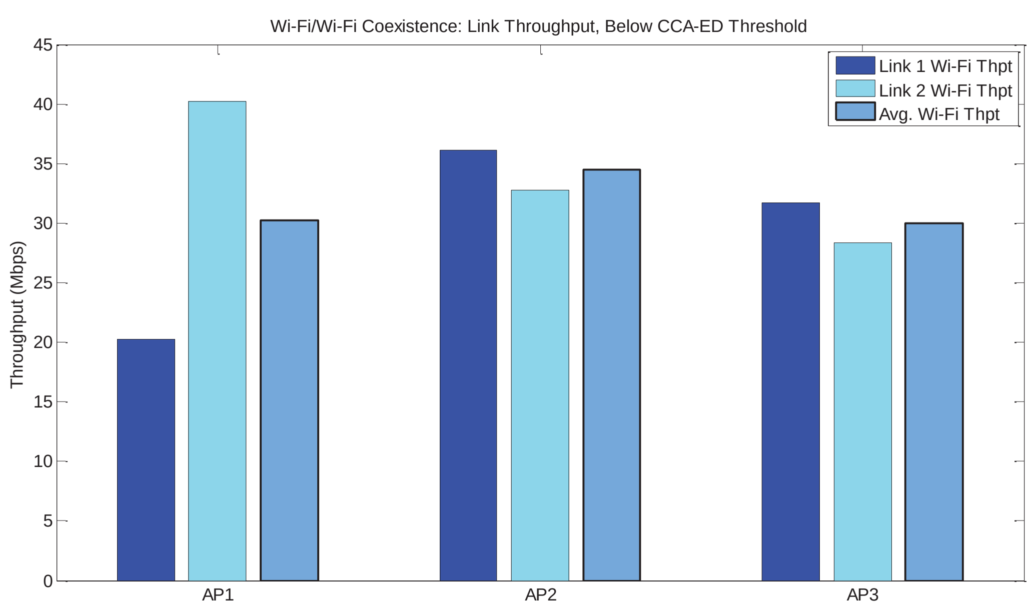


Figure 12. Wi-Fi/Wi-Fi Coexistence: Link Throughput, Below CCA-ED Threshold

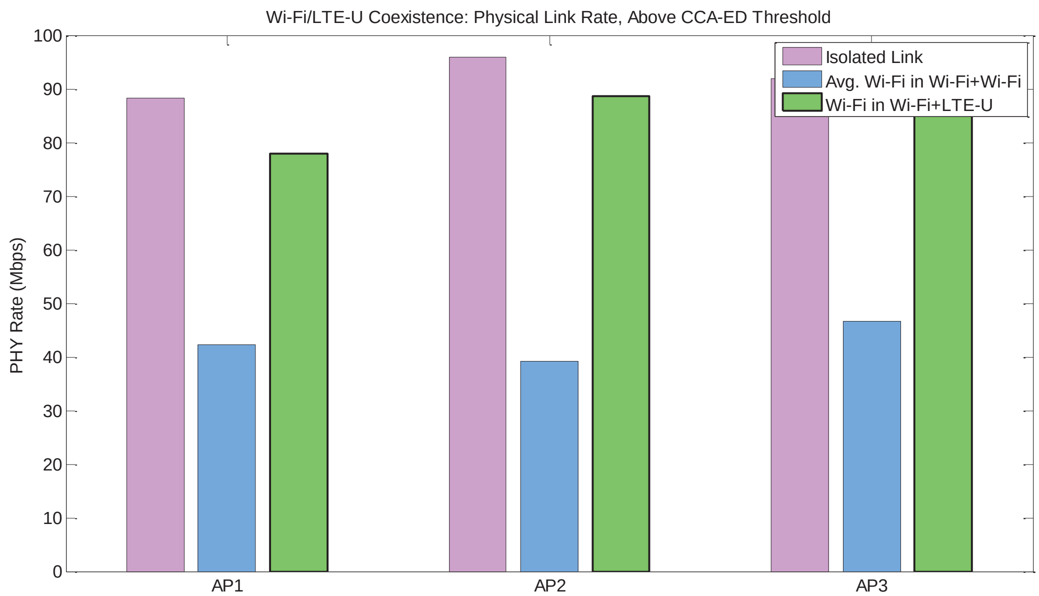


Figure 13. Wi-Fi/LTE-U Coexistence: Physical Link Rate, Below CCA-ED Threshold

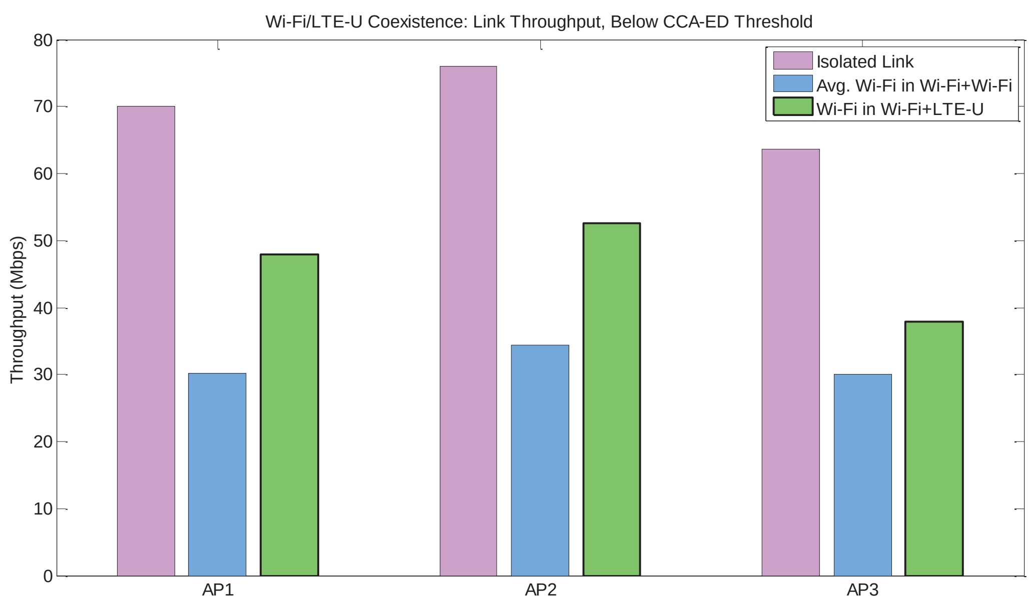


Figure 14. Wi-Fi/LTE-U Coexistence: Link Throughput, Below CCA-ED Threshold

As shown in Table 3 above, Wi-Fi performance tremendously improved with LTE-U compared to AP-AP. This occurred because in the AP-AP case, each node accesses 50% of the medium. In the AP-LTE-U case, the Wi-Fi node occupies 100% of the medium since it does not back off to LTE-U though LTE-U backs off to Wi-Fi. This can be seen in the duty cycle statistics in Table 3 above. During the LTE-U Off time, the Wi-Fi link runs at 30 dB. During the LTE-U On time, Wi-Fi nodes run at 10 dB. Overall Wi-Fi throughput does much better than AP-AP where ideally it would have gotten 50% of the air time at 30 dB.

This is an important and striking fact: LTE-U in the most relevant scenarios helps Wi-Fi performance.

Note also in Table 3 the discrepancy between the throughputs attained by the two nodes of vendor A. This discrepancy now seen below ED was shown previously above ED. This demonstrates that different Wi-Fi nodes do not share the medium fairly between themselves. This issue becomes much more striking when examining nodes from different vendors. Moreover, this is in sharp contrast to the assumptions made in Google's filing whose tests assume baseline Wi-Fi coexistence attaining 50% throughput of isolated link, something we have rarely seen in actual Wi-Fi networks but was used as Google's definition of fair sharing.

LTE-U, on the other hand, is consistently more fair and able to attain at least the 50% throughput point as shown in this report since it vacates the medium in a deterministic way after using a fair share.

To clarify this point even further, we conducted the experiment below.

3.4 Wi-Fi/LTE-U Airtime Fairness

The concept of fairness is mentioned in the filings from Google and others (*see* Refs.[6],[7],[11]&[16]). We conducted a test to examine the air-time fairness for AP-AP and AP-LTE-U. In this test we choose a set of 4 Wi-Fi APs {A, B, C, D}. Each AP was connected to a STA. We used two APs and associated STAs and ran a coexistence test. In the test, we ran full buffer traffic on each link and captured how fairly they shared the medium. The definition of fairness was the air-time, *i.e.*, how long each AP stays on the medium transmitting data. For each of the six possible combinations of two APs from the set, *i.e.*, A-B, A-C, A-D, B-C, B-D, C-D, we capture two numbers: AP1 air-time and AP2 air time. We then plot the Cumulative Distribution Function (CDF) of the 12 values.

Ideally, with fair Wi-Fi sharing as assumed in [6], each AP should occupy close to 50% of the air-time. The reality though is very different. We repeated the experiment putting one AP-STA link with an LTE-U-UE link in the same environment and again captured the air-time by Wi-Fi APs (4 points on CDF) and LTE-U (additional 4 points on CDF).

Figure 15, shows the CDF of AP-AP air-time sharing in blue, AP air-time share under LTE-U interference in green, and LTE-U air-time under Wi-Fi interference in red. Figure 15 shows that Wi-Fi sharing is far from 50% and spans from few percent use of the medium all the way to 80+ percent. With LTE-U though, Wi-Fi's share of the medium remains nearly constant among the different APs {A, B, C, D} and is almost 50%. This should not come as a surprise because LTE-U deterministically takes 50% of air-time for transmission (in this configuration) and backs off the other 50%. On the other hand, many of the existing implementations of Wi-Fi nodes are greedy in nature when either accessing the medium or staying On for longer than max TxOP as defined by 802.11

specifications [2], which was shown in Test 2 above. The sample set of APs chosen for this experiment was random.

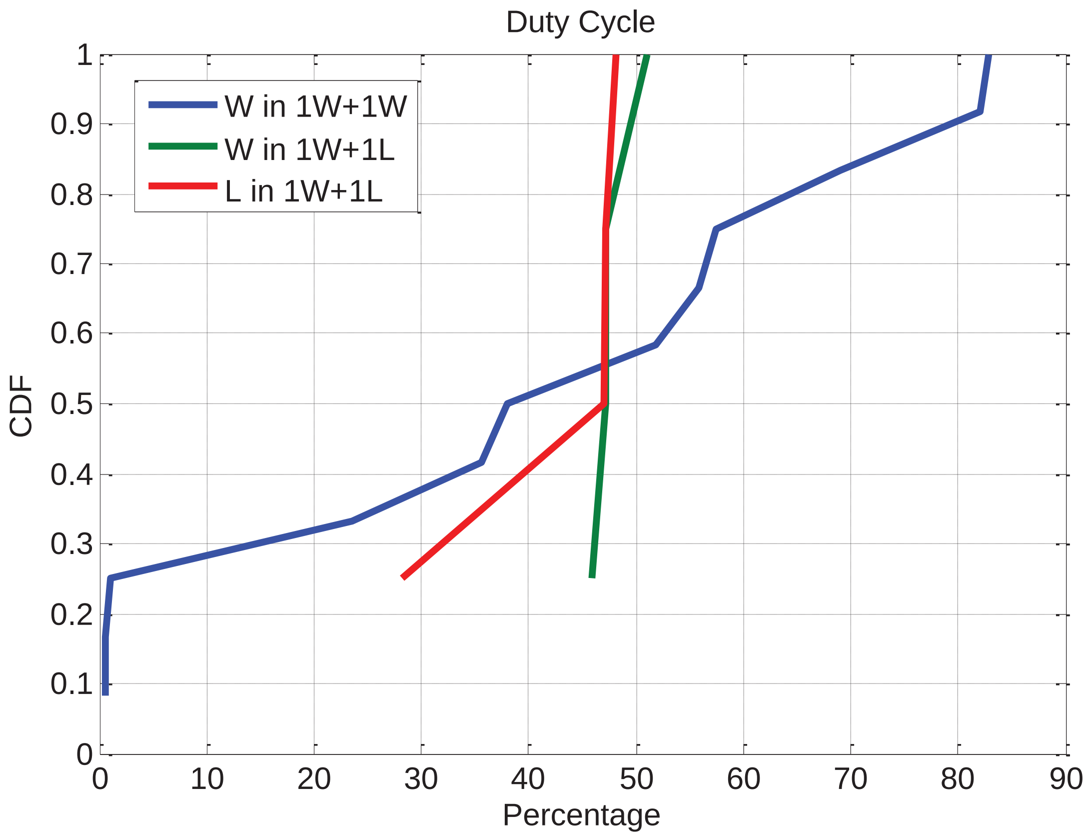


Figure 15. CDF of air-time share of APs and LTE-U: AP-AP share in blue, AP share in AP-LTE-U, LTE-U share in AP-LTE-U

3.5 Concern 3: Effectiveness of LTE-U Duty Cycle Approach in Protecting Latency Sensitive Applications

Another concern raised was on the effectiveness of the LTE-U duty cycle approach in protecting latency sensitive applications (*see* Refs.[6][8][9][11]). We first note that protection of latency sensitive applications of Wi-Fi has been considered a requirement in all tests specified by the LTE-U Forum [Ref.1, p.5]. The maximum On duration has to be less than 50 ms. In addition, a test was added recently to the coexistence specifications [Ref.1, Section 6.2.4] specifically to cover testing against VoIP applications.

We ran a more stringent test (5 VoIP calls instead of 4 and without puncture gaps) in an RF isolation chamber under exactly the same assumptions of 40 ms On/40 ms Off.[42] The test setup and results,

[42] The test waveform did not use any extra techniques like puncturing gaps or reducing duty cycle.

which are described below, once again show that LTE-U does not have any adverse impact on latency sensitive Wi-Fi applications.

3.5.1 Test 4: Multiple Bidirectional VoIP and Downlink Full Buffer Traffic Tests Above CCA-ED

This test examines the performance of multiple VoIP Wi-Fi links in the face of interference from a full buffer of LTE-U eNB traffic when the channel is shared. In addition to VoIP, the Wi-Fi AP also runs full buffer traffic.

The test is performed on a single available Wi-Fi primary channel for SCell in a 20 MHz unlicensed spectrum channel. A Wi-Fi link between AP1 and STA1 with full buffer UDP traffic is configured on that channel. Additionally, five Wi-Fi VoIP links from STA2, STA3, STA4, STA5 and STA6 to AP1 are configured. All links used the Chariot tool for traffic generation.

For a baseline, AP2 (the same vendor/model as AP1) is configured with 20 MHz SCell on that channel with a Wi-Fi STA7. Full buffer downlink UDP traffic is configured for AP2. RSSI from AP2 on AP1 and its associated STAs is above the CCA-ED threshold (*i.e.*, -62 dBm for 20 MHz).

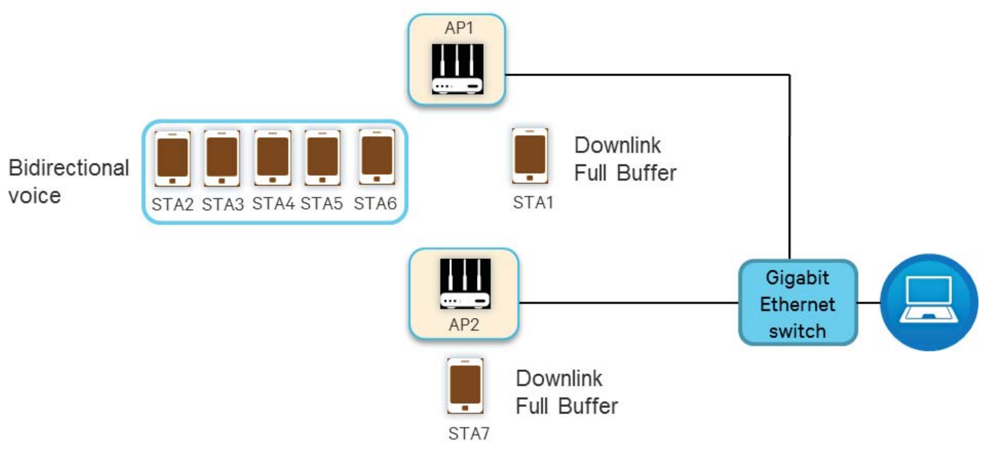


Figure 16 VoIP Test Baseline

For the coexistence test, AP2 and STA7 are replaced by LTE-U eNB and UE. Full buffer UDP traffic is configured for LTE-U eNB. RSSI from LTE-U eNB on Wi-Fi AP1 and its associated STAs is above CCA-ED threshold (*i.e.,* -62 dBm for 20MHz). LTE-U uses a CSAT cycle of a 40 ms On interval followed by 40ms Off.

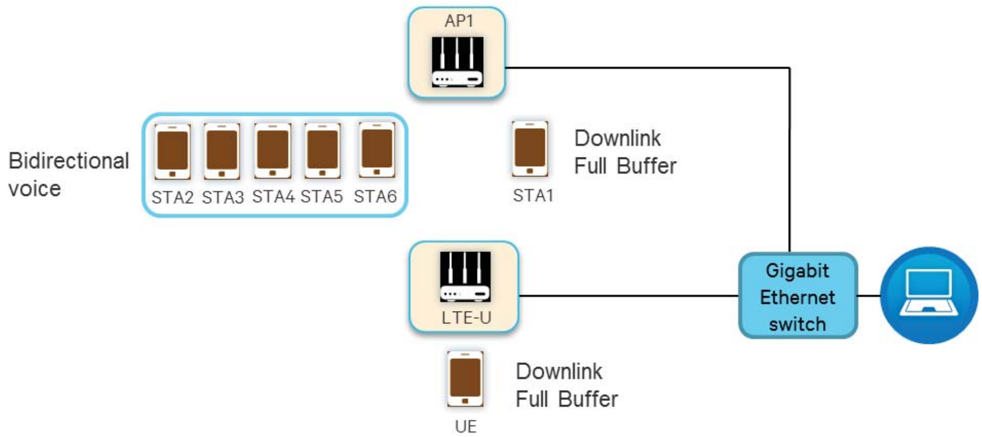


Figure 17 VoIP Test Coexistence

The above baseline and coexistence tests are performed over-the-air (OTA) and run for 120 sec, which is consistent with the Wi-Fi Alliance – Voice Enterprise (WFA-VE) certification program [20]. The following voice configuration is used to configure the voice QoS profile:

- Voice codec: Enterprise grade G.711 (64kbps) voice codec
- Jitter Buffer: A nominal de-jitter buffer delay of 40ms
- AC Tagging: DSCP marking is enforced by setting qWAVE=111000
- EDCA Parameters: IEEE 802.11 default EDCA parameters are used per Table 8-105 in the 802.11ac spec

The following stats are collected for the baseline and coexistence tests:

- The one-way delay
- The packet jitter[43]
- The packet loss rate
- The probability of 4 or more consecutive packet loss

Table 4 shows the summary of performance metrics results. As shown in the table, without using any puncture gaps, the maximum Wi-Fi VoIP latency across the 5 calls is within 50 ms per WFA requirements. The probability of jitter[44] exceeding 50 ms as required by WFA is met across all links 99% of the time. Packet loss is in the same ball park as baseline and always less than 1% per WFA requirements. The probability of losing more than 4 packets in a row is always zero per WFA requirements.

---

[43] Refer to Appendix E in the WFA-VE test plan for the definition and method for calculating packet jitter.

[44] For real time VoIP applications, a de-jitter buffer is used that typically allows more than 100 ms. We found that the main issue impacting VoIP performance is usually packet loss.

Scenario	VoIP direction	One-way delay maximum (ms)	Jitter (delay variation) maximum (ms)	Probability of Jitter > 50ms	Packet loss rate	Probability of 4 or more consecutive packet loss
Baseline	Downlink	48	21	0%	0%	0%
	Uplink	40	42	0%	0.03%	0%
Coexistence	Downlink	42	56	0.00%	0%	0%
	Uplink	50	79	0.76%	0.08%	0%

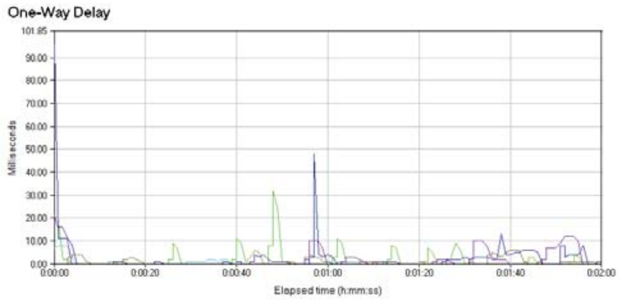
Table 4. Summary of AP-AP and AP-LTE-U avg VoIP perform metrics across the 5 links

Table 5 shows the individual statistics of the five VoIP links.

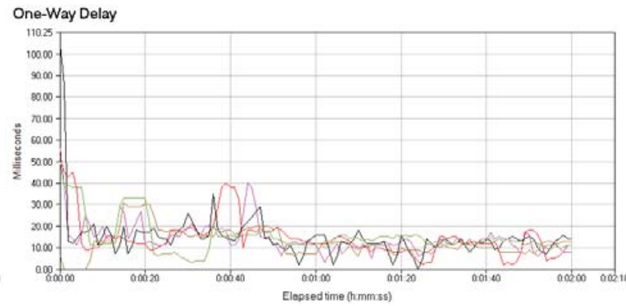
Scenario	VoIP direction	STA	One-way delay maximum (ms)	Jitter (delay variation) maximum (ms)	Probability of Jitter > 50ms	Packet loss Rate	Probability of 4 or more consecutive packet loss
Baseline	Downlink	STA2	32	15	0%	0%	0%
		STA3	8	15	0%	0%	0%
		STA4	6	15	0%	0%	0%
		STA5	48	13	0%	0%	0%
		STA6	21	21	0%	0%	0%
	Uplink	STA2	40	42	0%	0%	0%
		STA3	40	42	0%	0.02%	0%
		STA4	35	32	0%	0.02%	0%
		STA5	31	35	0%	0.03%	0%
		STA6	33	37	0%	0%	0%
Coexistence	Downlink	STA2	16	49	0%	0%	0%
		STA3	42	50	0%	0%	0%
		STA4	14	56	0.02%	0%	0%
		STA5	24	50	0%	0%	0%
		STA6	33	47	0%	0%	0%
	Uplink	STA2	47	70	0.77%	0.03%	0%
		STA3	46	79	0.92%	0%	0%
		STA4	41	65	0.49%	0%	0%
		STA5	32	66	0.95%	0.03%	0%
		STA6	50	64	0.67%	0.08%	0%

Table 5. Summary of AP-AP and AP-LTE-U individual VoIP performance metrics of the 5 links

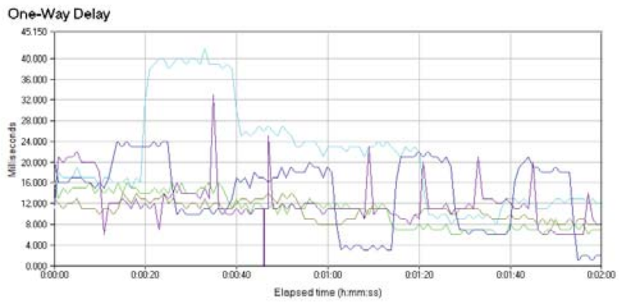
Statistics for DL and UL, for baseline and coexistence are shown below in Figure 18 and Figure 19.



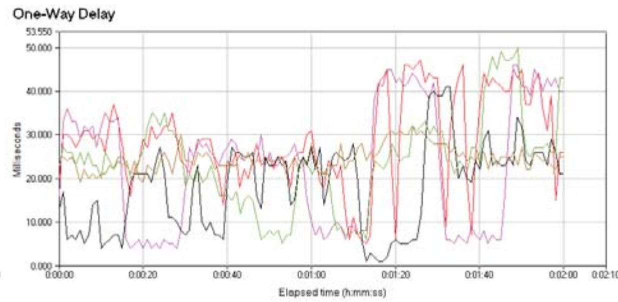
(a) Baseline: Downlink



(b) Baseline: Uplink

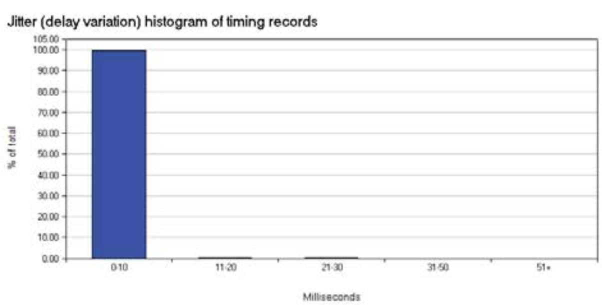


(c) Coexistence: Downlink

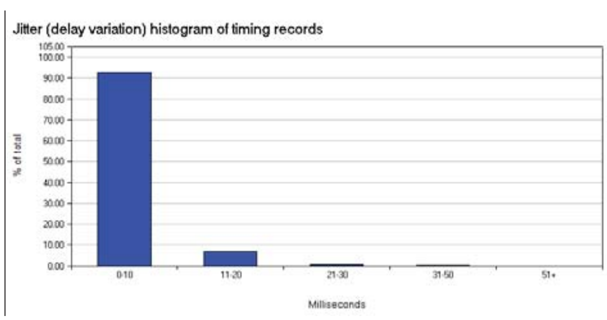


(d) Coexistence: Uplink

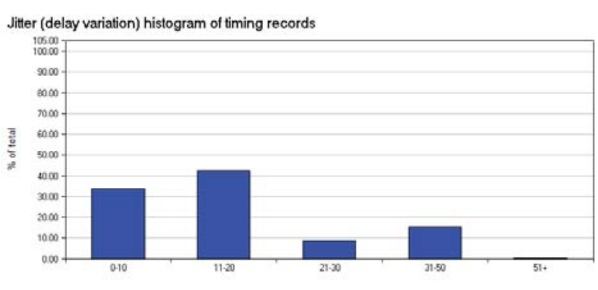
Figure 18. Time traces of the one-way latency of the five VoIP links



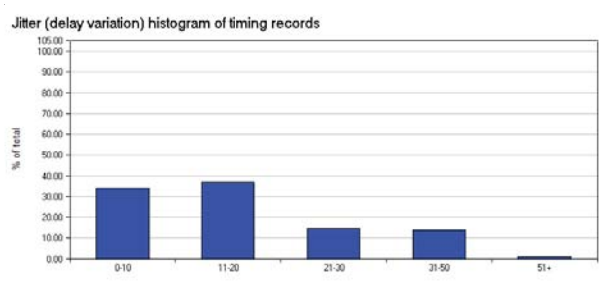
(a) Baseline: Downlink



(b) Baseline: Uplink



(c) Coexistence: Downlink



(d) Coexistence: Uplink

Figure 19. Jitter statistics for the five VoIP links

3.6 Concern 4: Impact of LTE-U Duty Cycle Approach on Wi-Fi Beacon Delivery and Client Device Power Consumption[6]

We clarify below the impact of LTE-U duty cycle transmission on Wi-Fi beacons and power save behavior, which was a concern mentioned in Google's filing.

It is critical to note that LTE-U transmissions can only conceivably impact the delivery of scheduled Wi-Fi beacons (once every 102ms) when the LTE-U shares the primary channel of a Wi-Fi node and the Wi-Fi node is in close proximity such that the RSSI of the LTE-U node is above the CCA-ED threshold.

As a first step, LTE-U nodes typically try to avoid co-channel operation with a Wi-Fi primary through dynamic channel selection. As explained previously, there are ten 20 MHz channels in UNII-1 and UNII-3 (including CH32), and the probability of an LTE-U and Wi-Fi node ending up in this scenario after channel coloring is very unlikely.

Second, even in a corner scenario where an LTE-U node has to overlap on a Wi-Fi primary channel above the CCA-ED threshold (where all other channels are more occupied), LTE-U can be configured to dynamically adapt its minimum On time proportionately (that is, go below 50% depending on the number of neighbor nodes) and leave a fair share of airtime to Wi-Fi.

The choice of duty cycle plays an important role in determining the effective delay observed by Wi-Fi beacons and the number of missed beacons. For a short cycle configuration of 80 ms {40 ms On, 40 ms Off} at 50% duty cycle, the impact of LTE-U transmissions on Wi-Fi beacons is minimal. The probability that two consecutive beacons are delayed is 0.225 and it can be shown that the probability of a straight miss of three consecutive beacons is 0, *i.e.*, a client device is guaranteed to see at least one beacon in every string of three consecutive beacons.[45] Further, with the right choice of T_{ON}/T_{OFF} parameters for a given duty cycle, the beacon collision probability can be completely avoided. For example, with the same CSAT cycle of 80 ms but an {On, Off} tuple of {20 ms, 60 ms}, the probability of missing two consecutive beacons is 0.[46] Similarly, for lower CSAT cycles of 40 ms and an {On, Off} tuple of {20 ms, 20 ms}, the probability of missing two consecutive beacons is very small (=0.05). In addition, with puncture gaps (not assumed in this analysis), Wi-Fi APs can grab the medium and transmit the beacon at the first opportunity within preferred inter frame spacing (PIFS=25usec) duration.

Further, the problem is even less relevant for the scenario where the LTE-U and Wi-Fi nodes are below the CCA-ED threshold. The Wi-Fi beacons are no longer delayed since the LTE-U node is received below CCA-ED, and the beacon hit/miss probability purely depends on the SINR at the client. Again, referring to the simulation results depicted in Figure 10, even the tail-tail user has an

[45] Specifically, this addresses the concern raised in Google's filing [Ref.6, p.12] on client disassociation because of missed beacons. It is important to understand that a sufficient number (typically tens) of missed beacons is necessary to trigger the client to disassociate from the AP. As explained in the body, with an appropriate choice of the duty cycle, this situation is completely avoided.

[46] The Annex contains the expressions used for deriving the beacon collision probabilities.

SINR above 5 dB, which is typically enough to decode the Wi-Fi beacon (*i.e.*, beacons are commonly sent at the lowest basic service set rate of 6 Mbps).

Based on the statistical analysis presented above, the event of missing two consecutive beacons can be made small, by the choice of T_{ON}/T_{OFF} and channel selection, and the event of missing three or more consecutive beacons can be completely eliminated. Also, if punctured gaps are used during T_{ON}, these probabilities only improve.

3.7 Concern 5: Effectiveness of LTE-U Duty Cycle Approach in Protecting Wi-Fi UL Traffic

This concern was mentioned in Google's filing [6] and others. We note that LTE-U is designed from the beginning to coexist with Wi-Fi DL or UL traffic. Recently a test was added to the LTE-U Coexistence specifications, in Section 6.2.3, which mandates coexistence in terms of equitable air time sharing between one LTE-U link and two Wi-Fi ULs.

3.8 Concern 6: LTE-U Interference on Wi-Fi When the Data Buffer is Empty

NCTA's filing raised a concern about LTE-U polluting the unlicensed band with unnecessary interference even when the data buffer at the LTE-U small cell is empty. The LTE-U Forum coexistence specification guarantees against such undesirable interference by requiring an LTE-U node to disable transmission in the unlicensed band when there is no need to use the band for traffic. This is captured by the test in Section 6.3.1 of the LTE-U Forum Coexistence Specification.

3.9 Concern 7: LTE-U Channel Selection to Protects Itself but not Wi-Fi

NCTA [7] claims LTE-U channel selection does not protect Wi-Fi because channel selection relies on sensing the energy level received from Wi-Fi nodes at the LTE-U node. The assumption here is that other nodes use similar transmit power so that the interference is reciprocal. In other words, if the Wi-Fi AP is a strong interferer to LTE-U, the opposite is also true. This is similar to the channel selection assumptions used by Wi-Fi. Thus, NCTA's claim is misplaced.

3.10 Concern 8: TxBF and MU-MIMO Modeling Assumptions for Wi-Fi/LTE-U Performance Evaluation

That is true to simplify studies since it is orthogonal to the coexistence problem addressed. Note LTE-U also supports beamforming and multi-user MIMO and that was never used/assumed in any of the studies.

4. Concerns on LAA Coexistence and Responses

Some concerns were raised in the FCC filings regarding whether LAA can coexist with other unlicensed technologies, especially with Wi-Fi [Refs.6,11]. While some of the concerns are common across LTE-U and LAA and therefore addressed in earlier sections of this Appendix, some technical concerns specifically targeting the design of LAA are addressed in this section.

It is noteworthy to point out that 3GPP has evaluated the coexistence between LAA and Wi-Fi in a wide range of scenarios. The results, based on contributions from many members including Wi-Fi vendors, have been summarized in 3GPP Technical Report 36.889[Ref.21]. The Technical Report concludes that "The studies show that when an appropriate channel access scheme, as defined in Section 8.2, is used, it is feasible for LAA to achieve fair coexistence with Wi-Fi, and for LAA to coexist with itself based on the evaluated scenarios."

4.1 Concern 1: LAA not required to perform LBT below CCA-ED limit

ETSI only requires LBT be performed to a threshold of -60 dBm. However, LAA is not solely designed based on what is required by the regulation, in particular fixed energy level detection. Detecting the presence of Wi-Fi, even when the received signal level is below a nominal energy level, and coexisting with Wi-Fi are very much within the scope of the LAA design objective. For example, detecting the preamble of a Wi-Fi signal can be done at a level much lower than the typical energy detection threshold. This also would address the concern of LAA impact on VoIP over Wi-Fi below CCA-ED limit raised by Broadcom [Ref.11]. The simulations by the 3GPP study include the below CCA-ED limit scenarios, and the results show good coexistence when an appropriate LAA channel access scheme is used.

It is notable that the current Wi-Fi spec does not require Wi-Fi to detect any non-Wi-Fi signal below energy threshold level and perform LBT accordingly. This raises the concern of how Wi-Fi protects other unlicensed technologies including LAA in below-ED scenarios.

4.2 Concern 2: LAA backoff parameters for LBT

Google claimed that unequal access results when an LTE device uses a zero backoff, a fixed non-zero backoff value or a different randomization of backoff values (from Wi-Fi) [Ref.6]. First, LAA design does not allow immediate transmission after channel becomes free. A random backoff needs to be performed, and only if the channel is still free after the backoff can LAA start to access the medium. Moreover, there is no connection between using fixed non-zero backoff value or a different randomization of the backoff value and unequal access to the channel. For example, a Wi-Fi node can be configured to be much more aggressive than another Wi-Fi node with a different configuration in accessing the medium, even though they both follow the same CSMA mechanism, or a Wi-Fi node can be configured to be more aggressive than another node with a fixed non-zero backoff.

Though use of an exponential backoff mechanism is one means Wi-Fi uses to adapt to channel loading, it is the only means of adaptive channel access. For Wi-Fi deployments without centralized coordination on medium access, it may be useful to use an exponential backoff mechanism to ensure system stability where a large number of Wi-Fi devices compete for the channel. LAA does not have this constraint as the access to the channel by LAA devices is controlled by an LAA eNB scheduler; thus, system stability is guaranteed no matter how many LAA UEs are part of the system. While LAA design is still ongoing, it is agreed that adaptive channel access will be supported.

Regarding Option A and B of the ETSI LBT rule, it is speculative to claim that Option A devices with different backoff windows from Wi-Fi or Option B devices would dominate channel access with respect to Wi-Fi users. Moreover, ETSI is currently studying how to best revise the LBT regulation rules for the 5 GHz band, including the initial deferral window. The objective is to support fair channel access between different technologies, including Wi-Fi and LAA. 3GPP is actively working with ETSI on this issue.

4.3 Concern 3: LAA transmission length

Google claimed that: "LTE, due to its basic protocol design and scheduled nature, generally transmits long frames (*i.e.*, multiple ms), whereas a large percentage of Wi-Fi frames are sub-millisecond in duration" [Ref.6]. In reality, however, Wi-Fi data packet transmissions are usually a few milliseconds in duration. LAA transmission duration is expected to be on the same order as the duration of Wi-Fi data packet transmission.

It should be noted that "how often a technology is able to start a transmission" and transmission length should not be the only metrics to ensure fair access. For example, as mentioned earlier, CSMA only focuses on fair access to the medium, but it does not guarantee fair sharing of the spectral resources among the contending nodes. A more comprehensive study of effective and fair coexistence between LAA and Wi-Fi has been performed in [Ref.21], with the objective that the LAA design should target fair coexistence with existing Wi-Fi networks so as to not impact Wi-Fi services more than an additional Wi-Fi network on the same carrier, with respect to throughput and latency.

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[8] Comments Of Cablevision Systems Corporation in FCC ET Docket No. 15-105.

[9] Comments of ViaSat in FCC ET Docket No. 15-105.

[10] Comments of Ruckus Wireless in FCC ET Docket No. 15-105.

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Annex: Beacon Delay Probability Calculations

In this section, we provide the probability expressions for beacon overlap with LTE-U On duration derived as a function of CSAT duty cycle (T_{CSAT}) and nominal beacon period (T_B). Assuming, a short CSAT cycle T_{CSAT} with On/Off times T_{ON}/T_{OFF} and beacon period T_B, and $T_{CSAT}<T_B$, the probability of i (i=1 or 2) consecutive beacons overlapping with T_{ON} can be shown to be:

$$\text{Prob(i = 1 beacon overlapping with } T_{ON} \text{ duration)} = \frac{T_{ON}}{T_{ON}+T_{OFF}}$$

$$\text{Prob(i = 2 consecutive beacons overlapping with } T_{ON} \text{ duration)} = \frac{T_{ON}}{T_{ON}+T_{OFF}} \times \boldsymbol{\alpha} \; where$$

$$\boldsymbol{\alpha} = \begin{cases} \max\left(0, \dfrac{mod\,(T_B, T_{CSAT}) + T_{ON} - T_{CSAT}}{T_{ON}}\right) & if\ mod\,(T_B, T_{CSAT}) \geq T_{ON} \\ \dfrac{T_{ON} - mod\,(T_B, T_{CSAT})}{T_{ON}} & if\ mod\,(T_B, T_{CSAT}) < T_{ON}. \end{cases}$$