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

COMMENTS OF QUALCOMM INCORPORATED

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SUMMARY

Qualcomm is pleased to respond to the FCC's Public Notice seeking information on LTE-U and LAA technology (collectively referred to as "LTE Unlicensed") to explain the extensive technical work that Qualcomm and its wireless industry partners have done to enable the successful implementation of LTE Unlicensed — to ensure that LTE Unlicensed will fairly share unlicensed spectrum with Wi-Fi and other uses without any adverse impact. Qualcomm has a strong vested interest in this result since we have a vibrant and expanding Wi-Fi business.

Qualcomm, on its own and with its partners, has worked closely with many companies on a bilateral and multilateral basis and through industry organizations, such as 3GPP, the LTE-U Forum, ATIS, IEEE 802, and the Wi-Fi Alliance ("WFA"), to develop clear and effective specifications for both LTE-U and LAA. There have been numerous face-to-face detailed technical briefings and exchanges with Wi-Fi equipment vendors, service providers, and their associations. Qualcomm has demonstrated LTE-U and LAA (which is still being developed) publicly at Mobile World Congress and provided numerous demonstrations in its lab and on its campus over the air to a wide variety of stakeholders. These demonstrations show that LTE-U and LAA can and will successfully coexist with Wi-Fi. 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, Qualcomm's demos showed that replacing a Wi-Fi node with LTE-U improves the average throughput for nearby Wi-Fi users. By all means, all industry participants will continue to work together to refine the technology and reach effective technical solutions.

For these reasons, despite the pleas of some, there is absolutely no basis for any new FCC regulation with respect to LTE-U and LAA. To the contrary, the development and eventual deployment of these new technologies are precisely the type of innovations that the FCC seeks to foster through its highly successful policies for unlicensed spectrum.

LTE Unlicensed will substantially improve consumers' mobile broadband experience. While the federal government, *i.e.*, the FCC, NTIA, OSTP, federal agencies that use spectrum, and Congress, along with the wireless industry are tirelessly working to make more spectrum available for mobile broadband use, consumer demand is outpacing the available spectrum, and, as a result, the wireless industry needs to use any and all available spectrum with the most efficient technologies possible. LTE Unlicensed enables a number of the advanced technical innovations of 4G LTE — an interface heretofore used exclusively in licensed spectrum operations — to be incorporated into small cells that will use licensed and unlicensed spectrum to provide greater capacity for smartphones and tablets and provide consumers a far better user experience. Moreover, LTE Unlicensed will bring into the unlicensed realm for the first time 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.

There are two versions of LTE Unlicensed that use an anchor channel in a licensed spectrum band, and Qualcomm also is developing a standalone version of LTE Unlicensed, called MuLTEfire,™ that will not use a licensed anchor. The two versions that rely upon a licensed anchor channel (LTE-U and LAA) implement carrier aggregation where the unlicensed band is used to supplement LTE operations in licensed spectrum. All three versions will coexist very well with Wi-Fi operations and successfully share spectrum with all unlicensed users.

The first version of LTE Unlicensed that uses a licensed anchor channel is referred to as LTE-U, and it will operate in a supplemental downlink-only mode in the 5 GHz U-NII-1 and U-NII-3 bands. LTE-U will not operate in the U-NII-2A and U-NII-2C bands, thereby leaving 355 MHz of spectrum exclusively for Wi-Fi and other unlicensed technologies. LTE-U works

with the version of LTE already standardized by 3GPP in Release 10/11/12 and aggregates the unlicensed spectrum as a secondary channel, and to avoid interfering with Wi-Fi and other unlicensed uses, it adds frequency selection and a listen-before-talk channel sensing technique called Carrier Sense Adaptive Transmission ("CSAT"). Before transmitting, the LTE-U small cell, much like a Wi-Fi access point, senses the nearby area and looks for a vacant unlicensed channel. If it cannot find a vacant channel, it finds the least crowded channel. Then, using CSAT, LTE-U users take turns with Wi-Fi users to enable successful coexistence when the two technologies are operating co-channel. LTE-U, using this on/off routine, will never use the unlicensed spectrum for longer than its proportionate share of the time. Even when LTE-U is transmitting, which is never longer than 50 milliseconds at a time, there are periods of off time, *i.e.*, gaps in the transmission on the order of at least 1 millisecond, to ensure that latency-sensitive Wi-Fi uses (*e.g.*, VoIP calls) are not impacted. Finally, the LTE-U small cell vacates the unlicensed spectrum when it is not needed, like an "on/off switch."

The second version of LTE Unlicensed that uses a licensed anchor channel is being standardized in 3GPP Release 13. It is called Licensed Assisted Access ("LAA"). LAA requires more extensive changes to the LTE air interface to incorporate changes to the LTE waveform and a specific Listen-Before-Talk protocol that is required in Europe and Japan. Like LTE-U, LAA will use frequency selection to find open frequencies to use and time-share when operating co-channel with Wi-Fi, and it will vacate the spectrum when it is not needed.

There also is a third standalone version of LTE Unlicensed that Qualcomm is actively developing. The standalone version, which is called MuLTEfire, will not use a licensed anchor channel and instead will operate entirely in unlicensed spectrum. This mode will use the signals, channelization, and other advanced features of LTE and thus will provide better performance

than currently available unlicensed technologies. The versions that use a licensed anchor, LTE-U and LAA, will be more robust than MuLTEfire because the licensed anchor channel supports the essential communications operations of acquisition, access, registration, paging, mobility, and control signaling. MuLTEfire will use unlicensed spectrum for all purposes, *e.g.*, data, signaling, and all other operations. Finally, all three versions of LTE Unlicensed will fully comply with the FCC's rules.

Assertions that LTE Unlicensed will drown out Wi-Fi and other unlicensed spectrum users are completely false. LTE Unlicensed, in all forms, has been carefully designed to fairly share spectrum with Wi-Fi. As the FCC well knows, the wireless industry relies heavily upon both Wi-Fi in unlicensed bands and 3G and 4G in licensed bands. Indeed, virtually all smartphones sold today support LTE and Wi-Fi, and consumers use both technologies every day and often at the same time. The industry at large has every incentive to ensure that devices that use Wi-Fi do not suffer interference and continue to perform well.

There is no question that Wi-Fi has a very bright future, and Qualcomm and the wireless industry at large are working to ensure that both Wi-Fi and LTE Unlicensed continue to improve, support increased capacity, and provide a great user experience. As LTE Unlicensed technology is developed and deployed, Wi-Fi will be enhanced in response, and vice versa. Qualcomm, which recently announced new advanced wireless solutions based on 802.11ac Wi-Fi for 5 GHz, will support Wi-Fi and LTE for many years to come.

Many companies are supporting both Wi-Fi and LTE Unlicensed, and all recognize the need for extensive technical exchanges with those only involved with Wi-Fi to ensure successful spectrum sharing among all unlicensed users. Accordingly, for many months, there have been extensive communications between LTE-U Forum members and the WFA as well as WFA

members on LTE-U, and between 3GPP and IEEE 802 on LAA. In fact, many of the same companies are members of 3GPP, IEEE and the WFA, and the LAA standardization effort in 3GPP involves many member companies that design, develop, manufacture and deploy both cellular and Wi-Fi technologies. Likewise, most of the key LTE-U Forum participants develop and/or widely deploy Wi-Fi products and services, and LTE-U Forum members are participants in the WFA coexistence evaluation group.

Indeed, on May 28, 2015, LTE-U Forum members Verizon, Alcatel-Lucent, Ericsson, Qualcomm, and Samsung hosted a full-day workshop attended by many leading Wi-Fi equipment, chipset, device, and OS vendors, as well as AT&T and T-Mobile, the WFA and IEEE 802. In all, 96 people from 29 different companies and organizations attended. The workshop included very detailed and extensive technical presentations covering the LTE-U Forum specifications and coexistence mechanisms and demonstrations both in the lab and the field. Qualcomm will continue working with all stakeholders to ensure a successful outcome.

In sum, LTE Unlicensed is one of many innovations that the wireless industry is developing to use each sliver of spectrum in the most efficient manner possible to enhance the user experience for consumers. The FCC's technology neutrality policy, which has worked exceedingly well for the nation, 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.

Qualcomm is more than happy to continue providing information on all aspects of LTE Unlicensed to the FCC, industry stakeholders, and the public. Still, there is no reason whatsoever for the FCC to consider taking any regulatory action with respect to LTE Unlicensed.

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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

COMMENTS OF QUALCOMM INCORPORATED

QUALCOMM Incorporated ("Qualcomm") respectfully submits these 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]

As explained herein, the entire wireless industry is working toward enabling the successful introduction of LTE Unlicensed. The Commission's successful technology neutral policy allows this innovative new technology to be developed and deployed. We applaud the FCC's recognition that it "has historically adopted rules that are technologically neutral and [that it] remains committed to this policy."[2] We also are very excited by the greater capacity and enhanced user experience that LTE Unlicensed will provide. And, as one of the technology developers, Qualcomm expects to sell wireless chips, software and firmware that support LTE Unlicensed for both small cells and user devices, such as smartphones and tablets.

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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 id*. at 2.

INTRODUCTION

Qualcomm is constantly developing technologies to enable more intensive and efficient use of spectrum in order to expand wireless capacity and provide consumers with the best possible user experience. This is precisely why Qualcomm and others developed LTE Unlicensed. Today, mobile operators use a technique called carrier aggregation to combine different spectrum bands virtually to create the widest possible data pipe to service a consumer's data needs. Mobile carriers currently aggregate multiple *licensed* spectrum bands to provide a wider data pipe, and LTE Unlicensed will allow carriers to aggregate *unlicensed* spectrum bands with licensed bands to provide an even wider data pipe. By virtually creating the widest possible data pipe to service the greatest number of users, mobile operators can noticeably improve the service to all consumers within a given service area.

Qualcomm in particular, and many companies in the wireless industry writ large, 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 technical meetings, both bilateral and multilateral, between and among companies developing LTE Unlicensed technology and those who develop and deploy Wi-Fi technology. There also have been extensive presentations and discussions within the Wi-Fi Alliance ("WFA"), IEEE 802 and 3GPP, as detailed herein. This work is ongoing and will continue as LTE Unlicensed is refined and ultimately deployed. Many of the companies developing LTE Unlicensed technology also develop and/or deploy Wi-Fi technology, so it is in everyone's interest that LTE Unlicensed successfully shares spectrum with Wi-Fi and all other unlicensed uses.

The FCC's light-touch, technology-neutral regulatory regime, which typically sets emission bandwidths, maximum transmit power levels, and out of band emissions limits, and allows any technology that complies with those requirements to be deployed, has worked well

for countless spectrum bands. For example, when the FCC first defined Part 15 unlicensed rules for the 2.4 GHz band, it had no idea that the band would eventually support Wi-Fi, Bluetooth, video game consoles, and wireless speakers.[3] Today, that band supports those uses and more, including Zigbee, cordless telephones, and radio control toys. The wide variety of uses in unlicensed spectrum would not have occurred had the FCC instituted rules specific to a given technology or use case. The FCC should continue this policy. There is no sound reason for the FCC to consider any regulatory change as a result of the development of LTE Unlicensed.

DISCUSSION

I. LTE Unlicensed Technology Will Provide A Greatly Improved User Experience For Consumers

In order to serve the ever-increasing demands of today's wireless consumers, the wireless industry is constantly researching and developing technologies to improve capacity and enhance the service provided to consumers, which includes means of accessing additional spectrum. In this regard, LTE Unlicensed seeks to make use of unlicensed spectrum to improve the mobile broadband experience for all consumers. The deployment of LTE Unlicensed will provide consumers with higher data download and upload speeds, lower latency connections, better coverage, and much smoother transitions between licensed and unlicensed spectrum bands.

LTE Unlicensed will be particularly useful in high traffic areas to provide increased data throughout and reliability. Today, many mobile carriers enable spectrum offloading to Wi-Fi in order to ease congestion on their networks and offer consumers additional connectivity options.

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[3] *See, e.g.*, Remarks of Commissioner Jessica Rosenworcel, "The Future Of Unlicensed Spectrum," Computer History Museum, Mountain View, CA (Sept. 11, 2014) at 2 ("Why should the FCC dictate what technologies should use these frequencies? What if we set some basic technical parameters instead? And what if we gave the public access to these airwaves? [W]here if you simply comply with the rules of the road you can do things and go places.")

That will not change, and thus, these carriers 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.

Because today's mobile consumers make use of licensed and unlicensed spectrum each and every day through use of smartphones, tablets, and other mobile devices that support a variety of spectrum bands, LTE Unlicensed has been carefully designed to not interfere with Wi-Fi and other uses of unlicensed spectrum. LTE Unlicensed has undergone extensive testing in the laboratory and in the field, using the latest version of 5 GHz Wi-Fi, called 802.11ac, running on a wide variety of top-selling 5 GHz Wi-Fi equipment. The tests have shown that LTE Unlicensed has no adverse impact on Wi-Fi. Qualcomm's extensive lab and field tests have shown that adding an LTE Unlicensed small cell provides a much improved user experience while introducing no more interference to a Wi-Fi access point when compared to adding another Wi-Fi access point. In fact, in Qualcomm's testing, replacing a Wi-Fi node with an LTE-U node often improves the throughput for adjacent Wi-Fi users. Moreover, in 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 You Tube over Wi-Fi, there was no degradation of any kind to Wi-Fi.

The outstanding technical performance of LTE Unlicensed is explained in greater detail below, in response to the questions in the Public Notice in Section V of these comments, and in the Slide Presentation and LTE-U Forum Technical Report that are provided as Appendices to these comments.

II. Qualcomm And The Wireless Industry Have Done Extensive Technical Work To Ensure That LTE Unlicensed Does Not Interfere With Wi-Fi

LTE Unlicensed has been designed to share spectrum successfully with Wi-Fi operations. Mobile operators and other service providers are keenly aware of the important role that Wi-Fi plays in providing mobile broadband services to consumers and have therefore taken steps to ensure that Wi-Fi and LTE Unlicensed will coexist successfully.

The first version of LTE Unlicensed that uses a channel anchored in a licensed spectrum band and works with existing 3GPP Releases 10/11/12, *i.e.*, "LTE-U," adds three mechanisms to avoid interfering with Wi-Fi. *First*, it uses a listen-before-talk technique in which the small cell scans the spectrum, using sensing to identify and begin operating in a vacant channel, or if there is no vacant channel, the least used channel. *Second*, where there are no vacant channels, LTE-U will implement an adaptive duty cycle using Carrier Sense Adaptive Transmission ("CSAT") that allows LTE-U to take turns with other users and vacates the channel to allow others to use it. LTE-U never uses the channel for longer than its proportionate share. Also, LTE-U never transmits for more than 50 milliseconds continuously, and when it does transmit, it has periods of off-time, or "punctures," on the order of at least 1 millisecond, so that Wi-Fi signals can successfully support Voice over Internet Protocol ("VoIP") calls and timely perform connection setup. *Third*, LTE-U uses an "on/off" switch so the unlicensed band is used only when needed and vacated quickly when it is not needed to allow others full access to use it.

The second version of LTE Unlicensed that uses a licensed anchor channel is being standardized in the upcoming 3GPP Release 13. This version is called LAA (for Licensed Assisted Access). LAA will incorporate certain bandwidth constraints required by the ETSI spec and a specific Listen-Before-Talk protocol that is required in Europe and Japan. In late May 2015, the 3GPP Release 13 LAA study item was successfully completed in the 3GPP RAN 1

group.[4] The study concluded with selection of the coexistence mechanisms (for downlink and uplink) that allow LTE 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.

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 explains in the detailed responses to the questions in the Public Notice in Section V of these comments, while MuLTEfire will lack the benefits of an anchor channel in licensed spectrum, it will still provide improved performance when compared to other currently available technologies that use unlicensed spectrum.

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

LTE Unlicensed has been tested extensively in the field and in labs and has no adverse impact on Wi-Fi. For example, tests for LAA (as presently understood by Qualcomm) and Wi-Fi coexistence were conducted with seven pairs of nodes, comprised of LTE base stations and devices or Wi-Fi access points and devices, operating co-channel, and they demonstrated very good coexistence. Qualcomm has conducted similar tests of LTE-U, actually with nine pairs of nodes operating over the air, and these tests show that LTE-U coexists very well with Wi-Fi. Qualcomm demonstrated these coexistence scenarios and capabilities at Mobile World Congress

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

in Barcelona in February 2015.[5] Also, Qualcomm has conducted extensive tests demonstrating that LTE-U and LAA coexist very well with each other and with all types of Wi-Fi devices.

To be sure, Wi-Fi has a very bright future. Qualcomm and others in the wireless industry are working to improve the capabilities of Wi-Fi. Most Qualcomm cellular (3G and LTE) chips include support for 802.11ac, and Qualcomm fully expects Wi-Fi and LTE operations in unlicensed bands to 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.[6] Qualcomm's latest 802.11ac solutions use four antennas to deliver 1.7 Gbps.[7] 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 Wi-Fi. Without question, Qualcomm will support Wi-Fi and LTE Unlicensed technologies for many years to come.

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[5] Videos of these demos may be accessed at https://www.qualcomm.com/invention/research/projects/lte-unlicensed.

[6] *See* Qualcomm Press Release, "Qualcomm Expands 802.11ac MU-MIMO Product Portfolio for Wi-Fi Access Points and Routers, Builds Momentum with Significant Customer Adoption — At Computex, Company Demonstrates New Products that Add 160 MHz Channel Support to Enable Higher Bandwidths" (June 1, 2015) *accessible at* https://www.qualcomm.com/news/releases/2015/06/01-0; *and see* Qualcomm Press Release, "Qualcomm Unveils Industry's First Hybrid Wireless Extender Utilizing HomePlug AV2 MIMO and 802.11ac Wi-Fi — Introducing an Industry First in Next-Generation Hybrid Networking as well as a New Low-Cost HomePlug AV2 SISO Solution; New Powerline Solutions Take HomePlug AV2 to a New Level of Wi-Fi Integration and Cost Optimization" (June 1, 2015) *accessible at* https://www.qualcomm.com/news/releases/2015/06/01-1.

[7] *See also* Qualcomm OnQ Blog, "Capacity is King" (June 1, 2015) *accessible at* https://www.qualcomm.com/news/onq/2015/06/01/capacity-king (Qualcomm is combining 802.11ac Wi-Fi and 60 GHz 802.11ad Wi-Gig technology, which delivers up to 7 Gbps, to provide fast Wi-Fi throughout a home or office, and high-capacity zones in living rooms, conference rooms and classrooms).

III. The Entire Wireless Industry Is Working Together To Ensure That LTE Unlicensed Successfully Coexists With All Other Uses of Unlicensed Spectrum

The entire wireless industry is working together via many bilateral and multilateral technical communications and face-to-face meetings to ensure successful spectrum sharing among all unlicensed technology uses. There have been extensive communications for many months on LTE-U between LTE-U Forum members and the WFA as well as WFA members, and between 3GPP and IEEE 802 on LAA. Many of the same companies are members of 3GPP, IEEE and the WFA, and the LAA standardization efforts in 3GPP involve many member companies that design, develop, manufacture, and deploy both cellular and Wi-Fi technologies. Likewise, most of 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. A detailed list of these interactions is in the response to Question 3 of the Public Notice provided in Section V of these comments.

On May 28, 2015, LTE-U Forum members Verizon Wireless, Alcatel-Lucent, Ericsson, Qualcomm and Samsung, hosted a day-long workshop attended by many leading Wi-Fi infrastructure, chipset, device, and OS vendors, as well as AT&T and T-Mobile, and the leadership from the WFA and IEEE 802. The workshop, which was attended by 96 people from 29 different companies and organizations, included detailed presentations covering the LTE-U Forum specifications, technical information on the coexistence mechanisms, and live demos of the advanced coexistence tools used by LTE Unlicensed technology. The materials presented during the workshop are available on the LTE-U Forum website. *See* http://lteuforum.org/workshop.html.

Accordingly, there have been, and there will continue to be, many bilateral and multilateral technical discussions among the companies that are working on LTE-U and LAA and companies who develop and deploy Wi-Fi technology over the coming months.

IV. The FCC Should Maintain Its Technology Neutral Approach To Spectrum Regulation

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. LTE Unlicensed is the latest innovative technology that significantly increases the efficiency of unlicensed spectrum use and dramatically improves consumers' mobile broadband experience.

In fact, the FCC's technology neutral policy approach to both licensed and unlicensed spectrum bands has supported perpetual innovation by the entire wireless industry. It has enabled LTE Unlicensed to be developed to provide a much-improved experience for mobile consumers. Before that, it supported the successful deployment of various 2G, 3G, and 4G technologies in licensed cellular bands and Bluetooth, ZigBee, Wi-Fi, NFC, and RFID technologies in unlicensed bands.

There is no question that the FCC should continue its successful tech 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."[8] With regard to the development and deployment of LTE Unlicensed, the FCC can be assured that this new technology will share spectrum with Wi-Fi and other unlicensed users in an equitable manner because doing so is in everyone's interest. Indeed, the companies developing and deploying LTE Unlicensed rely heavily upon reliable access to Wi-Fi, and they will continue to do so far into the future.

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[8] Public Notice at 2.

V. Qualcomm Is Pleased To Provide Detailed Responses To Each Of The Questions In The Public Notice

Q1: What different variations of LTE in unlicensed spectrum (e.g., LTE-U, LAA) are under active development or on a roadmap for future development? How do they relate to one another in terms of technology, potential use, and timing of availability?

Response: The two versions of LTE Unlicensed noted in the question, *i.e.*, LTE-U and LAA, will augment the LTE mobile broadband experience for consumers by enabling licensed operators to offload LTE mobile data traffic onto unlicensed spectrum using small cells and carrier aggregation technology. Qualcomm also is actively developing a standalone mode of LTE in unlicensed spectrum called MuLTEfire, which will not use any licensed spectrum at all. Details on MuLTEfire are provided in our response to Question 7.

LTE Unlicensed, in all the forms described in these responses, will provide significant improvements for consumers when compared to Wi-Fi and other technologies that presently operate in unlicensed spectrum. These improvements include wider coverage and a better user experience as a result of supporting much greater overall capacity. In addition, LTE Unlicensed brings in strong cellular traditions to unlicensed spectrum including uniformity of base station and device implementations, rigorous performance and conformance specifications, and certification procedures.

As LTE Unlicensed technology development is completed and deployed, Wi-Fi will continue to be enhanced in response, and vice versa. For 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. There is no question that Wi-Fi and

LTE Unlicensed have long and bright futures, and Qualcomm will support both technologies for many years to come.

As noted above, there are currently two variations of LTE Unlicensed that use an anchor channel in a licensed band:

1) **LTE-U**, based on Releases 10/11/12 of LTE with additional mechanisms added for coexistence, can operate in regions or countries, such as the United States and Korea, which do not have regulations mandating the implementation of a specific Listen-Before-Talk protocol. In the U.S., LTE-U will run in downlink-only mode and be deployed in the U-NII-1 and U-NII-3 bands, which leaves the 355 MHz in the U-NII-2A and U-NII-2C bands available exclusively for Wi-Fi and other unlicensed technologies. To coexist well and avoid causing interference to Wi-Fi and other technologies, LTE-U will implement frequency selection, a listen-before-talk technique (described in greater detail below) that senses the band and operates in an unused channel, if available, or shares the least used channel with other nearby users (such as Wi-Fi, other LTE-U users, and LAA users) by taking turns with these other users and vacating the channel to allow others to use it. And when the LTE-U signal is transmitted, the length of the transmission is no longer than 50 milliseconds, but even within that time, there are periods of silence, or "punctures," to ensure that there is no adverse impact on latency-sensitive Wi-Fi applications such as VoIP calls. LTE-U uses the unlicensed band only for downlink and only as a secondary channel.

2) **LAA** (for Licensed Assisted Access), to be incorporated into Release 13 of LTE, can operate in the 5 GHz band throughout the world because it includes changes to the LTE air interface necessary for operations in countries (like Europe and Japan) that have regulations mandating the implementation of a specific Listen-Before-Talk protocol and uplink waveform bandwidth restrictions. LAA needs to address specific bandwidth constraints for downlink and uplink in the ETSI spec, which requires any transmission to be at least 80% of the nominal bandwidth and thus necessitates changes to the LTE uplink waveform. LAA also will use frequency selection and other coexistence techniques including periodic channel vacation and random backoff. LAA uses unlicensed spectrum only as a secondary channel: i) in a downlink-only mode, and ii)

potentially in a TDD mode to support uplink and downlink, depending on the final outcome of the standardization of 3GPP Release 13. Recently, the 3GPP RAN 1 group completed its technical study item on LAA. The study item supports both downlink-only and TDD (uplink and downlink) modes of LAA. The study item concluded that LAA would coexist successfully with Wi-Fi in either mode.

While there are some technical differences between LTE-U and LAA, both share the same principles and objectives.

LTE-U and LAA both operate with an anchor channel in a licensed spectrum band (be it FDD or TDD) to ensure that use of the unlicensed spectrum band is minimized and to ensure that when the unlicensed band is used, consumers enjoy the best possible mobile broadband experience. The anchor channel supports control signaling and other essential processes, such as acquisition, access, registration, paging, and mobility. The anchor channel, which carries these primary operations, is aggregated with a set of secondary channels, each 20 MHz wide in the 5 GHz unlicensed band. These secondary channels are used for opportunistic data offload, either in downlink only, *i.e.*, supplemental downlink ("SDL"), or, depending on the final outcome of the 3GPP Release 13 standardization process, LAA could also be operated in a TDD mode to support both downlink and uplink. 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 operation possible.

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 from the outset, 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 node does not impact a Wi-Fi neighbor any more than another Wi-Fi node would impact a Wi-Fi neighbor.

LTE-U and LAA achieve this successful coexistence using a combination of techniques including:

(1) Channel selection, which is the ability to select a vacant channel, or if not, the "least crowded" unlicensed channel;

(2) Transmission on/off duty cycles in LTE-U, using a listen-before-talk technique called Carrier Sensing Adaptive Transmission ("CSAT"), enabling LTE-U operations to take turns with neighbors using Wi-Fi or another unlicensed technology;
Energy-based Listen-Before-Talk in LAA using a specific Clear Channel Assessment ("CCA"); and

(3) Adaptive channel occupancy based on detection of other Wi-Fi nodes in the vicinity (and nodes for other unlicensed technologies in the vicinity), and vacating the unlicensed channel when it is not needed.

Details of these techniques are presented in the slide deck in Appendix A to these comments. Moreover, these techniques are an integral part of LTE Unlicensed and it is not possible for any entity deploying the technology to disable these techniques. In addition, 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 enable a streamlined deployment process.

Finally, as explained below, LTE-U and LAA have been extensively tested and demonstrated — in the lab, in a very dense test chamber, over the air, and at Mobile World Congress in Barcelona in March 2015. These tests and demonstrations used the latest version of Wi-Fi, 802.11ac. The tests of LTE-U also were shown to the companies who attended the May 28, 2015 workshop in San Diego. The tests and demonstrations verified that LTE-U and LAA will not have any adverse impact on Wi-Fi and that they can and will successfully coexist with Wi-Fi and other unlicensed technologies.

Q2: What is the current state of development of the LTE-U and LAA standards and what is the anticipated schedule for completion of the LTE-U and LAA standards?

Response: As noted in response to Question 1, LTE-U works with the existing 3GPP Release 10/11/12 LTE specifications, and no changes to the LTE air interface itself are necessary for LTE-U. LTE-U takes advantage of existing LTE standards to provide an innovative use of the existing air interface protocol and adds the coexistence mechanisms via additional software added at each small cell eNB to provide the coexistence capabilities discussed above for LTE-U.

LTE-U was developed within a group called the LTE-U Forum. Verizon, Alcatel-Lucent, Ericsson, LG Electronics, Qualcomm Technologies, and Samsung were the key participating members of the LTE-U Forum. The LTE-U Forum publicly released a set of specifications for the small cell eNB and user equipment ("UE"), as well as extensive coexistence test specifications that require the implementation of the channel selection and CSAT techniques described above to ensure fair spectrum sharing between each given LTE-U node and neighboring nodes using other technologies operating in the band, such as Wi-Fi, LTE-U, and LAA. In this regard, the statements in the Public Notice that the LTE-U Forum is using a "pre-standard" version of LTE Unlicensed are not accurate. The LTE-U waveform is the standard LTE PHY/MAC from 3GPP Release 10/11/12; the band definition and coexistence test specification are provided in LTE-U Forum documentation.

The LTE-U Forum collaboratively developed and released a detailed Technical Report demonstrating that LTE-U will coexist successfully with, and not have any adverse impact on, Wi-Fi. The specifications and Technical Report are available at www.lteuforum.org. The Technical Report is attached as Appendix B to these comments.

LAA is being standardized in 3GPP as a part of the LTE Release 13 specification process. The study item phase is expected to be completed later in June, and final specifications are expected to be published by March 2016.

Q3: What is the status of coordination between 3GPP and the IEEE 802.11 on LTE-U and LAA, and what is the process for coming to agreement on appropriate sharing characteristics to ensure coexistence with the IEEE 802.11 family of standards?

Response: There have been, and will continue to be, extensive communications between 3GPP and IEEE 802.11 on LAA, and between LTE-U Forum members and the WFA and its members on LTE-U. In fact, many of the same companies are members of 3GPP, IEEE 802.11 and the WFA. Also, the LAA standardization effort in 3GPP involves members of the Wi-Fi industry. And, most of the key LTE-U Forum member companies develop and/or deploy Wi-Fi products and services, and these companies are participants in the WFA coexistence evaluation group. Moreover, there have been, and will continue to be, many bilateral and multilateral technical discussions among companies developing LTE-U and LAA and those who are not.

The discussions between the IEEE/WFA and 3GPP industry bodies, as well as the LTE-U Forum, were in the form of presentations and written liaison statements. A high-level summary of those efforts is provided below:

(1) "Coexistence Lessons Learned," liaison from IEEE 802 LAN/MAN Standards Committee to 3GPP TSG RAN, 08 November 2014.

(2) "3GPP & unlicensed spectrum," presentation by Dino Flore, Chairman of 3GPP TSG-RAN, to IEEE 802 Interim Session, Atlanta, USA, Jan 11-16, 2015.

(3) On March 9, 2015, Verizon and Qualcomm jointly presented a technical overview of LTE-U, including the coexistence features, to the WFA

(4) "Liaison Statement Regarding Clarification of LBT Categories," liaison from IEEE 802 LAN/MAN Standards Committee to 3GPP RAN, 11 March 2015.

(5) "Liaison to 3GPP related to LAA," liaison from IEEE 802 LAN/MAN Standards Committee to 3GPP RAN, 12 March 2015.

(6) "Response LS on Clarification of LBT Categories," liaison from 3GPP RAN1 to IEEE 802 LAN/MAN Standards Committee, 24 April 2015.

(7) "Response LS on LAA-802.11 Coexistence," liaison from 3GPP RAN1 to IEEE 802 LAN/MAN Standards Committee, 24 April 2015.

(8) "Study on Licensed-Assisted Access to Unlicensed Spectrum," presentation by Havish Koorapaty, 3GPP Study Item Rapporteur, to IEEE 802 Interim Session, Vancouver, Canada, May 10-15, 2015.

(9) "Proposed follow-up liaison to 3GPP related to LAA," liaison from IEEE 802 LAN/MAN Standards Committee to 3GPP RAN, 18 May 2015.

(10) "Response LS related to LAA-802.11 Coexistence," liaison from 3GPP RAN1 to IEEE 802 LAN/MAN Standards Committee, 29 May 2015.

(11) On May 28, 2015, LTE-U Forum members hosted a workshop attended by many leading Wi-Fi and cellular infrastructure, chipset, and device vendors as well as AT&T, T-Mobile and Verizon Wireless. The workshop, which involved 29 different companies and organizations (*i.e.*, WFA, IEEE 802.11 and CableLabs), included detailed, extensive presentations covering the LTE-U Forum specifications and technical information on coexistence mechanisms. The materials presented during the workshop have been posted on the LTE-U Forum website. *See* http://lteuforum.org/workshop.html.

(12) On June 8, 2015, the 3GPP RAN Chair gave a presentation to ATIS at its 5G Symposium on 3GPP Release 13 and LAA. The presentation is available on the ATIS 5G Symposium webpage. *See* http://www.atis.org/5G/presentations.asp.

We expect these industry collaborations and technical "deep-dives" in many forms to continue as LTE-U is deployed and as LAA and MuLTEfire are finalized and deployed. For example, we anticipate that there will be a joint workshop between IEEE and 3GPP in the next few months.

Q4: What are the anticipated technical characteristics (e.g. bandwidth(s), listen-before-talk, transmission durations, etc.) of LTE-U and LAA?

Response: Technical characteristics have been provided herein in the response to Q1. To the extent additional information is needed, please refer to the documents available on the LTE-U Forum website (www.lteuforum.org) and 3GPP website (Technical Report 36.889 *available at* http://www.3gpp.org/dynareport/36889.htm). The study item recently approved by 3GPP RAN 1, "Study on Licensed-Assisted Access Using LTE" is available at R1-153690.

Q5: What tests or analyses have been performed to understand the impact of LTE-U and LAA on the existing commercial wireless and unlicensed ecosystems?

Response: Qualcomm and others have performed very extensive coexistence analyses and verification through system simulations and testing in the lab and over-the-air, and the results have shown very good coexistence between Wi-Fi and LTE-U, and between Wi-Fi and LAA (as based on Qualcomm's 3GPP submissions). The LTE-U Forum coexistence specification defines multiple test cases covering a wide range of LTE-U/Wi-Fi and LTE-U/LTE-U coexistence test cases. The test cases span over multiple channel cases and single channel cases with up to three nodes comprised of a mix of LTE-U and Wi-Fi operating on the same channel. The test criteria include fairness of medium occupancy and the maximum duration of continuous LTE-U transmissions. Based on the feedback that LTE-U Forum received from Wi-Fi companies during the May 28, 2015 LTE-U Forum Workshop, two more

test cases were added to the LTE-U Forum coexistence specification Release 1.1, covering LTE-U coexistence with Wi-Fi uplink traffic and mixed VoIP/data traffic over Wi-Fi. The LTE-U coexistence spec thus is quite comprehensive. In contrast, the WFA currently tests for interoperability and does not test for coexistence.

The LTE-U/Wi-Fi coexistence tests included the following: (1) Testing conducted in a very dense deployment environment — an RF screened test chamber that was approximately 3 meters by 4.5 meters in which 9 Wi-Fi access points and client devices were sharing a single channel; (2) Testing in an over-the-air outdoor environment using a significant number of different brands of commercial Wi-Fi access points and client devices with Wi-Fi carrying VoIP calls, video, and a mixture of data and other traffic.

These tests 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. Indeed, LTE-U is as good a neighbor to Wi-Fi as well-behaving Wi Fi is to itself. Currently, there are some poor Wi Fi implementations that are bad neighbors to Wi Fi. While the WFA tests Wi-Fi equipment for interoperability, it does not test for Wi-Fi to Wi-Fi coexistence.

In Qualcomm's tests, as the number of nodes changed from Wi-Fi to LTE-U, the throughput of the remaining Wi-Fi nodes increased, and the LTE-U nodes produced substantial throughput gains as well. These tests thus showed that LTE-U will substantially improve the mobile broadband consumer experience.

The tests for LAA and Wi-Fi coexistence were conducted with seven pairs of nodes, comprised of LTE base stations and devices or Wi-Fi access points and devices, operating co-channel. The results demonstrate very good coexistence between LAA and Wi-Fi nodes. Qualcomm demonstrated these coexistence scenarios and capabilities — for both LTE-U and

LAA — at Mobile World Congress in Barcelona in February 2015. Videos of these demonstrations are available at https://www.qualcomm.com/invention/research/projects/lte-unlicensed.

In addition, Qualcomm has conducted extensive tests demonstrating that LTE-U and LAA (as presently understood by Qualcomm) coexist very well with each other and with all types of Wi-Fi devices.

Q6: Precisely how will LAA integrate licensed and unlicensed carriers, particularly with regard to controlling access to spectrum?

Response: As mentioned in the answer to Q1, LAA integrates licensed and unlicensed carriers in the same way that existing commercial deployments of LTE Advanced-based carrier aggregation bond multiple licensed spectrum carriers. The difference with LAA is that the primary anchor carrier (in either an FDD or TDD band) bonds the carrier or carriers using licensed spectrum with a set of secondary carriers operating in unlicensed spectrum, either in downlink-only mode or in downlink and uplink.

Q7: To what extent is a standalone form of LTE-U being developed, that is, a form that can operate without a licensed primary channel?

Response: Qualcomm is actively developing a standalone mode of LTE Unlicensed called MuLTEfire, which will not use a licensed anchor channel and will instead use only unlicensed spectrum. MuLTEfire will use the signals and channelization of LTE and unlicensed spectrum coexistence features. The actual release of MuLTEfire equipment for deployment will of course depend on market demand and customer request.

MuLTEfire will not require any licensed spectrum, but it will still offer performance that exceeds today's unlicensed technologies, and in certain instances and locations, approaches the performance of technologies that use licensed spectrum.

Nonetheless, LTE-U and LAA, which use a licensed anchor channel and carrier aggregation, are quite robust because the essential procedures of acquisition, access, registration, paging, mobility, and control signaling are carried out over the primary licensed anchor carrier. MuLTEfire, on the other hand, will have to operate solely in unlicensed spectrum for all purposes — including for data, signaling, and all other operations. Thus, it will lack the benefits that come from using a licensed channel as an anchor.

Q8: Are existing devices capable of software upgrades to implement LTE-U and LAA?

Response: No. A new generation of devices — both user equipment and small cells — with new 5 GHz RF and coexistence mechanisms are necessary to implement LTE Unlicensed, *e.g.*, LTE-U and LAA. Likewise, to deploy LTE Unlicensed at 3.5 GHz, a new generation of such devices with support for that band is necessary.

Q9: What frequency bands are envisioned for deployment of LTE-U and LAA?

Response: The frequency bands specified by the LTE-U Forum are the 5 GHz U-NII-1 and U-NII-3 bands, as noted in the response to Question 1. The band specification for LAA is not yet complete, but it is expected to include all 5 GHz U-NII bands. From a technology standpoint, LTE Unlicensed can be deployed in any unlicensed band and/or band that involves spectrum sharing, such as the 3.5 GHz band that the FCC has established for mobile operations.

LTE Unlicensed meets the FCC's Part 15 and Part 96 rules, enabling deployment at 5 GHz and 3.5 GHz.

Q10: What plans do carriers and manufacturers have for pre-standard deployment of LTE-U and LAA equipment including possible upgrades to 3GPP-based LTE-U or LAA and how would the above questions (particularly with respect to coexistence issues) be addressed relative to pre-standard versions of LTE-U and LAA?

Response: Qualcomm cannot comment on carrier or manufacturer plans. Qualcomm will be supporting the three versions of LTE Unlicensed described in these comments.

As explained in the response to Question 2, LTE-U is not a "pre-standard" version of LTE Unlicensed. LTE-U uses 3GPP LTE Release 10/11/12 and adds the coexistence techniques and tests specified in the LTE-U Forum documentation. The LTE-U Forum documentation does not set specific parameters for the techniques; rather, it provides a high-level description and leaves the implementation details to the equipment provider to allow for vendor differentiation. The 3GPP standardization process typically follows a similar approach, particularly in the upper layers. LAA is being standardized in 3GPP Release 13. And, as explained above, all versions of LTE Unlicensed will comply fully with the FCC's Part 15 and Part 96 rules, and all three versions will implement coexistence mechanisms that successfully share spectrum with one another and with all other users of the unlicensed bands, including Wi-Fi.

CONCLUSION

Qualcomm is very excited by the ability to offer mobile consumers the benefits of LTE Unlicensed. The wireless industry is working hard to ensure that this new technology can be introduced as soon as possible and will successfully coexist with all other unlicensed users in the 5 GHz band. In addition, as detailed in these comments, all facets of the wireless industry are working together to ensure that service providers deploy LTE Unlicensed in an open and transparent manner so that all users of unlicensed spectrum technologies will benefit. Finally, 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 services to many millions of consumers.

Respectfully submitted,

QUALCOMM INCORPORATED

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Dated: June 11, 2015

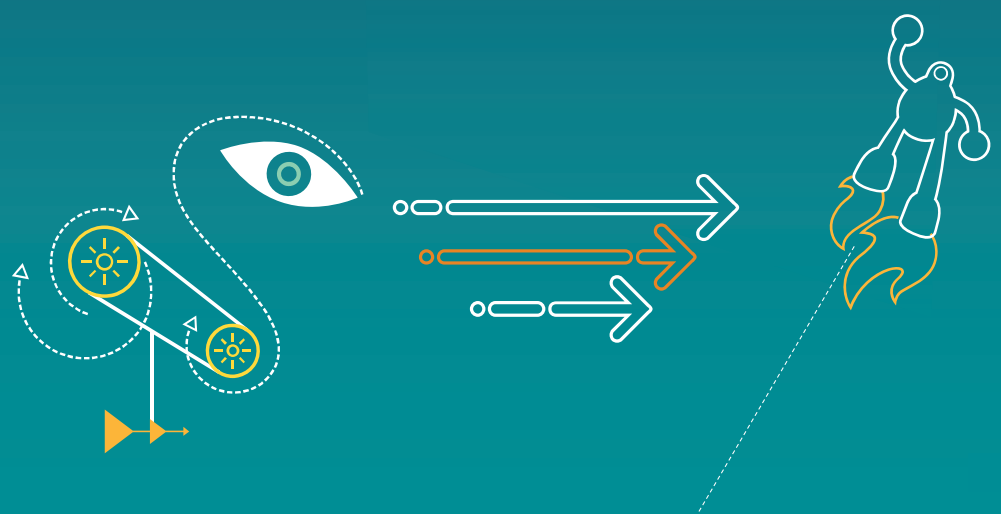
APPENDIX A – "LTE In Unlicensed Spectrum: Innovation And Coexistence"

Slide Presentation

June 11, 2015

LTE in Unlicensed Spectrum: Innovation and Coexistence

QUALCOMM®



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All Spectrum Types are Needed to Address Mobile Data Growth

Both licensed & unlicensed spectrum
(LTE, LTE Unlicensed and Wi-Fi evolution)

More licensed spectrum is the top priority
Use unlicensed spectrum opportunistically

- LTE Unlicensed for new unified small cells
- LTE & Wi-Fi aggregation for carrier Wi-Fi

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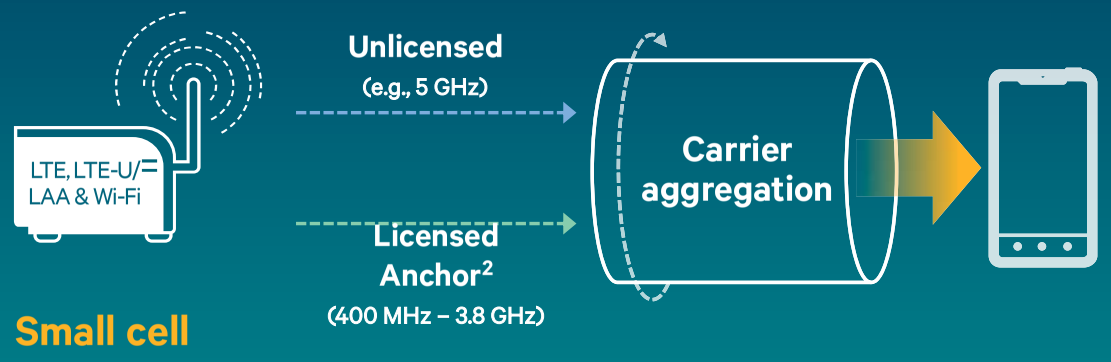
Extending the benefits of LTE Advanced to unlicensed spectrum



~2x capacity and range
Compared to Wi-Fi[1]

Enhanced user experience
Licensed anchor for robust control and mobility

Unified LTE network
Common management

A good neighbor to Wi-Fi
In many cases, a better neighbor to Wi-Fi than Wi-Fi itself

[1] Assumptions: R10-based LTE-U, two operators, dense Wi-Fi and small cell outdoor deployment, macro cell layout. 120 users per macro cell. 3GPP Bursty model. 4X40MHz channels @ 5GHz for unlicensed spectrum. LTE 10 MHz channel at 2 GHz. 2x2 MIMO for Wi-Fi , LTE and LTE in unlicensed with Rank 2 transmission.

[2] Note that the standalone version of LTE Unlicensed will not use a licensed anchor channel.

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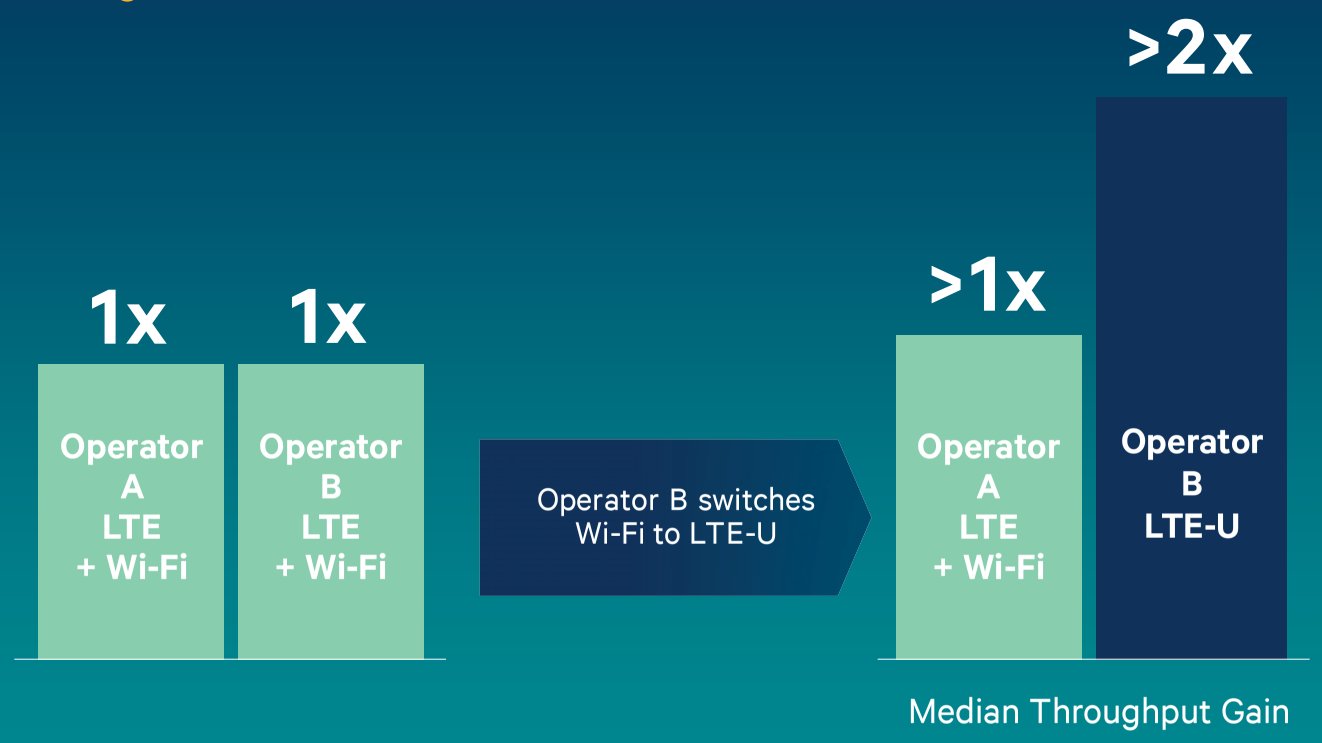
LTE Unlicensed: Delivering greater capacity without harming Wi-Fi

Often a better neighbor to Wi-Fi than Wi-Fi is to itself



Assumptions: R10-based LTE-U, dense Wi-Fi and small cell outdoor deployment based on 3GPP evaluation methodology macro cell layout. 120 users per macro cell. 3GPP Bursty model. 4X40MHz channels @ 5GHz for unlicensed spectrum. LTE 10 MHz channel at 2 GHz. 2x2 MIMO for Wi-Fi , LTE and LTE in unlicensed with Rank 2 transmission. FeICIC enabled for licensed band.

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LTE Unlicensed & Wi-Fi Coexistence: Key Points

- LTE Unlicensed is designed to share unlicensed spectrum with Wi-Fi in a fair manner
  - Uses frequency channel selection and time-domain channel sharing based on medium sensing
- Extensive testing shows that LTE Unlicensed is a very good neighbor to Wi-Fi
  - Testing compared user experience of 40/80 MHz 802.11ac Wi-Fi with another 802.11ac Wi-Fi neighbor or LTE Unlicensed neighbor, with applications such as TCP download, video streaming and VoIP
  - Stress test environment used a single 20-MHz channel in a dense deployment
- LTE-U and LAA commercial equipment will need to pass comprehensive coexistence tests
  - Test scenarios/criteria are comprehensive and stringent
  - LTE-U/LAA service providers are committed to the coexistence tests well beyond meeting FCC rules
  - LTE-U/LAA coexistence tests will promote improved unlicensed coexistence behavior
- Fair coexistence among Wi-Fi nodes today is not clearly defined or achieved
  - LTE-U/LAA is as good a neighbor to Wi-Fi as well-behaving Wi-Fi is to itself. Currently, there are poor Wi-Fi implementations that are bad neighbors to Wi-Fi
  - Wi-Fi Alliance currently tests for interoperability and does not test for coexistence

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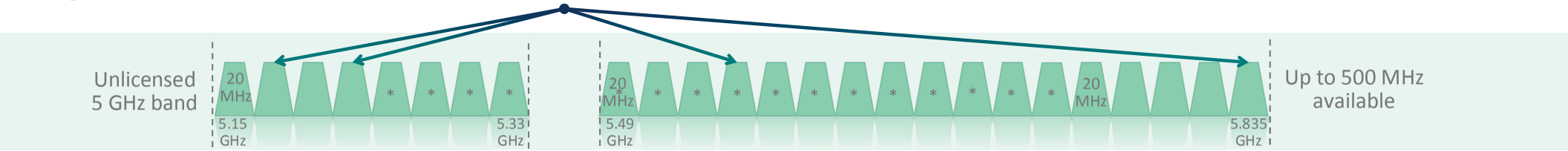
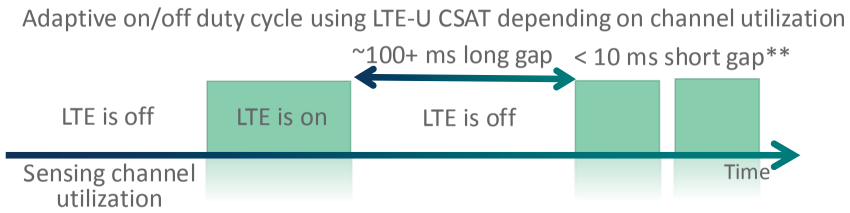
LTE Unlicensed is Designed to Coexist Very Well with Wi-Fi

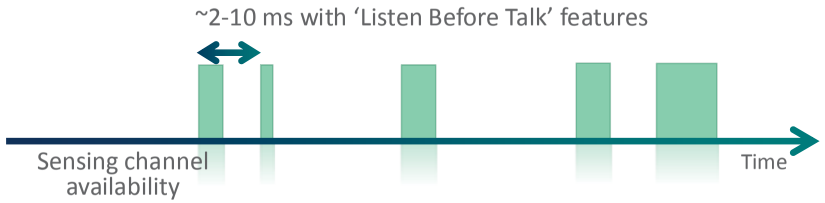
1 Dynamically select clear channel: channel selection based on interference



2 Mitigate if no clear channel is available: co-channel coexistence features



LTE-U Carrier Sensing Adaptive Transmission (CSAT) for fair coexistence with Wi-Fi with 3GPP R10/11/12 for non-LBT regions e.g. US, Korea, China.



Optimized LTE waveform for Listen-Before-Talk being defined as 3GPP R13 LAA to meet regulatory requirements for LBT regions, e.g. EU, Japan

3 Release unlicensed channel at low traffic load: fall back to licensed spectrum operation only

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* These 5GHz channels typically require DFS, Dynamic Frequency Selection and not a part of LTE-U Forum release 1.0
** Short gaps designed to protect QoS of delay sensitive Wi-Fi traffic, e.g., VoIP calls

LTE Unlicensed Will Successfully Coexist With Wi-Fi

- LTE-U uses 3GPP Release 10/11/12 LTE and adds dynamic channel selection, CSAT, & release of channel at low traffic load:
  - Meets FCC requirements and requirements in South Korea, China, India and other markets
  - Compatible with 3GPP LTE Rel-10/11/12
  - New RF band support (e.g., 5 GHz) needed at both UE and eNB
  - Coexistence and fair sharing are achieved using Rel-10 based radio resource management techniques
  - Coexistence and test specifications were defined by LTE-U Forum (Verizon, Qualcomm, Samsung, LGE, Ericsson, and Alcatel-Lucent)
- LAA (or Licensed Assisted Access) is being standardized in 3GPP and will use a modified LTE air interface including a specified Listen-Before-Talk spec:
  - Required for Europe, Japan and other regions & could be deployed elsewhere
  - Will add specific "Listen Before Talk" feature based on PHY/MAC enhancements
  - Being standardized as a new air interface in 3GPP Rel-13 LAA (Licensed Assisted Access)

Coexistence and fair sharing with Wi-Fi is a requirement for LTE Unlicensed in all regions

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Survey of Coexistence Techniques Used by Unlicensed Technologies

Technology	Frequency Selection	Time-domain sharing
Bluetooth	Fast hopping	None
Cordless Phone	Manual selection or hopping	None
ZigBee	Intelligent selection	CSMA with other ZigBee nodes CCA-ED with other technologies
Wireless USBs	Intelligent Selection	None
Wi-Fi	Intelligent selection	CSMA with other WLAN nodes CCA-ED (-62 dBm) with other technologies
LTE-U (Rel 10)	Intelligent selection	Operator can reuse channel on neighboring LTE-U small cells CSAT with WLAN, other LTE-U operators

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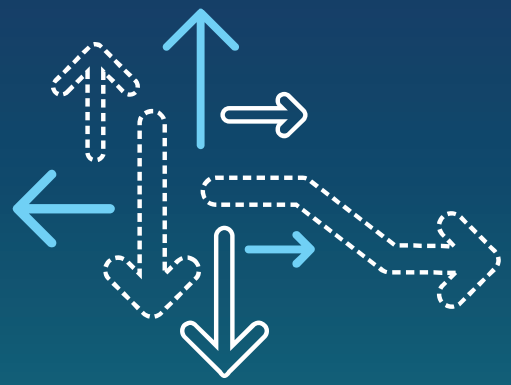
3GPP Release 10/11/12-based LTE-U



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LTE-U Meets All Applicable FCC Requirements for the 5 GHz U-NII-1 & 3 Bands

- Rel10-based LTE-U will use 5 GHz for Supplemental Downlink (SDL) in U-NII-1 and U-NII-3
- LTE-U will comply with all applicable FCC Part 15 rules for U-NII-1 and -3
- LTE-U commercial equipment also will comply with LTE-U Forum Performance and Conformance Spec

Key FCC requirements for 5 GHz UNII-1 & 3 Bands

- Maximum Transmit Power
- Emissions (in-band and out-of-band)
- Power Spectral Density (PSD)
- Minimum bandwidth requirement*

* Only applicable for U-NII-3 band.

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LTE-U Forum Objectives and Background

- LTE-U Forum Objectives
  - Develop a set of specifications for LTE-U products based on 3GPP Release 10 and beyond
- Scope
  - LTE operation in the 5GHz U-NII-1 and U-NII-3 bands as Supplemental Downlink (SDL) carriers, aggregated with an LTE deployment in licensed bands
  - Ensure proper validation of fair-sharing coexistence between LTE-U and Wi-Fi as well as between LTE-U operators based on published LTE-U Forum specification
- Forum was formed by industry members with both LTE and Wi-Fi expertise and interests:
  - ALU
  - Ericsson
  - LGE
  - Qualcomm Technologies Inc.
  - Samsung
  - Verizon

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LTE-U Forum Documents

- LTE-U Forum documents (Release 1.0) completed February 2015
  - Technical Report (TR) includes coexistence evaluation methodology and simulation results
  - SDL Coexistence specification (LTE-U/Wi-Fi, LTE-U/LTE-U)
  - eNB and UE Minimum Performance Spec in U-NII-1/3 bands
  - eNB and UE Conformance spec
- LTE-U Forum documents are available at:
  - http://www.lteuforum.org/
- LTE-U Industry Workshop was held on May 28, 2015 in San Diego, CA
  - Attended by 29 companies/organizations including operators, LTE-U vendors, Wi-Fi companies, WFA and IEEE 802
  - Workshop material available at http://lteuforum.org/workshop.html

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LTE-U Forum Technical Report Overview

- Background of LTE-U operation
  - 5 GHz band definition, channel numbers (EARFCN), LTE-U SDL CA band combinations
- LTE-U coexistence evaluation methodologies
  - Evaluation scenarios and performance metrics
- Evaluation results
  - Outdoor and indoor simulation results from multiple companies
- Recommendations for coexistence mechanisms
  - Channel selection
  - Medium-sensing-based SCell duty cycle in unlicensed spectrum (e.g., CSAT) with max on-time limit
  - Opportunistic Secondary Cell OFF in unlicensed spectrum
- Conclusions:
  - For a given operator, replacing LTE/Wi-Fi bearer selection by LTE + LTE-U carrier aggregation leads to substantial improvement in user experiences in terms of data throughput
  - For a high density Wi-Fi deployment, if part of the nearby Wi-Fi nodes are replaced by LTE-U nodes, the remaining Wi-Fi nodes throughput is no worse than before, and, in many cases, improves

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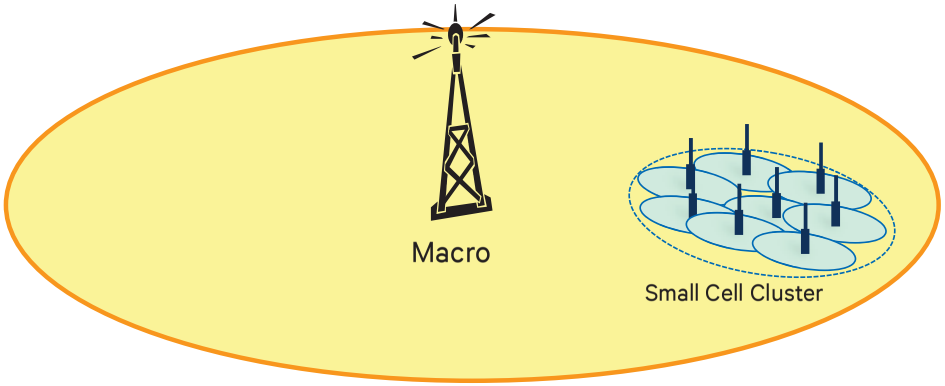
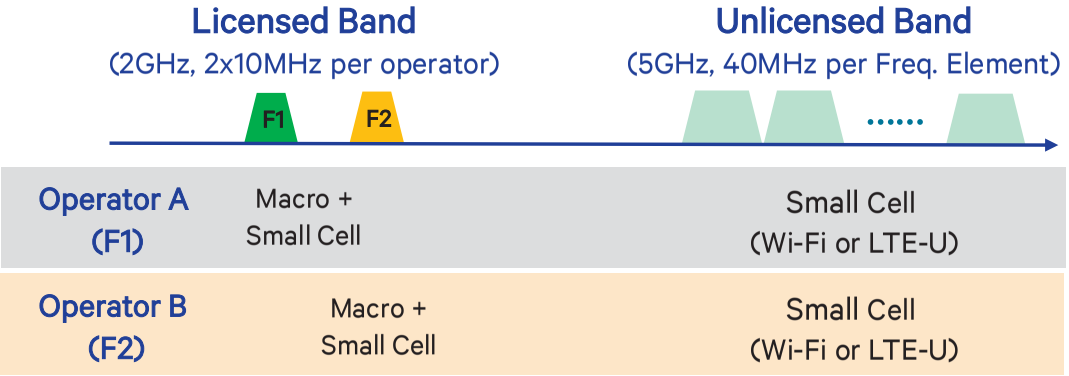
LTE-U Outdoor Simulation Scenarios (SO9-12)

- Two operators (A/B) deployment
  - 2x10MHz HetNet in Licensed band
  - Wi-Fi or LTE-U SDL in Unlicensed band
  - Wi-Fi model applies to enterprise or operator deployment
  - 4 FE (Freq Element) total in each hotspot
- All Wi-Fi with LDPC & Channel Selection
  - Wi-Fi: 802.11ac
  - LTE & Wi-Fi: 2x2 MIMO with max rank 2 transmissions
- Bursty traffic model based on modified 3GPP model 2
  - Traffic load increased to load all the cells

- 3GPP model* with 500m macro ISD
- Clustered Pico model
  - One hotspot cluster per Macro cell
    - 50 meter radius
  - 8 Picos per operator in a cluster
    - 10m minimum distance between Picos from different operators
- User distribution
  - 60 UEs per Macro cell per operator
  - 2/3 UEs are in 70m radius of cluster center



Clustered Pico Scenario



* 3GPP TR 36.872, LTE pico Tx pwr = 30dBm+5dBi antenna gain. LTE-U Pico//Wi-Fi AP Tx power (outdoor SC) = 24dBm+5dBi antenna gain. UE Tx pwr in licensed band =23dBm; Wi-Fi STA Tx power =18dBm. See the LTE-U Forum Technical Report for more details.

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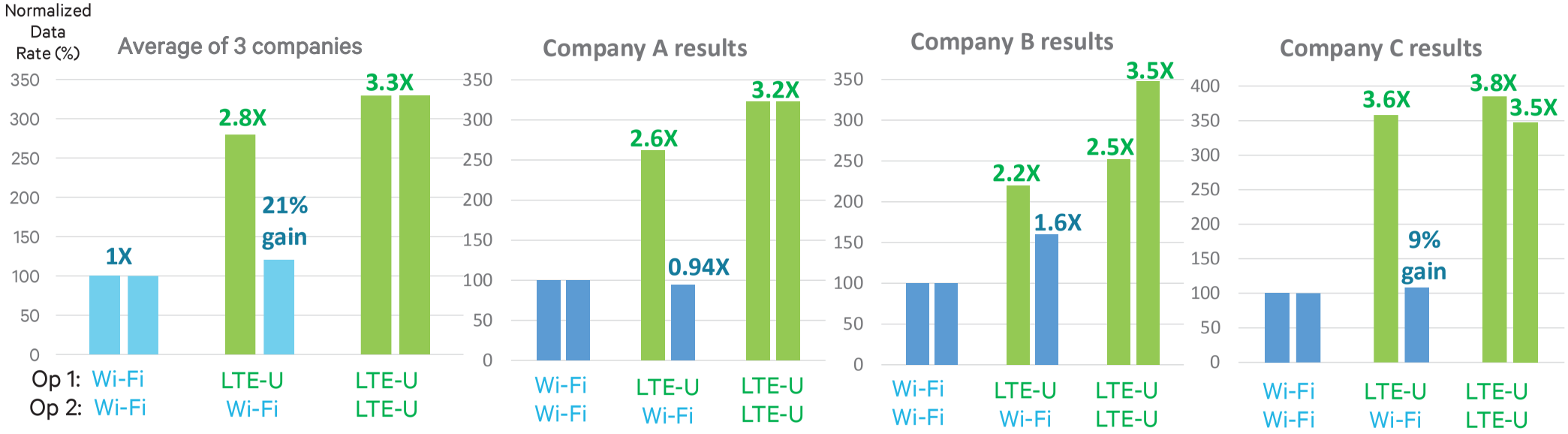
Simulated LTE-U and Wi-Fi Outdoor Performance

Very High Density Scenario (SO9-12) from Technical Report

Median DL User Throughput

(2 deployments x 8 outdoor Picos / cluster, 4x40MHz unlicensed spectrum)



In the LTE-U/Wi-Fi coex case, Wi-Fi performance is maintained/improved, while LTE-U's average gain is 180%

Outdoor results from simulation scenarios SO9-12: 2 operators with 8 nodes per operator in one cluster, 4 channels of 40MHz. LTE-U uses R-10/11 with coexistence techniques. See the Technical Report for more details.

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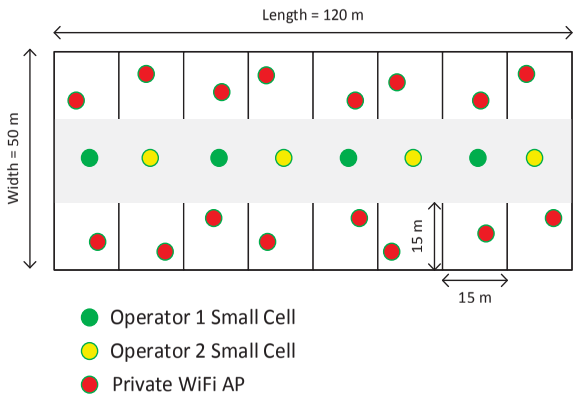
LTE-U Indoor Simulation Scenarios (SI5-8)

- Indoor hotspot scenario based on InH model from 3GPP 36.872
  - Single floor building with building plan close to shopping malls, enterprise or airport
    - 4 FE (4X40MHz) in unlicensed band shared by 2 operators in these scenarios
  - Serving node dropping: 4 access points or small cells per operator (denoted as operator 1 and 2)
    - Operator 1: regularly dropped in the middle of the hall
    - Operator 2: randomly dropped in the middle of the hall
    - Min. sep. distance 3m between Op1 and Op2 small cells and min separation distance 3m between Op2 small cells
  - Additional 16 private Wi-Fi APs: one per shop/office with random dropping
    - One Wi-Fi STA for each Wi-Fi AP in the same shop
- ITU propagation model: 3GPP 36.872 and 36.814
- LTE primary carrier will be co-channel with Macro (2GHz)
  - 21 cell Macro layout
  - Randomly drop 1 building per Macro
  - 60 UEs per macro cell per operator
    - 2/3 UEs are uniformly dropped inside the building
    - 1/3 UEs are dropped uniformly in the cell



See the LTE-U Forum Technical Report for more details.

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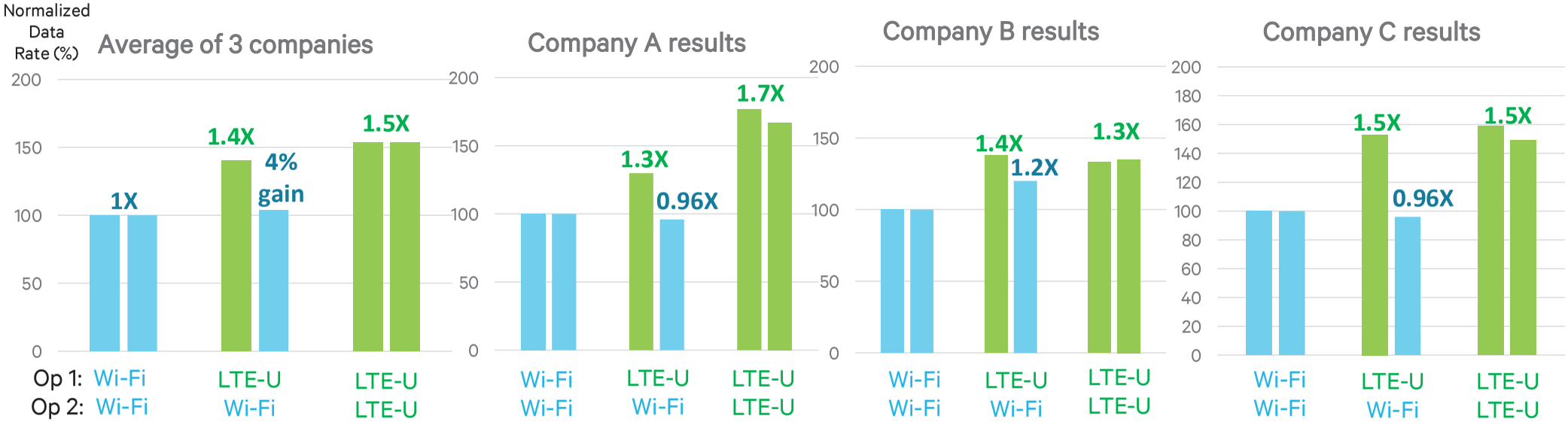
LTE-U and Wi-Fi Indoor Simulated Performance

High Density Scenario (SI5-8) from Technical Report

Median DL User Throughput

(2 deployments x 4 indoor small cells + 16 private Wi-Fi APs per building, 4x40MHz unlicensed spectrum)



In this indoor LTE-U/Wi-Fi coex case, Wi-Fi performance is maintained, while LTE-U average gain is 40%

Indoor results from test cases SI5-8: 2 operators with 4 nodes per operator in one building, and 16 private WiFi APs, 4 channels of 40MHz. LTE-U uses R-10/11 with coexistence techniques. See the Technical Report for more details.

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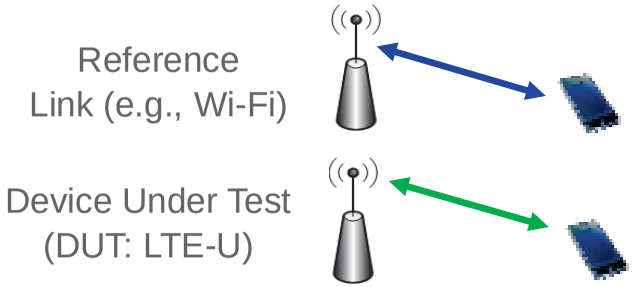
LTE-U Coexistence Test Spec

- Operators will require LTE-U commercial equipment to pass coexistence tests
  - Both LTE-U / Wi-Fi coexistence tests and inter-LTE-U coexistence tests
- Comprehensive LTE-U coexistence test scenarios:
  - Cover LTE-U channel selection, co-channel sharing and opportunistic SDL switch off
  - Coexistence scenarios include LTE-U/Wi-Fi, inter/intra operator LTE-U/LTE-U
  - Co-channel scenarios cover 2-node and 3-node coexistence cases
- Stringent test criteria relating to LTE-U co-channel coexistence include
  - Beyond just minimum throughput on reference Wi-Fi link
  - Fairness of medium occupancy
  - Max duration of continuous medium occupancy
    - To protect latency-sensitive services on reference link



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Summary of Coexistence Test Scenarios (Release 1.1)

Test#	#Channels	Coexisting Nodes	Objectives
6.1.1	2	LTE-U / Wi-Fi	LTE-U selects clean channel over Wi-Fi occupied channel
6.1.2	2	LTE-U / LTE-U / LTE-U (same + different operators)	LTE-U selects LTE-U occupied channel from the same operator over channel used by another LTE-U operator
6.2.1	1	LTE-U / Wi-Fi	Channel sharing w/ one downlink full-buffer Wi-Fi links
6.2.2	1	LTE-U / Wi-Fi / Wi-Fi	Channel sharing w/ two downlink full-buffer Wi-Fi links
6.2.3	1	LTE-U/ Wi-Fi / Wi-Fi	Channel sharing w/ two **uplink** full-buffer Wi-Fi links
6.2.4	1	LTE-U / Wi-Fi	Channel sharing w/ one Wi-Fi AP (mixed full-buffer and **VoIP** links)
6.2.5	1	LTE-U / LTE-U / Wi-Fi (different operators)	Channel sharing w/ Wi-Fi and another LTE-U operator
6.2.6	1	LTE-U / LTE-U (same operator)	Channel sharing w/ same operator LTE-U with higher channel reuse
6.3.1	1	LTE-U single link	Opportunistic SCell switch OFF

Test cases in blue have been added in Release 1.1 following the feedback that the LTE-U Forum received during the May 28 LTE-U industry workshop

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Example: 6.2.1 LTE-U/Wi-Fi Co-channel Coexistence Test

- Test setup:
  - Same 20MHz channel in 5 GHz occupied by Wi-Fi AP/STA link and LTE-U SCell
  - LTE-U and WiFi links interfering
    - All nodes within CCA-ED threshold (> -62dBm*)
  - Full-buffer UDP traffic on both Wi-Fi and LTE-U downlinks

- Test metrics/criteria:
  - LTE-U duty cycle (integral of Ton / all time of testing) <= 50%
  - LTE-U Ton,max <= 50 msec → limit impact to Wi-Fi delay
  - Wi-Fi throughput >= 4Mbps**
  - LTE-U throughput on SCell >= 4 Mbps

– *Note: above metrics chosen due to the current lack of defined Wi-Fi reference behavior*

* -62dBm is the CCA-ED (Energy Detection) threshold defined by IEEE Wi-Fi spec

** 4Mbps is the minimal Wi-Fi throughput criteria defined in WFA Wi-Fi specification

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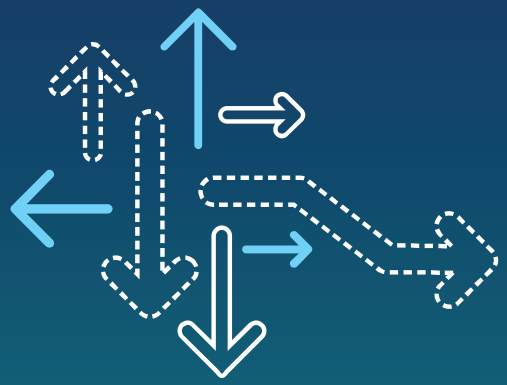

LTE-U & Wi-Fi Coexistence Test Observations

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LTE - Wi-Fi coexistence test chamber

Testing LTE-U in a very dense Wi-Fi environment

Wi-Fi Access Points (APs)

Wi-Fi Devices

Extremely dense network with harsh interference

- 8 Wi-Fi Access Points forced on a single 5 GHz channel
- Very high-density scenario in real life, since multiple channels are typically available
- No isolation between neighboring APs and devices

Equipment

- Commercial-off-the-shelf carrier-grade Wi-Fi APs
- Qualcomm test Wi-Fi devices
- Qualcomm test LTE-U small cell and devices

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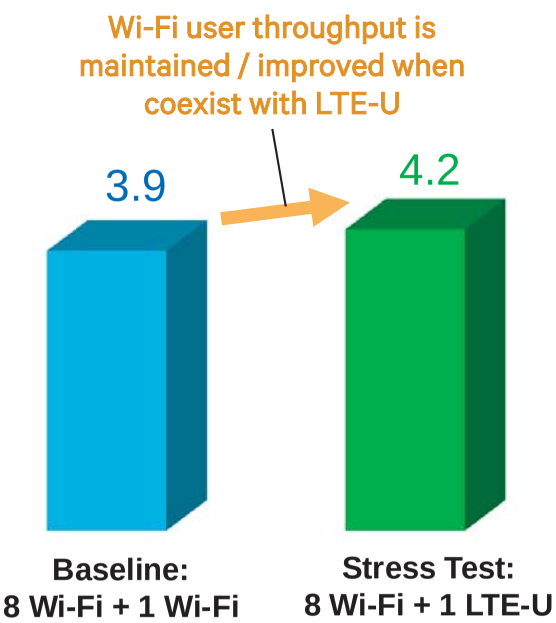
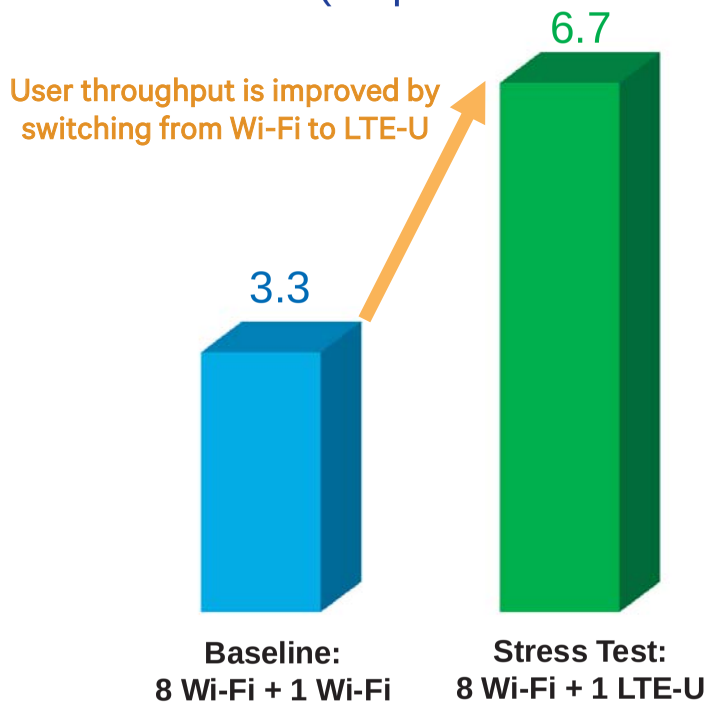
Coexistence Stress Test Results

A LTE-U node outperforms a Wi-Fi node it replaces, while maintaining the performance of other nearby Wi Fi nodes. LTE-U has no adverse impact on Wi-Fi.

Average Throughput of Background Wi-Fi
(8 Wi-Fi AP-device pairs)



Throughput of Device Under Test
(9th pair: Wi-Fi -> LTE-U)



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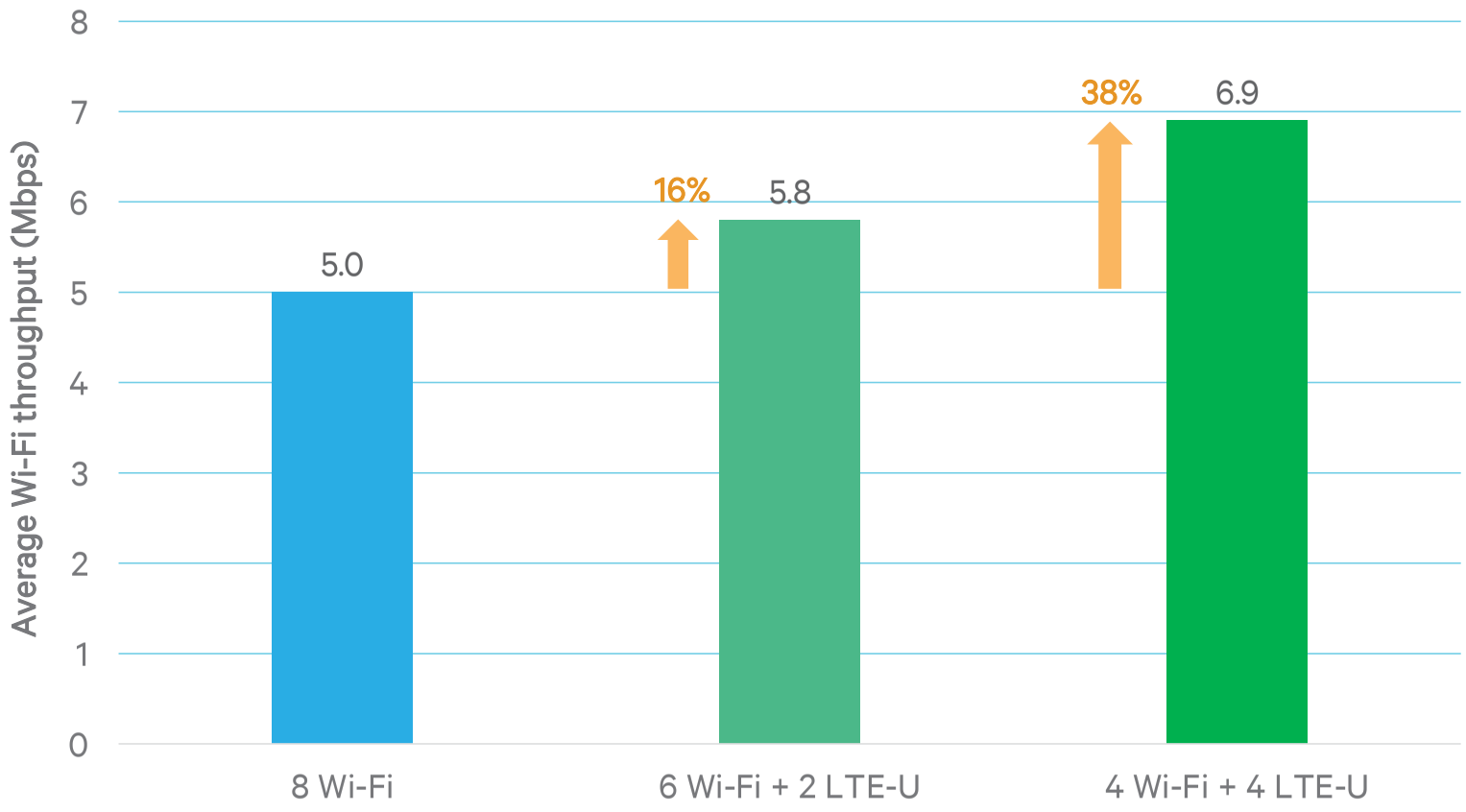
Replacing Wi-Fi Nodes with LTE-U: Test Results

When LTE-U nodes replace Wi-Fi nodes, average throughput of remaining Wi-Fi increases



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YouTube Streaming Results – Wi-Fi/Wi-Fi vs. Wi-Fi/LTE-U

Below ED

Metrics	AP 1		AP 2	
	Baseline (with Wi-Fi)	with LTE-U	Baseline (with Wi-Fi)	with LTE-U
No. of video stalls	**6.00**	**1.67**	**12.33**	**2.67**
Playback interrupt time (s)	7.94	7.40	4.77	2.00
Initial Buffer Time (s)	0.67	1.33	0.33	0.33
Avg. Thpt (Mbps)	3.49	4.49	3.17	5.89
Avg. PHY Rate (Mbps)	19.81	39.88	65.65	83.55

LTE-U with CSAT is a better neighbor to Wi-Fi than an additional Wi-Fi access point

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VoIP Performance over Wi-Fi Is Preserved by LTE-U

Metrics	AP 1		AP 2		AP 3	
	Baseline (with Wi-Fi)	with LTE-U	Baseline (with Wi-Fi)	with LTE-U	Baseline (with Wi-Fi)	with LTE-U
DL MOS	**4.1**	**4.3**	**4.2**	**4.2**	**4.2**	**4.1**
UL MOS	**4.2**	**4.2**	**4.1**	**4.2**	**4.2**	**4.1**

VoIP over Wi-Fi performance is comparable between Wi-Fi/Wi-Fi and Wi-Fi/LTE-U

- All the tests are done with close deployment of LTE-U and Wi-Fi AP/STA within CCA-ED range
  - Tested across range of CINR (LTE-U RSSI / Wi-Fi RSSI)
  - Wi-Fi is carrying only VoIP traffic, and interfering Wi-Fi/LTE-U is performing TCP download
- All the tests were run with stringent conditions for pass criteria based on latency/jitter/PER from WFA spec
  - WFA pass criteria are more stringent than commercial apps (e.g., Skype)
  - Packet losses in all cases are negligible

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Observations on Wi-Fi “Fairness”

- Wi-Fi Alliance currently tests for interoperability and does not test for coexistence
- Wi-Fi network is much more aggressive to non-Wi-Fi equipment in co-channel operation
  - Wi-Fi backs off with CSMA upon detecting another Wi-Fi preamble, typically at ~-82 dBm RSSI or below
  - Wi-Fi backs off with Energy Detection of non-Wi-Fi signals at ~-62 dBm RSSI or even higher

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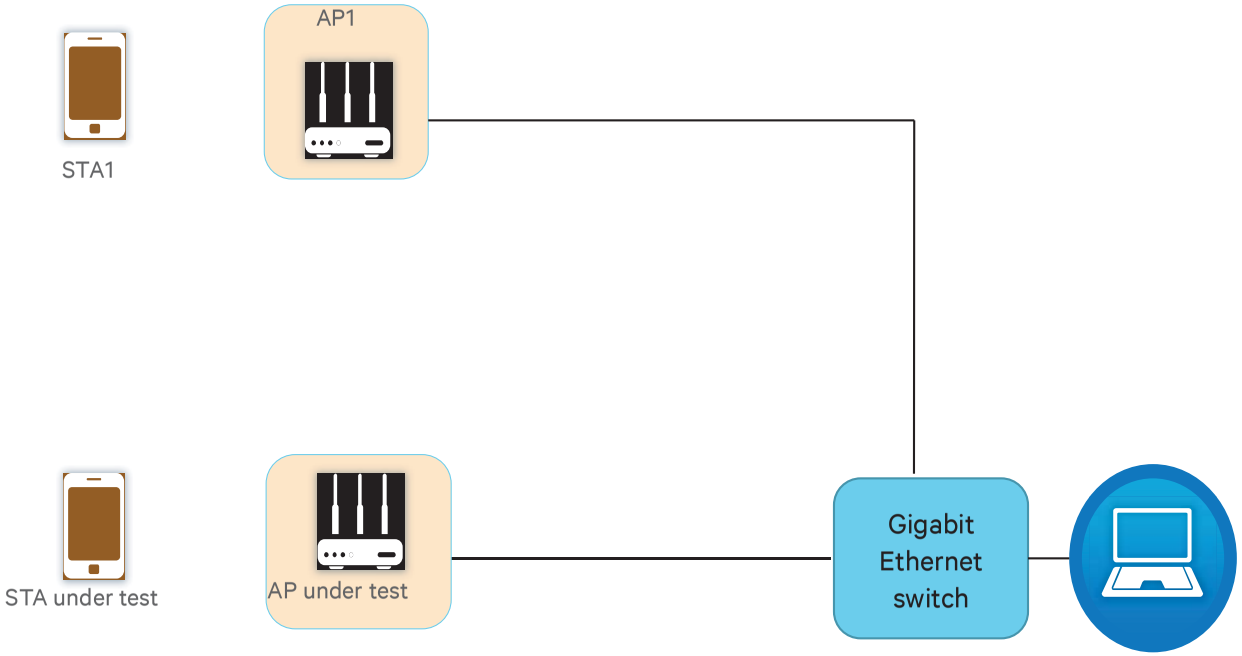
Fairness between Wi-Fi/Wi-Fi and Wi-Fi/LTE-U

Test Setup



Tests are performed using two Wi-Fi connection pairs across different AP models, and one LTE-U link with one Wi-Fi AP link across different AP models

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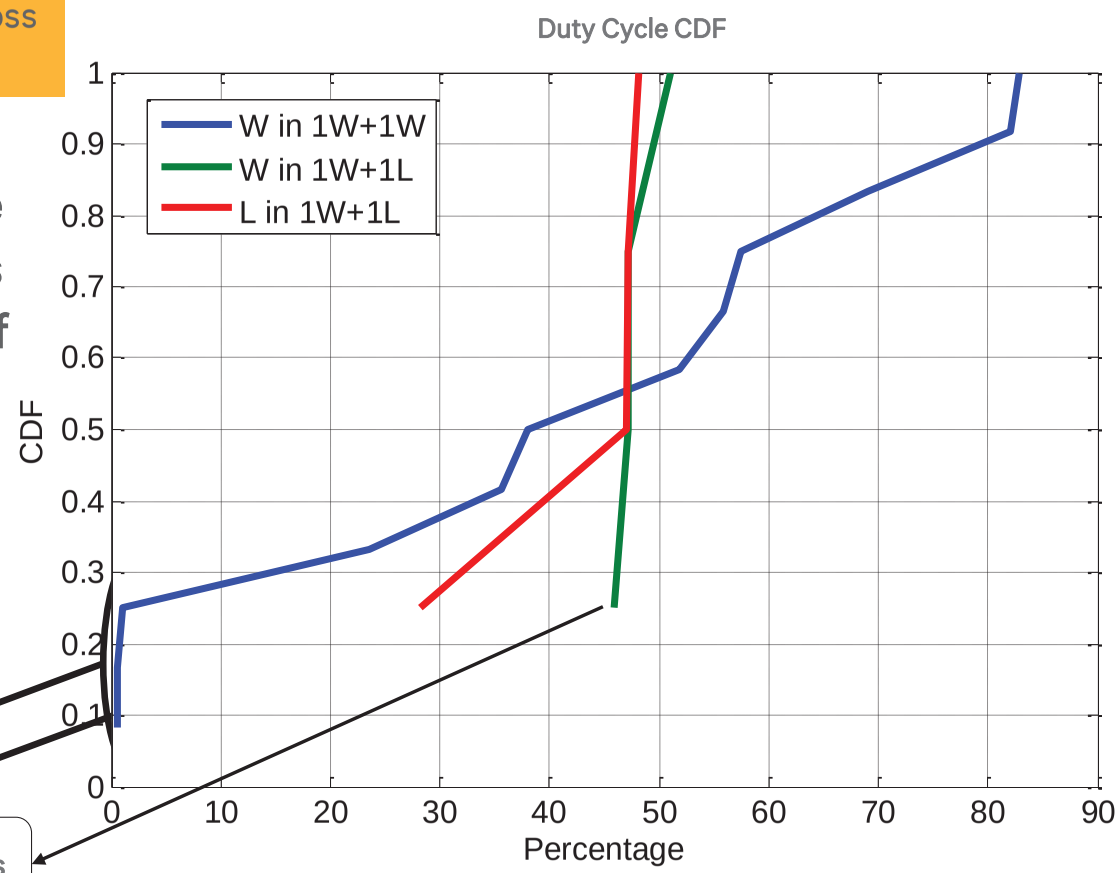
Sharing of air-time among residential Wi-Fi APs & LTE-U Nodes

Testing of pair-wise airtime sharing across 4 Wi-Fi AP models and with LTE-U

Testing shows that when one LTE-U & one Wi-Fi node share the same channel, LTE-U uses the spectrum less than 50% of the time. LTE-U was consistently a superior neighbor to Wi-Fi than Wi-Fi was to Wi-Fi.



- Points corresponding to coexistence with AP model A
- AP model A does not obey CCA-ED rule and does not backoff to LTE-U

Points corresponding to all 4 Wi-Fi AP models

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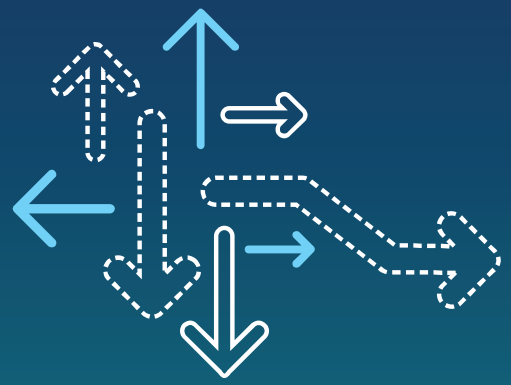
3GPP Release 13-based LTE Unlicensed (LAA)



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3GPP R-13 LAA Status and Path Forward

- 12/2013: First introduction of the concept at 3GPP RAN #62
- 6/2014: RAN workshop in Sophia Antipolis, France on Jun 13th (following 3GPP RAN #64)
- 9/2014: LAA was approved as a Rel-13 Study Item (SI) in 3GPP RAN #65
  - Supported by over 40 companies and the SI scope covers both SDL and CA(DL/UL)
- 5/2015: 3GPP Release 13 LAA study item successfully completed in 3GPP RAN #1
  - The studies show that when an appropriate channel access scheme 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.
  - Details in 3GPP technical report 36.889 or R1-153690
  - It is expected that SI conclusion will be followed by a Work Item (WI)
- There have been continuous interactions between 3GPP and IEEE/WFA

NOTE: 3GPP Rel-13 ASN.1 freeze is scheduled for 1H2016

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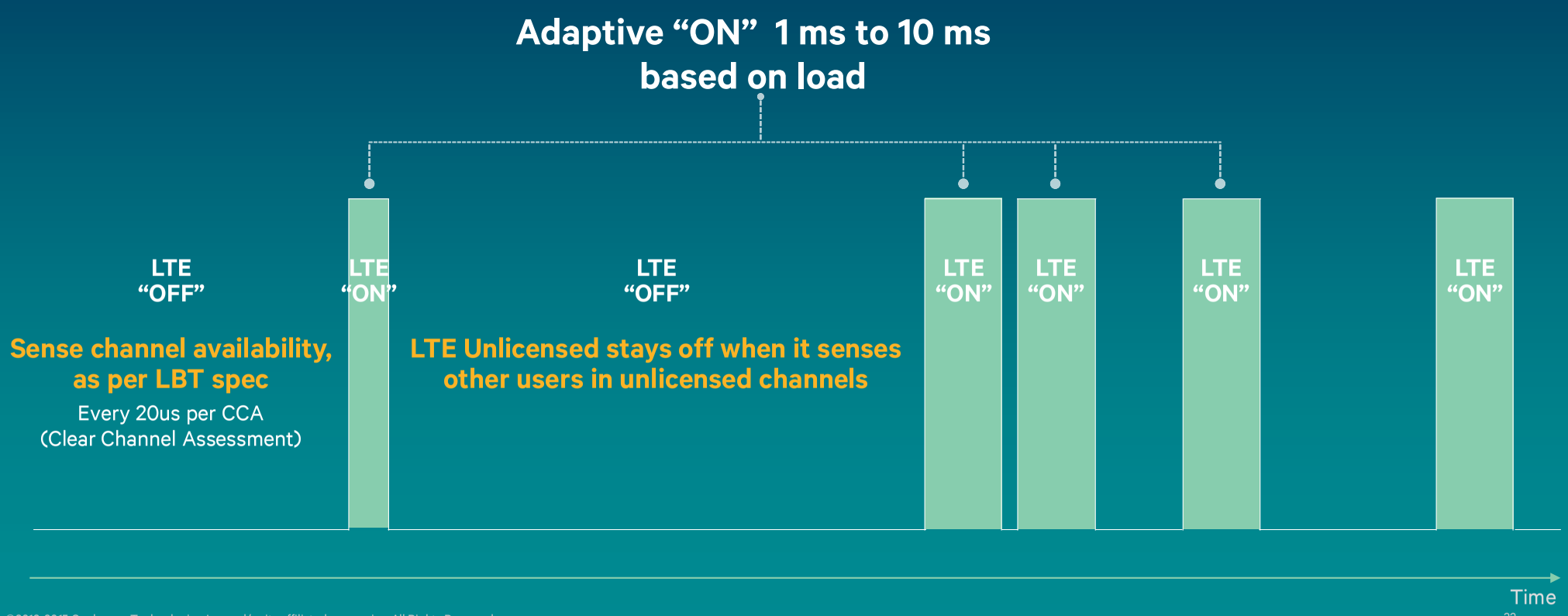
LAA Sharing with Wi-Fi

Example



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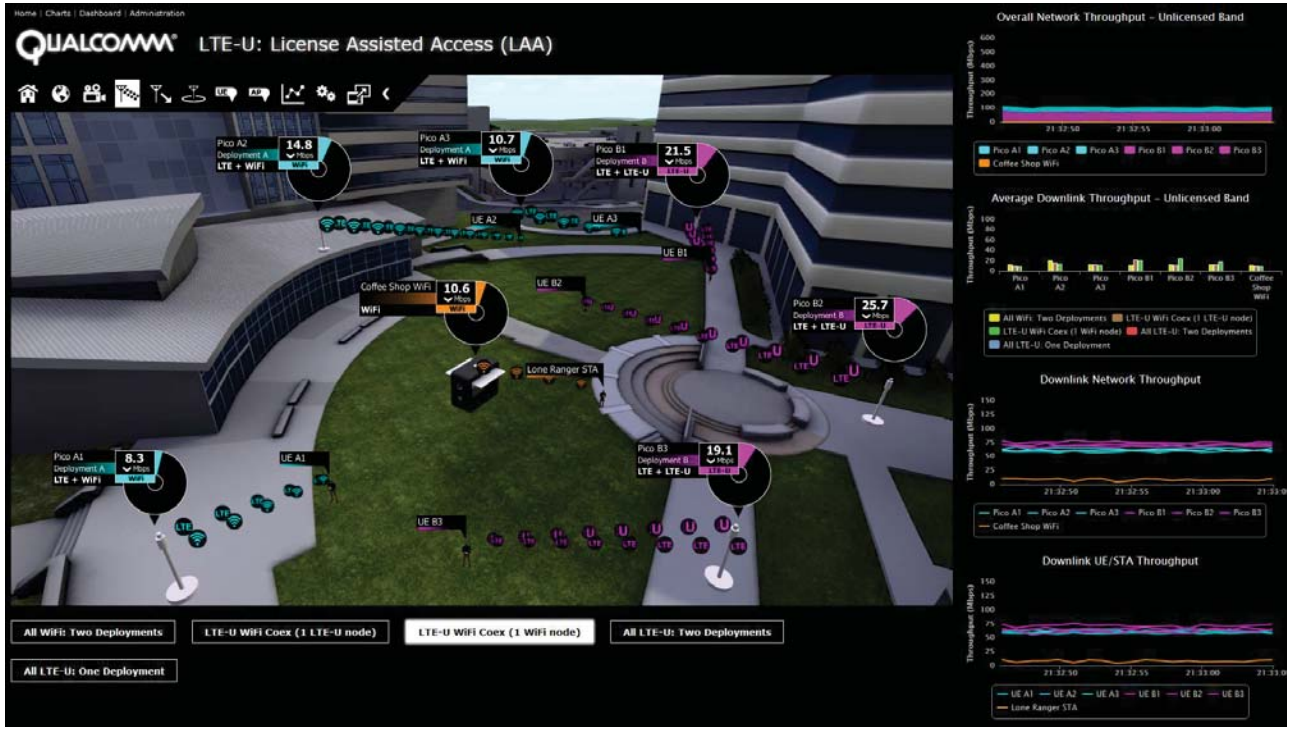
Qualcomm Release 13 LAA Demo

- Qualcomm demonstrated Release 13 LAA DL aggregation at MWC 2015
  - Based on QC proposal for Rel 13 LAA design
  - Multiple LAA prototype small cells and UEs
- Demo objectives:
  - New waveforms supporting specific Listen-Before-Talk (LBT) protocol and CCA
  - Improved user experience and network capacity from LAA vs. LTE + Wi-Fi Link aggregation
  - Coexistence and fair-sharing with Wi-Fi operations in the same channel



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Conclusions

- LTE Unlicensed will provide consumers with an improved user experience with significantly better throughput and range
- Extensive work is ongoing to ensure successful, fair coexistence with Wi-Fi and other LTE Unlicensed operations. The LTE-U Forum defined a comprehensive and stringent coexistence spec and test requirements for LTE-U. 3GPP is ensuring successful coexistence for LAA.
- Both LTE Unlicensed and Wi-Fi will continue to be improved, and Qualcomm will support both technologies for many years to come
- There is an ongoing technical dialogue directly, multi-laterally, and within standards groups among the cellular industry, the Wi-Fi industry, and many stakeholders (e.g., cable operators, Wi Fi equipment vendors, etc.) to better understand one another and provide even better coexistence

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APPENDIX B – LTE-U Forum Technical Report

Available at
http://www.lteuforum.org/uploads/3/5/6/8/3568127/lte-u_forum_lte-u_technical_report_v1.0.pdf

LTE-U Forum

LTE-U Forum:
Alcatel-Lucent, Ericsson, Qualcomm Technologies Inc., Samsung Electronics & Verizon

LTE-U Technical Report

Coexistence Study for LTE-U SDL V1.0 (2015 -02)

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Foreword

This Technical Report has been produced within the LTE-U Forum.

1 Scope

The present document contains the result of the study on coexistence between Wi-Fi and LTE-Unlicensed (henceforth referred to as LTE-U) and between LTE-U nodes within the LTE-U Forum.
The purpose of the present document is to help understanding of performance of Wi-Fi and LTE-U when they coexist in the same unlicensed spectrum. This document will provide a guidance for coexistence mechanism on LTE-U.

2 References

The following documents contain provisions which, through reference in this text, constitute provisions of the present document.

[1] "User Equipment (UE) minimum requirements for LTE-U SDL", LTE-U Forum

[2] "Base Station (BS) minimum requirements for LTE-U SDL", LTE-U Forum

[3] 3GPP TR 36.872: "Small cell enhancements for E-UTRA and E-UTRAN - Physical layer aspects".

[4] 3GPP TR 36.843: "Study on LTE device to device proximity services; Radio aspects".

[5] http://madwifi-project.org/svn/madwifi/trunk/ath_rate/minstrel/minstrel.txt

[6] "Broadband Wireless Access and Local Networks", Chapter 13, Byeong Gi Lee, Sunghyun Choi.

[7] IEEE 802.11-2007, IEEE Standard for Local and Metropolitan Area Networks—Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications, IEEE Std 802.11-2007, (Revision of IEEE Std 802.11-1999), June 12, 2007.

3 Definitions and abbreviations

3.1 Definitions

For the purpose of the present document, the following definitions apply.

Frequency element: a contiguous 40 MHz frequency block. This is the system bandwidth per LTE-U eNB or Wi-Fi AP in 5GHz band.

3.2 Abbreviations

CA	Carrier Aggregation
DTX	Discontinuous Transmission
FE	Frequency Element
LBT	Listen-Before-Talk
LTE-U	LTE-Unlicensed
PCell	Primary Cell
SC	Small Cell
SCell	Secondary Cell
SDL	Supplemental DownLink
U-NII	Unlicensed National Information Infrastructure

4 Background

LTE-U is a radio access technology that has been proposed for providing carrier-grade wireless service in the 5GHz unlicensed band. Until today, Wi-Fi (WLAN that uses the IEEE 802.11 standard) has been the most popular choice for radio access in the unlicensed space. However, recent studies have highlighted that LTE technology, originally envisioned for cellular operation in licensed bands, has significant performance gains over Wi-Fi when operating in the unlicensed band. The main advantages for LTE-U over Wi-Fi as an access technology stem from better link performance, medium access control, mobility management, and excellent coverage. These benefits combined with the vast amount of available spectrum (> 400MHz) in the 5GHz band make LTE-U a promising radio access technology in the unlicensed arena.

Since Wi-Fi devices are already widespread in the 5GHz unlicensed band, there is a need for newly deployed LTE-U Small Cell (SC) to coexist with the Wi-Fi ecosystem. Moreover, different LTE-U operators may occupy the same spectrum in the unlicensed band to provide data services to their users. Such an unplanned and unmanaged deployment of LTE-U SCs (femtocells, picocells) may result in excessive RF interference to the existing co-channel Wi-Fi and other operator LTE-U nodes in the vicinity. It is therefore critical for LTE-U SCs to choose the best operating channel while minimizing the interference caused to nearby Wi-Fi and LTE-U networks. However, there are scenarios where all available channels are occupied by Wi-Fi devices which forces LTE-U SC to operate on the same channel as Wi-Fi. Wi-Fi devices do not back off to LTE-U unless its interference level is above the energy detection threshold (-62dBm over 20MHz). Without proper coexistence mechanisms, LTE-U transmissions could cause considerable interference on Wi-Fi network relative to Wi-Fi transmissions.

Among many possible LTE-U deployment options, this document focuses on supplemental downlink (SDL) deployment in unlicensed band, which will be paired with a licensed LTE carrier as carrier aggregation mode in legacy LTE (up to 3GPP Rel-12). This deployment will target the regions without listen-before-talk (LBT) requirements such as US (for example, U-NII radio bands in the US covering 5.15 GHz – 5.85 GHz regulated by the FCC).

The following three sub-clauses summarize the LTE-U band & EARFCN numbering and CA combinations defined in [1] and [2].

4.1 Band definitions for LTE-U in 5 GHz

The 5GHz unlicensed spectrum in the US is divided into mainly three different bands with different RF requirements. These are the three Unlicensed National Information Infrastructure (U-NII) bands. These three bands are U-NII-1 (5150-5250MHz), U-NII-2 (5250-5725MHz), and U-NII-3 (5725-5850MHz). Note that 5350-5470MHz segment in U-NII-2 is restricted from usage by FCC. In addition, the 60MHz in 5590-5650MHz are currently blocked by FCC for TDWR interference issues.

Considering that U-NII-2 band has the additional requirement of DFS, it is recommended that U-NII-2 band can be considered for LTE-U in the future.

It should be noted that for SDL, only FDD carrier aggregation (CA) is needed for the CA with a LTE FDD licensed carrier. The following band numbering will be used for the U-NII bands.

- U-NII-1
  - Band number 252 for U-NII-1 spectrum (5150-5250MHZ).
- U-NII-2
  - Band numbers 253 and 254 are reserved for U-NII-2 spectrum (5250-5725MHZ) for future usage.
- U-NII-3
  - Band number 255 for U-NII-3 spectrum (5725-5850MHZ).

4.2 Channel numbers (EARFCN) for LTE-U bands

The existing LTE has a 100 kHz channel raster. This will be problematic for a very wide spectrum such as 5 GHz unlicensed band, given that the search space (hypothesis) is too large for eNB (or UE).

Considering that LTE deployment of interest in 5 GHz unlicensed spectrum is 20 MHz, it makes sense to align the channel raster with 20 MHz Wi-Fi channel, which is one every 20 MHz. In addition to these carrier frequencies (e.g., f_1, f_2 (=f_1+20MHz), f_3(=f_1+40MHz), ...), it would be necessary to introduce additional carrier frequencies around 20 MHz channel raster to allow aligning the subcarriers for the case of intra-band contiguous CA where the carrier spacing should be a multiple of 300 kHz as per the current specification. For example, around f_1, f_1-200kHz, f_1-100kHz, f_1, f_1+100kHz, f_1+200kHz can be introduced, around f_2, f_2-200kHz, f_2-100kHz, f_2, f_2+100kHz, f_2+200kHz, and so on.

In order to allow future extension for additional channel locations, all the channels with a 100 kHz channel raster will be reserved over 700 MHz (5150 – 5850 MHz) spectrum in 5 GHz unlicensed spectrum. However, the LTE-U operation will be limited only to the following carrier frequencies for U-NII-1 and U-NII-3, respectively.

- U-NII-1
  - {f-0.2, f-0.1, f, f+0.1, f+0.2 | f = 5160, 5180, 5200, 5220, 5240} MHz
- U-NII-3
  - {f-0.2, f-0.1, f, f+0.1, f+0.2 | f = 5745, 5765, 5785, 5805, 5825} MHz

With these reduced set of carrier frequencies, the search space by eNB (or UE) can be significantly reduced. The proposed EARFCN is illustrated in Figure 4.2-1 and presented in Table 4.2-1.

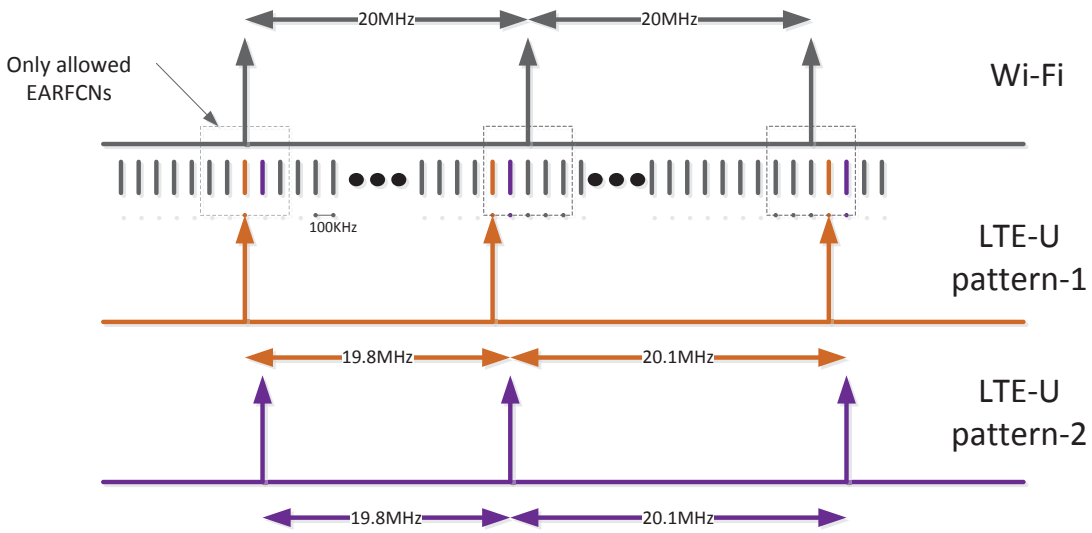


Figure 4.2-1: Example of EARFCN for LTE-U

Table 4.2-1: EARFCN and band numbers for LTE-U

Band Number	F_{DL_low} [MHz]	$N_{Offs-DL}$	Range of N_{DL}
252	5150	255144	255144-256143
255	5725	260894	260894-262143

For operations in Band 252, only the following set of DL EARFCNs is allowed.

$N_{DL,allowed}$ = {n-2, n-1, n, n+1, n+2 | n = 255244, 255444, 255644, 255844, 256044}

For operations in Band 255, only the following set of DL EARFCNs is allowed.

$N_{DL,allowed}$ = {n-2, n-1, n, n+1, n+2 | n = 261094, 261294, 261494, 261694, 261894}

Note 1: There is no Wi-Fi channel at 5160 MHz. The first 20 MHz Wi-Fi channel starts at 5180 MHz. Therefore, the first 5 allowed EARFCNs (255242-255246) for band 252 do not correspond to the 20 MHz Wi-Fi channel.

Note 2: There is no EARFCN corresponding to the lower edge (5725-5735 MHz) and the upper edge (5835-5850) of U-NII-3 due to the lack of 20 MHz channel availability.

4.3 LTE-U SDL CA scenarios

The LTE-U SDL CA scenarios under consideration are summarized in Table 4.3-1. All cases are FDD CA with unlicensed being DL only, i.e., SDL use case.

Table 4.3-1: LTE-U SDL CA scenarios

#	Band Combination	Licensed Band	Unlicensed Band	BW (MHz)	CA configuration
1	B13+B252+B252	B13	U-NII-1	10+20+20	inter-band + unlicensed intra-band contiguous DL CA w/o UL CA
	B13+B255+B255	B13	U-NII-3	10+20+20	
2	B13+B252	B13	U-NII-1	10+20	inter-band DL CA without UL CA
	B13+B255	B13	U-NII-3	10+20	
3	B2+B252+B252	B2	U-NII-1	[5,10,15,20]+20+20	inter-band + unlicensed intra-band contiguous DL CA w/o UL CA
	B2+B255+B255	B2	U-NII-3	[5,10,15,20]+20+20	
4	B2+B252	B2	U-NII-1	[5,10,15,20]+20	inter-band DL CA without UL CA
	B2+B255	B2	U-NII-3	[5,10,15,20]+20	
5	B4+B252+B252	B4	U-NII-1	[5, 10, 15, 20] +20+20	inter-band + unlicensed intra-band contiguous DL CA w/o UL CA
	B4+B255+B255	B4	U-NII-3	[5, 10, 15, 20] +20+20	
6	B4+B252	B4	U-NII-1	[5, 10, 15, 20] +20	inter-band DL CA without UL CA
	B4+B255	B4	U-NII-3	[5, 10, 15, 20] +20	

5 Evaluation Methodology

This clause captures simulation assumptions to evaluate coexistence performance between Wi-Fi and LTE-U and between LTE-U nodes. The simulation assumptions will include the deployment layout, channel model, available spectrum and detailed parameters for LTE-U, operator Wi-Fi and private Wi-Fi.

Common (LTE-U/Wi-Fi)

Common simulation assumptions for LTE-U and Wi-Fi are summarized in Table 5-1.

- Most parameters and values are based on 3GPP TR36.872 v12.1.0 [3].
- Adjacent channel interference (ACI) model has not been considered.

Table 5-1: Common Simulation Parameters (LTE-U/Wi-Fi)

Parameter	Value	Note
Layout	21 cell Macro layout	Per 3GPP TR 36.872 The macro sites for the operators are assumed to be the same.
ISD	500 m	
System bandwidth (namely, Frequency Element (FE), see Note)	2x20 MHz	For 2x20 MHz, two adjacent 20 MHz carriers are assumed for LTE-U and one 40 MHz carrier for Wi-Fi.
Carrier frequency on unlicensed	5 GHz	
Macro Tx power	46 dBm	
Tx power on unlicensed for eNB and AP	24 dBm for indoor 24 and 30 dBm for outdoor	Based on FCC rule limit for U-NII-1/3(outdoor) and U-NII-2(indoor)
Number of FEs for LTE-U or operator Wi-Fi	10, 4	10 or 4 FEs for 24 dBm (U-NII-1/2/3), 4 FEs for 30 dBm (U-NII-1/3)
UE noise figure	9 dB	Per 3GPP TR 36.872
Distance-dependent pathloss/Shadowing/Fading	Indoor: ITU InH (Pico-to-Pico, Pico-to-UE: ITU InH UE-to-UE: 3GPP TR 36.843 (D2D) [4]) Outdoor: ITU UMi (Pico-to-Pico, Pico-to-UE: ITU UMi UE-to-UE: 3GPP TR 36.843 (D2D))	Indoor: If UE is in the same building then InH pathloss model is used, while if UE is outdoor or indoor in a different building UMi pathloss model is used. InH is valid for d>3m, and UMi is valid for d>10m. For the case 3m<d<=10m, InH model is used regardless of UE locations. In any case, the minimum distance cannot be smaller than 3m. 5.5 GHz carrier frequency shall be used and there is no additional pathloss for 5 GHz. The minimum distance between AP-UE, AP-AP, UE-UE is 3 m, since InH and D2D models are only valid for d>3m
Penetration	Same as ITU with additional 4 dB for 5 GHz	
Antenna pattern	2D Omni-directional is baseline	Per 3GPP TR 36.872
Antenna gain + connector loss	5 dBi	Per 3GPP TR 36.872
Antenna gain of UE	0 dBi	Per 3GPP TR 36.872
Antenna configuration	2Tx2Rx in DL, Cross-polarized	Per 3GPP TR 36.872
Indoor cluster Building	Single floor Building	
Number of building per macro cell in indoor hotspot	1	
Number of clusters per macro cell in outdoor hotspot	1	
Number of Small Cells (SCs) or operator Wi-Fi Aps	Indoor: 4 cells per building per operator Outdoor: 4, 8 per cluster per operator	
Number of users	60 per macro cell per operator	
User association	User will always be associated to a licensed layer (either Macro or small cell), *i.e.*, a user is associated to a SC over unlicensed band if it is also associated over licensed to the same small cell over licensed band. If user is associated with small cell licensed layer, it can receive Wi-Fi or LTE-U if within its coverage. Some users served on licensed small cell can be out of coverage of LTE-U or Wi-Fi.	
LTE-U small cell dropping	Indoor: Operator 1: regularly dropped in the middle of the hall Operator 2: randomly dropped in the middle of the hall, min. separation distance 3m between Op1 and Op2 small cells and min. separation distance 3m between Op2 small cells Small cells are placed in the middle of the hall	Per 3GPP TR 36.872 For outdoor: It should be 20m except that with high node density, 10m is needed for packing (Even 10m may need to be relaxed in the cases with average 4SCs/FE.)

	Outdoor: Operators dropped randomly with min. distance of 20m between small cells of the same operator, 10m between small cells from different operators	
User dropping	Indoor cluster: As per Scenario 2b in TR 36.872 Outdoor cluster: As per Scenario 2a in TR 36.872	
Traffic model	Modified 3GPP Traffic Model 2 Variable reading time to control system load File size 0.5 MB for small cell users with unlicensed layer 0.025 MB for other users Loading: 70% on unlicensed Wi-Fi	The same traffic model is applicable for all the users connected to macro, small cells or APs. See sub-clause 5.1 for the definition of the loading. The same reading time will be used for Wi-Fi and LTE-U for comparison. For calibration simulation, 3GPP Traffic Model 2 will be used. For capacity evaluation in sub-clause 6.3, the loading varies.
UL traffic	Wi-Fi ACK only	
UE receiver	MMSE-IRC as baseline	Per 3GPP TR 36.872
UE speed	3km/h	Per 3GPP TR 36.872
Network synchronization between different operators (LTE-U or Wi-Fi)	Asynchronous between different operators	
DL transmission	LTE-U UEs have access to both licensed and unlicensed carriers for DL transmission. Wi-Fi-capable UEs have access to either LTE on a licensed carrier or Wi-Fi on unlicensed carriers (not simultaneously) depending on the coverage of Wi-Fi.	

LTE-U

LTE-U specific simulation assumptions are summarized in Table 5-2.

- Most parameters and values are based on 3GPP TR36.872 v12.1.0.

Table 5-2: LTE-U Simulation Parameters

Parameter	Value	Note
LTE primary carrier frequency	2 GHz	Per B4 and B2
eNB Tx power on licensed carrier	24 dBm for indoor 30 dBm for outdoor	
Minimum LTE-U on period	20-100 ms	
Duty cycle of LTE-U on/off	Proprietary	
Range extension	9 dB for licensed carrier FeICIC	Per 3GPP Rel-11 RAN4 spec Note: No range expansion for the LTE-U small cell.
MCS	QPSK/16QAM/64QAM	
Rate control	Proprietary	
Channel selection	Proprietary	

Operator Wi-Fi

Operator Wi-Fi specific simulation assumptions are summarized in Table 5-3.

- Most baselines use mandatory features of 802.11ac.

Table 5-3: Operator Wi-Fi Simulation Parameters

Parameter		Value	Note
Wi-Fi device (STA) Tx power		18dBm	
MAC	Coordination	DCF	
	SIFS, DIFS	SIFS, DIFS	
	Detection	Energy detection & preamble detection	
	RTS/CTS	N/A	
	Contention window	Min : 15 slot, Max : 1023 slot	
Frame aggregation		A-MPDU	
MIMO		2x2 , SU-MIMO	
CCA-ED		-62dBm	Energy Detection
CCA-CS		-82dBm (See Note)	CSMA triggers at -82 dBm but the Wi-Fi device still needs to be able to decode the preamble (the required SNR≈4 dB). Therefore, CSMA should not be solely based on the pathloss.
MCS		0~9 in MCS table	
MPDU		Fixed (1500B or 6000B) MPDU size (variable transmission duration) Or Fixed 1ms MPDU transmission duration	
TXOP		3 ms Asynchronous to LTE packets	
Channel coding		LDPC	
ACK Modeled		Yes	
Duplexing		Yes	
Rate control		Minstrel algorithm [5]	Initialization 6.5 Mbps is used for all the rates in normal and look around rate. Rate prediction update rate: 100 ms EWMA calculation $P_{new} = P_{success_this_time_interval}*0.75 + P_{old}*0.25$ Look around probability = 0.1
Channel selection		AP-based sequential channel selection in Annex B.1	

Private Wi-Fi

Private Wi-Fi specific simulation assumptions are summarized in Table 5-4.

- Most baseline uses mandatory features of 802.11ac.

Table 5-4: Private Wi-Fi Simulation Parameters

Parameter		Value	Note
Wi-Fi AP TX power		24 dBm	
Wi-Fi device (STA) Tx power		18dBm	
Antenna gain + connector loss		0 dBi	
Indoor cluster private Wi-Fi AP deployment		Probability: 0.5, 1 for each room	It corresponds to 8 or 16 private Wi-Fi APs. Some can be considered as mobile hotspots.
Indoor cluster private Wi-Fi AP access rule		Operator Wi-Fi STAs cannot be associated to a private Wi-Fi AP.	
Indoor cluster private Wi-Fi STA deployment		1 per private Wi-Fi AP in the same room	
Indoor cluster private Wi-Fi STA association		Private Wi-Fi STA can be associated to a private Wi-Fi AP in a different room.	
MAC	Coordination	DCF	
	SIFS, DIFS	SIFS, DIFS	
	Detection	Energy detection & preamble detection	
	RTS/CTS	N/A	
	Contention window	Min : 15 slot, Max : 1023 slot	
Frame aggregation		A-MPDU	
MIMO		2x2 , SU-MIMO	
CCA-ED		-62dBm	
CCA-CS		-82dBm (See Note)	CSMA triggers at -82 dBm but the Wi-Fi device still needs to be able to decode the preamble (the required SNR≈4 dB). Therefore, CSMA should not be solely based on the pathloss.
MPDU		Fixed (1500B or 6000B) MPDU size (variable transmission duration) Or Fixed 1ms MPDU transmission duration	
TXOP		3 ms Asynchronous to LTE packets	
Channel coding		LDPC	
ACK Modeled		Yes	
Duplexing		Yes	
Rate control		Minstrel algorithm	
Channel selection		AP-based sequential channel selection in Annex B.1	

Some additional aspects related to interference modeling is captured in Table 5-5.

Unlike the typical TTI-based system simulations used in 3GPP, for LTE-U studies, a model based on sub-TTI sampling needs to be used. The main reason for such approach is to capture the asynchronous nature of Wi-Fi the impact of interference to and from LTE-U on system performance. The packet processing though is still considered to be on 1msec basis even for Wi-Fi, however for the latter, the beginning of a packet doesn't align with LTE-U sub-frames boundaries.

As an example, a 3msec TxOP is divided into 3 MPDUs each of 1msec. Each MPDU is further split into 72us slots (LTE OFDM symbol size), and this is the granularity used for estimating post detection effective SINR (defined below) across all tones of all OFDM symbols included in the 72usec slot. For one LTE packet, the effective SINR is then calculated as the average across the 14 slots in one sub-frame. The effective SINR is then mapped to a short term link curve based on the MCS format used to decide to whether the packet is in error or not.

For one Wi-Fi packet, the effective SINR is chosen to be the minimum across all slots in the 1msec MPDU since Wi-Fi is more sensitive to bursty interference. Since each MPDU has a separate CRC, for a 3msec TXOP, the three individual effective SINRs are mapped to a short term link curve based on the MCS format to decide if the MPDUs were in error or not.

Note that, for the purpose of interference calculation in each 72us slot on a given tone, a partial and complete interference overlap of another packet in a given 72us slot is not distinguished.

Table 5-5: Interference modeling

Parameter	Value	Note
LTE CRS transmission	2-port CRS transmitted for ON LTE-U carriers	CRS interference (without data transmission) should be modelled
SINR slot (SINR calculation resolution)	72 us	
Wi-Fi MPDU effective SINR	Worst slot SINR	
LTE-U effective TB SINR	Average slot SINR	

5.1 Performance metrics

The following metrics are considered for coexistence performance evaluation. User throughput is mainly used for the coexistence evaluation in Clause 6. Detailed analysis based on the rest of metrics is captured in Annex C.

- User throughput
  - Data rate over the time from the packet arrival to delivery (a.k.a., burst rate or perceived throughput)
    - Wi-Fi user: throughput over 40 MHz
    - LTE-U user: throughput over 50 MHz
    - Macro cell user: throughput over 10 MHz
    - Small cell user without unlicensed layer: throughput over 10 MHz
- SINR on unlicensed layer
  - Instantaneous signal-to-interference ratio for a given TTI reflecting instantaneous received signal powers from different cells (or APs). Wi-Fi user SINR distribution is contingent on decoding the preamble, i.e., the user knows that it has an MPDU to receive. LTE-U SINR distribution is independent of decoding. SINR for the i-th user for small-cell/AP j of operator k for a TTI t is defined by

$$SINR_{i,j,k,t} = \frac{S_{i,j,k,t}}{N_{th} + \sum_{l \in \Theta(t)} I_{i,j,k,l,t}}$$

  where $S_{i,j,k,t}$ is the received signal power from the serving small cell/AP j, N_{th} is the thermal noise at user i, $I_{i,j,k,l,t}$ is the received signal power from the interfering node (small cell or AP) l, and $\Theta(t)$ is the set of interfering nodes transmitting during a TTI t. If a node does not have any transmission during a TTI t (e.g., due to empty queue or CCA back-off), the node is not included in $\Theta(t)$. The distribution of $S_{i,j,k,t}$ over i, j, t for a given operator k will be reported.
- Loading on unlicensed layer
  - Let $q_{i,j,k,t}$ be the size of the queue for the ith user connected to the jth small cell for the kth operator (k=1 or 2) at time t (TTI granularity). Loading over the unlicensed layer per AP/Small-Cell can be defined as

$$L_{j,k} = \left(\frac{\sum_t 1\left(\sum_{i \in \Omega} q_{i,j,k,t} > 0\right)}{T} \right)$$

  where 1(.) is the indicator function, T=total simulation time, and Ω is the set of users within 5GHz coverage. Queue size is for data to be sent on both licensed and unlicensed components. $Mean_j(L_{j,k})$ can be reported as average loading across the operator network. For better calibration, $CDF(L_{j,k})$ for the specific mean values we target (e.g. 30%, 50%, 70%) can be reported as well.
- Resource utilization on unlicensed layer
  - Resource utilization can be defined as

$$U_{j,k} = \left(\frac{\sum_t 1\left(P_{j,kt}\right)}{T} \right)$$

  where $P_{j,k,t}=1$ if AP/Small-Cell j of operator k is transmitting at time t over unlicensed layer (i.e., to one of the users in Ω). $Mean(U_{j,k})$ and $CDF(U_{j,k})$ can be reported.
- Congestion metric on unlicensed layer
  - Congestion metric can be defined as

$$R_{j,k} = 1 - \left(\frac{\sum_t 1\left(P_{j,kt}\right)}{\sum_t 1\left(\sum_{i \in \Omega} q_{i,j,k,t} > 0\right)} \right).$$

5.2 Coexistence evaluation scenarios

5.2.1 Outdoor scenarios

4 sets of outdoor scenarios are studied for the evaluation of coexistence performance between Wi-Fi and LTE-U and between LTE-Us as follows:

1. Low density case: Fewer nodes (8 in total) than the number of FEs(10) between 2 operators in a cluster
    - SO5-8 in Table 5.2.1-1
2. High density case: More nodes (16 in total) than the number of FEs(10) between 2 operators in a cluster
    - SO1-4 in Table 5.2.1-1
3. Very high density case: High-density high-power Pico case with 4 FEs (assuming U-NII-1 & U-NII-3 only) between 2 operators in a cluster
    - SO9-12 in Table 5.2.1-1
4. 3 Operators case: 12 nodes in total (4 nodes per operator) over 4 FEs
    - SO13-14 in Table 5.2.1-1

The detailed parameters for each scenario are summarized in Table 5.2.1-1.

Table 5.2.1-1: Outdoor simulations scenarios for LTE-U coexistence studies

Scenario #	Description	Number of FEs	Number of nodes per operator	Coexistence solutions	Unlicensed Tx Power (dBm)	Comments
SO1	Two operators: Operator 1: Wi-Fi Operator 2: Wi-Fi	10	8	NA	24	SO1-4 study the scenarios when there are more nodes (16 in total) than the number of FEs(10)
SO2	Two operators: Operator 1: LTE-U Operator 2: Wi-Fi	10	8	No	24	
SO3	Two operators: Operator 1: LTE-U Operator 2: Wi-Fi	10	8	Yes	24	
SO4	Two operators: Operator 1: LTE-U Operator 2: LTE-U	10	8	Yes	24	
SO5	Two operators: Operator 1: Wi-Fi Operator 2: Wi-Fi	10	4	NA	24	SO5-8 study the scenarios when there are fewer nodes (8 in total) than the number of FEs(10)
SO6	Two operators: Operator 1: LTE-U Operator 2: Wi-Fi	10	4	No	24	
SO7	Two operators: Operator 1: LTE-U Operator 2: Wi-Fi	10	4	Yes	24	
SO8	Two operators: Operator 1: LTE-U Operator 2: LTE-U	10	4	Yes	24	
SO9	Two operators: Operator 1: Wi-Fi Operator 2: Wi-Fi	4	8	NA	30	SO9-12 study high-density high-power Pico case with 4 FEs (U-NII-1 & U-NII-3 only)
SO10	Two operators: Operator 1: LTE-U Operator 2: Wi-Fi	4	8	No	30	
SO11	Two operators: Operator 1: LTE-U Operator 2: Wi-Fi	4	8	Yes	30	
SO12	Two operators: Operator 1: LTE-U Operator 2: LTE-U	4	8	Yes	30	
SO13	Three operators: Operator 1: Wi-Fi Operator 2: Wi-Fi	4	4	NA	30	SO13-14 study 3 operator coexistence

	Operator 3: Wi-Fi					
SO14	Three operators: Operator 1: LTE-U Operator 2: LTE-U Operator 3: Wi-Fi	4	4	Yes	30	

5.2.2 Indoor scenarios

3 sets of indoor scenarios are studied for the evaluation of coexistence performance between Wi-Fi and LTE-U and between LTE-Us as follows:

1. Low density case with private Wi-Fi: 8 operator nodes (between 2 operators) over 10 FEs with 16 private Wi-Fis
    - SI1-4 in Table 5.2.2-1
2. High density case with private Wi-Fi: 8 operator nodes (between 2 operators) over 4 FEs with 16 private Wi-Fis
    - SI5-8 in Table 5.2.2-1
3. High density case without private Wi-Fi: 8 operator nodes (between 2 operators) over 4 FEs without private Wi-Fi
    - SI9-12 in Table 5.2.2-1

The detailed parameters for each scenario are summarized in Table 5.2.2-1.

Table 5.2.2-1: Indoor simulations scenarios for LTE-U coexistence studies

Scenario #	Description	Number of FEs	Number of nodes per operator	Coexistence solutions	Unlicensed Tx Power (dBm)	Comments
SI1	Two Operators + Private Wi-Fi (p=100%) Operator 1: Wi-Fi (Regular drops) Operator 2: Wi-Fi (Random drops)	10	4	NA	24	SI1-4 are added to study lower density cases. p=100% means 16 private Wi-Fi APs per floor, or 24 nodes in total over 10 FEs
SI2	Two Operators + Private Wi-Fi (p=100%) Operator 1: LTE-U (Regular drops) Operator 2: Wi-Fi (Random drops)	10	4	No	24	
SI3	Two Operators+ Private Wi-Fi (p=100%) Operator 1: LTE-U (Regular drops) Operator 2: Wi-Fi (Random drops)	10	4	Yes	24	
SI4	Two Operators+ Private Wi-Fi (p=100%) Operator 1: LTE-U (Regular drops) Operator 2: LTE-U (Random drops)	10	4	Yes	24	
SI5	Two Operators + Private Wi-Fi (p=100%) Operator 1: Wi-Fi (Regular drops) Operator 2: Wi-Fi (Random drops)	4	4	NA	24	SI5-8 are added to study high density cases over 4 FEs (U-NII-1 & U-NII-3 only). p=100% means 16 private Wi-Fi APs per floor, or 24 nodes in total.
SI6	Two Operators + Private Wi-Fi (p=100%) Operator 1: LTE-U (Regular	4	4	No	24	

	drops) Operator 2: Wi-Fi (Random drops)					
SI7	Two Operators+ Private Wi-Fi (p=100%) Operator 1: LTE-U (Regular drops) Operator 2: Wi-Fi (Random drops)	4	4	Yes	24	
SI8	Two Operators+ Private Wi-Fi (p=100%) Operator 1: LTE-U (Regular drops) Operator 2: LTE-U (Random drops)	4	4	Yes	24	
SI9	Two Operators: Operator 1: Wi-Fi (Regular drops) Operator 2: Wi-Fi (Random drops)	4	4	NA	24	SI9-12 are added to study the impact of private Wi-Fi against SI5-8.
SI10	Two Operators: Operator 1: LTE-U (Regular drops) Operator 2: Wi-Fi (Random drops)	4	4	No	24	
SI11	Two Operators: Operator 1: LTE-U (Regular drops) Operator 2: Wi-Fi (Random drops)	4	4	Yes	24	
SI12	Two Operators Operator 1: LTE-U (Regular drops) Operator 2: LTE-U (Random drops)	4	4	Yes	24	

6 Coexistence Evaluation

Without modifying Rel. 10/11/12 LTE PHY/MAC standards, three mechanisms can be used to safeguard that LTE is a "good neighbour" in unlicensed bands (Figure 6-1) as well as better system in performance in many scenarios than Wi-Fi. First, channel selection enables small cells to choose the cleanest channel based on Wi-Fi and LTE measurements. This ensures the interference is avoided between the small cell and its neighbouring Wi-Fi devices and other LTE-U small cells, provided an unused channel is available. The channel selection algorithm monitors the status of the operating channel on an on-going base, and if needed will change and select a more suitable one.

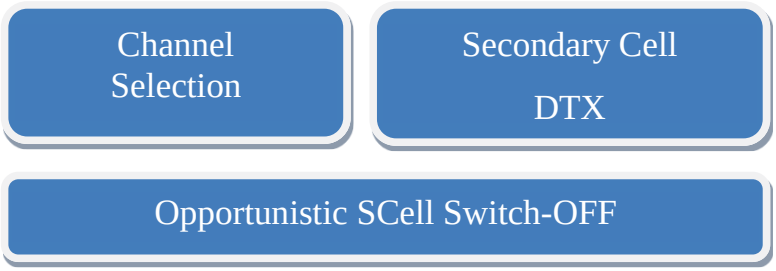


Figure 6-1 Co-existence mechanisms for LTE-U in markets without LBT requirements

In the event that no clean channel is available, SCell DTX algorithm is used to apply adaptive or static TDM transmission to LTE-U small cells, based on 10s-100s of msec carrier sensing of co-channel Wi-Fi activities. This ensures that even in very dense deployments, LTE-U nodes can share the channel fairly with the neighbouring Wi-Fi APs.

In addition, opportunistic SCell switch off can reduce interference to Wi-Fi due to CRS when SCells are not needed. This decision can be made based on traffic demand of unlicensed band associated users compared to what PCell can provide. Note that this is possible since the primary carrier is always operating in the licensed band.

In simulations, the exact mechanisms of coexistence were left to the different companies' discretion. For instance, while channel selection algorithm for Wi-Fi is the part of evaluation methodology (as shown in Annex B), the corresponding one for LTE-U was made propriety in simulations. For SCell DTX, whether duty cycle is controlled in adaptive or static manner as well as the metrics used to run the algorithm are left for the designer. Finally, the conditions to turn off a SCell is again left to the implementation.

The agreement between the LTE-U forum members was not to strictly stick to one approach of design or even some of the assumptions as long as TR captures those used in simulations. This is expected to enrich the technical contribution with the performance of multiple scenarios that while highly correlated, not exactly the same.

6.1 Outdoor evaluation

6.1.1 2 operator low density deployment (SO5-8)

4 nodes per operator in a cluster and 10 FEs are assumed (0.8 nodes/FE on average)

User throughput comparison results from Company A, B, C are shown in Figure 6.1.1-1, Figure 6.1.1-2 and Figure 6.1.1-3 respectively. SO5 is the baseline Wi-Fi/Wi-Fi coexistence scenario, SO6 is the LTE CA[1]/Wi-Fi coexistence scenario, SO7 is the LTE-U/Wi-Fi coexistence scenario, and SO8 is LTE-U/LTE-U coexistence scenario. 5%, 50% and 95% user throughput gain over the baseline Wi-Fi/Wi-Fi scenario are shown in Figure 6.1.1-4, Figure 6.1.1-5 and Figure 6.1.1-6.

[1] LTE CA refers to LTE-U without coexistence solution.

Observations:

- When LTE is simply deployed in unlicensed spectrum without any coexistence mechanism, LTE causes significant performance degradation on coexisting Wi-Fi (SO6 over SO5).
- LTE-U behaves as a comparable neighbour to Wi-Fi compared to Wi-Fi as a neighbour, while LTE-U significantly outperforms Wi-Fi. (SO7 over SO5).
    - Average gain of LTE-U in SO7 over Wi-Fi in SO5 is 182% @ 5% user throughput.
    - Average gain of LTE-U in SO7 over Wi-Fi in SO5 is 96% @ 50% user throughput.
    - Average gain of LTE-U in SO7 over Wi-Fi in SO5 is 27% @ 95% user throughput.
- LTE-U/LTE-U scenario significantly outperforms Wi-Fi/Wi-Fi scenario (SO8 over SO5).
    - Average gain of LTE-U in SO8 over Wi-Fi in SO5 is 248% @ 5% user throughput.
    - Average gain of LTE-U in SO8 over Wi-Fi in SO5 is 123% @ 50% user throughput.
    - Average gain of LTE-U in SO8 over Wi-Fi in SO5 is 36% @ 95% user throughput.

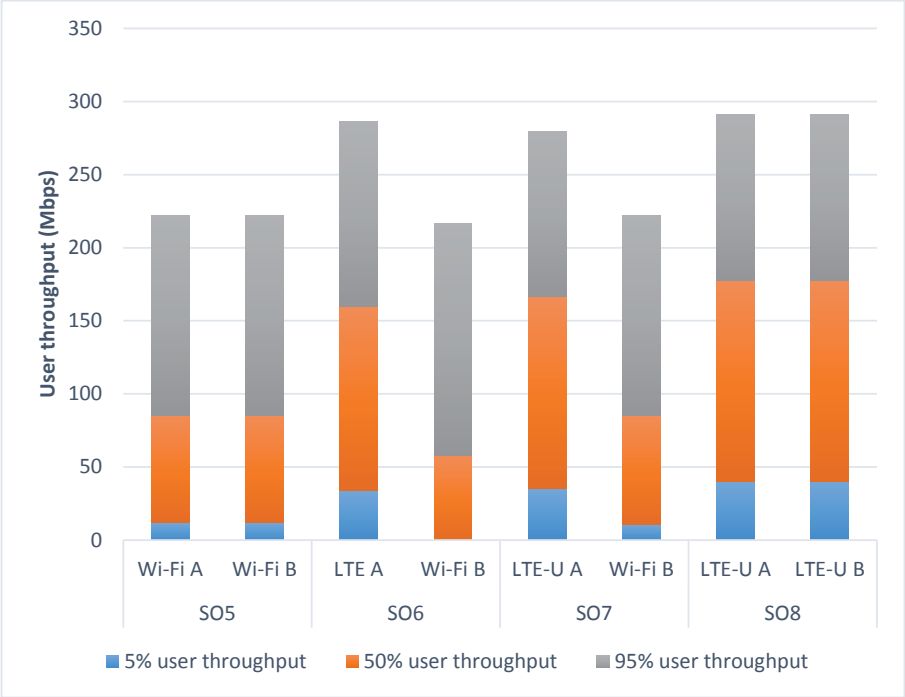


Figure 6.1.1-1: User throughput comparison (Company A)

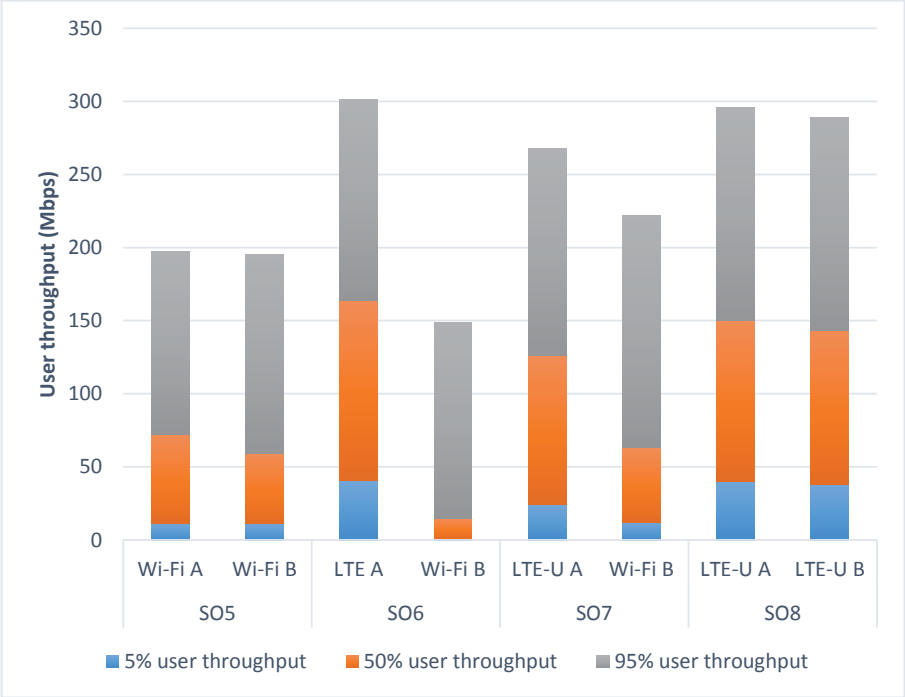


Figure 6.1.1-2: User throughput comparison (Company B)

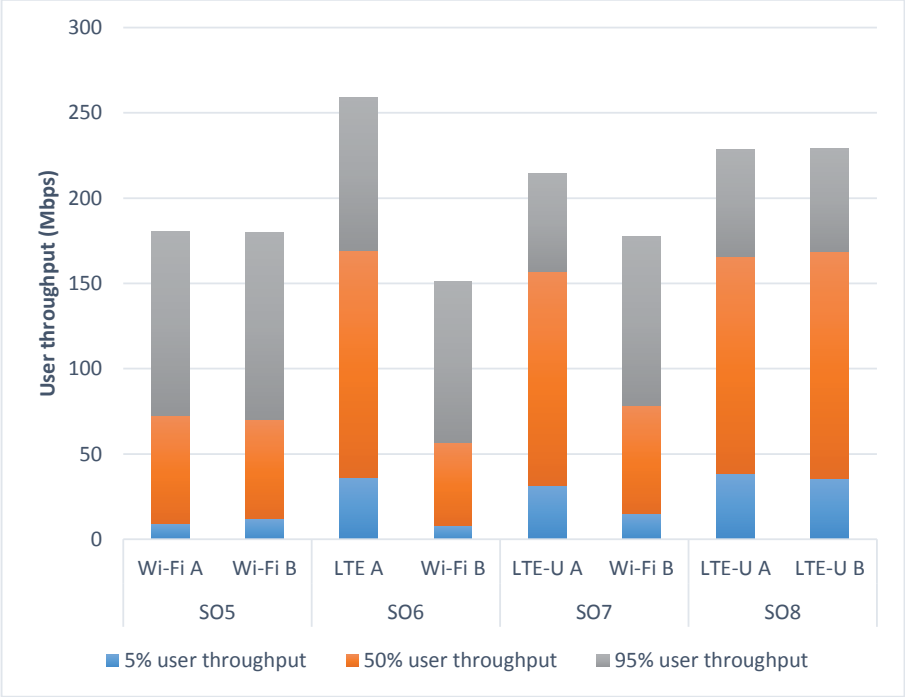


Figure 6.1.1-3: User throughput comparison (Company C)

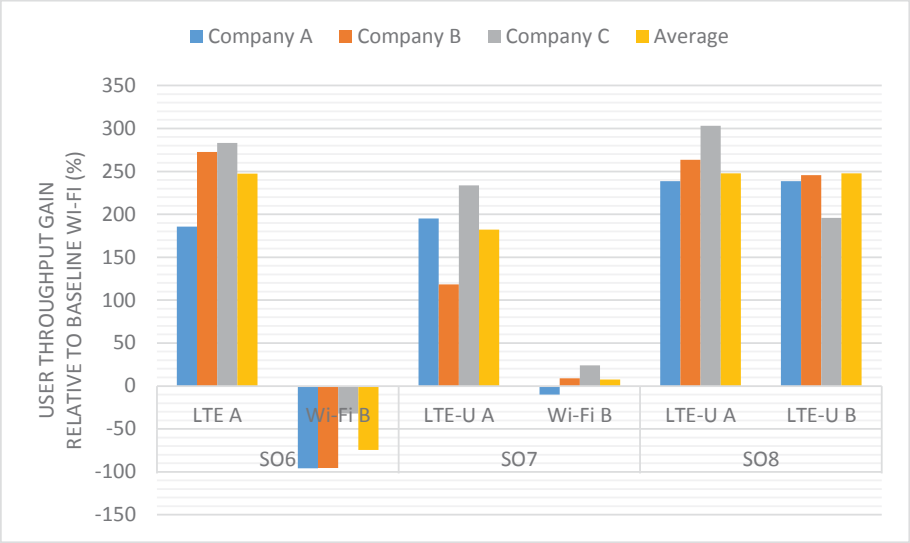


Figure 6.1.1-4: 5% user throughput gain over baseline Wi-Fi/Wi-Fi scenario (SO5)

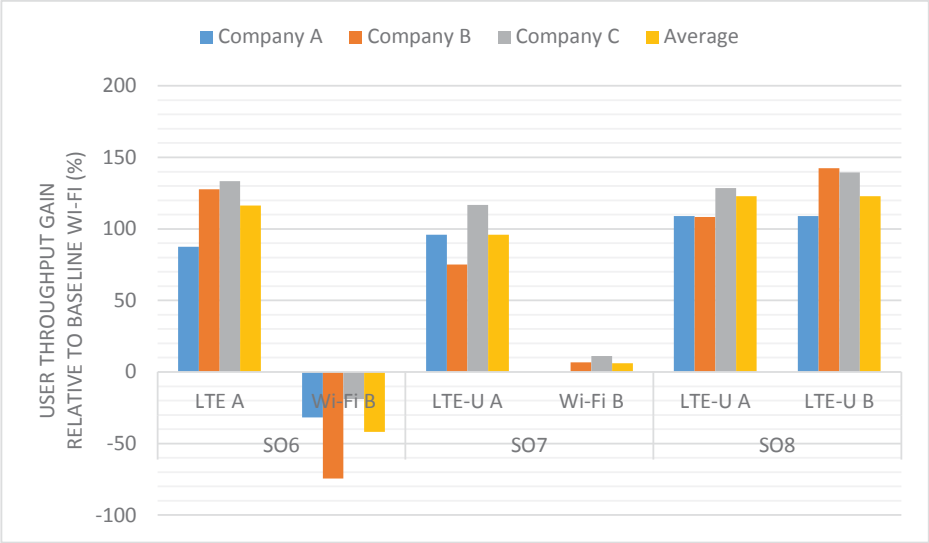


Figure 6.1.1-5: 50% user throughput gain over baseline Wi-Fi/Wi-Fi scenario (SO5)

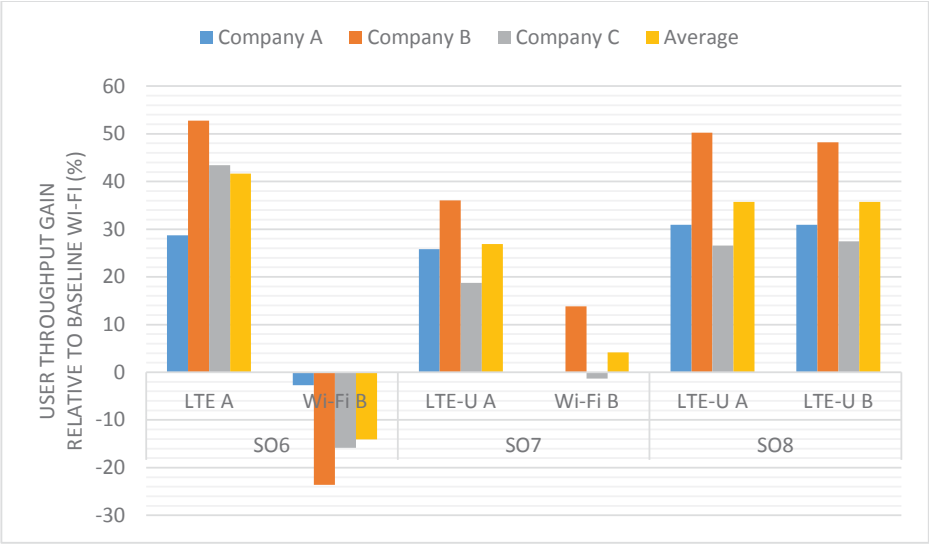


Figure 6.1.1-6: 95% user throughput gain over baseline Wi-Fi/Wi-Fi scenario (SO5)

6.1.2 2 operator high density deployment (SO1-4)

8 nodes per operator in a cluster and 10 FEs are assumed (1.6 nodes/FE on average).

User throughput comparison results from Company A, B, C are shown in Figure 6.1.2-1, Figure 6.1.2-2 and Figure 6.1.2-3 respectively. SO1 is the baseline Wi-Fi/Wi-Fi coexistence scenario, SO2 is the LTE CA/Wi-Fi coexistence scenario, SO3 is the LTE-U/Wi-Fi coexistence scenario, and SO4 is LTE-U/LTE-U coexistence scenario. 5%, 50% and 95% user throughput gain over the baseline Wi-Fi/Wi-Fi scenario are shown in Figure 6.1.2-4, Figure 6.1.2-5 and Figure 6.1.2-6.

<u>Observations:</u>

- When LTE is simply deployed in unlicensed spectrum without any coexistence mechanism, LTE causes significant performance degradation on coexisting Wi-Fi (SO2 over SO1).
- LTE-U behaves as a comparable or slightly better neighbour (16% Wi-Fi median user gain on average) to Wi-Fi compared to Wi-Fi as a neighbour, while LTE-U significantly outperforms Wi-Fi. (SO3 over SO1).
    - Average gain of LTE-U in SO3 over Wi-Fi in SO1 is 167% @ 5% user throughput.
    - Average gain of LTE-U in SO3 over Wi-Fi in SO1 is 111% @ 50% user throughput.
    - Average gain of LTE-U in SO3 over Wi-Fi in SO1 is 39% @ 95% user throughput.
- LTE-U/LTE-U scenario significantly outperforms Wi-Fi/Wi-Fi scenario (SO4 over SO1).
    - Average gain of LTE-U in SO4 over Wi-Fi in SO1 is 220% @ 5% user throughput.
    - Average gain of LTE-U in SO4 over Wi-Fi in SO1 is 133% @ 50% user throughput.
    - Average gain of LTE-U in SO4 over Wi-Fi in SO1 is 43% @ 95% user throughput.

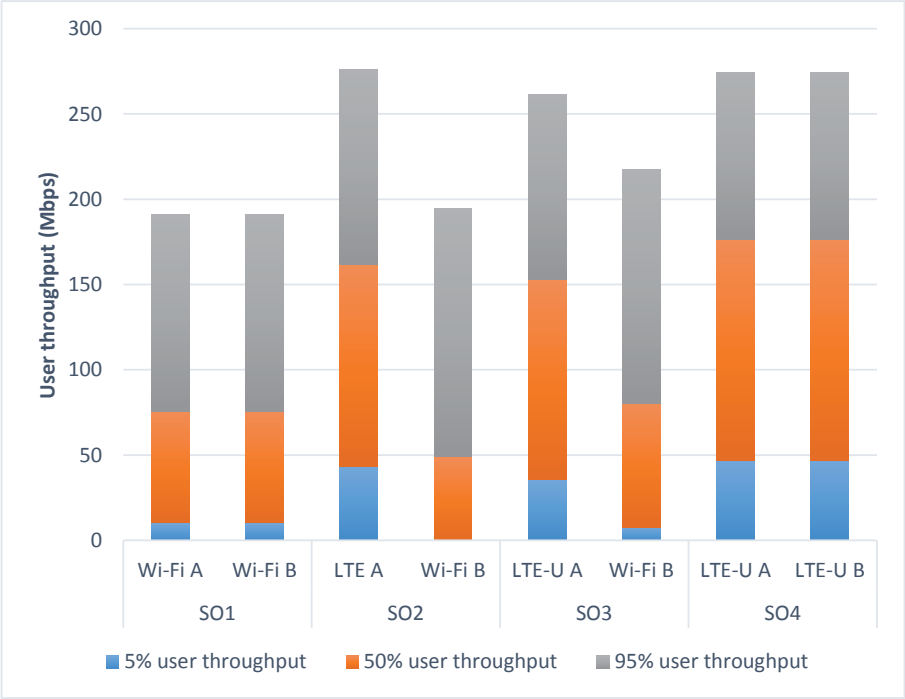


Figure 6.1.2-1: User throughput comparison (Company A)

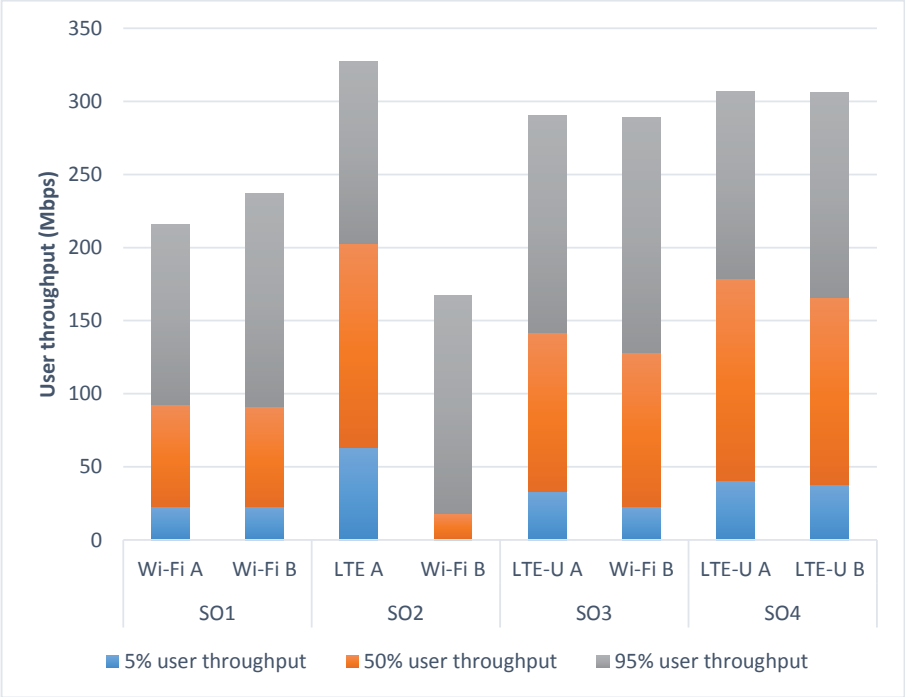


Figure 6.1.2-2: User throughput comparison (Company B)

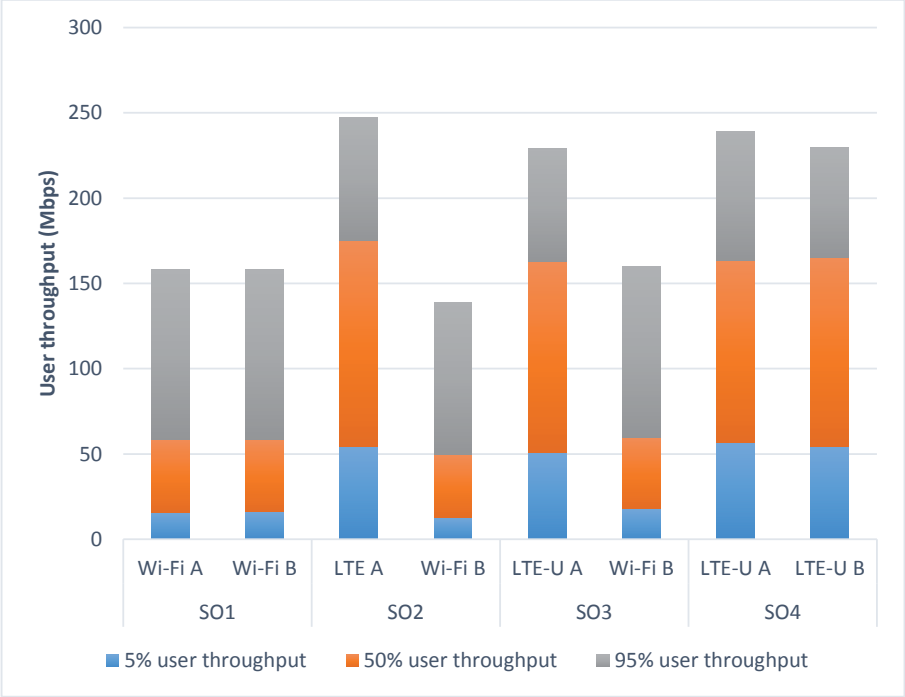


Figure 6.1.2-3: User throughput comparison (Company C)

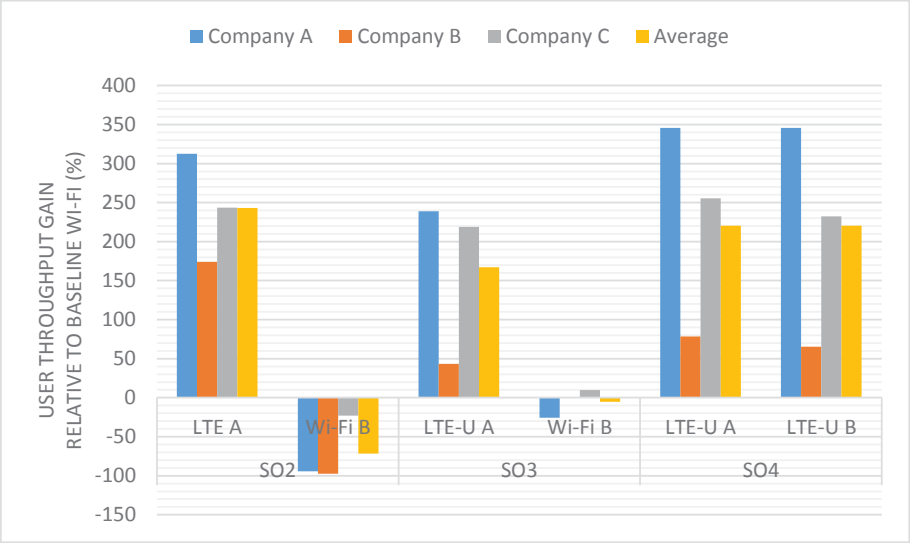


Figure 6.1.2-4: 5% user throughput gain over baseline Wi-Fi/Wi-Fi scenario (SO1)

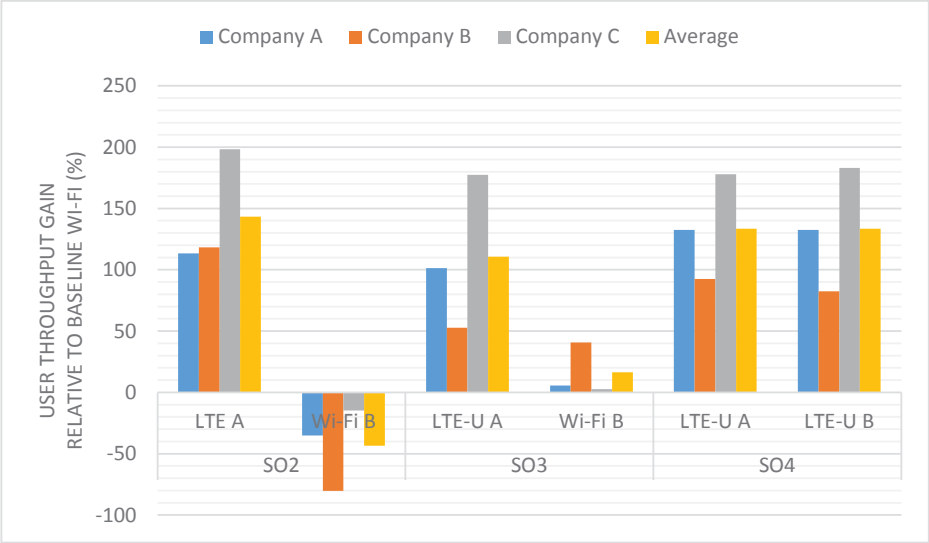


Figure 6.1.2-5: 50% user throughput gain over baseline Wi-Fi/Wi-Fi scenario (SO1)

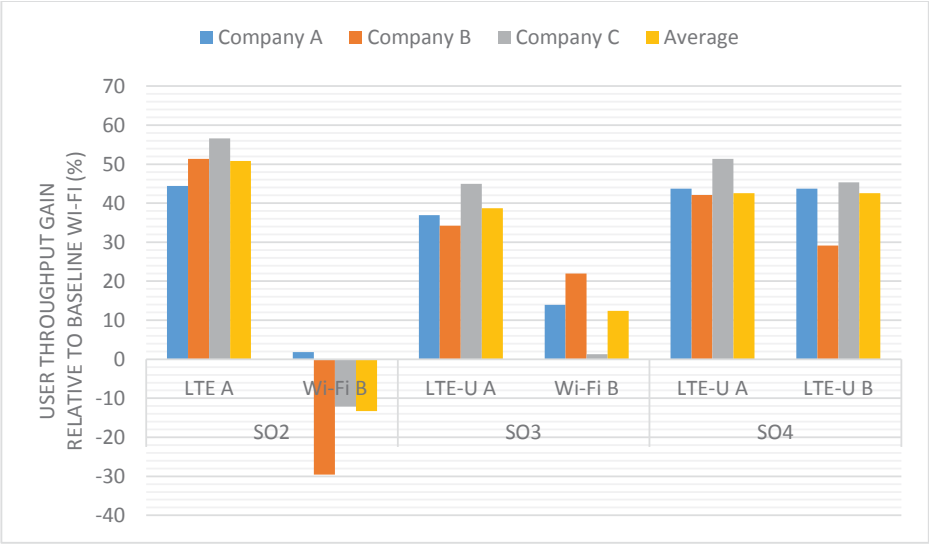


Figure 6.1.2-6: 95% user throughput gain over baseline Wi-Fi/Wi-Fi scenario (SO1)

6.1.3 2 operator very high density deployment (SO9-12)

8 nodes per operator in a cluster and 4 FEs are assumed (4 nodes/FE on average).

User throughput comparison results from Company A, B, C are shown in Figure 6.1.3-1, Figure 6.1.3-2 and Figure 6.1.3-3 respectively. SO9 is the baseline Wi-Fi/Wi-Fi coexistence scenario, SO10 is the LTE CA/Wi-Fi coexistence scenario, SO11 is the LTE-U/Wi-Fi coexistence scenario, and SO12 is LTE-U/LTE-U coexistence scenario. 5%, 50% and 95% user throughput gain over the baseline Wi-Fi/Wi-Fi scenario are shown in Figure 6.1.3-4, Figure 6.1.3-5 and Figure 6.1.3-6.

<u>Observations:</u>

- When LTE is simply deployed in unlicensed spectrum without any coexistence mechanism, LTE causes significant performance degradation on coexisting Wi-Fi (SO10 over SO9).
- LTE-U behaves as a comparable or slightly better neighbour (21% Wi-Fi median user gain on average) to Wi-Fi compared to Wi-Fi as a neighbour, while LTE-U significantly outperforms Wi-Fi. (SO11 over SO9).
    - Average gain of LTE-U in SO11 over Wi-Fi in SO9 is 783% @ 5% user throughput.
    - Average gain of LTE-U in SO11 over Wi-Fi in SO9 is 180% @ 50% user throughput.
    - Average gain of LTE-U in SO11 over Wi-Fi in SO9 is 85% @ 95% user throughput.
- LTE-U/LTE-U scenario significantly outperforms Wi-Fi/Wi-Fi scenario (SO12 over SO9).
    - Average gain of LTE-U in SO12 over Wi-Fi in SO9 is 1055% @ 5% user throughput.
    - Average gain of LTE-U in SO12 over Wi-Fi in SO9 is 229% @ 50% user throughput.
    - Average gain of LTE-U in SO12 over Wi-Fi in SO9 is 104% @ 95% user throughput.

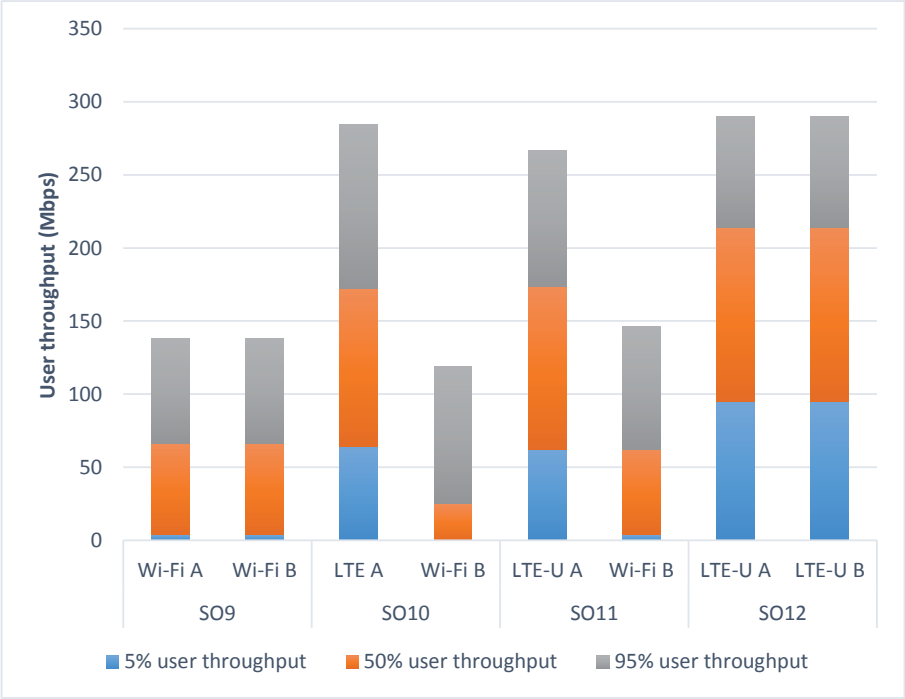


Figure 6.1.3-1: User throughput comparison (Company A)

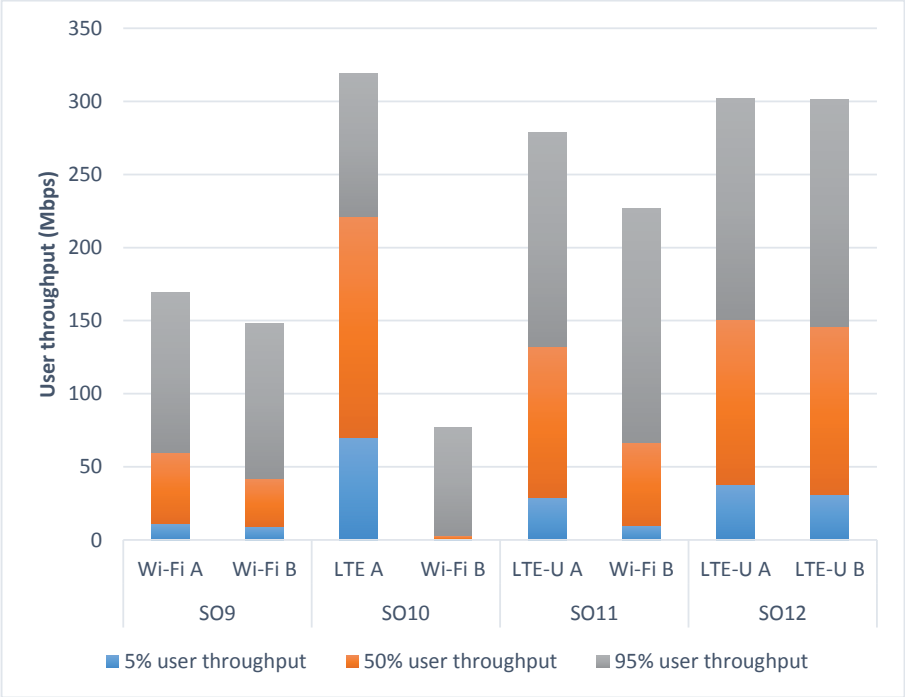


Figure 6.1.3-2: User throughput comparison (Company B)

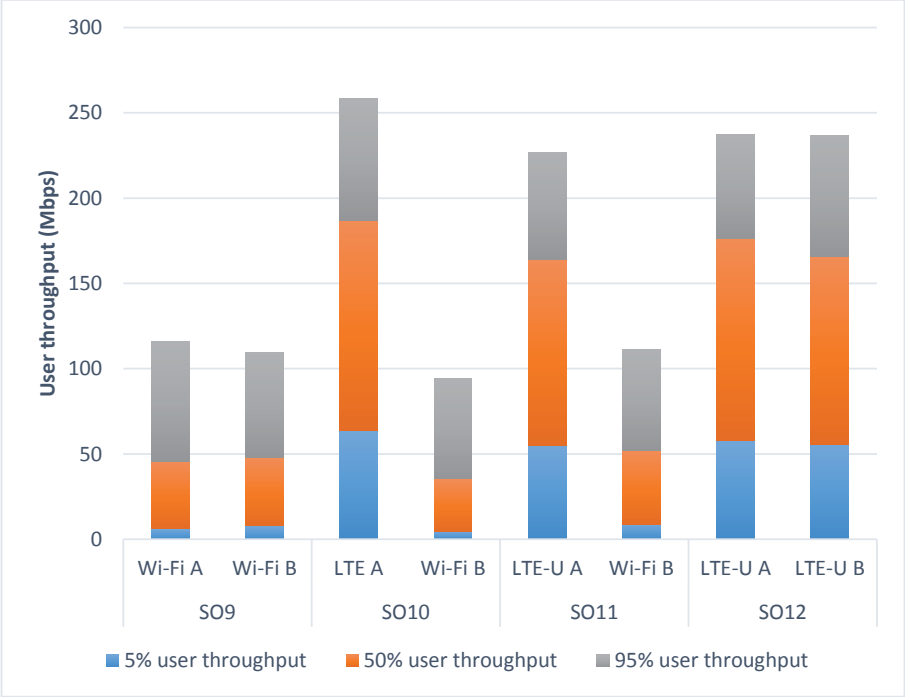


Figure 6.1.3-3: User throughput comparison (Company C)

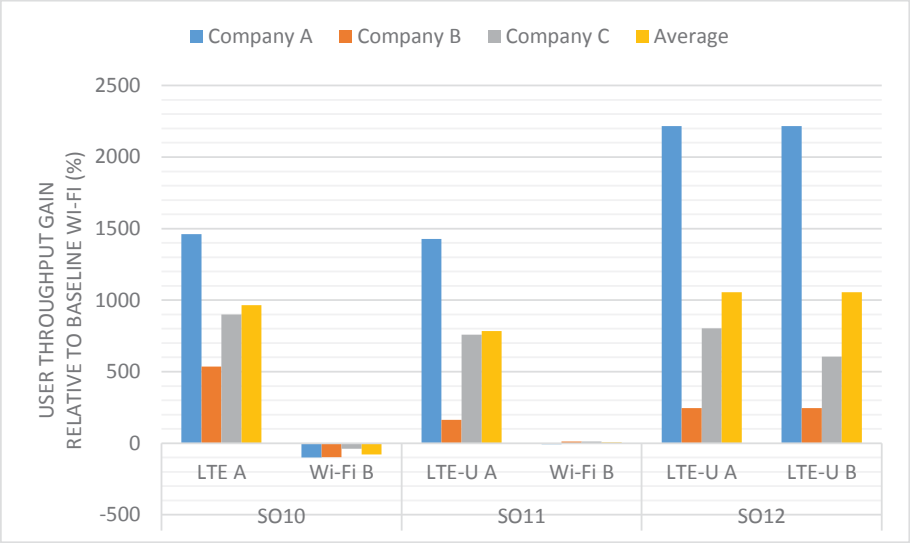


Figure 6.1.3-4: 5% user throughput gain over baseline Wi-Fi/Wi-Fi scenario (SO9)

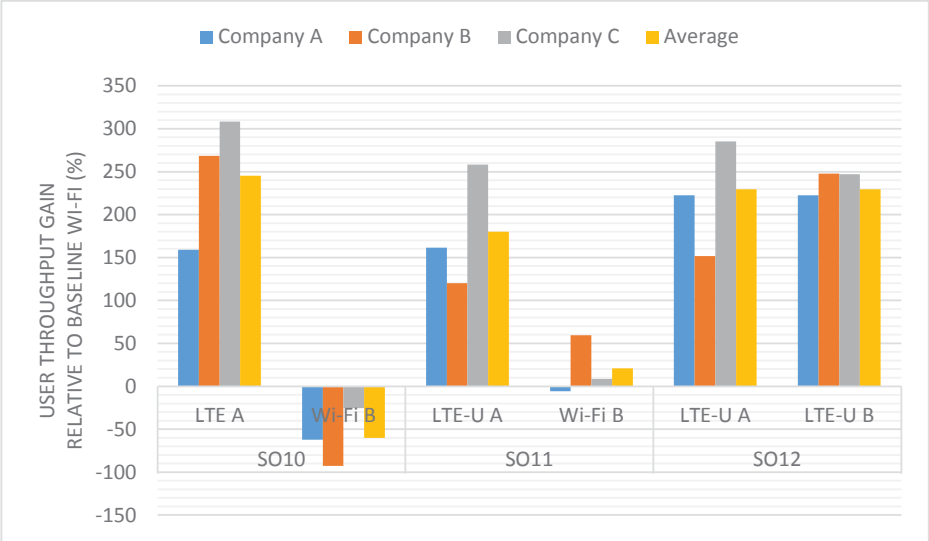


Figure 6.1.3-5: 50% user throughput gain over baseline Wi-Fi/Wi-Fi scenario (SO9)

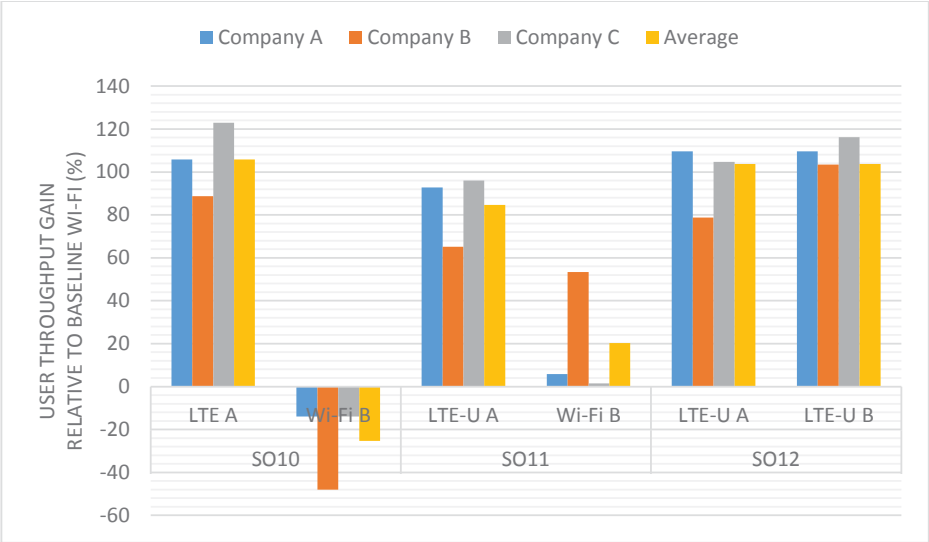


Figure 6.1.3-6: 95% user throughput gain over baseline Wi-Fi/Wi-Fi scenario (SO9)

6.1.4 3 operator deployment (SO13-14)

4 nodes per operator in a cluster and 4 FEs are assumed (3 nodes/FE on average).

User throughput comparison results from Company A, B, C are shown in Figure 6.1.4-1, Figure 6.1.4-2 and Figure 6.1.4-3 respectively. SO13 is the baseline Wi-Fi/Wi-Fi/Wi-Fi coexistence scenario, and SO14 is LTE-U/LTE-U/Wi-Fi coexistence scenario. 5%, 50% and 95% user throughput gain over the baseline Wi-Fi/Wi-Fi/Wi-Fi scenario are shown in Figure 6.1.4-4, Figure 6.1.4-5 and Figure 6.1.4-6.

<u>Observations:</u>

- LTE-U behaves as a better neighbour to Wi-Fi compared to Wi-Fi as a neighbour (52% Wi-Fi median user gain on average), while LTE-U significantly outperforms Wi-Fi. (SO14 over SO13).
    - Average gain of LTE-U in SO14 over Wi-Fi in SO13 is 1087% @ 5% user throughput.
    - Average gain of LTE-U in SO14 over Wi-Fi in SO13 is 181% @ 50% user throughput.
    - Average gain of LTE-U in SO14 over Wi-Fi in SO13 is 75% @ 95% user throughput.

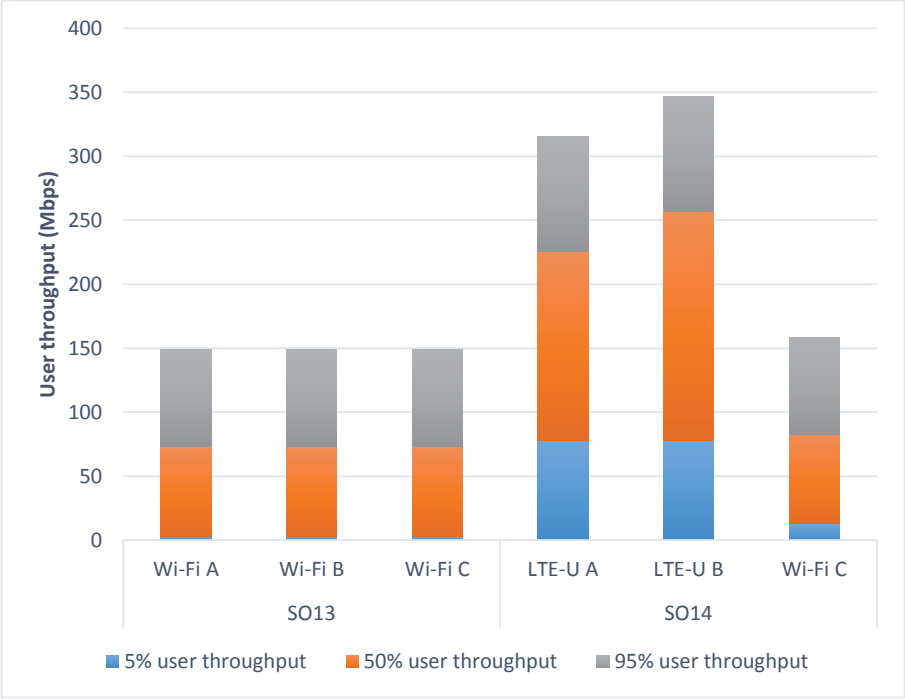


Figure 6.1.4-1: User throughput comparison (Company A)

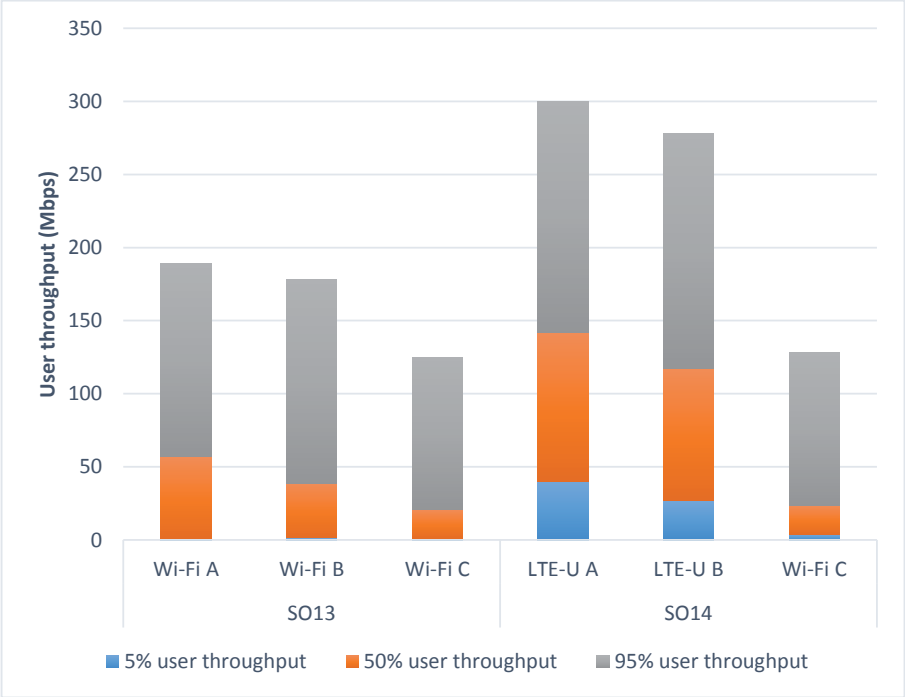


Figure 6.1.4-2: User throughput comparison (Company B)

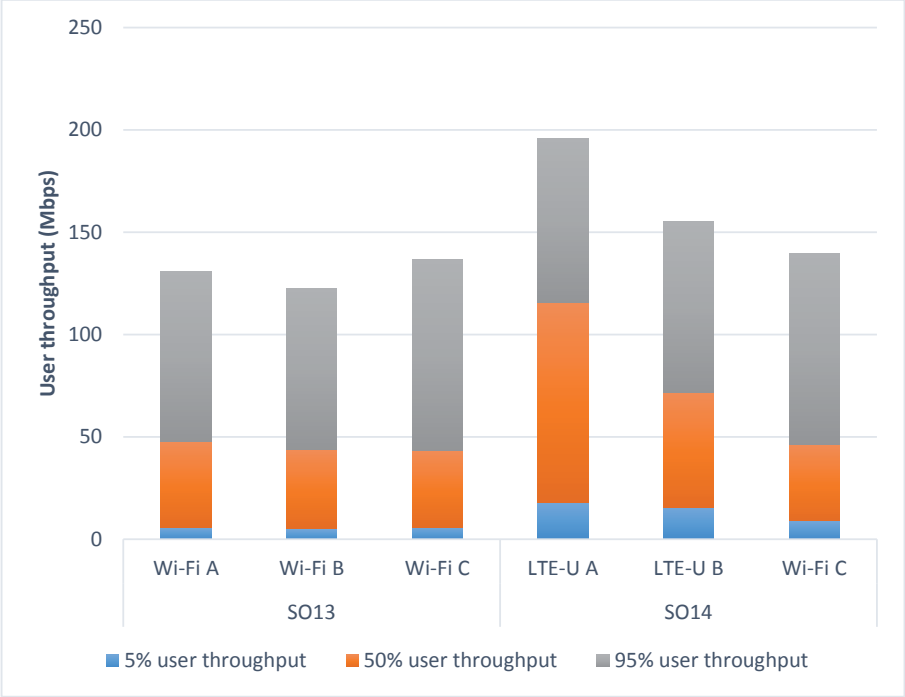


Figure 6.1.4-3: User throughput comparison (Company C)

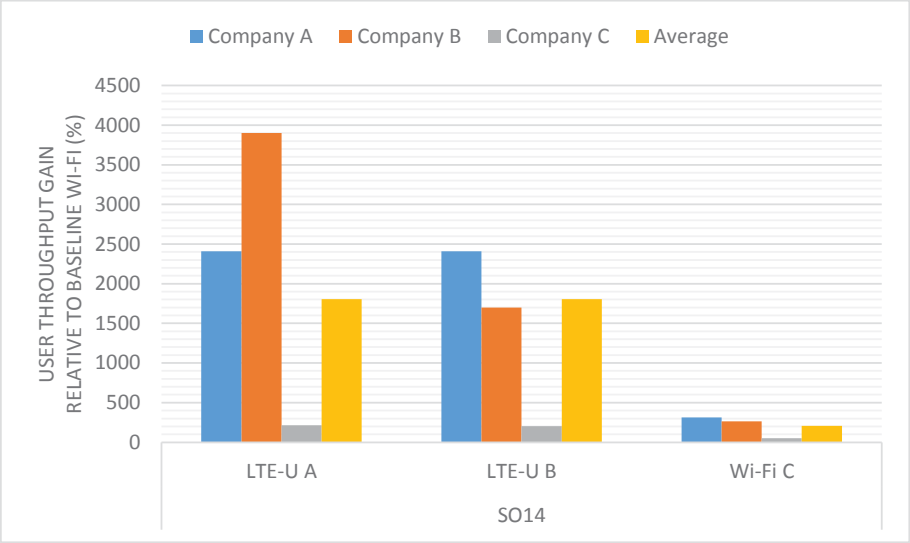


Figure 6.1.4-4: 5% user throughput gain over baseline Wi-Fi/Wi-Fi/Wi-Fi scenario (SO13)

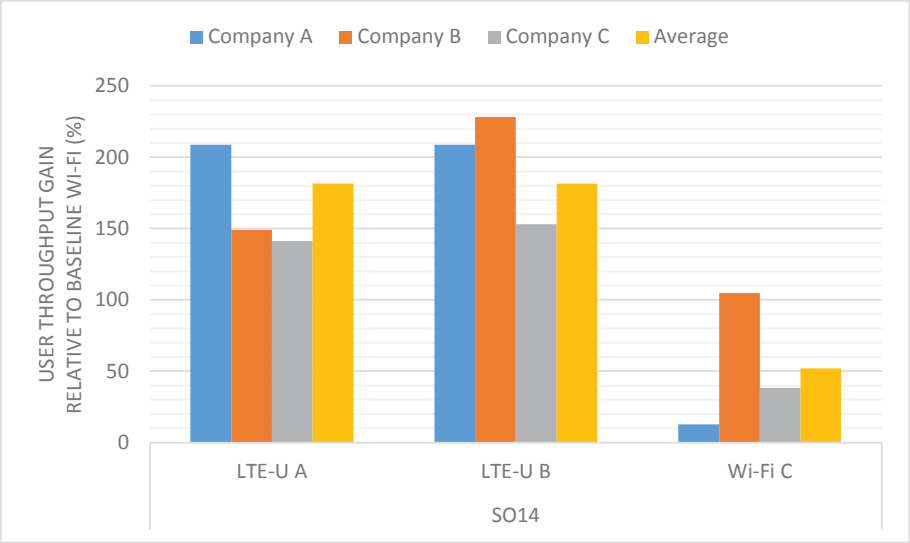


Figure 6.1.4-5: 50% user throughput gain over baseline Wi-Fi/Wi-Fi/Wi-Fi scenario (SO13)

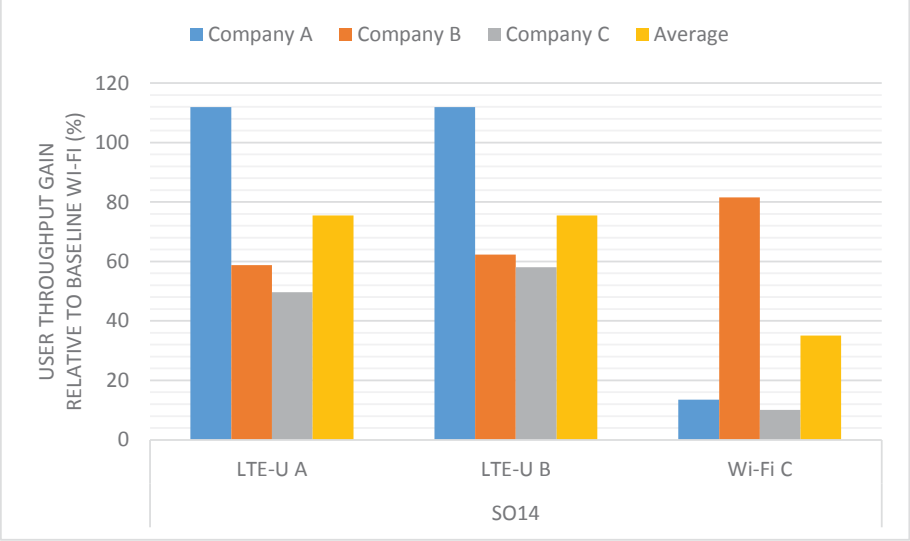


Figure 6.1.4-6: 95% user throughput gain over baseline Wi-Fi/Wi-Fi/Wi-Fi scenario (SO13)

6.1.5 Summary for outdoor evaluation

When LTE is simply deployed in unlicensed spectrum without any coexistence mechanism, it was observed that LTE can cause significant performance degradation on coexisting Wi-Fi. However, when LTE-U is deployed with reasonable coexistence mechanisms (see clause 7 for recommendations for coexistence mechanism), it was shown that LTE-U behaves as a comparable or better neighbour to Wi-Fi compared to Wi-Fi as a neighbour while LTE-U significantly outperforms the replacing Wi-Fi deployment.

In the studied 2 operator scenarios, the average gain of 96%-180% for the median user throughput was observed when one of Wi-Fi operator deployment is replaced by LTE-U. The average gain of 6%-21% for the median user throughput was also observed for the coexisting Wi-Fi. When the Wi-Fi deployment of both operators is replaced by LTE-U, LTE-U/LTE-U scenario significantly outperforms Wi-Fi/Wi-Fi scenario. The observed average gain for the median user throughput is 123%-229%. The gain is bigger for the low percentile users and smaller for the high percentile users compared to the gain in median user throughput in general. It was also observed that the gain of LTE-U over Wi-Fi is getting bigger in denser deployment scenario.

LTE-U coexistence performance was also verified with more than 2 operators. The average gain of 181% for the median user throughput was observed for LTE-U operators while the average gain of 52% for the median user throughput was observed for the coexisting Wi-Fi.

6.2 Indoor evaluation

6.2.1 Low density deployment with private Wi-Fi (SI1-4)

4 nodes per operator in a cluster (building) with 16 private Wi-Fi APs and 10 FEs are assumed (0.8 nodes/FE excluding private Wi-Fi, 2.4 nodes/FE including private Wi-Fi on average).

User throughput comparison results from Company A, B, C are shown in Figure 6.2.1-1, Figure 6.2.1-2 and Figure 6.2.1-3 respectively. SI1 is the baseline Wi-Fi/Wi-Fi coexistence scenario, SI2 is the LTE CA/Wi-Fi coexistence scenario, SI3 is the LTE-U/Wi-Fi coexistence scenario, and SI4 is LTE-U/LTE-U coexistence scenario. 5%, 50% and 95% user throughput gain over the baseline Wi-Fi/Wi-Fi scenario are shown in Figure 6.2.1-4, Figure 6.2.1-5 and Figure 6.2.1-6.

<u>Observations:</u>

- When LTE is simply deployed in unlicensed spectrum without any coexistence mechanism, LTE causes significant performance degradation on coexisting Wi-Fi (SI2 over SI1).
- LTE-U behaves as a slightly better neighbour (12% Wi-Fi median user gain on average) to Wi-Fi compared to Wi-Fi as a neighbour, while LTE-U significantly outperforms Wi-Fi. (SI3 over SI1).
    - Average gain of LTE-U in SI3 over Wi-Fi in SI1 is 56% @ 5% user throughput.
    - Average gain of LTE-U in SI3 over Wi-Fi in SI1 is 36% @ 50% user throughput.
    - Average gain of LTE-U in SI3 over Wi-Fi in SI1 is 17% @ 95% user throughput.
- LTE-U/LTE-U scenario outperforms Wi-Fi/Wi-Fi scenario (SI4 over SI1).
    - Average gain of LTE-U in SI4 over Wi-Fi in SI1 is 115% @ 5% user throughput.
    - Average gain of LTE-U in SI4 over Wi-Fi in SI1 is 37% @ 50% user throughput.
    - Average gain of LTE-U in SI4 over Wi-Fi in SI1 is 18% @ 95% user throughput.

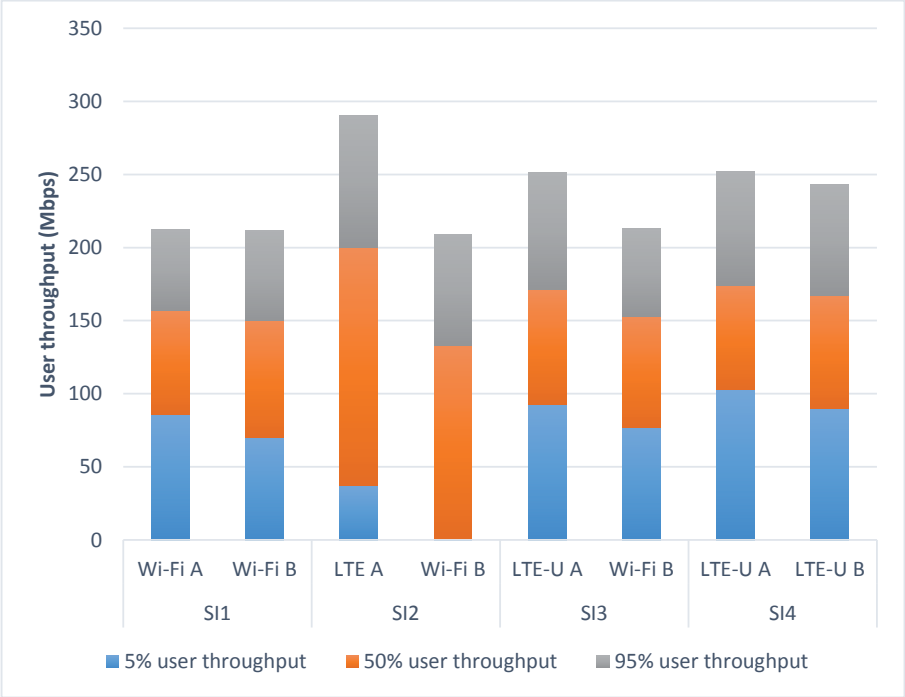


Figure 6.2.1-1: User throughput comparison (Company A)

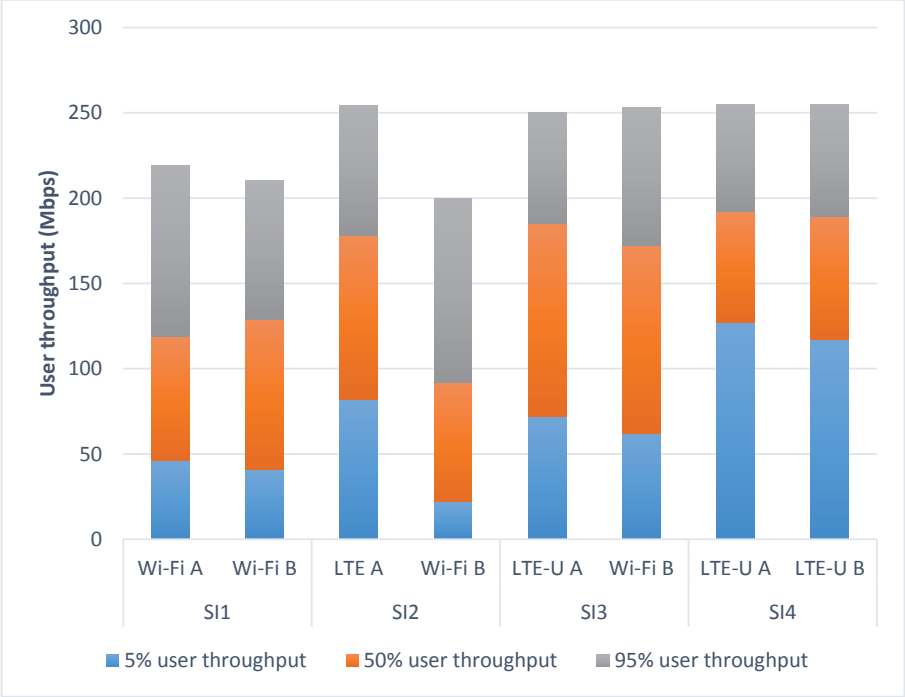


Figure 6.2.1-2: User throughput comparison (Company B)

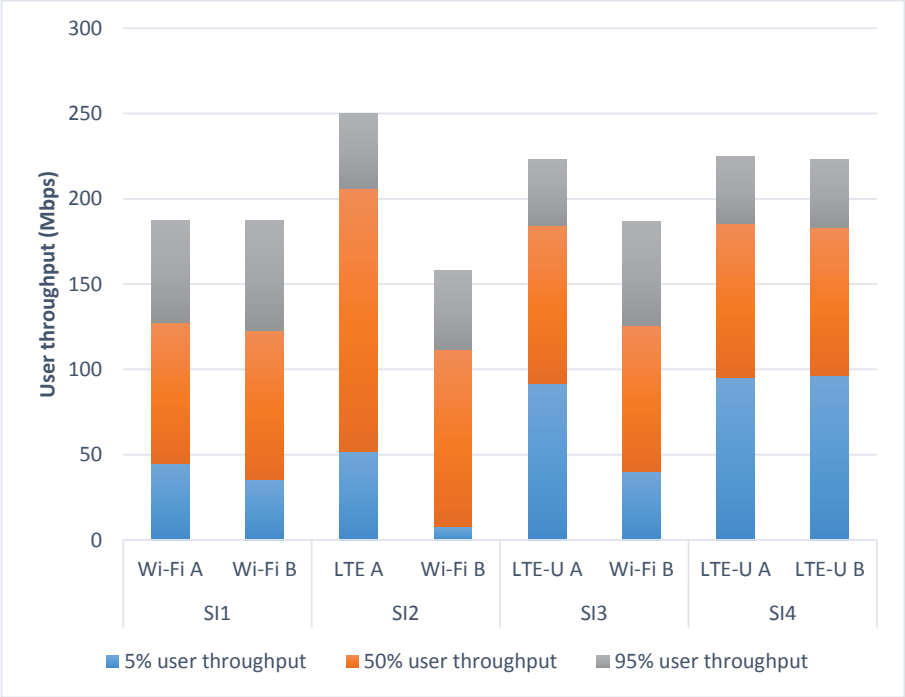


Figure 6.2.1-3: User throughput comparison (Company C)

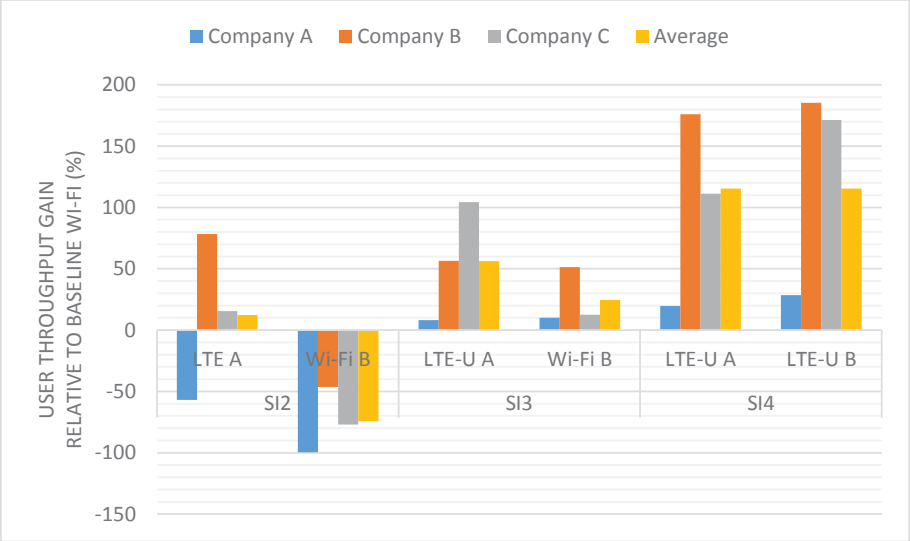


Figure 6.2.1-4: 5% user throughput gain over baseline Wi-Fi/Wi-Fi scenario (SI1)

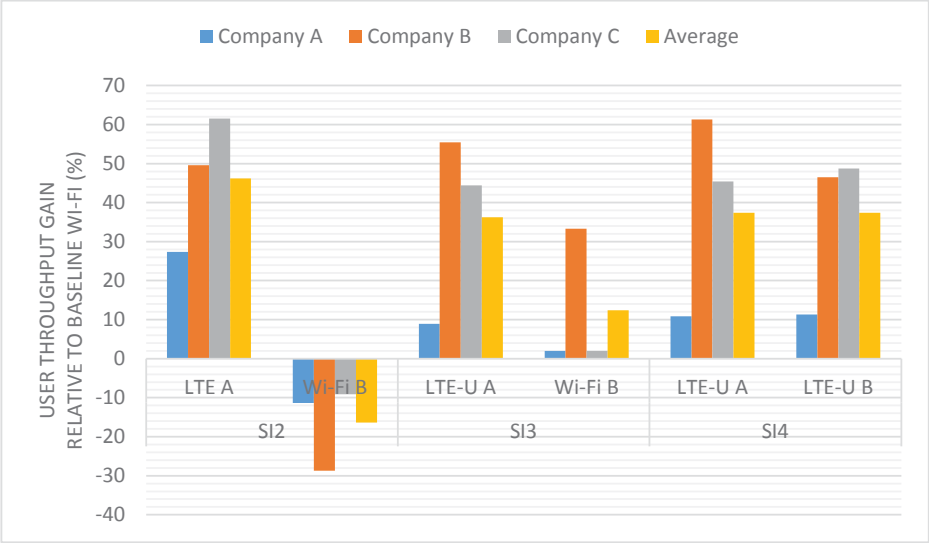


Figure 6.2.1-5: 50% user throughput gain over baseline Wi-Fi/Wi-Fi scenario (SI1)

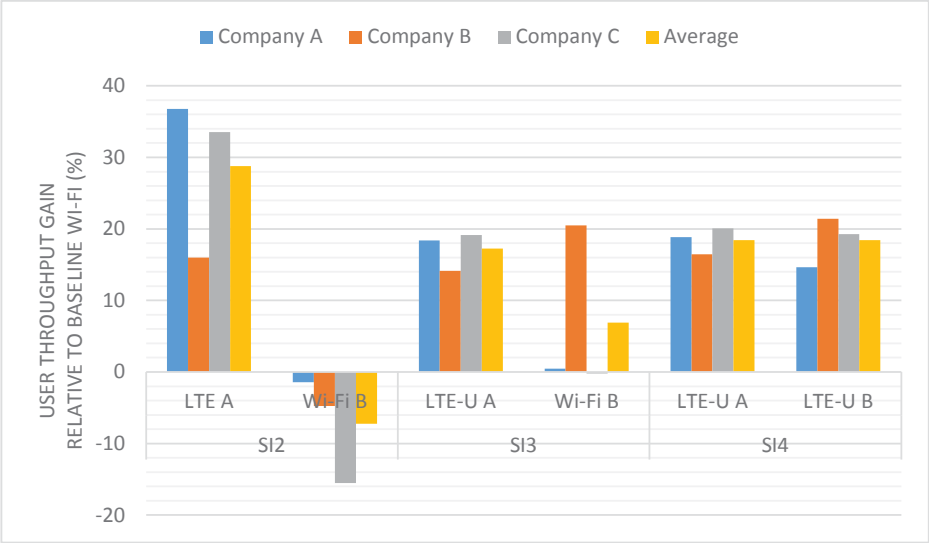


Figure 6.2.1-6: 95% user throughput gain over baseline Wi-Fi/Wi-Fi scenario (SI1)

6.2.2 High density deployment with private Wi-Fi (SI5-8)

4 nodes per operator in a cluster (building) with 16 private Wi-Fi APs and 4 FEs are assumed (2 nodes/FE excluding private Wi-Fi, 6 nodes/FE including private Wi-Fi on average).

User throughput comparison results from Company A, B, C are shown in Figure 6.2.2-1, Figure 6.2.2-2 and Figure 6.2.2-3 respectively. SI5 is the baseline Wi-Fi/Wi-Fi coexistence scenario, SI6 is the LTE CA/Wi-Fi coexistence scenario, SI7 is the LTE-U/Wi-Fi coexistence scenario, and SI8 is LTE-U/LTE-U coexistence scenario. 5%, 50% and 95% user throughput gain over the baseline Wi-Fi/Wi-Fi scenario are shown in Figure 6.2.2-4, Figure 6.2.2-5 and Figure 6.2.2-6.

<u>Observations:</u>

- When LTE is simply deployed in unlicensed spectrum without any coexistence mechanism, LTE causes significant performance degradation on coexisting Wi-Fi (SI6 over SI5).
- LTE-U behaves as a comparable or slightly better neighbour (some gain in 5% Wi-Fi user and comparable performance in 50%/95% Wi-Fi users) to Wi-Fi compared to Wi-Fi as a neighbour, while LTE-U significantly outperforms Wi-Fi. (SI7 over SI3).

- Average gain of LTE-U in SI7 over Wi-Fi in SI5 is 67% @ 5% user throughput.
- Average gain of LTE-U in SI7 over Wi-Fi in SI5 is 40% @ 50% user throughput.
- Average gain of LTE-U in SI7 over Wi-Fi in SI5 is 28% @ 95% user throughput.

- LTE-U/LTE-U scenario significantly outperforms Wi-Fi/Wi-Fi scenario (SI4 over SI1).
  - Average gain of LTE-U in SI8 over Wi-Fi in SI5 is 93% @ 5% user throughput.
  - Average gain of LTE-U in SI8 over Wi-Fi in SI5 is 53% @ 50% user throughput.
  - Average gain of LTE-U in SI8 over Wi-Fi in SI5 is 44% @ 95% user throughput.

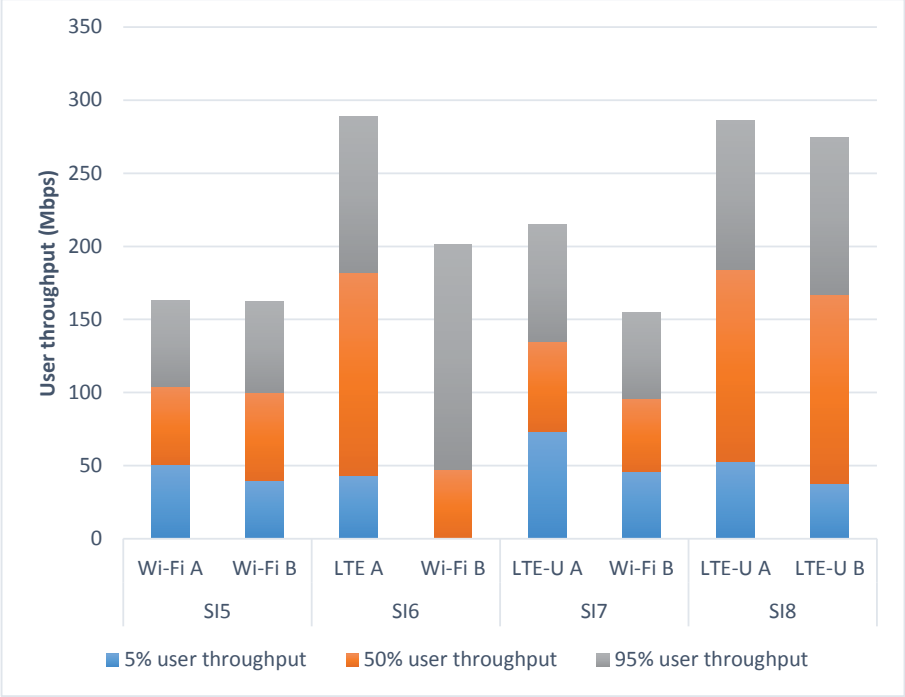


Figure 6.2.2-1: User throughput comparison (Company A)

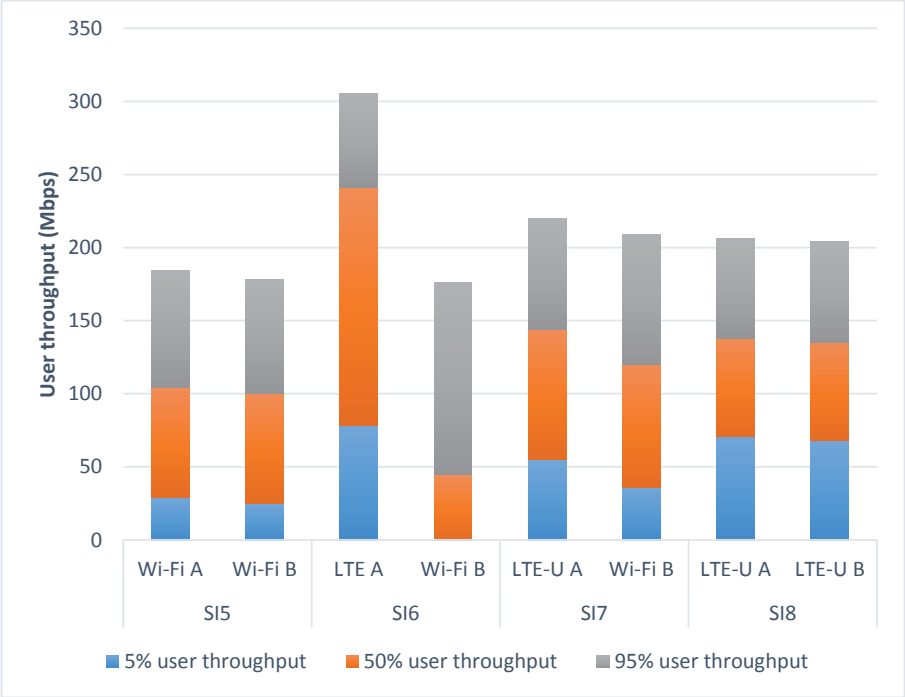


Figure 6.2.2-2: User throughput comparison (Company B)

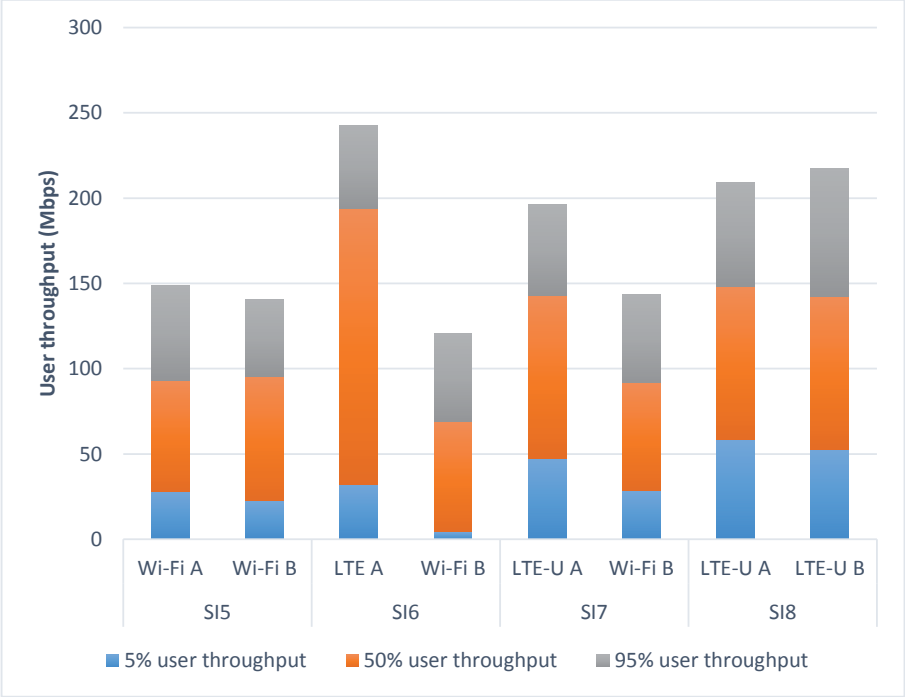


Figure 6.2.2-3: User throughput comparison (Company C)

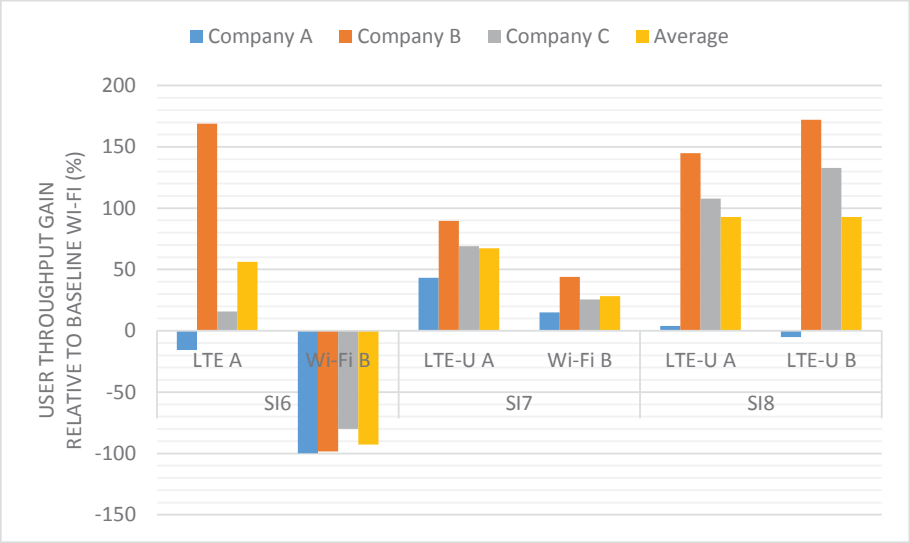


Figure 6.2.2-4: 5% user throughput gain over baseline Wi-Fi/Wi-Fi scenario (SI5)

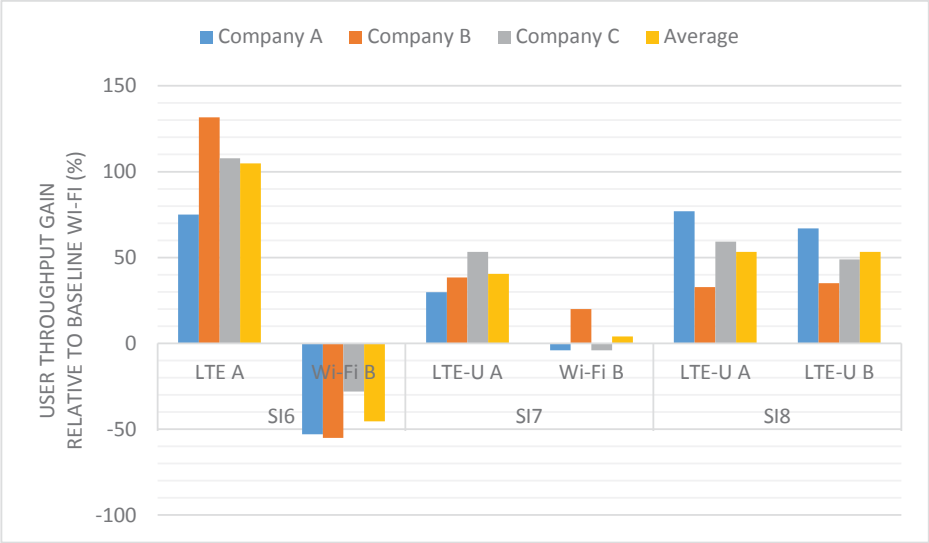


Figure 6.2.2-5: 50% user throughput gain over baseline Wi-Fi/Wi-Fi scenario (SI5)

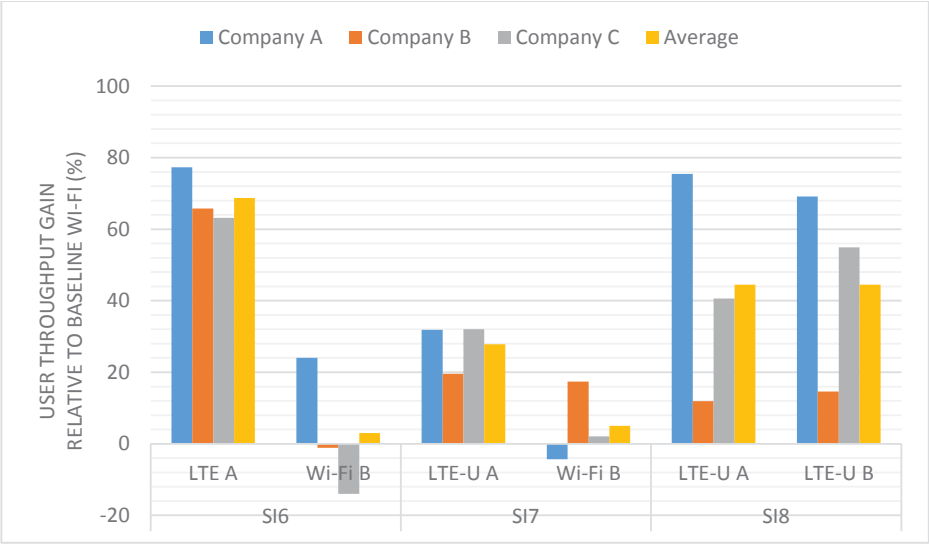


Figure 6.2.2-6: 95% user throughput gain over baseline Wi-Fi/Wi-Fi scenario (SI5)

6.2.3 High density deployment without private Wi-Fi (SI9-12)

4 nodes per operator in a cluster (building) and 4 FEs are assumed (2 nodes/FE on average).

User throughput comparison results from Company A, B, C are shown in Figure 6.2.3-1, Figure 6.2.3-2 and Figure 6.2.3-3 respectively. SI9 is the baseline Wi-Fi/Wi-Fi coexistence scenario, SI10 is the LTE CA/Wi-Fi coexistence scenario, SI11 is the LTE-U/Wi-Fi coexistence scenario, and SI12 is LTE-U/LTE-U coexistence scenario. 5%, 50% and 95% user throughput gain over the baseline Wi-Fi/Wi-Fi scenario are shown in Figure 6.2.3-4, Figure 6.2.3-5 and Figure 6.2.3-6.

<u>Observations:</u>

- When LTE is simply deployed in unlicensed spectrum without any coexistence mechanism, LTE causes significant performance degradation on coexisting Wi-Fi (SI10 over SI9).
- LTE-U behaves as a comparable or slightly better neighbour (some gain in 5% Wi-Fi user and comparable performance in 50%/95% Wi-Fi users) to Wi-Fi compared to Wi-Fi as a neighbour, while LTE-U significantly outperforms Wi-Fi (SI11 over SI9).
    - Average gain of LTE-U in SI11 over Wi-Fi in SI9 is 50% @ 5% user throughput.
    - Average gain of LTE-U in SI11 over Wi-Fi in SI9 is 31% @ 50% user throughput.
    - Average gain of LTE-U in SI11 over Wi-Fi in SI9 is 23% @ 95% user throughput.
- LTE-U/LTE-U scenario significantly outperforms Wi-Fi/Wi-Fi scenario (SI4 over SI1).
    - Average gain of LTE-U in SI12 over Wi-Fi in SI9 is 76% @ 5% user throughput.
    - Average gain of LTE-U in SI12 over Wi-Fi in SI9 is 69% @ 50% user throughput.
    - Average gain of LTE-U in SI12 over Wi-Fi in SI9 is 51% @ 95% user throughput.

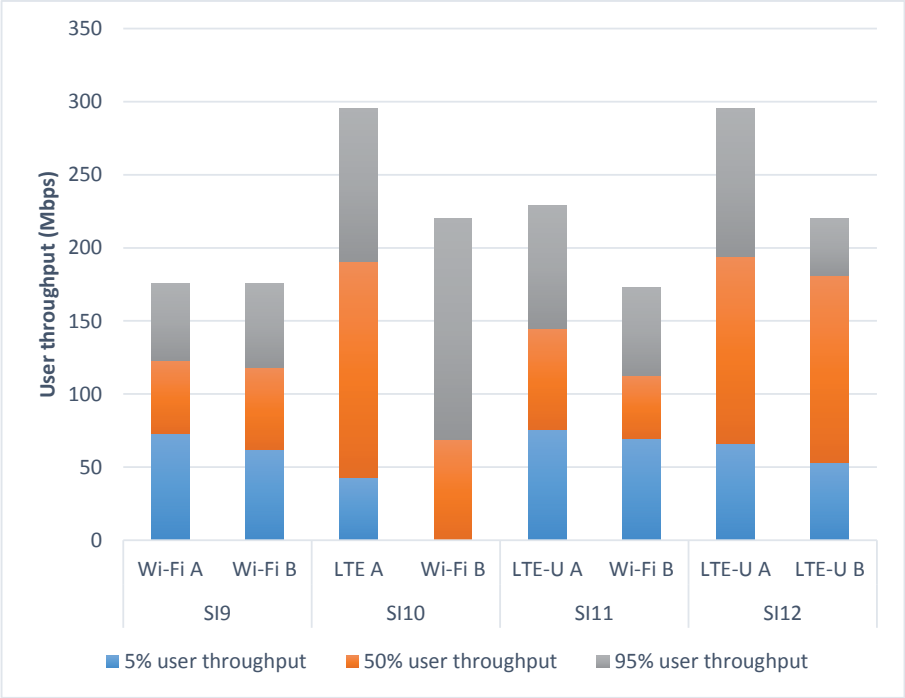


Figure 6.2.3-1: User throughput comparison (Company A)

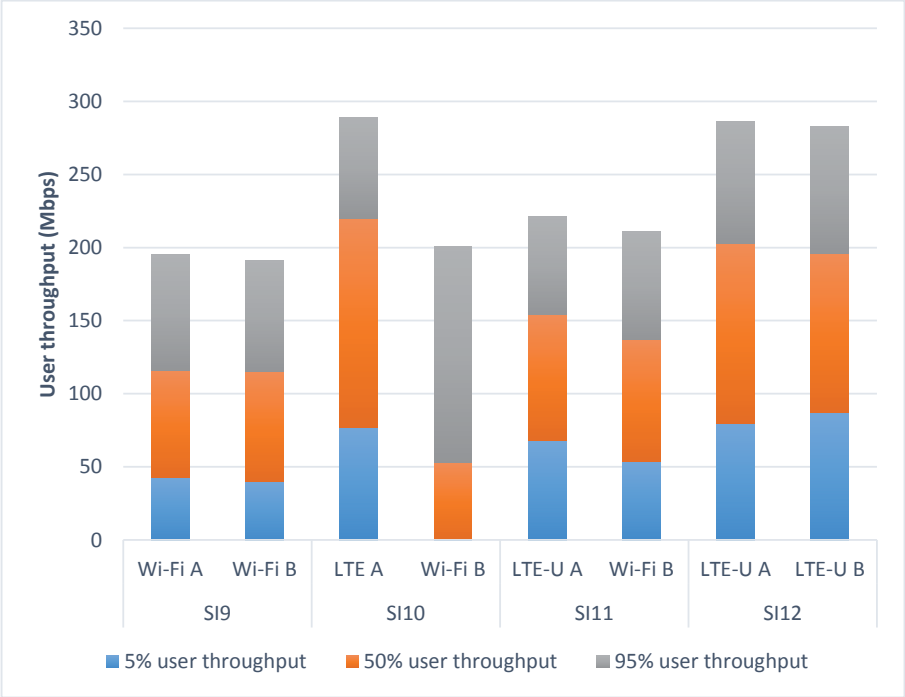


Figure 6.2.3-2: User throughput comparison (Company B)

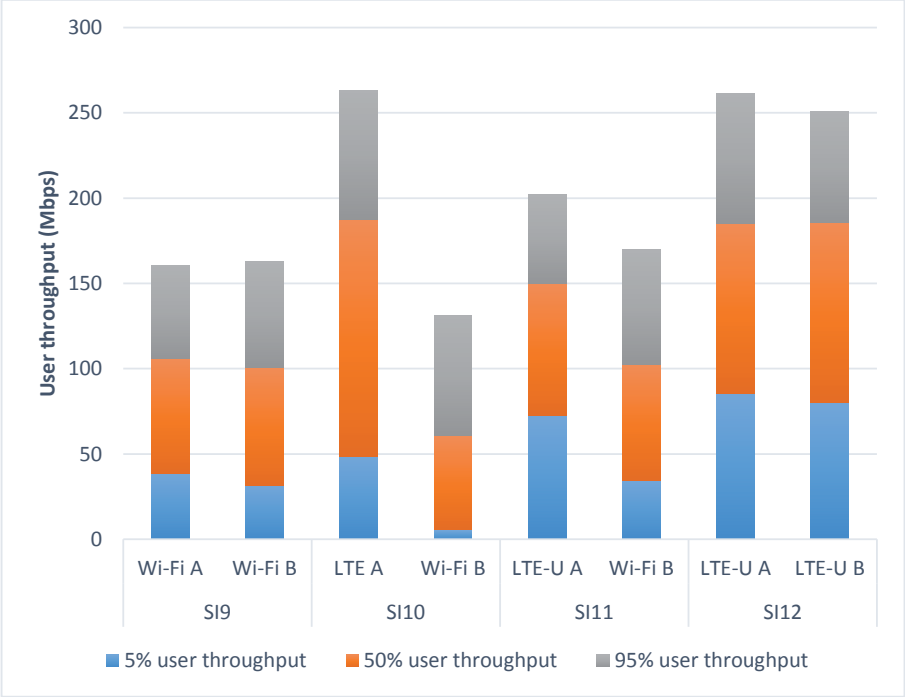


Figure 6.2.3-3: User throughput comparison (Company C)

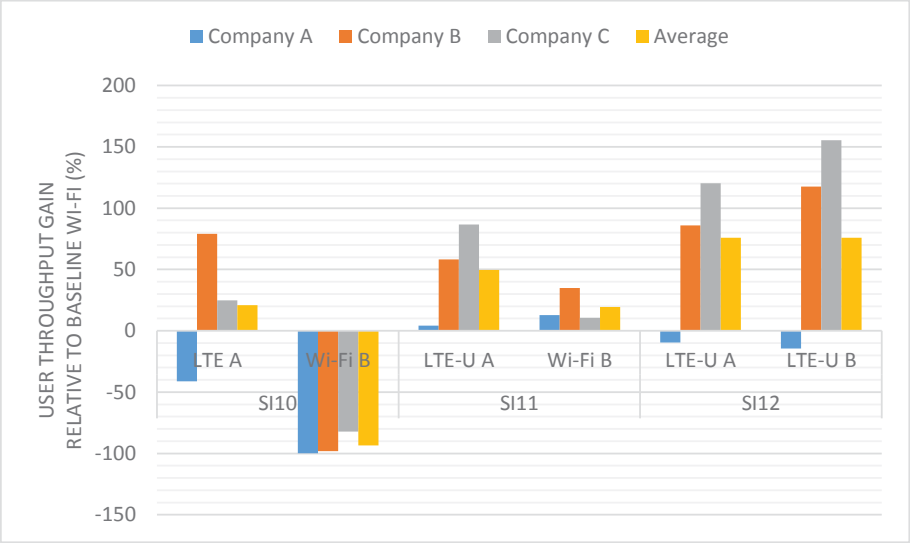


Figure 6.2.3-4: 5% user throughput gain over baseline Wi-Fi/Wi-Fi scenario (SI9)

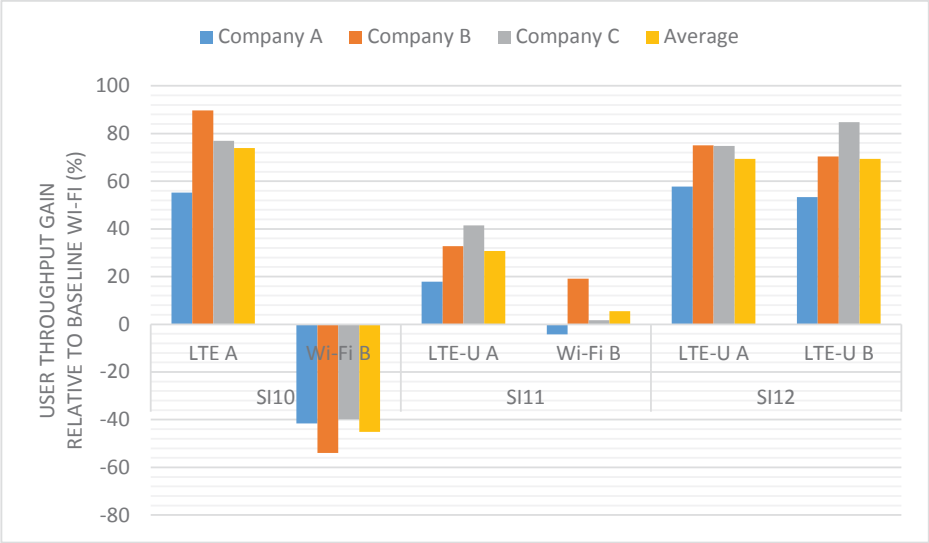


Figure 6.2.3-5: 50% user throughput gain over baseline Wi-Fi/Wi-Fi scenario (SI9)

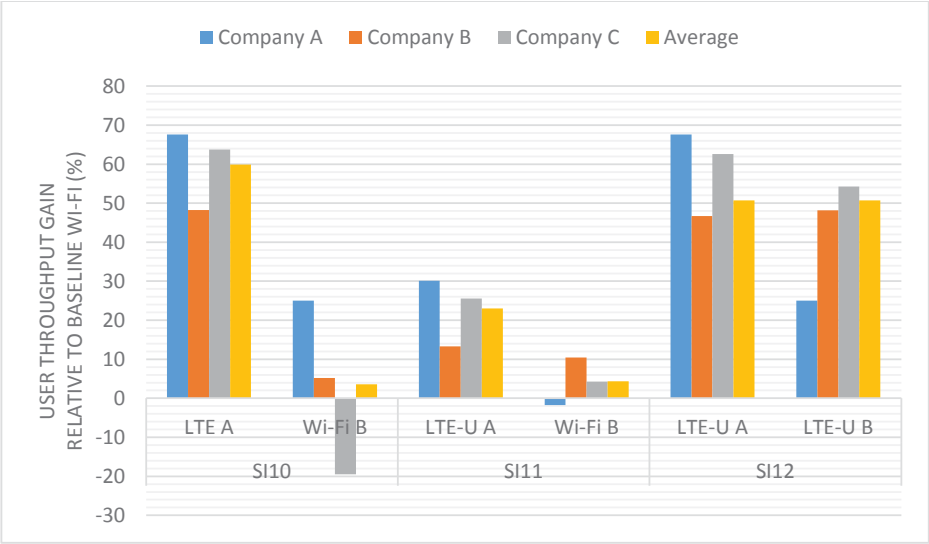


Figure 6.2.3-6: 95% user throughput gain over baseline Wi-Fi/Wi-Fi scenario (SI9)

6.2.4 Summary for indoor evaluation

Similar to outdoor evaluation, when LTE is simply deployed in unlicensed spectrum without any coexistence mechanism, it was observed that LTE can cause significant performance degradation on coexisting Wi-Fi. However, when LTE-U is deployed with reasonable coexistence mechanisms (see clause 7 for recommendations for coexistence mechanism), it was shown that LTE-U behaves as a comparable or better neighbour to Wi-Fi compared to Wi-Fi as a neighbour while LTE-U significantly outperforms the replacing Wi-Fi deployment.

In the studied 2 operator scenarios, the average gain of 31%-40% for the median user throughput was observed when one of Wi-Fi operator deployment is replaced by LTE-U. The average gain of 4%-12% for the median user throughput was also observed for the coexisting Wi-Fi. When the Wi-Fi deployment of both operators is replaced by LTE-U, LTE-U/LTE-U scenario outperforms Wi-Fi/Wi-Fi scenario. The observed average gain for the median user throughput is 37%-69%.

In general, the observed gain of LTE-U was smaller in indoor environments relative to outdoor. The main reason was due to the very high SINR condition for the Wi-Fi users in the specific environments in simulation. The gain of LTE-U could be bigger in other indoor scenarios with different composition of line-of-sight and scattered components in the radio environment as well as the size of the building and etc.

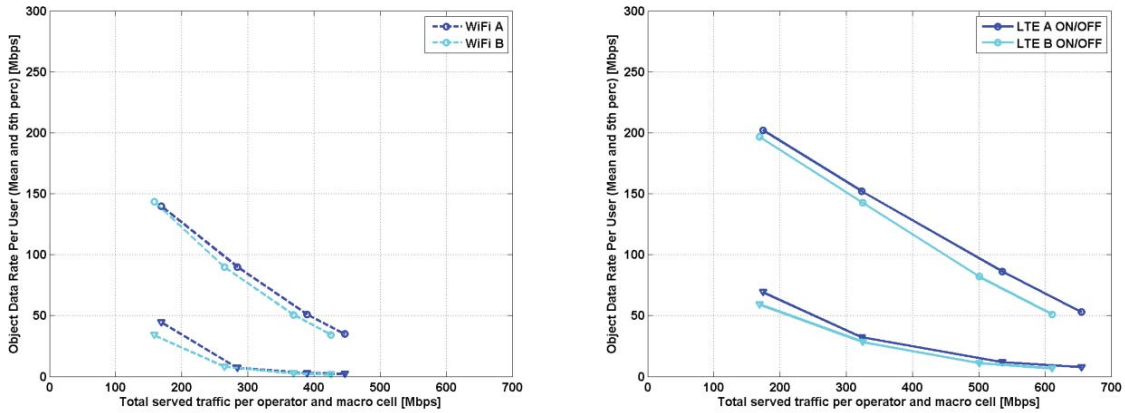
6.3 System capacity evaluation

In this section, the traffic load offered to the system is varied by adjusting the file arrival rate of the modified FTP 2 model. Collecting the user throughput statistics under different served traffic loads in the system affords an analysis on the traffic carrying capacity characteristic of different systems.

In Figure 6.3-1, we provide outdoor system capacity evaluation results for Wi-Fi and LTE-U systems assuming two operators sharing 10 frequency elements. Each operator deploys four small cells in a hot-spot cluster in each macro cell to provide offloading of traffic from the macro system with limited spectrum resources. When both operators use Wi-Fi offloading solutions, each macro cell can carry around 250Mbps of traffic if the operators target the cell-edge user MAC layer throughput of 5Mbps. When both operators adopt LTE-U as the offloading solutions, each macro cell can carry more than 500Mbps of traffic targeting the same cell-edge user throughput. In Figure 6.3-2, we further provide the system capacity evaluation result when one operator uses Wi-Fi offloading and the other uses LTE-U offloading solutions. With proper coexistence solutions, we observe that the Wi-Fi offloading network can still carry 250Mbps of traffic in each macro cell and the LTE-U offloading network can also carry more than 500Mbps of traffic targeting the same cell-edge user throughput of 5Mbps.

The capacity advantages of the LTE-U system in the outdoor deployment scenarios come from two intrinsic design features of the LTE-U system.

- First, the LTE control channels are designed for wide coverage and high reliability in interference-limited operation environment. The coverage and reliability is achieved by minimization/compression of control information bits and very lower coding rates. The amount of transmission acknowledgement bits in LTE is compressed to a small fraction of the size in Wi-Fi. The effective code rate of the LTE control channel can be lower than 1/10 while that for the Wi-Fi is fixed at 1/2. Since the LTE-U UL control channel is transmitted on the licensed band primary carrier, its coverage further benefits from lower path losses at lower carrier frequencies than the unlicensed carriers in the 5GHz bands. The reliability and wider coverage of the control channels thus enables the LTE-U system to take in more mobile users and achieves greater offloading of traffic.
- Secondly, the LTE physical data channels and protocols are designed to handle unpredictable radio environment and to recover gracefully from unexpected interference. LTE data traffic can be encoded with powerful rate 1/3 channel code while the lowest coding rate for Wi-Fi traffic is at 1/2. Furthermore, when an LTE data transmission is not decoded successfully, the received signals are buffered by the LTE UE and are combined with later retransmission(s) to enable enhanced decoding performance. This hybrid automatic retransmission request (HARQ) protocol in the LTE system improves the retransmission performance by several dB when compared to the simple automatic retransmission request (ARQ) protocol in the Wi-Fi system.



(a) System capacity evaluation for SO5 (b) System capacity evaluation for SO8

Figure 6.3-1 Wi-Fi and LTE-U outdoor system capacity evaluation results

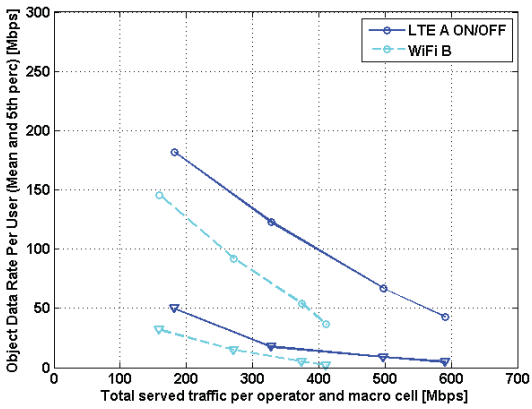


Figure 6.3-2 Outdoor system capacity evaluation result for Wi-Fi and LTE-U coexistence SO7

For the indoor scenario considered in this technical report, we observe that all users in the hot-spot building are adequately covered by the Wi-Fi APs. Potential interference from outside of the building and other cells is substantially reduced by the penetration losses through the building walls. Therefore, we observe the deployment of the LTE-U offloading solution does not substantially change the system capacity levels relative to a Wi-Fi offloading solution for the specific indoor building scenario considered in this technical report. However, the LTE-U system enables high user MAC layer throughputs relative to the Wi-Fi solution as discussed in Section 6.2. It's noted that the coverage and capacity advantages of the LTE-U solution may be observed in other indoor scenarios with different composition of line-of-sight and scattered components in the radio environment.

7 Recommendations for Coexistence Mechanism

In order to achieve good coexistence in 5 GHz unlicensed spectrum with other technologies (e.g., Wi-Fi) as well as other LTE-U deployments, it is recommended to have the following capabilities for LTE-U. It should be noted that this recommendation is targeted for LTE-U deployment in markets where LBT is not required.

- Secondary Cell in unlicensed spectrum channel selection
  - Select least interfering channel(s)
  - Monitor channel usage periodically
  - Re-select new channel(s) if necessary
  - Avoid the channel with strong LTE-U link(s) of other operator as much as possible
- Secondary Cell in unlicensed spectrum operation
  - SCell duty cycle:

        - SCell ON-state: SCell is transmitting according to 3GPP LTE Rel-10 or later releases specification
        - SCell OFF-state: SCell ceases all transmissions, including sync signal, SI signals, CRS, and etc., except 3GPP Rel-12 discovery signal when configured
        - ON/OFF cycle may range in 10s to 100s msecs
    - Adaptive SCell duty cycle (for example, based on channel usage)
    - Maximum continuous transmission time limited to protect latency sensitive transmission from other links
- Opportunistic Secondary Cell OFF in unlicensed spectrum
    - SCell in OFF-state when SCell is not needed such as no UE in SCell coverage or there is no data in buffer for users in SCell coverage

8 Conclusions

To summarize, LTE-U is designed to extend the efficiency of LTE air interface into unlicensed band to provide robust control and higher spectral efficiency, while at the same time being a good neighbour to near-by Wi-Fi deployments. With deployment setting range from typical to highly densified network of Wi-Fi and LTE nodes, the evaluation for a down-link only LTE-U system realizable completely using 3GPP Rel-10 onwards LTE CA protocol demonstrated the following trend:

1. For a given operator, replacing LTE/Wi-Fi bearer selection by LTE + LTE-U carrier aggregation leads to substantial improvement in user experiences in terms of data throughput. The performance improvement comes from a combination of higher LTE link efficiency (due to advanced techniques such as H-ARQ) and higher MAC efficiency due to universal frequency reuse of LTE.

2. For a given Wi-Fi deployment, if part of the nearby Wi-Fi nodes are replaced by LTE-U nodes, the remaining Wi-Fi nodes throughput is no worse than before, and, in many cases, improve comparing to the baseline case where all nodes are Wi-Fi.

The underlying design that allows LTE-U to achieve high spectral efficiency while being a good neighbour to Wi-Fi even in dense deployment is achieved through a set of carefully designed coexistence techniques, including channel selection, Secondary Cell duty cycle in unlicensed spectrum, and opportunistic Secondary Cell OFF in unlicensed spectrum. These coexistence techniques are practically feasible and can be commercially realized for a LTE-U eNB with carrier sensing capabilities. With a set of well-designed coexistence algorithms, the level of protection that LTE-U nodes provide to nearby Wi-Fi deployment can be better than what Wi-Fi itself provides, especially given the wide range of practical commercial Wi-Fi equipment behaviours that do not necessarily carry the full set of 802.11 spec features. Just as commercial LTE equipment, LTE-U commercial equipment are expected to go through rigorous performance and coexistence testing procedures, where the coexistence procedures would focus on LTE-U/Wi-Fi coexistence as well as LTE-U/LTE-U inter-operator coexistence.

Annex A:
Wi-Fi MAC Simulation Model

In this section essential components of Wi-Fi modeling in the systems simulator are covered. This includes the important aspects of the MAC, packet structure assumed, and channel BW.

A.1 Distributed Coordination Function (DCF)

The basic 802.11 multiple access control (MAC) layer uses the distributed coordination function (DCF) to share the medium between multiple stations. DCF relies on carrier sense multiple access/collision avoidance (CSMA/CA) to share the medium between stations (see [6]). The basic DCF channel access is shown in Figure A.1-1. Before accessing the medium to transmit a data frame, every Wi-Fi node (AP/STA) waits for distributed inter-frame spacing time (DIFS). After DIFS duration, if the medium is available the node picks a uniform random back-off counter from [0,CW] and decrements it for every idle slot. When the counter reaches zero, the node transmits the frame immediately. However, if the medium is sensed to be busy while counting down, the back-off counter value is frozen until the medium goes free for at least DIFS duration after which the counter is decremented from its previous state.

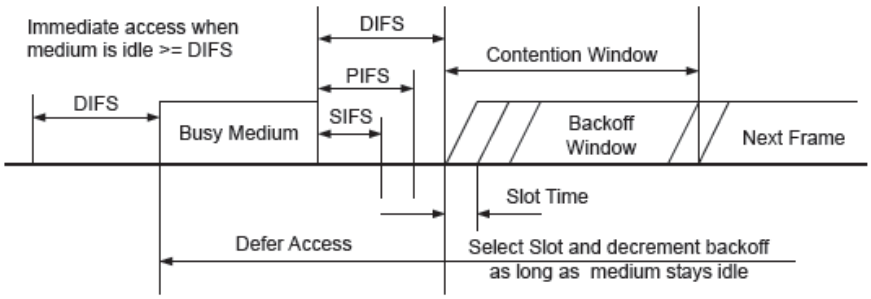


Figure A.1-1: IEEE 802.11 DCF channel access (after [7])

A slot in Wi-Fi is the smallest quantized unit of time and is set to 9us in the simulation. A slot is determined to be busy/free (for back-off purposes) at the physical layer based on a clean channel assessment (CCA) procedure. There are two types of CCA that is possible:

1. CCA-Energy Detect (CCA-ED)
   - Energy detection based deferral for Wi-Fi and non-Wi-Fi interference
   - The threshold for CCA-ED is -62 dBm over 20 MHz i.e., nodes will defer access to the medium if the RSSI > -62 dBm over the primary 20MHz.
2. CCA-Preamble Detect (CCA-PD)
   - Wi-Fi preamble based deferral for Wi-Fi interference
   - If the preamble can be decoded successfully and the packet is not destined to a receiver, defer the medium for a duration equal to TxTime+SIFS+ACK
   - CCA-PD threshold to decode the PLCP SIG header is based on the minimum SINR requirement (for 1% PER) for MCS0 (6Mbps, 20MHz, 1SS).

The back-off procedure in DCF is often referred to as binary exponential back-off. The contention window (CW) size is initially assigned CW_{min} and increases when a transmission fails (i.e., the transmitted data frame has not been acknowledged). After any unsuccessful transmission attempt, another back-off is performed using a new CW value updated by $CW := 2 \times (CW + 1) - 1$, with the upper bound of CW_{max}. After each successful transmission, the CW value is reset to CW_{min}. The actual values of CW_{min} and CW_{max} used in the simulations are 15 and 1023 respectively. The simple state machine in Figure A.1-2 describes the CSMA/CA protocol.

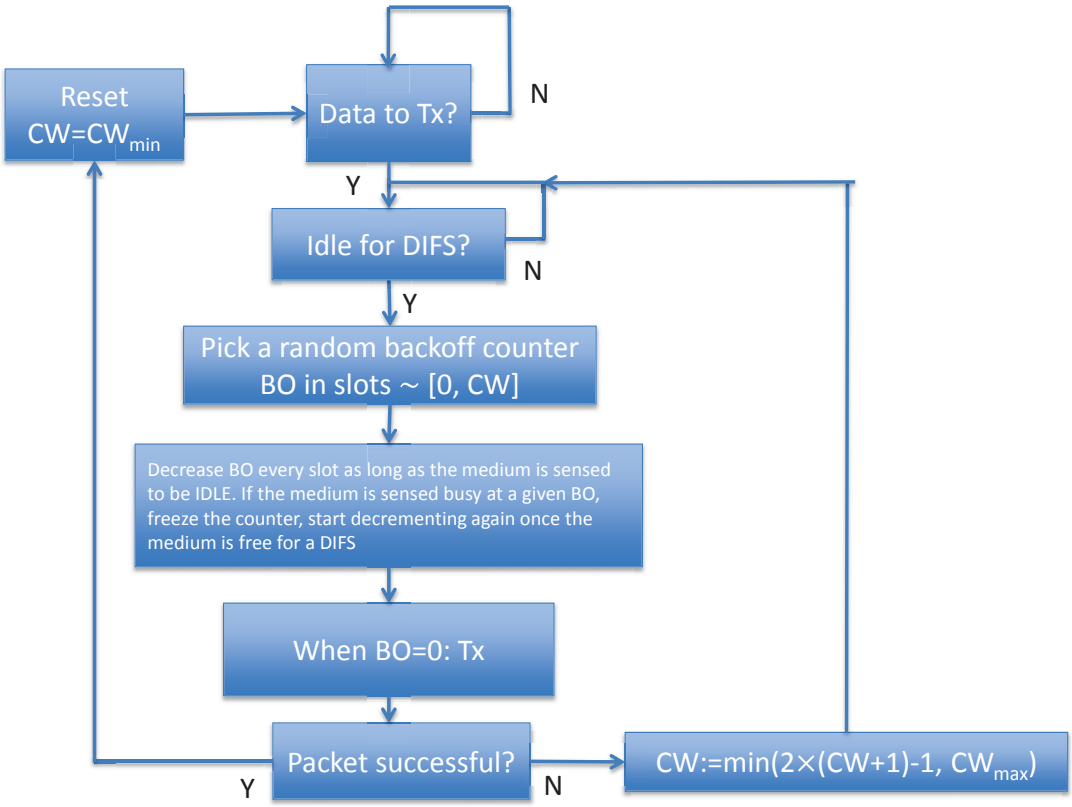


Figure A.1-2: Flowchart Describing the CSMA/CA Protocol

Figure A.1-3 shows an example of a successful directed frame exchange.

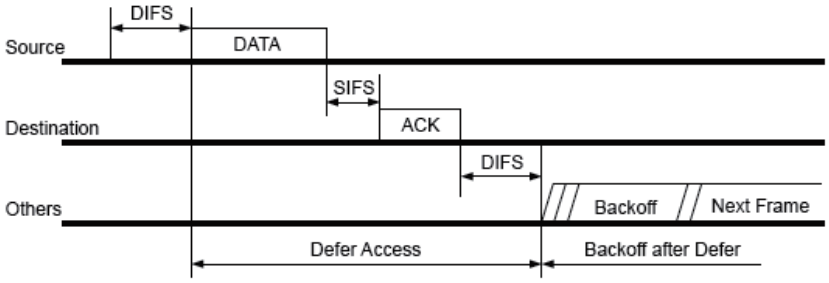


Figure A.1-3: ACK transmission after a successful directed frame reception (after [7])

A.2 Wi-Fi packet model

The IEEE 802.11 Wi-Fi protocol is asynchronous by nature and this need to be captured by the simulation modeling i.e., a Wi-Fi packet transmission can start at any time slot during the simulation. Every packet begins with a physical layer convergence protocol (PLCP) preamble and PHY header which is 20us in length. The duration of the data transmission following the preamble/header is fixed to 3ms i.e., once an AP grabs the medium it can transmit data for 3ms. In every transmission opportunity (TxOP), an 802.11n aggregated Wi-Fi packet is transmitted. An aggregated Wi-Fi packet is composed of three MAC Protocol Data Units (MPDUs) with duration is fixed to 1ms. The size the MPDU itself is variable and is determined from the MPDU duration and the MCS used for transmitting this aggregated-MPDU (A-MPDU). Since the three MPDUs are transmitted at the PHY as one A-MPDU transmission, the MCS of all MPDUs in the TxOP are identical. Although the physical layer coding is common for the three MPDUs, it is worth noting that each MPDU has its own cyclic redundancy check (CRC). Following the 3ms A-MPDU transmission, if the burst was decoded successfully, there is a Block Acknowledgement (ACK) transmitted.

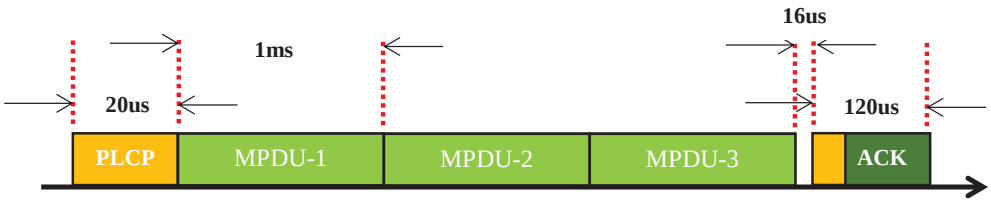


Figure A.2-1: A-MPDU & Block ACK Modelling for Wi-Fi (not to scale)

A.3 Wi-Fi 5GHz channelization & BW

Figure A.3-1 illustrates the channelization used by Wi-Fi in the 5GHz unlicensed band for the US regulatory domain. The minimum channel bandwidth for Wi-Fi in this band is 20MHz and the channels are all non-overlapping with one another. The figure also indicates the specific channels that require Dynamic Frequency Selection (DFS) – a mechanism to enforce radar avoidance in the 5GHz band.

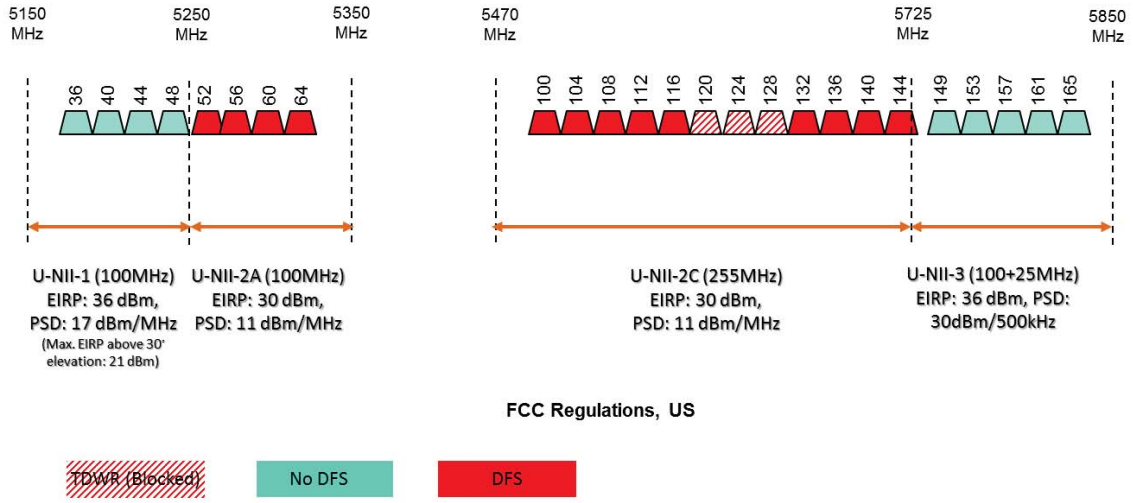


Figure A.3-1: IEEE 802.11 channelization in the 5GHz unlicensed band (as of April 2014)

As illustrated in Figure A.3-1, there are a total of 24 20MHz channels available to Wi-Fi. Of those, 9 channels do not require DFS while the remaining 13 channels require support for DFS. For the Wi-Fi evaluation methodology, all Wi-Fi nodes are assumed to use a (contiguous) 40MHz bonded channel. Further, because of the contiguous channel bonding constraint, each node can choose from at most 5 40MHz channels if we do not require DFS or 10 40MHz channels including DFS channels.

Since DFS requirements are common between Wi-Fi and LTE-U and nothing to suggest any limitations on the latter to meet compared to the former, this aspect does not need to be taken care of in simulations. That is, for network simulations simplicity, there is no distinction between DFS and non DFS channels and the presence of a set of 10 homogenous channels with 40MHz BW each is considered.

Annex B: Channel Selection

LTE-U channel selection is considered to be a proprietary implementation. On the other hand, for Wi-Fi, a common channel selections scheme is important to ensure different results from different companies are comparable. For instance, a scheme used by one company tends to cluster Wi-Fi nodes on few channels versus another scheme which tends to spread them apart, can result in different coexistence performance with LTE-U. In addition, the adopted channel selection should reflect practical implementation in the field.

B.1 Wi-Fi channel selection

There are several channels in the 5GHz U-NII bands and each Wi-Fi AP needs to select one channel for operation in an autonomous manner. The channel assignment across APs happens in the beginning of the simulation after the network topology is created i.e., right after APs and users are dropped in the cell area. Once an AP selects a channel, the assignment does not change until the end of the simulation. Moreover, all Wi-Fi APs in the network are assumed to use the same bandwidth configuration and have the same set of channels to choose from.

It is recommended to use a channel selection scheme that minimizes the number of neighbors from other Wi-Fi. Details are as follows.

AP-based Sequential Channel Selection

This is the enhanced channel selection mode for Wi-Fi where each AP in the network, in an iterative fashion, listens to the beacons of neighboring APs and picks the channel that has the least number of co-channel neighbors (within a deferral range). This channel selection mode is a greedy algorithm and can be shown to converge (in terms of the overall network utility) in a finite number of steps. The following pseudo code explains the sequential channel selection algorithm and the utility metric that each AP optimizes across iterations.

Result: Channel Allocation Vector Across *N* APs After *M* Rounds: $\boldsymbol{f}^M = [f_1^M, f_2^M, \ldots, f_N^M]$
Initialize $\boldsymbol{f}^0 = [f_1^0, f_2^0, \ldots, f_N^0]$ where $f_i^0 \sim$ Uniform(1, 2, . . . ,K);
while *round: m ≤ M* **do**
    Randomly permute the N APs: *shuffle*($AP_1, AP_2, \ldots, AP_N$);
  while *index: n ≤ N* **do**
    $f_n^m = argmin_{k \in \{1,2,\ldots,K\}} U_n(k; \boldsymbol{f}^m)$
    where $U_n(k; \boldsymbol{f}^m)$ is the # of neighbors within deferral range of AP_n in channel *k*.
    n = n + 1;
  end
  m = m + 1;
end

To initialize the algorithm, each AP is assumed to choose a random channel among the set of available channels. Then in each round, the ordering of APs for channel selection is randomized by shuffling the list (this ensures that a particular AP does not have an unfair advantage by making the decision after the rest have chosen a channel). The APs then choose the best channel sequentially in the order present in the randomly permuted list for this round. To determine the best channel, the AP first collects the count of APs it can detect in each channel within a threshold power level specified by the parameter BeaconDetectionRSSI (-84dBm, for example). Then it picks the channel with the least number of neighbors satisfying the above criterion. In the event that there is a subset of candidate channels with the same minimum count of neighbors, one channel is chosen from this subset at random. The same steps above are repeated for multiple rounds until the overall network utility, which is the sum of the utility across APs in a round, converges.

Annex C:
Detailed Simulation Statistics

This clause provides additional analysis for Wi-Fi and LTE-U coexistence based on detailed statistics.

The results for 8 nodes per operator in a cluster with 4 FEs in outdoor scenario (SO9-SO12) are shown as an example to provide insight for LTE-U coexistence mechanism behavior relative to baseline Wi-Fi deployment scenario. LTE-U without coexistence mechanism (SO10) is not included in this comparison since it was clearly shown in clause 6 that certain coexistence mechanism is beneficial for coexistence with Wi-Fi and other LTE-U deployments. The behavior in other scenario is slightly different from scenario to scenario but the trends are in general similar.

The CDFs of user throughput, SINR, resource utilization, congestion metric and loading are presented from Figure C-1 to Figure C-5 respectively. Compared to the baseline Wi-Fi/Wi-Fi scenario, when one Wi-Fi operator is replaced with LTE-U deployment, it is shown in Figure C-1 that the performance of the other Wi-Fi operator can be comparably maintained across the entire population of the users while the operator switching to LTE-U achieves significant gain in terms of user throughput distribution. When both operators are switched to LTE-U, it is shown that both operators significantly outperform baseline Wi-Fi/Wi-Fi scenario for the entire population of users.

In terms of SINR distribution in Figure C-2, the Wi-Fi has higher SINR than LTE-U due to the built-in CSMA operation in Wi-Fi. This results in lower spatial reuse causing lower system capacity; therefore, higher SINR was not translated into higher user throughput. There is small degradation in average user SINR distribution for Wi-Fi with LTE-U neighbors compared to Wi-Fi neighbors because of less back-off in Wi-Fi, given that Wi-Fi does not back off to LTE-U below -62 dBm. Due to LTE-U SCell duty cycle operation, per user SINR distribution of Wi-Fi gets also wider with LTE-U neighbors. This results in inefficiency in Wi-Fi transmission with Wi-Fi Minstrel rate control. Because of this inefficiency, Wi-Fi performance was not improved with LTE-U neighbors (it gets only comparable) even with higher resource utilization as shown in Figure C-3. If Wi-Fi has a rate control based on instantaneous channel quality, Wi-Fi performance could be improved with LTE-U neighbors. In Figure C-3, it is also shown that LTE-U users less over the air transmission (lower resource utilization) while delivering higher user throughput as shown in Figure C-1 (i.e., better efficiency).

In Figure C-4, it is observed that LTE-U also improves the Wi-Fi congestion metric, because Wi-Fi only backs off to LTE-U at -62dBm and above (20dB higher than threshold to back off to other Wi-Fi). When Wi-Fi backs off to a -62 dBm and above LTE-U neighbour, it has more chances to access the medium because a LTE-U neighbour finishes faster with smaller resource utilization than a Wi-Fi neighbour.

In Figure C-5, it is also observed that LTE-U neighbours maintain the Wi-Fi loading comparably to Wi-Fi neighbours. LTE-U has much less loading due to higher efficiency compared to Wi-Fi.

In summary, LTE-U neighbours slightly degrade the coexisting Wi-Fi SINR but improves the congestion metric, resulting in comparable user throughput/loading for the coexisting Wi-Fi while LTE-U itself achieves significant gain in user throughput. LTE-U in general has lower SINR than Wi-Fi but provides much less congestion metric/resource utilization/loading, resulting in higher efficiency and user throughput.

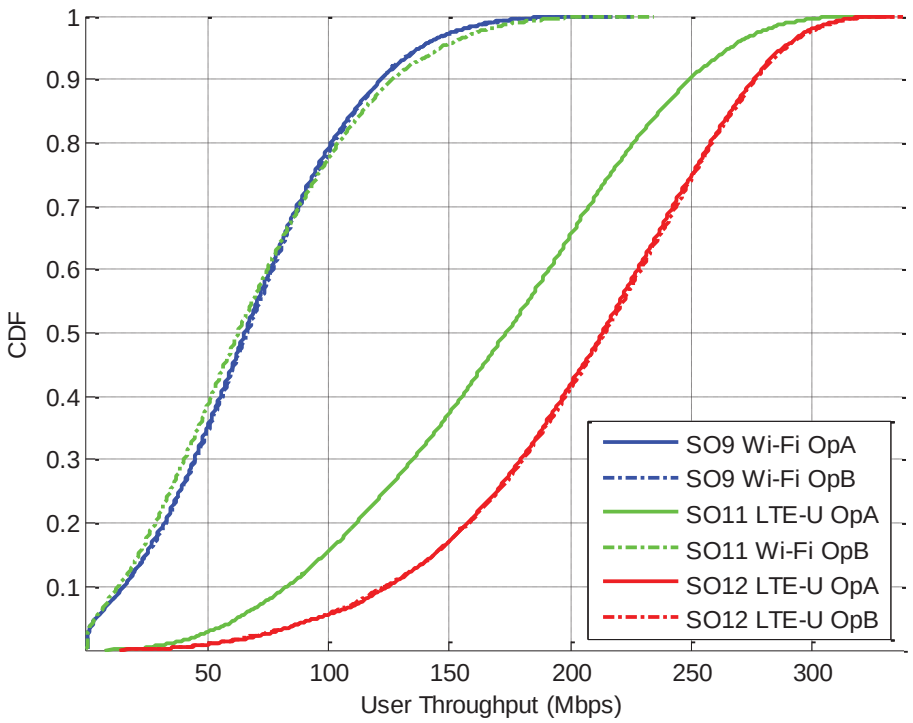


Figure C-1: User throughput CDF comparison for SO9, SO11 and SO12 (Company A)

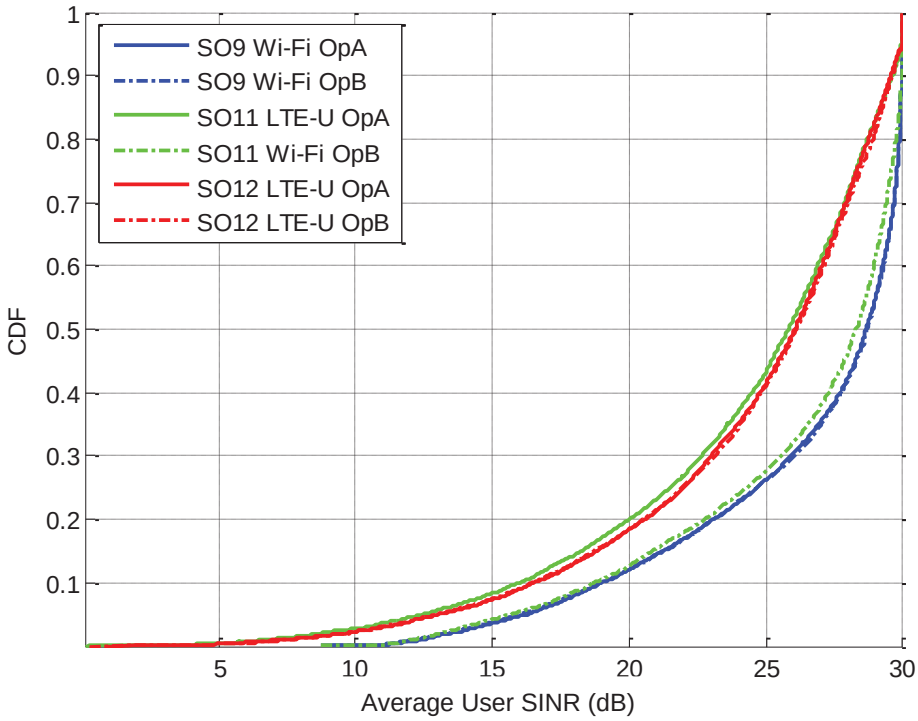


Figure C-2: Average user SINR CDF comparison for SO9, SO11 and SO12 (Company A)

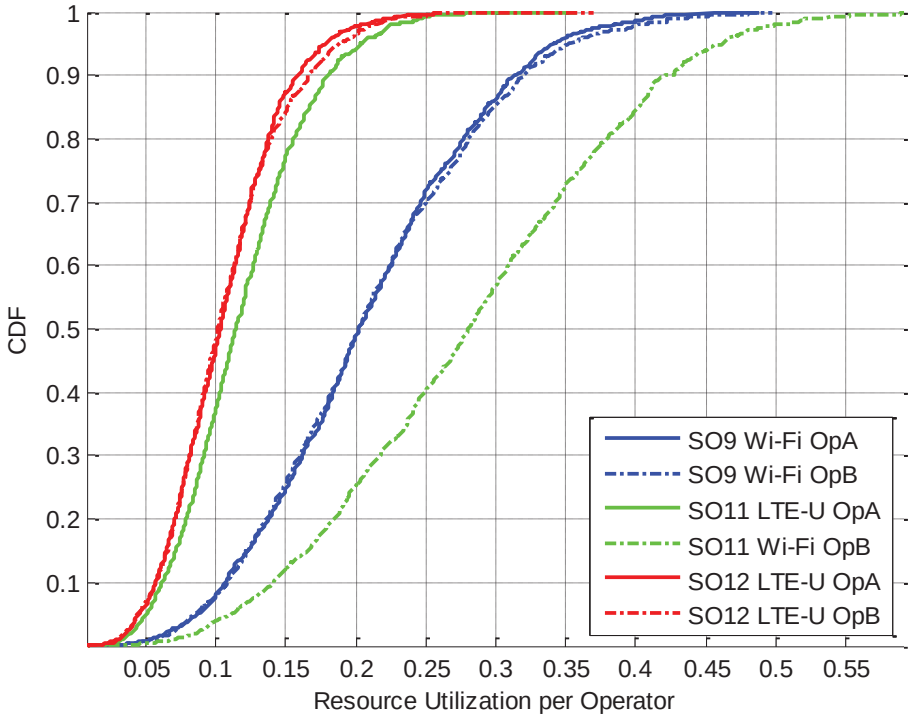


Figure C-3: Resource utilization CDF comparison for SO9, SO11 and SO12 (Company A)

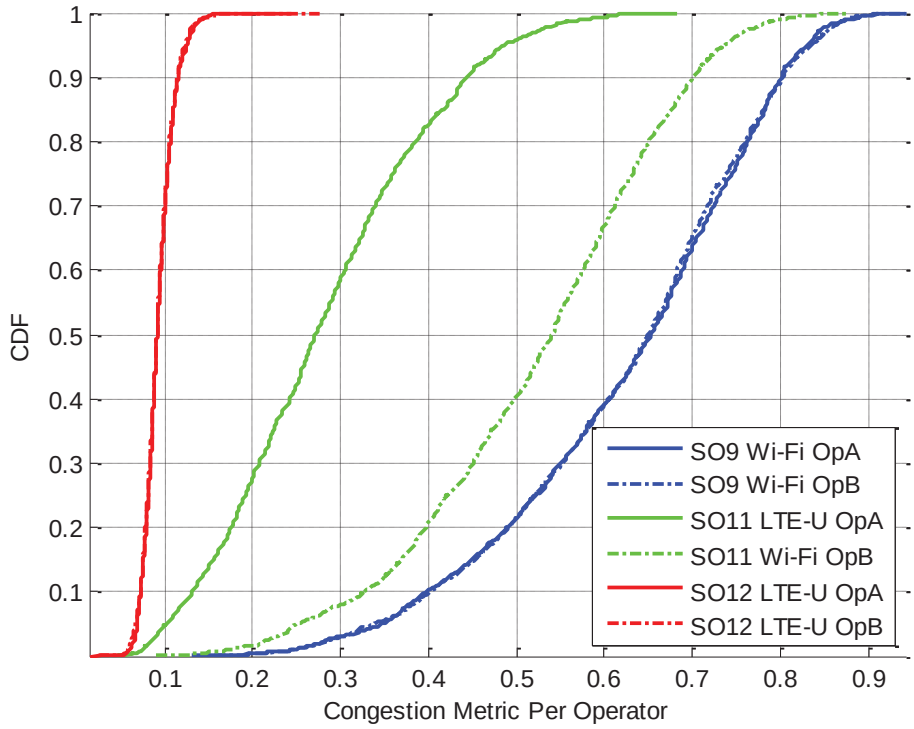


Figure C-4: Congestion metric CDF comparison for SO9, SO11 and SO12 (Company A)

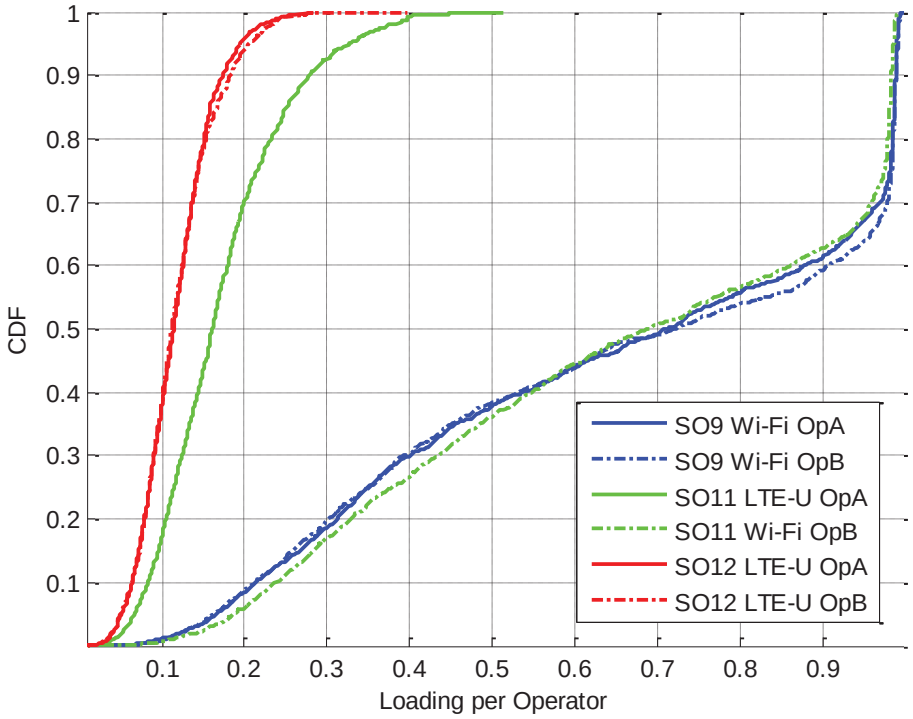


Figure C-5: Loading CDF comparison for SO9, SO11 and SO12 (Company A)

Annex D:
Examples of Further Coexistence Enhancements for Latency Sensitive Applications

As captured in clause 7, it is recommended to limit the LTE-U maximum continuous transmission time to protect delay sensitive applications on other co-channel links. The existing SCell activation and deactivation procedure imposes significant overhead if frequent activation and deactivation is adopted for coexistence in unlicensed spectrum. In order to maximize the useful time of the SCell and reduce the latency for Wi-Fi services such as TCP or Wi-Fi VoIP, two potential approaches (possibly even beyond current specifications) are described below:

1. Increase the duration during which the SCell is transmitting while the LTE-U SCell implements almost blank subframe, i.e., some physical channels of the SCell has zero transmit power in order to allow other services access the channel.

2. Reduce the SCell transmission duration. This approach requires that the activation procedure minimizes the delay in sending the first DL data assignment to the UE after sending MAC activation CE.

   The eNB can send MAC activation CE before turning SCell RF ON. The UE must be ready to receive DL assignments from eNB a few subframes after activation and SCell RF ON.