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10th August, 2016

Shri RS Sharma,
Chairman, Telecom Regulatory Authority of India
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Jawaharlal Nehru Marg
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Sub: Response on TRAI's Consultation Paper on "Consultation Paper on Proliferation of Broadband through Public Wi-Fi Networks"

Dear Sir,

Qualcomm appreciates the opportunity to comment on the Telecommunications Regulatory Authority of India (TRAI) Consultation Paper on "*Consultation Paper on Proliferation of Broadband through Public Wi-Fi Networks*" dated 13th July 2016.

Qualcomm endorses TRAI's priority to speedy rollout of broadband in India. It especially recognizes the focus on regulatory measures to facilitate access to broadband networks and expanding data usage. The TRAI document also rightly reflects the importance of wireless technologies for penetration of broadband in India since extending India's sparse fixed line connectivity will require much more time and funds. Access to the radio frequency spectrum is therefore central to India's broadband aspirations. A conducive environment for growth of wireless networks holds the key to developing data markets in India.

Mobile broadband can be deployed by using either licensed or unlicensed spectrum. It may be noted that deployments using unlicensed spectrum can only be a subsidiary network used for offloading by TSPs using licensed spectrum. Globally also, nowhere any largescale deployment of a standalone broadband network using only unlicensed spectrum has been successful. Such deployments will also require extensive backhaul rollout connecting each hotspot with the core network. In Qualcomm's view best use case for unlicensed spectrum for broadband is deploying micro/small networks (LTE-Wi-Fi, LTE-U / LAA, MulteFire, etc.)/for offloading by TSPs.

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Typically unlicensed spectrum used for broadband is above 1 GHz. We have 2.4 GHz, 5 GHz and 60 GHz as globally harmonized unlicensed bands for broadband. Unlicensed sub 1 GHz spectrum is not ideal for wireless broadband because interferences between networks make operations impossible. Other techniques like database also do not help as it will need "exclusion zones" (which have to be kept vacant) and these are very large (100s of km) in the case of lower frequency bands (as these travel far compared to higher frequencies).

Unlicensed spectrum is not exclusively owned, so there is no central entity managing the effective use of this spectrum. This results in potentially unpredictable performance and the QoS cannot be guaranteed. **There will be a need to manage Interference (to support unlicensed mode) which undermines the advantages of the low-frequency spectrum.** Firstly, transmission power needs to be lowered significantly (than convention wireless) and therefore, signals cannot travel far compared to if used in a licensed manner - which can transmit at normal power (defeating the whole purpose). Secondly, only a fraction of the total spectrum can be used for supporting traffic at a time, as most will end up being consumed as a backup resource to support "frequency hopping" as we do in case of conventional WiFi (In 2.4 GHz band which is used by conventional WiFi, 1/10th of the spectrum is used as any time to total available and assigned).

Lower frequencies are bad for TDD (Time division duplex) mode of transmission which is typically used in unlicensed technologies like WiFi. The reason is that the receivers and transmitters of towers share the same blocks of spectrum and therefore need to offset themselves in time to block transmissions from nearby towers arriving at a delay due to a larger time taken (though is fractions of seconds) by the signals to travel to nearby towers which are spaced apart by larger distance compared to those at higher frequencies (where the towers are packed close to each other, and hence travel time is less). This ends up wasting a lot of spectrum resources (reducing spectral efficiency). Hence, the lower frequency spectrum is best used in an FDD manner where transmitters and receivers use different blocks of exclusive spectrum. A paper on issues involved with unlicensed usage of Sub GHz spectrum is enclosed as Annexure (**Annexure I**) to this response.

Selection of right frequency bands is essential to achieve the targeted broadband data rates. This implies that for meeting a certain minimum data rate on unlicensed frequency bands there will be a necessity of having a certain minimum spectrum. 60 GHz is an ideal capacity band for unlicensed indoor/outdoor usage. A paper on identification of 60 GHz band for license-exempt usage is enclosed as **Annexure II.** Qualcomm estimates that at least 1280 MHz of spectrum is needed to offer 1 Gbps throughput in specific residential and enterprise scenarios (**Annexure III**). Therefore in Qualcomm's view, unlicensed operation should be encouraged only in higher frequency bands (2.4 GHz and above). In higher frequency bands (5 GHz, 60 GHz) we can find a lot of spectrum for supporting frequency hopping and the interference gets naturally managed as the signals at these frequencies do not travel far. A paper on making best use of unlicensed spectrum for broadband growth is enclosed as Annexure **(Annexure IV)**.

We will be delighted to provide additional inputs to this task of manifest national importance.

Sincerely,

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Annexure I

Unlicensed Usage of Sub GHz Spectrum : Issues Involved

Introduction

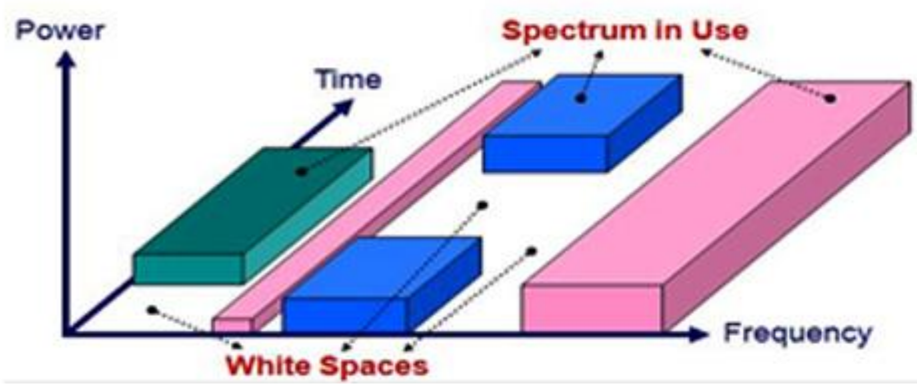
There has been a discussion about TV White Spaces in 470-698 MHz band in India. Naturally so, as the targeted TV UHF Band IV spectrum (470 - 585 MHz) is at a much lower frequency - enabling the radio signals to travel much further. Whereas the mobile telephony spectrum bands operate at a higher frequency, the lowest among them is the 800 MHz CDMA band (824-844/869-889 MHz). Hence, if we operate cellular technologies in the TV UHF Band IV spectrum, then the coverage will be much better compared to all other cellular bands currently in use.

The lower frequencies (i.e. sub GHz frequencies) have very good propagation characteristics and can therefore travel larger distances, with a better penetration irrespective of technology deployed. If not managed properly, these low frequencies will cause harmful interference to other legitimate users. Therefore, Governments all over the world control and regulate the use of these lower frequency transmission by licensing spectrum in these bands. Cellular technologies (e.g: LTE) are designed to provide mobile broadband over large distances and are ideally suited for deployment in the sub GHz frequencies. Thus, the sub GHz frequencies in licensed mode become ideal choice for providing pan-India coverage (including rural / suburban deployment).

Unlicensed spectrum is not exclusively owned, so there is no central entity managing the effective use of this spectrum. This results in potentially unpredictable performance when more than one system competes for the same 'free' resource. This problem is severe at sub GHz levels, due to signals from a relatively larger distance interfering with each other.

What is the definition of TV White Spaces

As per definition, TV whitespace are the unused vacant slots available between analog broadcasting channels. TV White Spaces refer to the unused TV channels between the active ones in the broadcasting spectrum, typically referred to as the "buffer" channels. In the past, these buffers were placed between active TV channels to protect broadcasting interference. These can also be due to channels becoming available while converting analog broadcasting to digital. Typically white spaces, or "TV white spaces," consist of unused spectrum in the television broadcasting bands (470-790 MHz in Europe and 470-698 MHz in USA). There is unused spectrum mainly because of the geographical separation required between television stations of the same channel and also part of the spectrum dedicated to the regional TV stations which remain unused in certain areas.



Status of TV White Spaces in India - In India "whitespaces" do not exists but loads of unused spectrum

Before we even consider White Space technologies, there is a need to quantify the amount of "white spaces" in the TV UHF band IV that cannot be used by conventional licensed cellular technologies without interfering with the broadcast spectrum. A recent study done by IIT Mumbai (see Table III of page 5 of the PDF in this link) points out that more than 80% of the TV UHF band IV (470-585 MHz) is totally free and lying unused. If we go with this study then there are no real "white spaces", but only free and unused spectrum that exists in India. In other words, the TV UHF band IV is as free as any other newly auctioned spectrum band (100% free and unused spectrum does not fall under the definition of "whitespace", otherwise all free and unused spectrum in any others band should also be described as "whitespace").

Therefore, no special "whitespace" technologies are required to use unused spectrum. It is essential that the TRAI continues to remain technology agnostic, and keep the scope of technology adoption outside the purview of its definition.

Regulatory Measures Required

As a regulatory measure, for the effective usage of unlicensed spectrum, the transmit power is considerably limited to avoid interference. Due to this limitation, the range of transmission is always low. Consequently, unlicensed transmission will not be able to exploit the large distance propagation characteristics of the sub GHz band and will be an inefficient use of this precious and limited natural resource. It is for this very reason, higher frequency bands are the preferred choice for this kind of unlicensed usage. Efficient system designs therefore make use of the lower parts of the spectrum for coverage (using cellular technologies such as 3G and 4G LTE), and rely on higher bands of the spectrum for capacity offload (using a combination of cellular and unlicensed technologies such as WiFi).

Accordingly, major frequency bands which have been identified for unlicensed usage are above 1 GHz (e.g 2.4 GHz, 5 GHz) and there are efforts to delicense some more spectrum in 60 GHz band to provide much higher capacity networks (RLAN).

In our view the TRAI should not recommend spectrum assignment based on any specific technology. The spectrum policy in India is to remain technology agnostic and should continue so for all spectrum bands used/being planned for commercial usage. This will also ensure that the spectrum is utilized most efficiently as envisaged in the National Frequency Allocation Plan.

During the last WRC (WRC-2015), many countries, like USA, identified spectrum in band 470-698 MHz for IMT. India also supported identification of this band for IMT. USA is auctioning spectrum in this band for IMT and it is expected that IMT will grow in this band driving economies of scale.

Impact on the Economy

Since there are no "whitespaces" and most of the spectrum in the TV UHF band IV is lying free, assigning it administratively to replicate the same set of services which the cellular operators are providing under the unified license, will be a big problem. The 900 MHz band (880-915/925-960 MHz) currently sold @ Rs 9000 Cr/ MHz, which is at a much higher frequency than UHF band IV. A block of 20 MHz of TV UHF band should be priced at Rs 90,000 Cr (adjusting the paired frequency with unpaired). **On the other hand if the spectrum is unlicensed, then not only the government has to forgo precious revenue, but coverage capability of the band will be significantly reduced, as the unlicensed technologies by regulation have to transmit at much lower power to prevent it interfering with other users who might be in the vicinity (just like WiFi operating at 2/5 GHz).** That is the reason why all the unlicensed usages are at higher bands, as at these frequency levels the reach of signals are anyways constrained, and does not travel too far. Typically, the economies of scale is achieved when there is a global harmonization of a particular spectrum band (e.g. 2.1 GHz for 3 G, 900/1800 MHz for GSM, 2.4/5 GHz for WiFi). There is currently no broadband system in operation, in an unlicensed mode, at the sub GHz band. Thus, economies of scale is unlikely to happen in the near future. Lack of global economies of scale implies higher cost of equipment/devices and limited consumer choice.

Conclusion

The government is facing huge challenges in their endeavor to connect 600 K villages. The first step is to get the OFC backbone ready. Then one has to deal with the challenge of carrying broadband to the villages. Since there are hardly any "white spaces", license assignment of UHF spectrum will be a problem (due to huge price of spectrum), and unlicensed assignment will need power regulation and therefore, signals will not travel too far to be able to connect the villages. **The best way to connect the villages could be to use the existing frequency bands already assigned to the cellular operators. These spectrum bands (800/900/1800/2100/2300 MHz) have large potential to cover rural areas and villages where the services are required to be carried, and hence spectrum availability is not the problem. The real challenge is to incentivize the operators so that they are motivated to take the 3G/4G networks to the villages.** To extract maximum value all spectrum and technologies needs to interwork with each other and none can work in isolation, and so should be the TV UHF band IV.

Annexure II

Unlicensing 60 GHz for Indoor and Outdoor Deployments

Introduction

During the last decade, telecom regulators of many countries have followed an initiative started by the US Federal Communications Commission (FCC) and have allocated a continuous block of 7 GHz spectrum between 57 and 64 GHz ('V' Band) for wireless communications. A major factor in this allocation with a significant impact operation of equipment supporting this band, is that the spectrum is delicensed.

The 57-64 GHz band is located in the *millimeter-wave (mmW)* portion of the electromagnetic spectrum, where the wavelength varies from ten millimeters (30 GHz) down to one millimeter (300 GHz). Until recently, the millimeter-wave portion of the RF spectrum has been largely unexploited for commercial wireless applications. That is now changing and a number of manufacturers are producing mmW products and technologies operating in that spectrum that enable two-way wireless communications at data rates that previously could only be accomplished with fiber optic cable. In addition to the high-data rates that can be accomplished in this spectrum, energy propagation in the 60 GHz band has unique characteristics that makes possible many other benefits such as excellent immunity to interference, high security, and frequency re-use.

Oxygen (O_2) Absorption

The interest of various telecom regulators in this 60 GHz frequency band stems from a phenomenon of nature: the oxygen molecule (O_2) absorbs electromagnetic energy at 60 GHz like a piece of food in a microwave oven (see Figure 1). This absorption occurs to a much higher degree at 60 GHz than at lower frequencies typically used for wireless communications. This absorption weakens (attenuates) 60 GHz signals over distance, so that signals cannot travel far beyond their intended user. ITU-R has also carried out detailed studies in this regard (Recommendation ITU-R P.676-3).

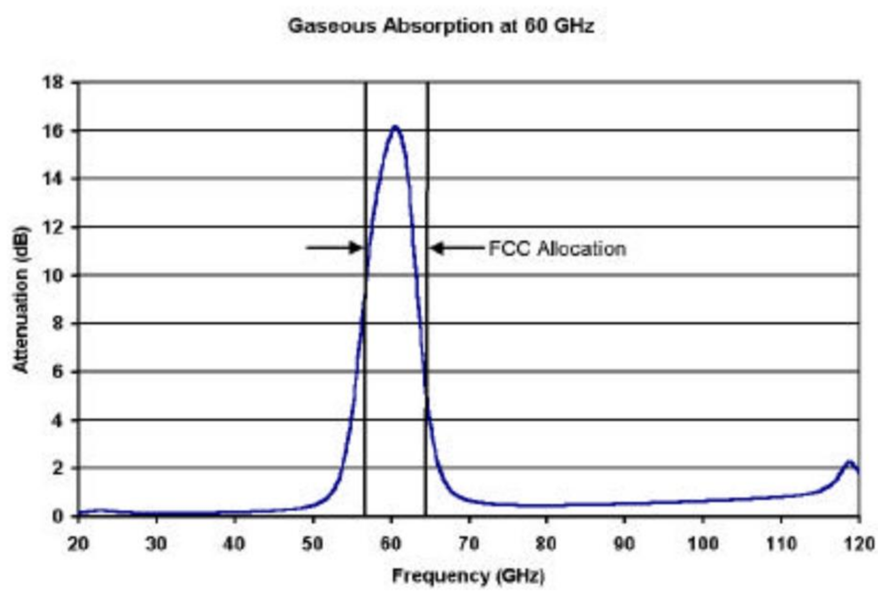


Figure 1a – O_2 attenuation versus frequency

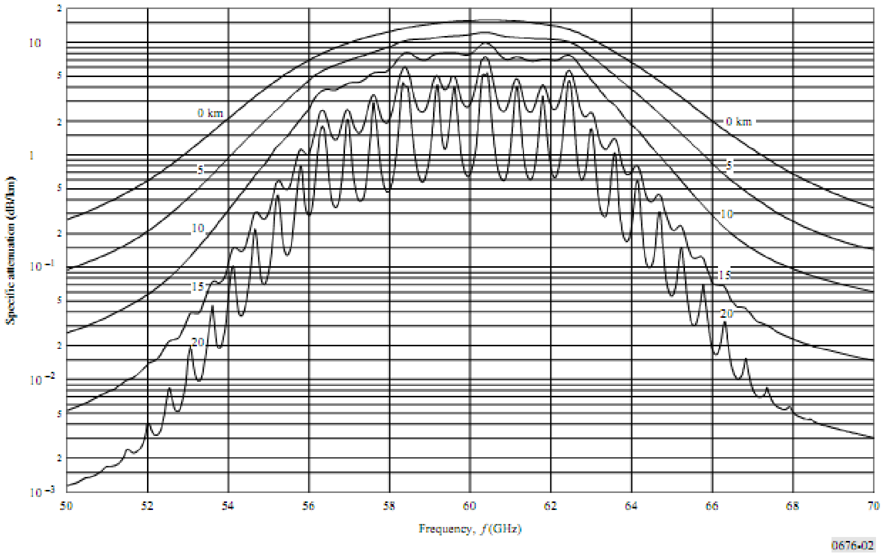


Figure 1b – O_2 attenuation versus frequency in range 50-70 GHz

Another consequence of O_2 absorption is that radiation from one particular 60 GHz radio link is quickly reduced to a level that will not interfere with other 60 GHz links operating in the same geographic vicinity. This reduction enables higher “frequency reuse” – the ability for more 60 GHz links to operate in the same geographic area than links with longer ranges. As an example, let’s compare two different links, one operating near 60 GHz and the other at a frequency that is less affected by O_2 absorption. The second link could be operating at another unlicensed frequency such as 2.4 GHz or 24 GHz. Consider a typical operating scenario where both links are operating over a distance of one kilometer with the transmitter’s power output adjusted such that the signal level at the receiver is 30 decibels (dB) above the background noise. Figure 2 shows how the signal level drops with distance beyond the receiver in the two cases.

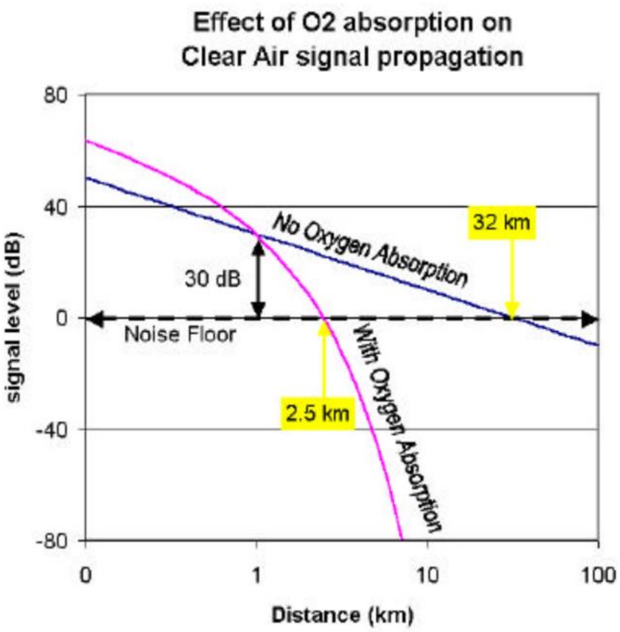


Figure 2 – Radiation Limiting by O2 Absorption

For the link unaffected by O_2 absorption, it takes 32 kilometers (km) for the transmitted signal to drop down to the background noise level. In other words, that signal would interfere with any other signal at that same frequency **for more than 30 kilometers beyond its original recipient**. That reduces the number of links at that frequency that can be installed in a fairly large area. Also, this means that the lower-frequency signal could be intercepted up to more than 30 kilometers beyond its intended recipient. In contrast, the transmitted signal at 60 GHz drops down to the noise level in a mere 2.5 km. Consequently, more 60 GHz links can be used in the same area without worrying about interference. Also, the 60 GHz links are far more secure given their limited range.

For this reason, 60 GHz is an excellent choice for short distance wireless systems with primarily use of multi-antenna phased arrays, making them highly directional, enabling much higher spectral reuse in any given area. Tens of 60 GHz antennas can be jammed into the area of a single 2.4 GHz antenna where these multiple antennas work together as an array to focus and direct transmission beams. Therefore, a room full of 60 GHz (also referred to as WiGig) devices can have all users in the same channel operating at near maximum speed, without significant performance loss.

Antenna Focus

Directivity is a measure of how well an antenna focuses its energy in an intended direction. Point-to-Point radios should have highly directional antennas as the goal is to connect to end points of a link. Ideally, all the transmitted energy is directed just at the intended recipient. Highly focused antennas jointly minimize the possibility of interference and the risk that the transmission will be intercepted, whilst maximizing performance.

Operating at higher frequencies inherently results in a more focused antenna. Antenna directivity is limited by the physical principle of diffraction that states that the beam width is inversely proportional to the operating frequency. Therefore at 60 GHz, the beam width is far narrower than at the lower frequency unlicensed bands. Table 1 shows the beam width for several unlicensed frequency bands. These results are shown graphically in the next section.

Frequency	99.9% Beam Width
2.4 GHz	117 degrees
24 GHz	12 degrees
60 GHz	4.7 degrees

Table 1 – Beam Width for Several Unlicensed Frequency Bands
For 30cm diameter antennas

Radiation Limiting at 60 GHz

The combined effects of O_2 absorption and narrow beam spread result in high security, high frequency re-use, and low interference for 60 GHz links. Figure 3 shows two buildings that are 1km apart. The segments show the radiation pattern from 2.4, 24 and 60 GHz links operating with the same performance at 1 km. The links have equivalent 30cm diameter antennas. The three segments show the locations where the radiation at each frequency remains high. The largest segment represents the radiation pattern from a 2.4 GHz link. The 60 GHz link has the narrowest and shortest segment and can be barely be seen except in the enlargement. The segments for 2.4 and 24 GHz links are substantially larger than the 60 GHz link, even though their operational link distance is the same (1 km).

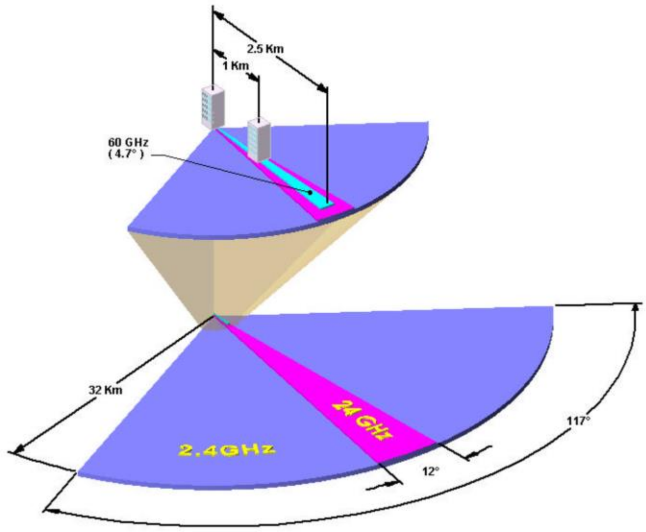


Figure 3 – Radiation maps for 2.4, 24 and 60 GHz Links

The practical implications of these graphics are obvious. A 60 GHz link can only be intercepted in the tiny wedge and will only interfere with another 60 GHz link in that wedge. A 24 GHz link has interference and interception risks over a much longer and somewhat broader wedge, while a 2.4 GHz link has interference and interception risks over a very large area, both in distance and in breadth.

O_2 versus Rain

It may be asked - "doesn't O_2 absorption limit the maximum link range?" The answer is that it does, with the resulting benefits described above. However, link distances of millimeter-wave radios operating in the real world are limited primarily by rain and atmospheric humidity. Users of these products typically want the links to provide robust communication capability to the order of 99.999% which is demanded by almost every carrier. Rainfall statistics are so well known for locations around the globe that range and availability can be accurately predicted. Figure 4 shows the attenuation due to rain (solid line) compared to O_2 absorption (dashed line).

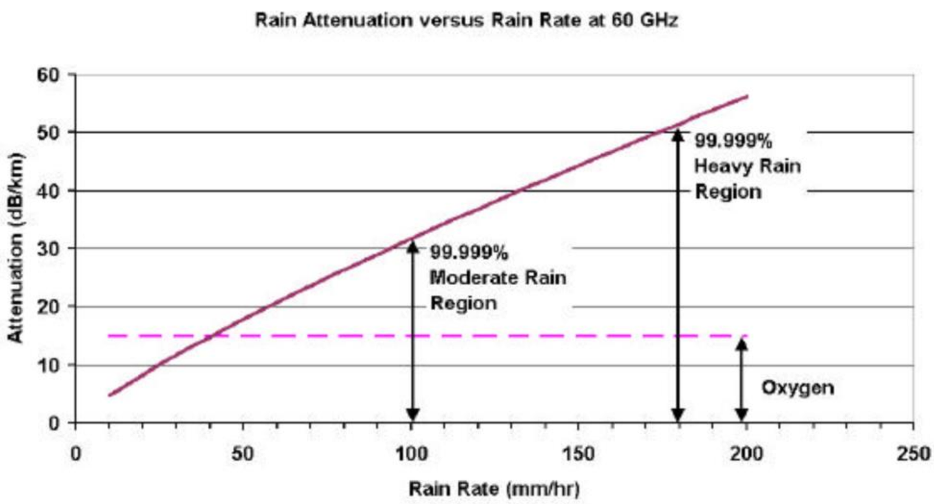


Figure 4 – Attenuation versus Rain Rate

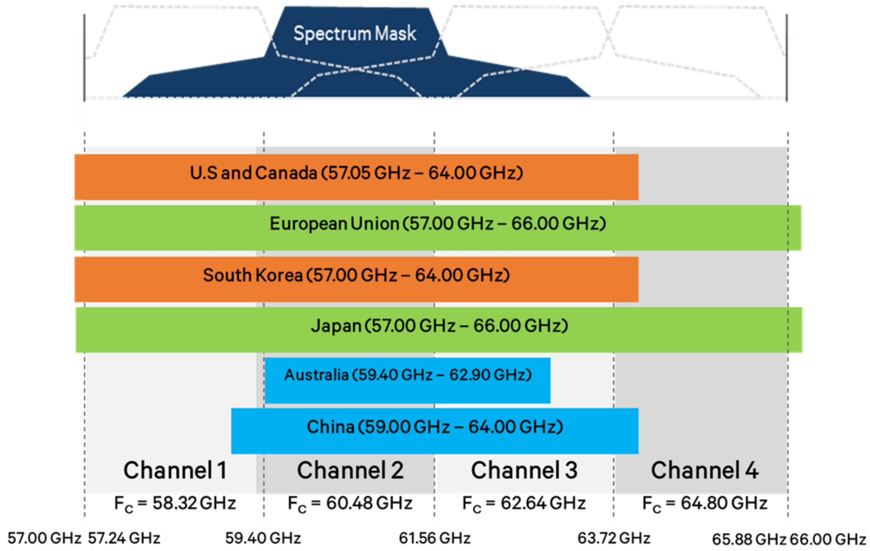
In moderate rain regions, the rain attenuation is about twice the oxygen attenuation, and in heavy rain regions, the rain attenuation is more than three times the oxygen attenuation. So, this combination of oxygen and rain absorption will be a major challenge for outdoor deployments in 60 GHz band. Therefore, it is pertinent to plan usage of 60 GHz spectrum indoors and outdoors so as to provide a robust communication system with very high capacity.

Global Adoption

Globally 60 GHz is being delicensed for ISM usage and in some cases short range backhauls using WiFi standards only. Some of the countries which have made necessary regulatory provisions for unlicensed usage of this band using WiFi standards are as follows –

- Australia, Chile, New Zealand, Singapore, South Africa, Middle East countries, European Union, LATAM countries, USA, Canada, Japan, Taiwan

Typical channel bandwidth is 2.16 GHz and there are 3-4 channels with EIRP limitation of 43 dBm max as shown below -



Summary

The 60 GHz band is an excellent choice for both indoor and outdoor high-speed and high capacity data networks offering the following key highlights-

(a) Unlicensed operation – easy to deploy with equipment being available off the shelf

(b) Highly secure and virtually interference-free operation – resulting from short transmission distances due to oxygen absorption and narrow antenna beam width

(c) High level of frequency re-use enabled – communication needs of multiple customers within a small area (e.g. Malls, Airports, Railway stations, public places, etc.) can be satisfied

(d) Fiber optic data transmission speeds possible – 7 GHz of continuous bandwidth available compared to <0.3 GHz at the other unlicensed bands

(e) WiGig, also known as IEEE 802.11ad, operating in the 60 GHz license-free ISM band, will break up the congestion on the 2.4 GHz and 5 GHz bands and add orders of magnitude more network capacity.

(f) Compared to Wi-Fi networks that support maximum data rates between 54 Mbps and about 300 Mbps, 60 GHz protocols support rates above 1Gbps up to 7 Gbps.

(g) This frequency band has been deliberated in great depth in various ITU-R meetings and their outcome is available as ITU-R Report ITU-R M.2227 (11/2011) and ITU-R Recommendation ITU-R M.2003-1 (01/2015) on **Multiple Gigabit Wireless Systems in frequencies around 60 GHz**.

(h) An industry body called the Wireless Gigabit Alliance is overseeing WiGig technology standards/development and is working to ensure that suitable device ecosystem is in place.

Qualcomm Technologies, Inc.

A Quantification of 5 GHz Unlicensed Band Spectrum Needs

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Table of Contents

1 Executive Summary

To better understand future requirements for spectrum for unlicensed usage, Qualcomm Technologies, Inc. analyzed projected requirements for WLAN (Wireless Local Area Networking) use in dense urban and enterprise environments.

The analysis involved simulations assuming the use of the most advanced, 802.11ax based WLAN technology, to determine the amount of spectrum required to reach a target throughput performance of 1 Gbps throughout simulated residential apartments and enterprise scenarios. In addition, the requirements for 100 Mbps, 500 Mbps, and 2.5 Gbps coverage were analyzed.

The analysis covered the following networking topologies/configurations for a dense residential scenario with either 2 or 4 antennas at the device/client side (STA):

- 1 access point (AP) per apartment
- 4 APs per apartment (one per room), Ethernet backhaul
- 4 APs per apartment, WiGig 60 GHz last hop, 5 GHz WLAN backhaul
- 4 APs per apartment, 5 GHz WLAN last hop, 5 GHz WLAN backhaul

Furthermore, a dense enterprise deployment scenario was analyzed for either 2 antenna STAs or 4 antenna STAs. In colloquial terms, one can equate the analysis with someone measuring Network throughput with a 'speed meter' for each of the AP/STA location combinations in the analysis. The required spectrum is determined by finding the minimum amount of spectrum needed to achieve the target throughput rate
(100 Mbps/500 Mbps/1 Gbps/2.5 Gbps).

Some key outcomes of the analysis are summarized in Figure 1, where the required spectrum is plotted for each of the all wireless network deployment configurations analyzed by target throughput.

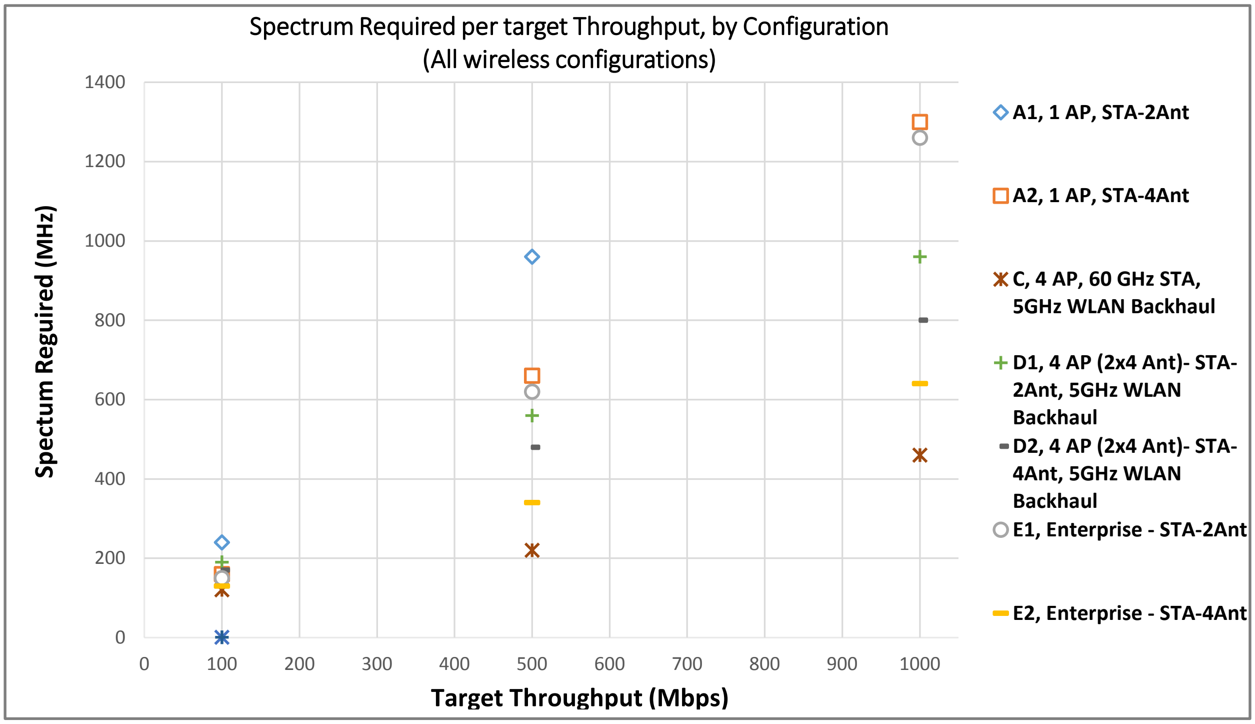

Figure 1. Overview of spectrum required by target throughput (100, 500, and 1000 Mbps) for all wireless configurations

This analysis leads to the following recommendations:

1. To enable future WLAN-type application and usage scenarios, regulators should plan for around 1280 MHz of unlicensed spectrum centered around the 5 GHz band for use by unlicensed technologies, to enable common deployment scenarios such a single access points for apartments (Configuration A) and 2 antenna client devices in dense enterprise settings (Configuration E).

2. Higher throughput coverage scenarios in dense environments require extensive use of 160 MHz channel bandwidth modes; regulators should strive towards making multiple (i.e., 3 or more) 160 MHz wide channels available for unlicensed use.

3. Service providers, consumer electronics vendors, networking vendors, and building construction companies should adopt topologies of 1 AP per room (including combo APs with 60 GHz mmWave technology).

4. Device vendors should adopt 2 or more spatial stream capable radios in future product designs and 60 GHz mmWave technology where possible.

2 Context and Objectives

The tremendous growth in traffic over Wi-Fi networks has been well documented. In conversations with regulators and industry, the question of how much unlicensed spectrum is needed to enable future growth and sustain acceptable user experiences comes up regularly. The intent of this whitepaper is to provide numerical input into future spectrum requirement discussions and submissions.

This research focuses on two key bottleneck areas where end users are expected to use unlicensed spectrum technologies in their day to day use. These areas are dense residential settings and dense enterprise deployments. This whitepaper does not focus on other bottle neck areas such as railway stations, malls and sports stadium settings.

The primary target of the whitepaper is to identify the required amount of spectrum to provide sustainable 1 Gbps coverage to end users. We believe this forward looking target is relevant since it establishes wired experience equivalence where 1 Gbps Ethernet is now the norm. Furthermore, 1 Gbps coverage is listed as a target in the context of 5G cellular discussions and this target is expressed by service providers, e.g., cable companies, as a customer requirement. For context we also analyzed the minimum amount of spectrum required to sustain 100 Mbps, 500 Mbps, and 2.5 Gbps.

The objectives of this whitepaper are:

- Provide a top down, engineering driven, analysis of required spectrum to achieve 'wired equivalent' performance for unlicensed spectrum technologies in dense networking environments
- Derive inputs for regulatory efforts regarding future spectrum requirements and allocations
- Derive preliminary conclusions about future device configurations (e.g., the number of antennas per client and/or access point) and deployment topologies to achieve the target data rates

3 Highlights of Findings

It may be stating the obvious for some, but the analysis demonstrates the huge impact of density and overlapping networks on overall spectrum needs. For example under Configuration B (4 APs per apartment, Ethernet backhaul) a 10x10 bungalow on the prairie (i.e., no interference from overlapping networks) would require 80 MHz of spectrum for 1 Gbps coverage in every room, whereas in the dense scenario, the required spectrum is 320 MHz (for 4 antenna STAs).

To meet future throughput requirements, residential network deployments will need to evolve to topologies that make extensive use of multiple access points per dwelling, including access points with 60 GHz connectivity for the last hop. For example, under Configuration A (1 AP per apartment, 1 STA), the 1 Gbps requirement can only be met with 4 antenna stations, requiring 1280 MHz of spectrum. In Configuration C, with 60 GHz last hop, only 480 MHz of 5 GHz spectrum is required. Under Configuration D (4 APs per apartment with 5 GHz WLAN backhaul between APs) stations requires 800 MHz of spectrum.

Both access points and devices need to upgrade the number of antennas in order to benefit from advanced features such as MIMO, MU MIMO, and transmit beamforming.

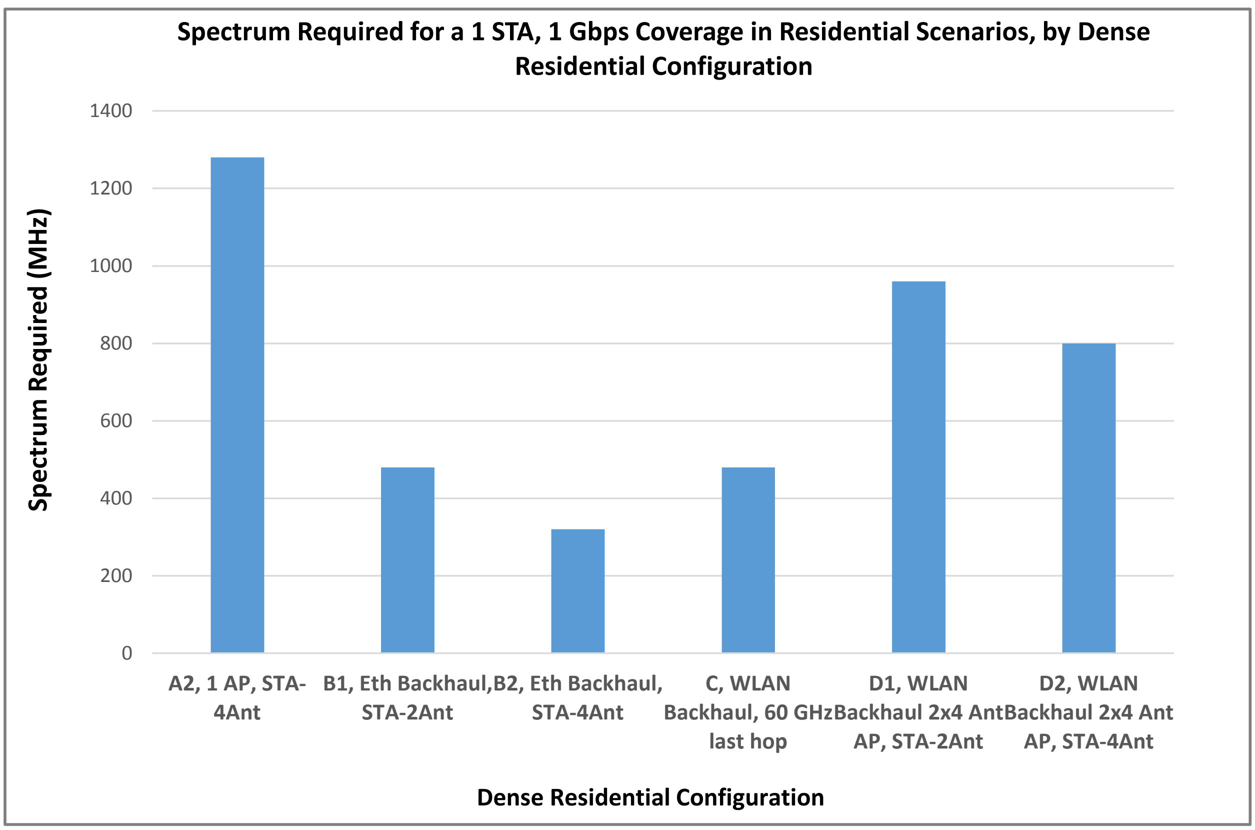

Figure 2. Spectrum required to achieve 1 Gbps coverage in a dense residential setting, by configuration

4 Methodology and Simulation Environments

4.1 High level approach

To determine forward looking spectrum requirements, we analyzed the amount of spectrum required to sustain a 1 Gbps throughput level for wireless coverage in dense residential and dense enterprise environments, in every location in the home/office (downlink). In addition, we also conducted the analysis with longer time horizon in mind for 2.5 Gbps coverage, as well as current requirements for 100 Mbps and 500 Mbps sustained coverage.

Our analysis is based on the IEEE simulation scenarios for dense residential [Reference 1] and for enterprise [Reference 2]. We also modified the residential scenario so it would better match some empirical measurements.

For the dense residential scenario, we assume a 3-story apartment building with 10 apartments on each floor. Each apartment consists of 4 rooms and its total size is 10m x 10m. We assume a wall loss of 11 dB (both for inner and outer walls) and an 18 dB loss for floors. The considered topology is illustrated in Figure 3.

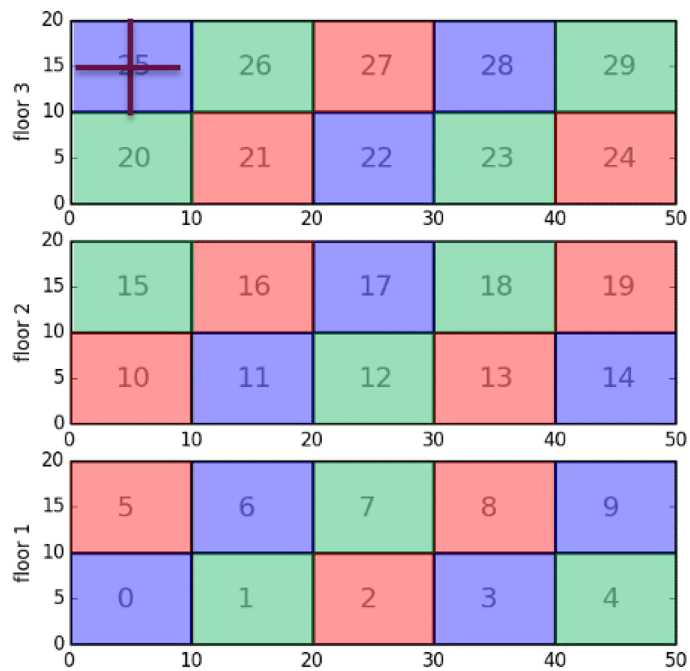

Figure 3. Layout of the IEEE dense residential simulation scenario

In our analysis we assumed the best available 802.11 technology (incl. 802.11ax) with maximum channel bandwidths of 160 MHz. For example, the analysis assumes the use of .11ax numerology, the use of BSS color, MU MIMO, and transmit beamforming.

The required spectrum is calculated from a perspective of using traditional WLAN, i.e., as deployed currently in the 2.4 and 5 GHz band. That means that mmWave (60 GHz) is excluded from this particular analysis. However, we do consider one scenario where 802.11ax WLAN is used for backhaul inside an apartment, and 60 GHz is used for the link between access point and client device.

From a high level perspective, we calculate the required spectrum by determining the required frequency bandwidth for the most challenging AP-to-client link in the simulation environment to sustain the target throughput (e.g., 1 Gbps). The second key factor in determining the overall spectrum requirement is the frequency reuse which is needed to sustain the same target throughputs in neighboring apartments in the dense residential setting, or for neighboring BSSs in the enterprise scenario.

The calculation of the required spectrum thus turns out to be:

> Overall required spectrum = Required bandwidth to sustain target throughput (e.g., 1 Gbps) in a dense network for the optimal frequency reuse factor * Optimal frequency reuse factor

4.2 Determining the frequency bandwidth per AP-to-client link and frequency reuse factor

In our analysis we assumed a 70% MAC efficiency. For example, to support 1 Gbps throughput, a PHY link rate of 1.43 Gbps is required.

Determining the minimum frequency bandwidth required for any given AP-to-client link to meet the performance threshold (e.g., 1 Gbps) in the simulation environments is an iterative process. By iterating through different reuse factors (e.g., 1, 3, 4, 6, 8, and 12), and looking at the spectrum requirements in each case, the optimal reuse factor can be determined and used for the final spectrum requirements calculation.

Calculating the spectrum requirements takes the following into account:

- Simulating potential placements of access points and clients in an apartment and its neighboring apartments
- Collecting the resulting 'signal quality' as defined in SINR (Signal-to-Interference + Noise-Ratio) at each of the simulated potential placements of access points and clients
- Determining the SINR in the most challenging client location (99th percentile on the CDF curve of SINR that results from the simulations)
- Calculating the link-rates corresponding to this SINR at various channel bandwidth options (20/40/80/160 MHz)
- Determining the minimum bandwidth required to support the performance target (taking the 70% MAC efficiency into account)

Using the best reuse factor and smart channel selection to compute the final bandwidth requirements leads to a conservative estimate of the necessary bandwidth, since in reality APs in dense urban environments may not choose the optimal channel, and the networks may operate at suboptimal reuse factors.

4.3 Summary of assumptions

To summarize, we use the following assumptions in our analysis:

- Use of 802.11ax features (numerology, use of color)
- 20/40/80 and 160 MHz channel bandwidths, with Tx beamforming and MIMO
- Multiple antenna configurations (AP: 4 and 8 antenna, Client 2 and 4 antenna)
- Standard Tx powers: 21 dBm per antenna for AP, 15 dBm per antenna for STA

- 70% MAC efficiency
- Single client per AP; i.e., no contention or collision losses are taken into account
- All the networks in the simulation run full buffer downlink traffic
- Optimal channel planning; APs are assumed to choose a 'good' channel based on the environment they see (the analysis does not take 'rogue' APs into account)
- Channel planning is optimized for each scenario/configuration analyzed; i.e., the number of channels/reuse factor is chosen to give the best performance for each scenario
- Simulations were conducted in three dimensions, i.e., adjacent apartments above and below and on the same level were taken into account
- Potential impacts of adjacent channel interference (ACI) are not taken into account in the analysis
- Operations were assessed using 802.11ax WLAN networks only
- Target throughput is achieved for 99% of the space included in the simulation (unless documented otherwise) and, in the case of multiple access points per dwelling, the target throughput is assumed for each room (i.e., AP-STA combination)

4.4 Simulation scenarios/configurations

This whitepaper contains results for the following configurations:

- **Configuration A**
  Residential (Single AP, Single STA)
- **Configuration B**
  Residential (4 APs, 1 AP per room, 1 STA, Ethernet backhaul)
- **Configuration C**
  Residential (1 STA 60 GHz, 4 APs per apartment, 5 GHz WLAN backhaul, spectrum calculation for 5 GHz WLAN backhaul)
- **Configuration D**
  Residential (4 APs, 1 STA per apartment, 5 GHz WLAN backhaul, spectrum calculation for both last hop and backhaul)
- **Configuration E**
  Enterprise (Single STA per AP)

5 Detailed Results per Configuration

This chapter describes the setup of each configuration and presents the results of the analysis for each individual configuration analyzed.

5.1 Configuration A, Residential, Single AP

This configuration assumes a single 5 GHz access point equipped with 4 antennas per apartment. The simulations are conducted for the case where the device (STA) in the apartment has 2 antennas and the case where the devices has 4 antennas. The access point is assumed to have a wired interface to an access network.

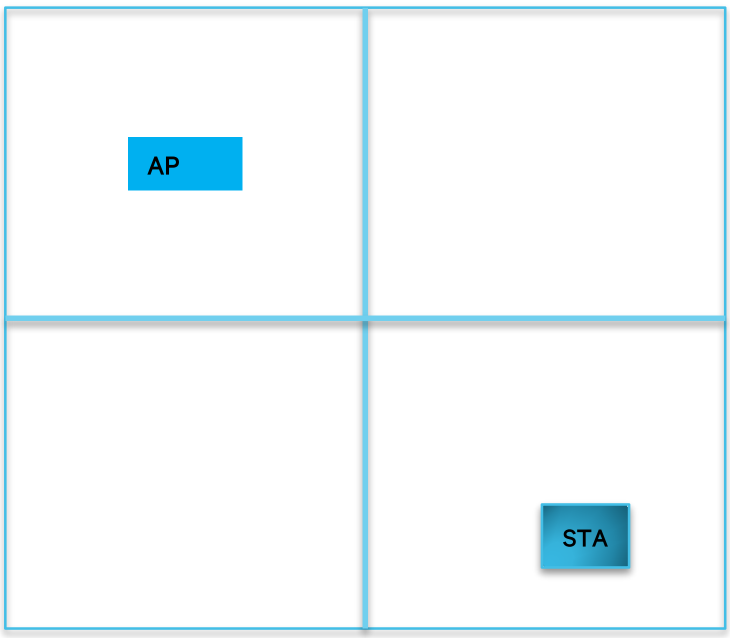

Figure 4. Configuration A, Single AP per apartment

As described in Chapter 4, *Methodology and Simulation Environments*, the simulations conducted contemplate the various placement scenarios of the AP and STA in the apartment, as well as the various placement scenarios of the overlapping networks (i.e., the networks that can be observed from the apartment that is the focus of the simulation).

The results table includes the required spectrum for each of the target throughputs – for 99% of the apartment covered – analyzed for the different device (STA) antenna configurations (2 or 4 antennas). For comparison we have also listed the amount of spectrum required for the case whereby the dwelling does not experience any interference (bungalow in the prairie scenario).

	2 Antenna per STA (4 @ AP)				4 Antenna per STA (4 @ AP)			
Target Throughput	100 Mbps	500 Mbps	1 Gbps	2.5 Gbps	100 Mbps	500 Mbps	1 Gbps	2.5 Gbps
Required Frequency Bandwidth	240 MHz	960 MHz	Cannot meet	Cannot meet	160 MHz	640 MHz	1280 MHz	Cannot meet
Frequency Bandwidth if no interference	20 MHz	80 MHz	Cannot meet	Cannot meet	20 MHz	80 MHz	160 MHz	Cannot meet

Table 1 Minimum required frequency bandwidth calculations for Configuration A

Where we list that we 'cannot meet' the required throughput for this configuration, the constraining factor is the link budget (i.e., the link-rate supported at the outer edges of the required coverage area is too low). The link budget could be expanded by using wider channels, higher output powers, or higher order MIMO for example (if the AP had more antennas).

5.2 Configuration B, Residential 4 APs, 1 STA per AP, Ethernet backhaul

This residential scenario assumes 4 APs per dwelling, one in each room. The APs have 4 antennas. The connection between the APs is assumed to be over a wired connection. All APs in the apartment use the same channel. The simulations are conducted for one STA for locations throughout the dwelling.

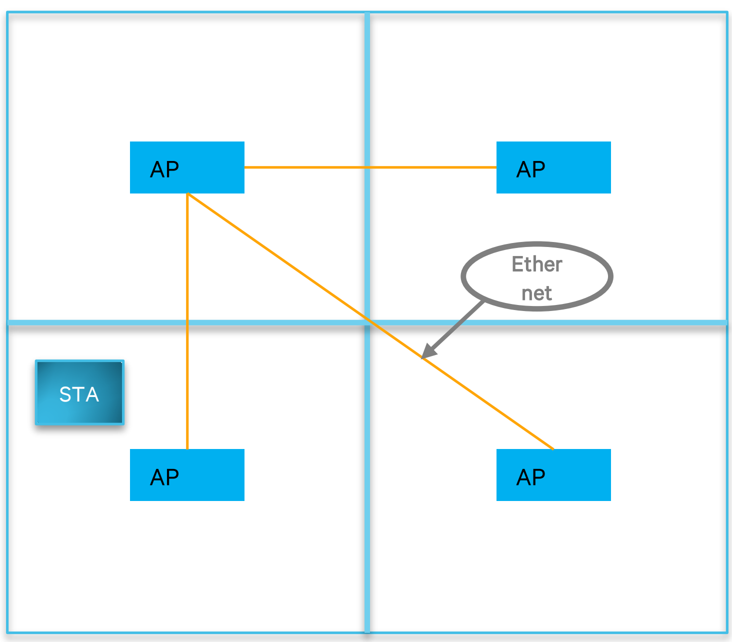

Figure 5. Configuration B, 4 APs per apartment, Ethernet connection between APs

The results table includes the required spectrum for each of the target throughputs analyzed for the different device (STA) antenna configurations (2 or 4 antennas) and random placements in the room of both AP and STA, covering 99% of the apartment. For comparison we have also listed the amount of spectrum required for the case whereby the dwelling does not experience any interference (bungalow in the prairie scenario).

	2 Antenna per STA (4 @ AP)				4 Antenna per STA (4 @ AP)			
Target Throughput	100 Mbps	500 Mbps	1 Gbps	2.5 Gbps	100 Mbps	500 Mbps	1 Gbps	2.5 Gbps
Required Frequency Bandwidth	40 MHz	240 MHz	480 MHz	Cannot meet	40 MHz	160 MHz	320 MHz	960 MHz
Frequency Bandwidth if no interference	20 MHz	80 MHz	160 MHz	Cannot meet	20 MHz	40 MHz	80 MHz	160 MHz

Table 2 Minimum required frequency bandwidth calculations for Configuration B

For this scenario the 2.5 Gbps target cannot be met for 2 antenna STAs because with 2 spatial streams the maximum link-rate at 160 MHz channel bandwidth mode is 1.92 Gbps.

5.3 Configuration C, Residential, 60 GHz last hop, WLAN backhaul

This scenario assumes that the last hop connection between the device (STA) and the access point in the room is over a 60 GHz link. Each of the 4 rooms has an access point. One of the access points is connected to the access network over a wired link. The other access points are connected to each other over 5 GHz WLAN connections. The spectrum requirements analysis only takes the connections between the access points in the dwelling into account.

The analysis is conducted with APs with 4 antennas and APs with 8 antennas. With 8 antennas up to 8 spatial streams can be supported in communications between the APs in the apartment (under favorable link conditions).

An additional assumption was made for this scenario regarding the placement of the APs in the apartment. Instead of the 1% SINR point that is assumed for the STA locations, we assume a 10% SINR point, i.e., the AP can be placed at the 90th percentile of a room. A justification for this is that the consumer in this case will have some prior knowledge/advice about access point placement in rooms.

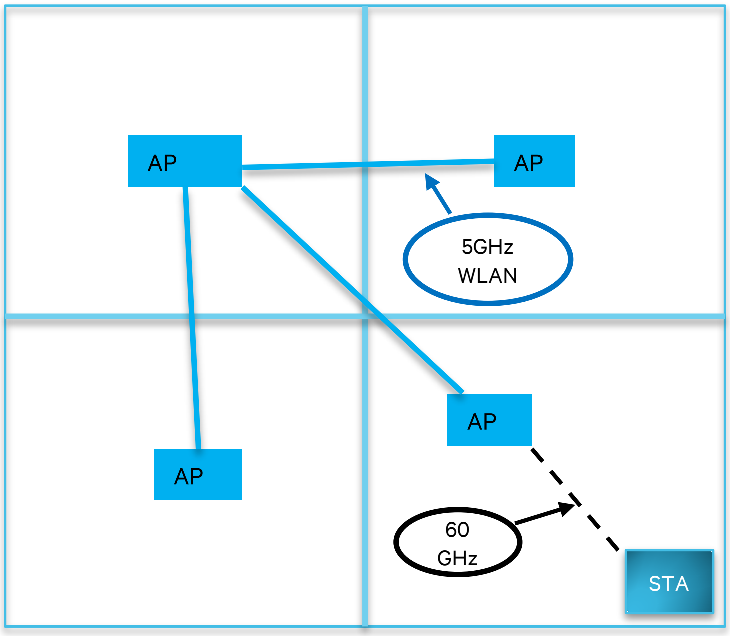

Figure 6. Configuration C, 60 GHz last hop connection between STA and AP, 4 APs per apartment, 802.11ax WLAN connection between APs

	4 Antenna per Access Point				8 Antenna per Access Point			
Target Throughput	100 Mbps	500 Mbps	1 Gbps	2.5 Gbps	100 Mbps	500 Mbps	1 Gbps	2.5 Gbps
Required Frequency Bandwidth	120 MHz	320 MHz	480 MHz	Cannot meet	120 MHz	240 MHz	480 MHz	1920 MHz
Frequency Bandwidth if no interference	20 MHz	40 MHz	80 MHz	Cannot meet	20 MHz	20 MHz	40 MHz	160 MHz

Table 3 Minimum required frequency bandwidth calculations for Configuration C

The bottleneck in this scenario is the requirement for the access point that has the connection to the access network to support service to the AP in the kitty corner apartment. For those instances where 'cannot meet' is listed, the link budgets cannot support the required throughput, with the wall penetration losses incurred.

5.4 Configuration D, Residential, 4 APs per apartment, WLAN last hop, WLAN backhaul

In this scenario we are analyzing the spectrum requirements for an 'all 5 GHz WLAN layout' in the apartment. Each room has a dual radio AP (4 antenna per radio) and all APs are wirelessly connected to the one AP with the connection to the access network. The channel configuration is such that all APs in the apartment use the same channel for the STA to connect to, but the backhaul uses a different channel (on the second radio in the dual radio AP).

The analysis is conducted for two different STA configurations: 2 or 4 antennas.

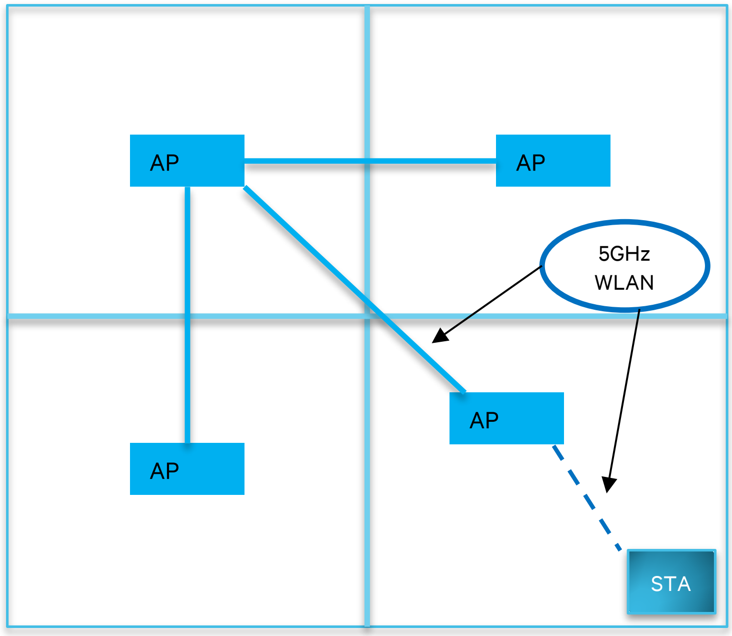

Figure 7 Configuration D, 5 GHz WLAN last hop connection between STA and AP, 4 APs per apartment, 5 GHz WLAN connection between APs

	2 Antenna per STA (2 x 4 @ AP)				4 Antenna per STA (2 x 4 @ AP)			
Target Throughput	100 Mbps	500 Mbps	1 Gbps	2.5 Gbps	100 Mbps	500 Mbps	1 Gbps	2.5 Gbps
Required Frequency Bandwidth	160 MHz	560 MHz	960 MHz	Cannot meet	160 MHz	480 MHz	800 MHz	Cannot meet
Frequency Bandwidth if no interference	40 MHz	120 MHz	240 MHz	Cannot meet	40 MHz	80 MHz	160 MHz	Cannot meet

Table 4 Minimum required frequency bandwidth calculations for Configuration D, WLAN last hop and WLAN backhaul

As noted, the APs in one apartment are assumed to be on the same frequency in the results shown in the table. The reason for this is that we assume the single STA is connected to one AP at any given time. However this assumption would change if there are active STAs in multiple rooms and spectrum requirements will increase as a result of this, e.g., to enable 500 Mbps in each of the 4 rooms in scenario D would require 1600 MHz of spectrum for the 2 antenna STA case and 1280 MHz in the 4 antenna STA case.

5.5 Configuration E, Enterprise

The setup for the enterprise configuration follows the IEEE Enterprise model. The layout is for one floor in an office building. The floor consists of 8 rooms, with 4 WLAN networks (BSSs) each; 32 networks in total. Each BSS covers an area of 10x10 meters. The APs are ceiling mounted, in the center of their respective BSS coverage areas.

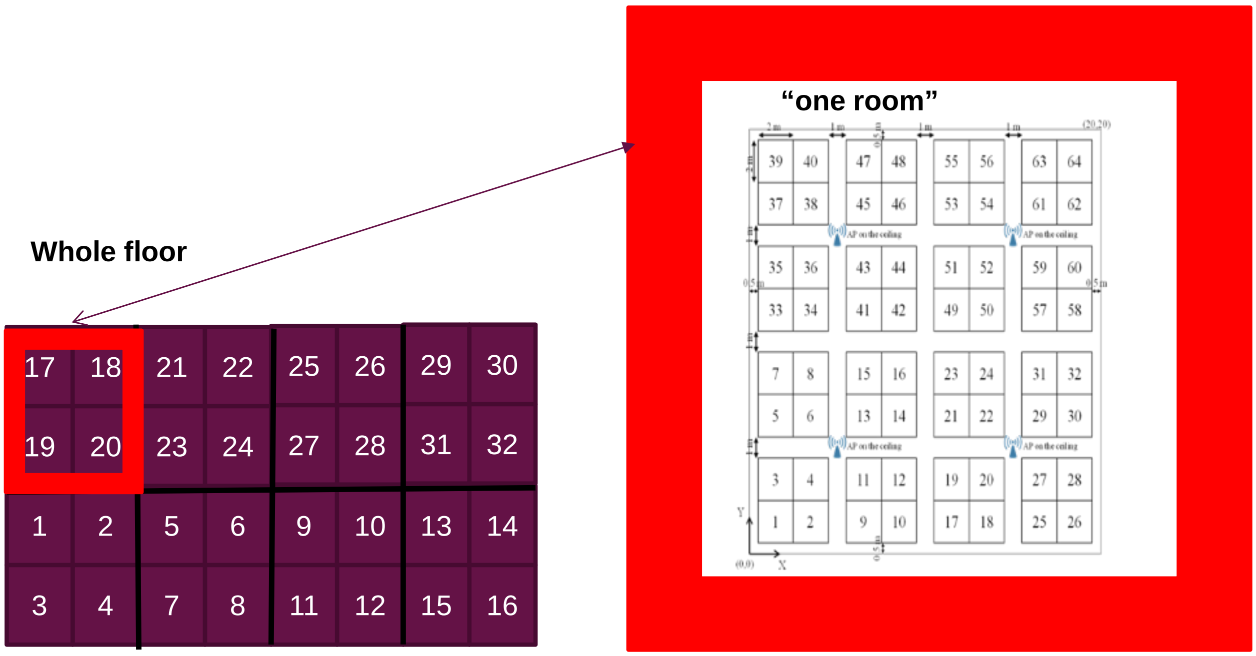

Figure 8. Configuration E, Enterprise scenario

	2 Antenna per STA (4 @ AP)				4 Antenna per STA (4 @ AP)			
Target Throughput	100 Mbps	500 Mbps	1 Gbps	2.5 Gbps	100 Mbps	500 Mbps	1 Gbps	2.5 Gbps
Required Frequency Bandwidth	160 MHz	640 MHz	1280 MHz	Cannot meet	160 MHz	320 MHz	**640 MHz**	1280 MHz
Frequency Bandwidth if no interference	20 MHz	80 MHz	160 MHz	Cannot meet	20 MHz	40 MHz	80 MHz	160 MHz

Table 5. Minimum required frequency bandwidth calculations for Configuration E, Enterprise

For this scenario, the 2.5 Gbps target cannot be met for 2 antenna STAs because with 2 spatial streams the maximum link rate at 160 MHz is 1.92 Gbps.

6 Discussion of Assumptions

Generally the assumptions used in the analysis are conservative, i.e., they point toward a lower amount of spectrum required to achieve the targets. The key assumptions driving the analysis include:

- The analysis is focused on dense deployment scenarios since that is where the likely spectrum bottlenecks will occur.
- For each scenario we assume the optimal reuse factor. For example, in the case of the Single AP scenario we use a reuse factor of 8 for 500 Mbps with 4 antenna AP and 4 antenna STA, because reuse-8 provides just enough SINR needed to meet the data-rate requirement, whereas reuses less than 8 (say, reuse 3, reuse 6, etc.) does not provide the required SINR. On the other hand, even though reuse-12 would have provided higher SINR, it would require more spectrum overall.
- In our analysis we are targeting the sustained coverage at the specific data-rate for a coverage area of 99% of the surface of the apartment in the residential scenarios and office floor space in the enterprise scenario. For example, if we were to relax the requirement to say 90% of the space, in scenario A, the target throughput of 1 Gbps could just be met for a 2 antenna STA, requiring 960 MHz of spectrum (the 99% coverage can't be met).
- In the analysis we assume operations only from 802.11ax WLAN networks. The actual situation may be different in the planning horizon for this analysis. We also assume there are no interfering 'rogue' access points.
- We don't take adjacent channel interference (ACI) into account (i.e., the interference resulting from networks that use other frequency bands that are close in the frequency domain to the network under analysis. In reality such transmissions may still impact the performance of networks under analysis due to the signals emitted out of band. Taking ACI into account in the analysis would lead to increase spectrum requirement estimates.
- In our analysis we assume a minimum of 2 antennas per device. This is a forward looking assumption, since the vast majority of client devices in the market today have only one antenna.
- Since we are conducting the analysis for a single STA in the residential scenario, we are assuming that the four APs in configurations B and D can be on the same channel (the STA will be connected to only one AP at a time). In reality, networks will likely be deployed with different frequencies for each room, e.g., to enable 500 Mbps simultaneously in each of the 4 rooms in Scenario D would require 1600 MHz of spectrum for 2 antenna STAs and 1280 MHz in the 4 antenna STA case.
- In our analysis we model downlink performance only and assume full buffer traffic; one could look at this that we are modeling the downlink 'speed test' application and report the results we see.
- Lastly we are assuming that the networks will implement the key feature-set from the upcoming 802.11ax standard (e.g., use of MU MIMO, transmit beamforming, use of BSS color, etc.). Obviously, this is a forward looking assumption since the 802.11ax standard is still under development and .11ax based products have not entered the market yet.

7 Conclusions and Recommendations

7.1 Conclusions

Figure 9 provides a summary of spectrum requirements for a target of 1 Gbps coverage.

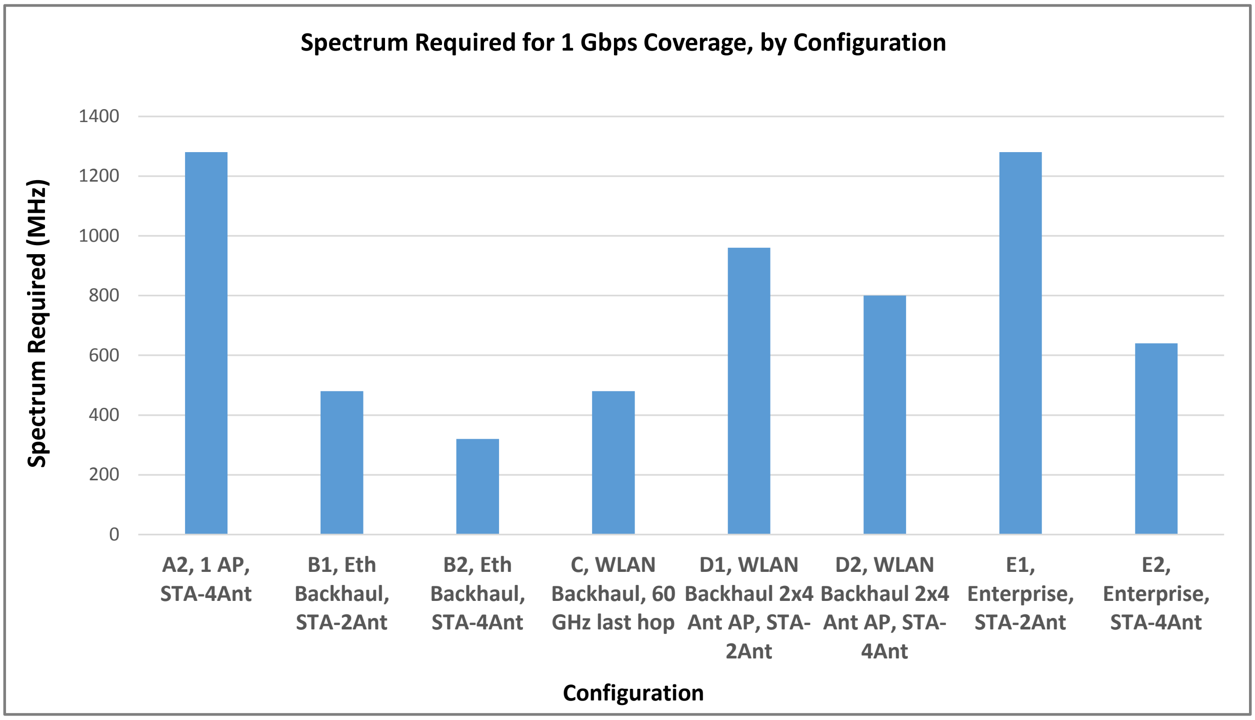

Figure 9. Spectrum required to achieve 1 Gbps coverage by configuration

Of note regarding the results in the bar chart:

- The target of 1 Gbps coverage of the apartment in the dense residential setting could **not** be met with a single AP and a 2 antenna STA
- Full 5 GHz WLAN implementation configurations with a 2 antenna STA indicate a requirement of a minimum of around 1280 MHz of spectrum (Configurations D1, E1)

Combining the analysis from all scenarios and configurations and throughput targets, provides the following picture:

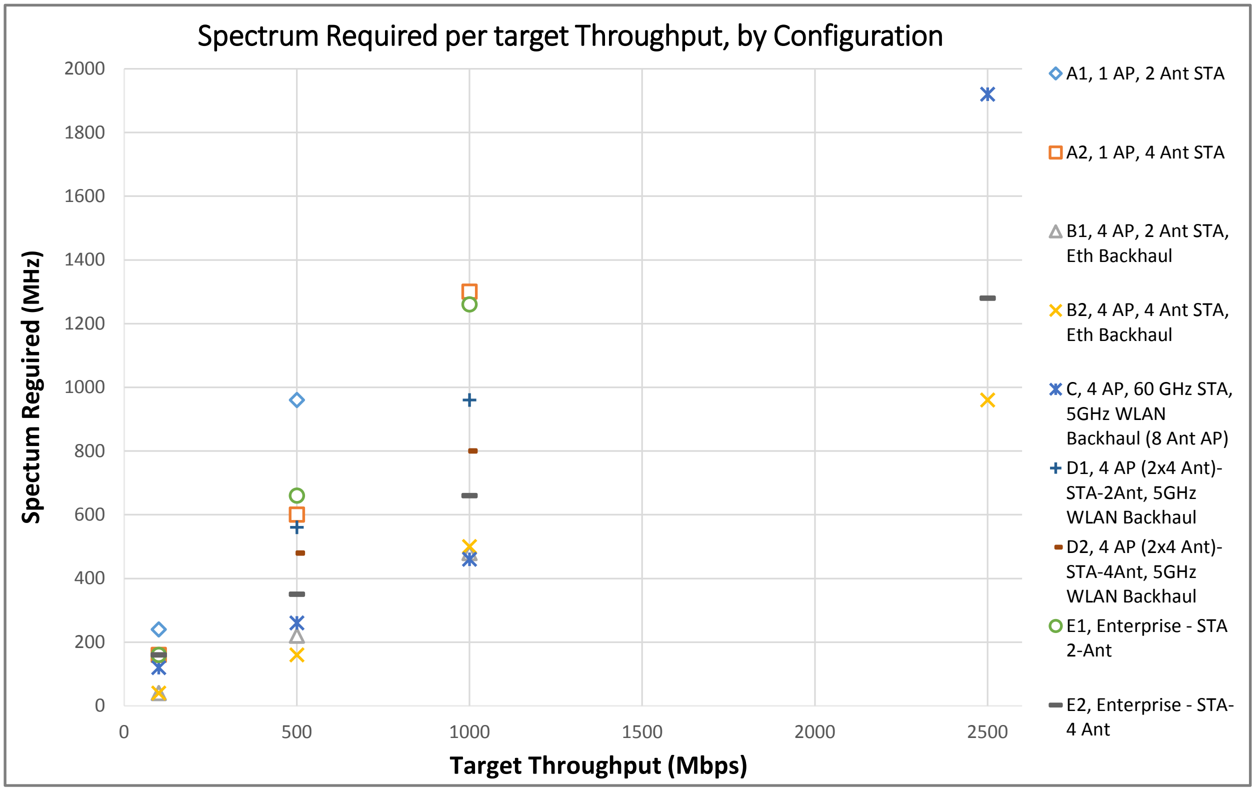

Figure 10. Overview of spectrum required by target throughput (100, 500, 1000, 2500 Mbps), all configurations

One can derive the following conclusions from this additional perspective:

- Forward looking scenarios rely on:
  - Multiple APs per dwelling (one per room)
  - Use of multiple antennas at the client devices (STAs) and access points
- Large scale use of 60 GHz technology for last hop links (between AP and STA) can significantly help mitigate some of the impacts of insufficient spectrum around the 5 GHz band.

Lastly, the analysis led to the following insights:

- The majority of the higher throughput scenarios (1 Gbps and 2.5 Gbps) require the use of 160 MHz channel bandwidth modes. Particularly, the 1 Gbps scenarios for 2 antenna STA configurations all require the use of the 160 MHz bandwidth mode. See Figure 11.

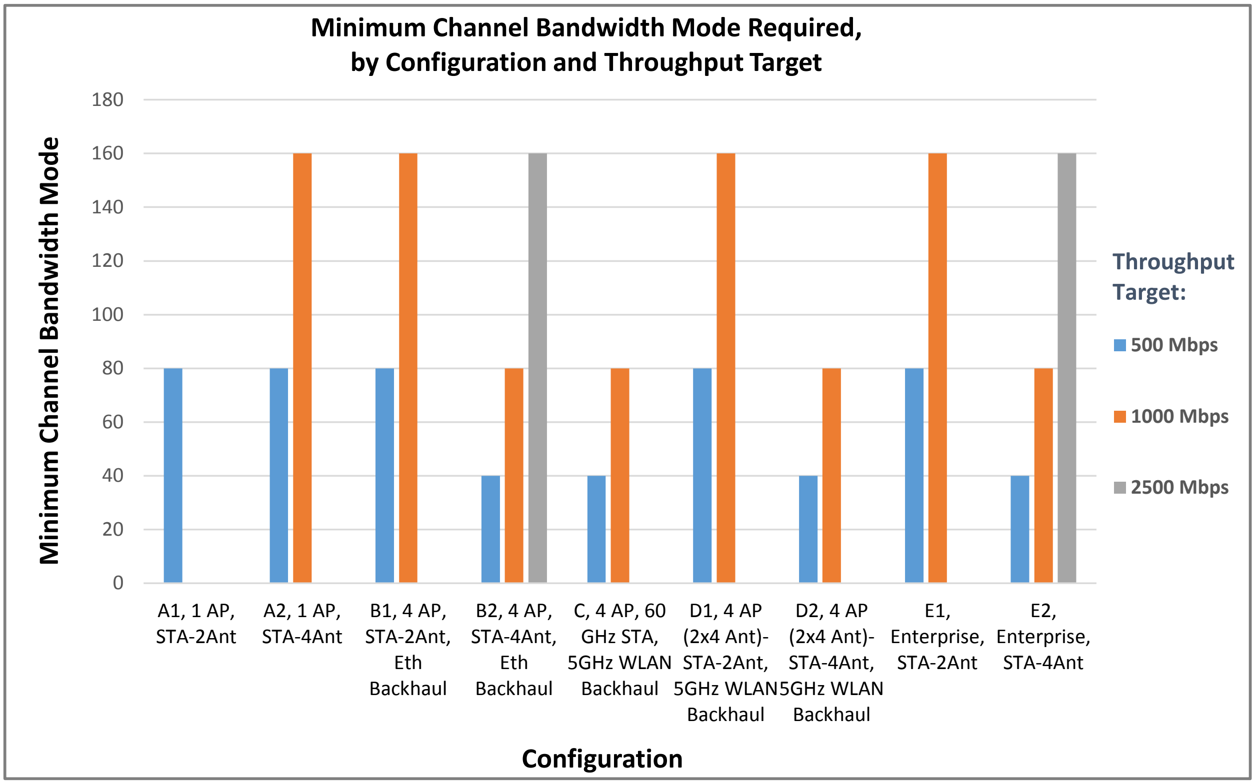

Figure 11. Minimum required bandwidth channel mode by configuration and throughput target

7.2 Recommendations

1. To enable future WLAN-type application and usage scenarios, regulators should plan for around 1280 MHz of unlicensed spectrum centered around the 5 GHz band for use by unlicensed technologies, to enable common deployment scenarios such a single access points for apartments (Configuration A) and 2 antenna client devices in dense enterprise settings (Configuration E).

2. Higher throughput coverage scenarios in dense environments require extensive use of 160 MHz channel bandwidth modes; regulators should strive towards making multiple (i.e., 3 or more) 160 MHz wide channels available for unlicensed use.

3. Service providers, consumer electronics vendors, networking vendors and building construction companies should adopt topologies of 1 AP per room (including combo APs with 60 GHz mmWave technology)

4. Device vendors should adopt 2 or more spatial stream capable radios in future product designs and 60 GHz mmWave technology where possible.

SEPTEMBER 2015

Making the Best Use of Unlicensed Spectrum for 1000x

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Contents

1 Executive summary

Trail-blazing innovations were at the heart of Qualcomm Technologies, Inc.'s 1000x vision when we introduced the concept some three years ago. In the eventful journey since, many of the innovations we cited, such as hyper-dense small cells, Licensed Shared Access, and others have evolved from mere concepts to viable commercial technologies. After rigorous prototyping, intensive testing, trials, and productization, they are now ready to enter the mainstream. Following the same trajectory, we are bringing new innovations that take one key component of the 1000x vision, more and better use of spectrum, even farther. These innovations enable operators to make the best use of unlicensed spectrum, through aggregation.

Although licensed spectrum is the foundation for mobile operators in addressing the 1000 data challenge, opportunistically utilizing the unlicensed spectrum is becoming increasingly important to respond to the growth of traffic in an economical manner. The best way for mobile operators to use the unlicensed spectrum is to aggregate it with an LTE anchor in the licensed spectrum. There are two general approaches: 1) LTE – Wi-Fi link aggregation, to leverage their Wi-Fi networks using both 2.4 GHz and 5 GHz bands; or 2) Even tighter, LTE operating in unlicensed 5GHz spectrum (LTE unlicensed), suitable for small cell deployments. Both of these options provide higher capacity and an enhanced user experience through a single unified network (versus separate LTE and Wi-Fi networks). The choice between the two aggregation options is dictated by the operator's existing assets and deployment plans, and we expect many operators to utilize both.

LTE - Wi-Fi link aggregation needs support from both device and network sides. On the device side, the aggregation happens deep at the modem-level. On the network side, it can either be between collocated or separate (but coordinated) Wi-Fi and LTE Wi-Fi access points (APs). LTE – Wi-Fi link aggregation is part of the larger LTE – Wi-Fi convergence that has already started happening, and is defined for 3GPP Rel 13. We demonstrated LTE – Wi-Fi link aggregation at MWC 2015, and are working with partners to bring pre-standard LTE – Wi-Fi link aggregation solutions to market as early as 2016.

LTE Unlicensed, in the form of LTE-U or LAA, offers the tightest possible aggregation. It can provide 2x or more capacity and better coverage than Wi-Fi. LTE Unlicensed is designed to fairly coexist with Wi-Fi, with features that go above and beyond minimum requirements, including regulatory, standards, and conformance testing. LTE Unlicensed provides multiple deployment options for operators. In countries such as the US, Korea and India, LTE-U can be deployed using existing Rel 10/11/12 with fair coexistence features as early as 2016. In Europe, and Japan, both of which have "Listen Before Talk" (LBT) regulatory requirements, standard changes are needed, which is being standardized in Rel. 13 and called Licensed Assisted Access (LAA).

The mobile industry has shown strong support for LTE-U and LAA, with trials and product announcements. Qualcomm Technologies, Inc. (QTI) is a founder member of LTE-U forum, a collaboration between industry players formed to harmonize specifications. QTI has announced LTE-U device and small cell solutions. And we demonstrated the performance of both LTE-U and LAA and how they will coexistence fairly with Wi-Fi, at MWC 2015.

LTE – Wi-Fi link aggregation and LTE Unlicensed solutions are tools for mobile operators in solving the 1000x challenge. Beyond mobile operators, Wi-Fi will continue to be the main option for private, and enterprise local areas access for years to come. QTI is committed to bringing path-breaking innovations to all aspects of the wireless ecosystem, be it licensed or unlicensed spectrum, LTE or Wi-Fi technologies, network operators or private users.

2 Opportunistically using unlicensed spectrum for 1000x

For operators addressing the 1000x challenge, licensed spectrum is the foundation. At the same time, opportunistically using the available unlicensed spectrum to augment the capacity is also extremely important. Many operators already have deployed their own Wi-Fi networks or are working with third party providers, or doing both. But the challenge is seamless interworking, as these Wi-Fi networks in many cases are not integrated with 3G/4G networks. This makes it difficult for devices to seamlessly discover and connect to them, without user intervention. Moreover, mobile operators have no control over the quality of the service. Both 3GPP and Wi-Fi communities (WFA et al.) have been working toward tighter LTE – Wi-Fi interworking. The resulting convergence, is shown here in Fig.1.

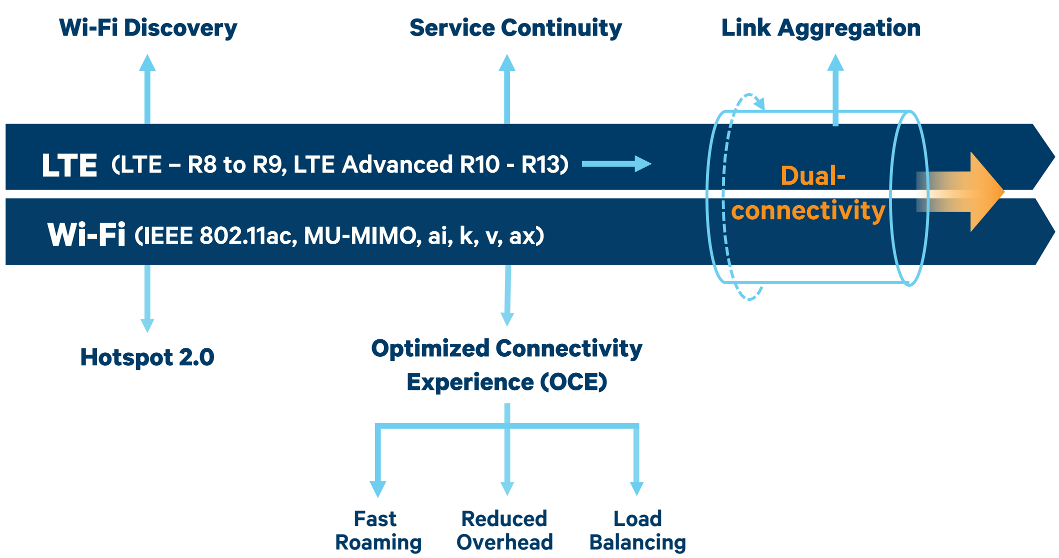

Fig. 1: 3GPP and Wi-Fi communities working toward tighter interworking of LTE and Wi-Fi

The elements of this "tighter' interworking range from seamless Wi-Fi discovery, to service continuity to link aggregation. For example, Hotspot 2.0, allows operators to extend SIM card-based authentication to Wi-Fi, and is deployed in commercial networks. Hotspot 2.0 coupled with discovery mechanisms defined in 3GPP, are making the process of discovering and connecting to Wi-Fi from LTE (and 3G) much more seamless. Following discovery was seamless service continuity of operator services from LTE to Wi-Fi networks, especially VoLTE and VoWi-Fi. Service continuity is being deployed in commercial networks.

Wi-Fi has evolved rapidly over the last decade, and continues to advance, offering successively higher data rates, capacity, and user experience. The latest version, 802.11ac realistically breaks the 1 Gbps barrier and its MU-MIMO feature delivers in increase in capacity. The next version, 802.11ax which is now in the works, will further increase performance. Most of these enhancements are benefiting private/enterprise and mobile operator deployments alike. The upcoming initiative called Optimized Connectivity Experience (based on 802.11ai, 11k and 11v) is especially focused on solving the challenges associated with dense deployments, which significantly benefit Wi-Fi networks deployed by mobile operators (often referred to as carrier Wi-Fi). Some of the features being introduced are: 1) Faster roaming between different APs or networks, which enables seamless, real-time services; 2) Marked reduction in management overhead; and 3) Intelligent load balancing, wherein, the users are steered towards APs that can provide the best connectivity based on loading, rather than only focusing on signal strength.

Looking at LTE – Wi-Fi interworking, what takes the performance much farther is going beyond standard defined interworking techniques and moving towards LTE – Wi-Fi convergence. As shown in Fig. 2, convergence involves providing an optimized link selection, seamless services, interference mitigation, and link aggregation between the LTE (and 3G) and Wi-Fi links, and beyond.

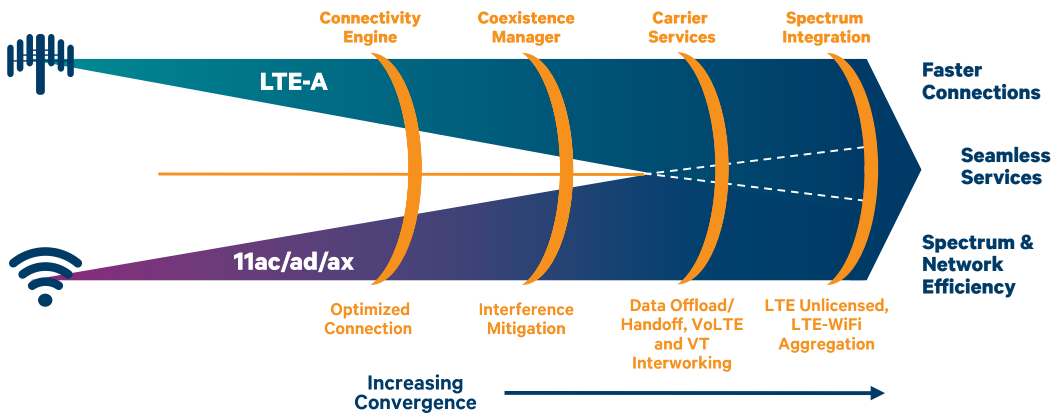

Fig. 2: LTE and Wi-Fi convergence

Convergence requires many enhancements in addition to the standard defined features, for example, the Connectivity Engine (CnE) from QTI in addition to supporting Hotspot 2.0, and discovery mechanisms defined in 3GPP, also incorporates proprietary algorithms to make the link selection much more intelligent. CnE also has all the key elements and smart algorithms needed to effectively deliver seamless service continuity, and so on.

2.1 Aggregating with a licensed anchor to get most out of unlicensed spectrum

In a wireless link, the signaling and control information is very crucial to not only maintain the robustness of the link but also to make sure the resource allocation is managed properly. It becomes even more critical in a dense deployment, where there is a lot of interference and all the nodes in the network are competing with each other for resources. In such cases, managing the resources and making sure that they are allocated in an orderly way is a basic need. Also, the resource allocation and the other signaling/control information has to be reliably communicated between the APs and devices—a task best handled by a robust link on licensed spectrum. This is one of the reasons, among many, why getting best performance out of unlicensed spectrum requires its aggregation with an LTE anchor in the licensed spectrum.

There are two options to achieve this aggregation, as shown in Fig. 3: LTE – Wi-Fi link aggregation and LTE Unlicensed (LTE-U or LAA).

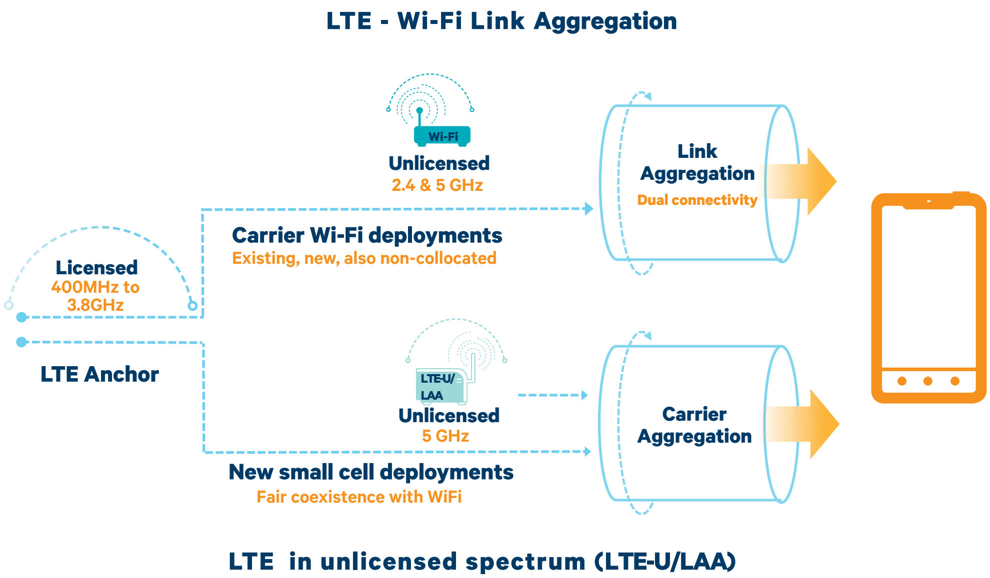

Fig. 3: Two options for aggregation: licensed and unlicensed spectrum. Many operators will use both

LTE – Wi-Fi link aggregation is for leveraging carrier Wi-Fi networks and uses both 2.4 GHZ and 5 GHz unlicensed bands. In this option, the LTE base station (eNodeB) will control the amount of traffic scheduled over Wi-Fi, and thereby ensuring proper load balancing between the LTE and Wi-Fi links.

LTE Unlicensed (LTE-U/LAA) is for new small cell deployments and uses 5 GHz unlicensed band. For both LTE-U and LAA, all the signaling and control is sent through the reliable, licensed anchor (the LTE network) and the unlicensed link is used only for data. This is one of the reasons why LTE Unlicensed can perform better than Wi-Fi alone.

Both options use a single, unified core network that provides cost efficiency and simplicity of management to operators, while offering seamless service continuity and a better broadband experience to users. The choice between the two aggregation options depends on the operators' current assets and future networks plans. We expect many operators to deploy both options.

3 LTE – Wi-Fi link aggregation for Carrier Wi-Fi

Simply put, LTE – Wi-Fi link aggregation combines a link from Wi-Fi with the anchor from LTE on licensed spectrum. As shown in Fig. 4 LTE and Wi-Fi APs don't even have to be collocated for aggregation.

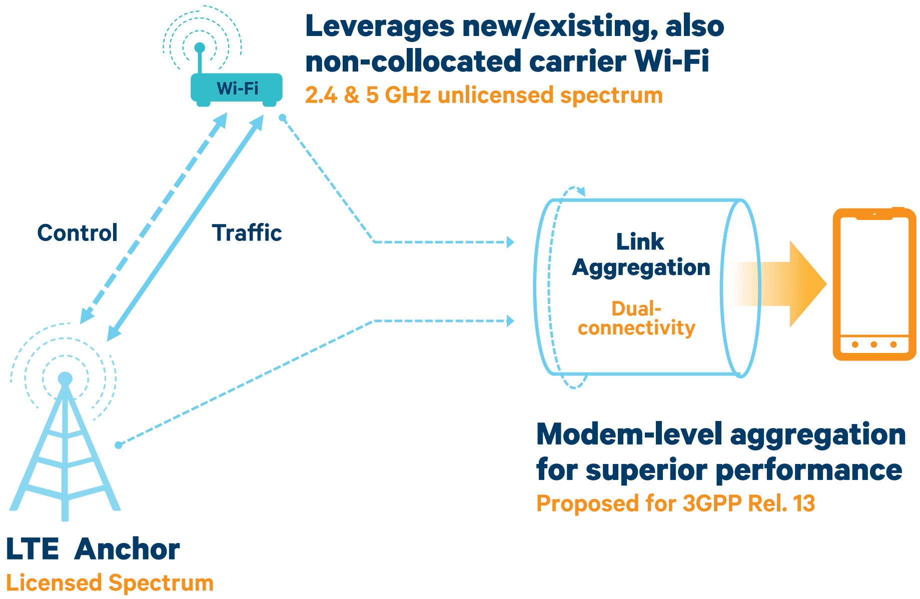

Fig. 4: LTE – Wi-Fi link aggregation for carrier Wi-Fi networks

Users will be simultaneously connected to both the links, enjoying higher data rates, and seamless mobility, as compared to separate (stand-alone) LTE and Wi-Fi networks. As mentioned before, many operators have already deployed their own Wi-Fi networks, and LTE – Wi-Fi link aggregation provides an excellent solution to better integrate them with the LTE network, and improve the overall performance. From the network perspective, Wi-Fi APs will be connected to the LTE network, just like any small cell would, and fully utilize LTE's core network, encryption, control, authentication, and other systems. The result is that LTE base station manage resource allocation of Wi-Fi AP. More importantly, since LTE and Wi-Fi APs don't have to be collocated, even LTE macros could be utilized. This means, once devices that support these features are deployed, the benefits of LTE – Wi-Fi aggregation will be available in short order, since only minimal changes will need to be made to the LTE and Wi-Fi infrastructure (depending on the vendors).

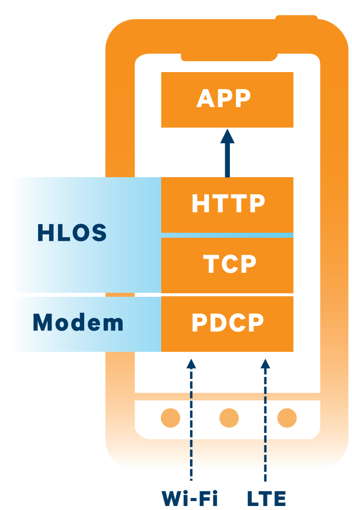

Fig. 5: Modem-level LTE – Wi-Fi link aggregation

Both 2.4 GHz and 5 GHz bands are supported and aggregation happens at the device, deep at the radio link level (PDCP layer) in the modem, as shown in Fig. 5

This is important because modem-level aggregation provides better load balancing (compared to other options) as LTE network is always aware of the loading and signal conditions of both the links and can balance traffic on the links accordingly. Additionally, it can quickly adapt to the fast changing link conditions, as compared to other options such as combining at the HTTP layer, in the high level operating system (HLOS), which are slow to adapt.

From the users' perspective, they are connected to both the networks, whenever available, and their data is intelligently distributed between the two links to provide the best performance. The aggregation of Wi-Fi link is seamless without any manual intervention, and is done whenever available and needed.

LTE – Wi-Fi link aggregation is proposed for 3GPP Rel 13, which is expected to be finalized in early 2016. We are working with partners to bring pre-standard LTE – Wi-Fi link aggregation solutions to market as early as 2016.

QTI has conducted a live demonstration of LTE – Wi-Fi link aggregation between a non-collocated LTE and Wi-Fi APs at MWC 2015, utilizing its over-the-air test network in San Diego. The demo also highlighted the seamless mobility between LTE – Wi-Fi aggregation and LTE only regions, as well as the performance of aggregation with less-than-ideal backhaul, which some Wi-Fi deployment might have1.

So, in essence, LTE – Wi-Fi link aggregation is an excellent choice for mobile operators to leverage their Wi-Fi networks, even when non-collocated, while utilizing both 2.4 GHz and 5 GHz bands to provide enhanced user experience, and better performance using a unified network.

4 LTE Unlicensed for new small cells

LTE Unlicensed extends the benefits of LTE Advanced to unlicensed 5 GHz spectrum and comes in three flavors; LTE-U and LAA aggregates unlicensed spectrum with a licensed spectrum anchor. The latest addition, MuLTEfire™ operates solely in unlicensed spectrum and broaden the LTE ecosystem to new deployment opportunities. MuLTEfire is not the focus here, but will also benefit mobile operators as an offload solution. LTE-U and LAA uses already commercial carrier aggregation feature to combine LTE on both licensed and unlicensed spectrums. LTE Unlicensed is ideal for new small cell deployments targeting 5 GHz unlicensed spectrum, which has up to 500 MHz[2] of bandwidth available in many regions of the world. LTE-U and LAArepresents the highest level of aggregation possible between the two spectrum types, as the same technology, same core network, and even the same small cells are used, as shown in Fig. 6.

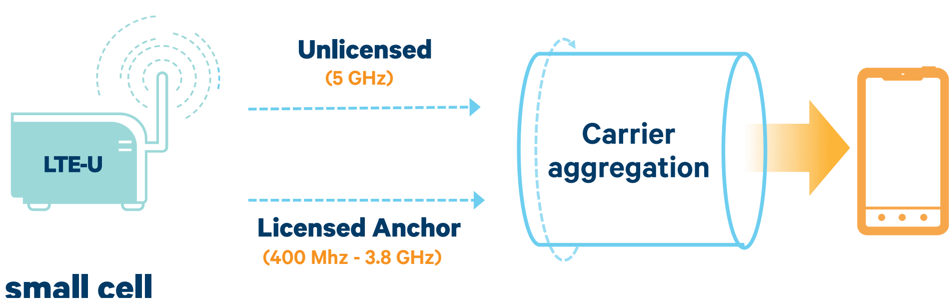

Fig. 6: LTE Unlicensed for new small cells

LTE-U and LAA can be deployed in either Supplemental Down Link (SDL) configuration, where unlicensed spectrum is used only for the downlink, or in a TDD configuration[3], in which, unlicensed spectrum is used for both uplink and downlink. Because of its simplicity, initial deployments will utilize SDL. LTE-U is defined as SDL and the initial release of LAA in Release 13 supports SDL, with evolution in Release 14 that is expected to define additional aggregation combinations.

All LTE Unlicensed solutions use the same LTE technology that has been designed for mobility from day one. LTE supports

MuLTEfire is an initiative of Qualcomm Technologies, Inc.
[1]I n the demo, non-ideal backhaul was simulated though increase in latency of up to 4 msecs
[2]Initial deployments may use a subset of the available spectrum, such as US UNII 1 and 3 bands

coordinated, synchronized scheduling of resources (instead of the contention-based approach used in Wi-Fi), and has an efficient radio link with features such as scaling to lower date rates, handling larger delay spreads, Hybrid ARQ (HARQ), among many others. Because of these features, along with the use of a robust and highly-reliable, licensed anchor for all signaling and control functions, LTE-U and LAA can provide 2x or more capacity under similar conditions in dense deployments. See Fig. 7.

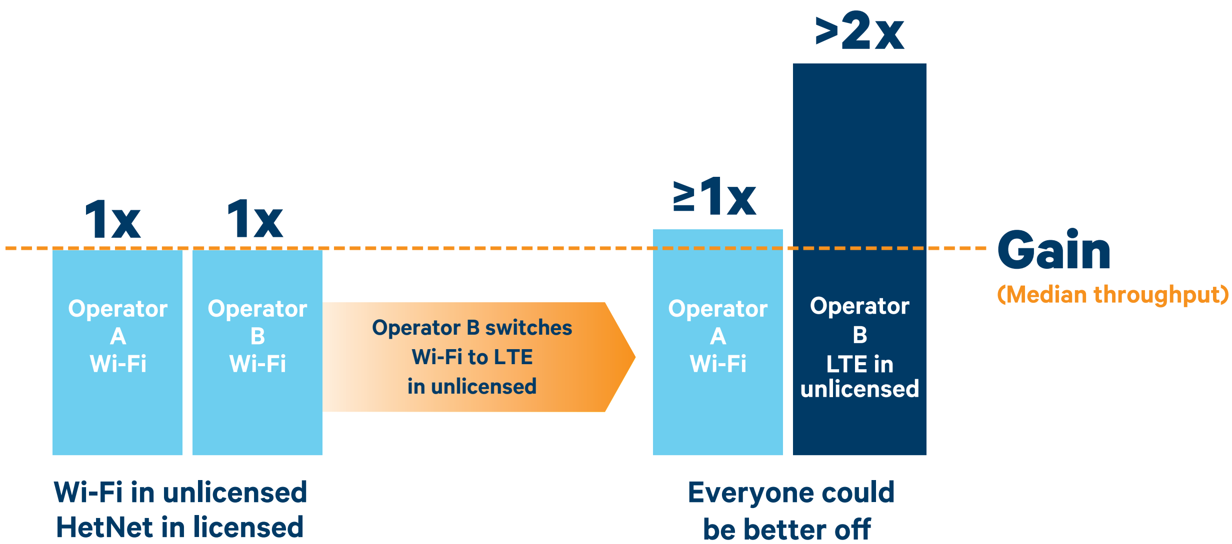

Fig. 7: LTE-U/LAA >2x better performance than Wi-Fi

A part of the higher capacity of LTE Unlicensed can also be traded off to provide better coverage as well. So, operators benefit from the higher capacity, better coverage and efficiencies of a common unified network. From the users' perspective, they enjoy enhanced, seamless user experience while using both the spectrum types, along with a “fatter” data pipe providing improved data rates (compared to LTE in licensed bands only).

Interestingly, LTE Unlicensed can also improve the performance of Wi-Fi in its vicinity, as shown in Fig.6. This is because, LTE being a coordinated system, all the devices collectively behave like a single device (from contention for resources perspective), effectively reducing overall interference. Thus LTE Unlicensed in many cases can be a better neighbor to Wi-Fi than Wi-Fi itself.

Right from conceptual state of LTE Unlicensed, we have paid a special attention to its fair coexistence with Wi-Fi— to be a good neighbor. The design incorporates many features that go above and beyond minimum requirements to ensure this fair coexistence.

LTE-U, a version of LTE Unlicensed defined by the LTE-U forum, can be commercially deployed in many countries such as the US, Korea, and India using existing 3GPP Rel 10/11/12, along with fair coexistence features. For Europe, Japan and beyond that have specific channel occupancy requirements, called “Listen Before Talk” (LBT), changes to the LTE waveform will be required, and hence a new standard will be needed. The new waveform and other changes are part of a work item for Rel 13, called Licensed Assisted Access (LAA)

The next section explains the concept of fair coexistence in detail.

Assumptions: Two operators. 48 Pico+108 Femto cells per operator. 300 users per operator with 70% indoor. 3GPP Bursty model. 12x40MHz @ 5GHz for unlicensed spectrum; LTE 10 MHz channel at 2 GHz; 2x2 MIMO, Rank 1 transmission, eICIC enabled; LTE-U – LAA R13, 2x2 MIMO (no MU-MIMO).; Wi-Fi - 802.11ac 2x2 MIMO (no MU-MIMO), LDPC codes and 256QAM).

4.1 LTE-U/LAA and Wi-Fi fair coexistence – going above and beyond minimum requirements

The need for fair coexistence with Wi-Fi is at the core of the LTE Unlicensed system design, and has been a major consideration from day one. To that end, enabling features are weaved in at multiple levels, which go above and beyond the minimum regulatory requirements. As illustrated in Fig. 8, coexistence features range from customary regulatory compliance to transmission levels and power levels, to features meticulously designed for early deployments in the US, Korea, and India using Rel 10/11/12-based LTE-U, to adherence to specific LBT channel occupancy requirements in regions such as Europe and Japan with Rel 13, Licensed-Assisted Access (LAA), and finally conformance testing before commercialization, which is expected to be more rigorous than testing performed for today's Wi-Fi systems.

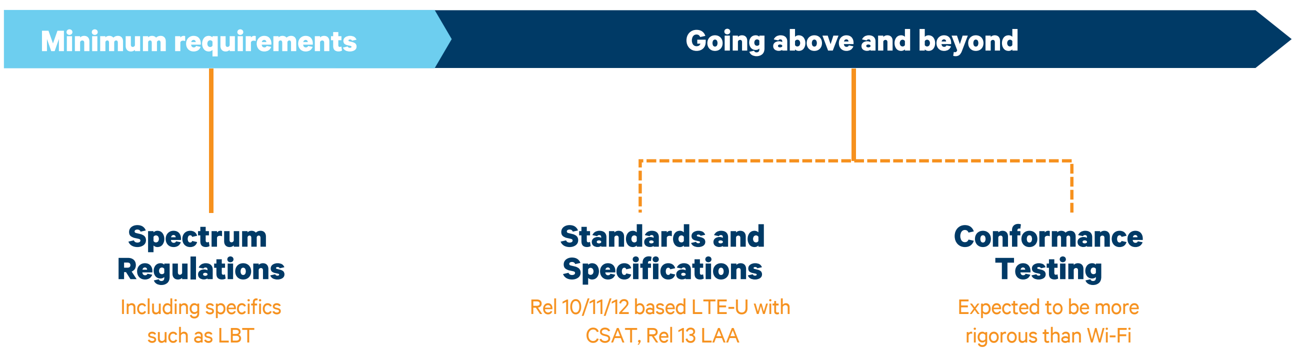

Fig. 8: LTE Unlicensed and Wi-Fi fair coexistence, going above and beyond minimum requirements

Both LTE-U and LAA uses unlicensed spectrum only when the data boost is needed, or else it will only rely on the licensed spectrum. When using unlicensed spectrum, it dynamically selects a channel that is not occupied by Wi-Fi (or other LTE Unlicensed users). With up to 500 MHz of available spectrum in the 5GHz band, there is a good possibility that it can get a free channel. If it can't, it has to share the channel with Wi-Fi (aka co-channel), and that's when the fair coexistence mechanisms kick-in. Depending on the geography, fair coexistence works in two ways. In countries such as the US, Korea, and India, where LTE-U can be deployed using Rel 10/11/12, coexistence will be achieved through an approach we call CSAT (Carrier Sensitive Adaptive Transmission). In regions such as Europe and Japan, the coexistence will be based on Rel-13 LAA, which inherently supports LBT channel occupancy regulatory requirements.

The basic idea of co-channel coexistence is time sharing based on channel sensing. The time scale can be a bit longer in CSAT and very short with LAA. Fig. 9 illustrates the working of CSAT with an example.

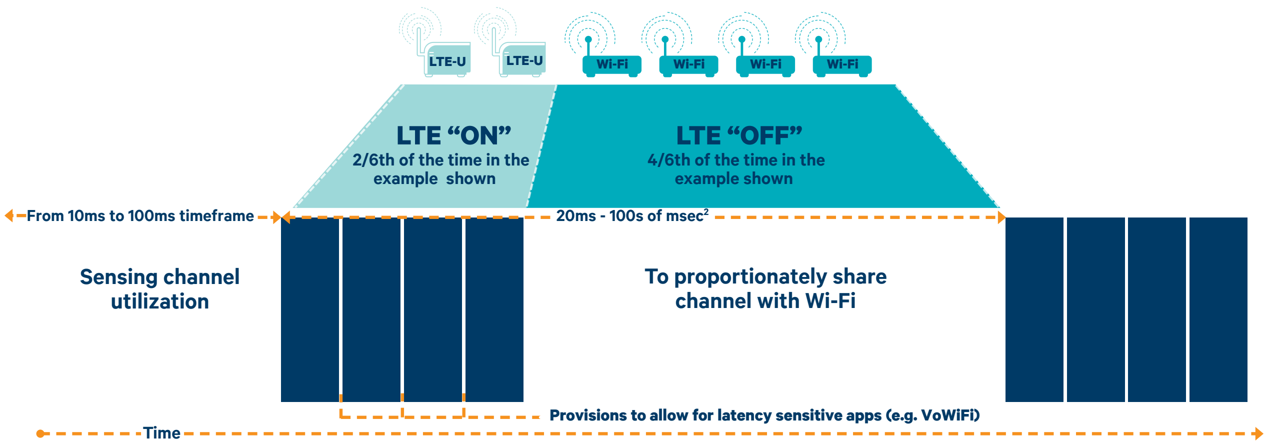

Fig. 9: Illustration of LTE-U/Wi-Fi fair coexistence based on CSAT

When LTE-U is off, it senses channel utilization by estimating the number of Wi-Fi APs, and turns itself OFF to give proportionate time to Wi-Fi. In the example shown, LTE-U senses the channel and understands that there are four active Wi-Fi APs in the vicinity. And of course it knows there are two LTE-U APs. So, it keeps LTE-U ON for 2/6th of the time, and LTE-U OFF for 4/6th of the time, allowing Wi-Fi APs to use the channel as they would normally do. The time scale for CSAT is configurable and can be as short as 20milliseconds to as long as 100s of milliseconds. Additionally, LTE-U also turns OFF for several times for a very short duration, during its designated ON time, to allow for latency sensitive applications such as VoIP over Wi-Fi to send and receive their packets.

QTI is a founding member of a consortium of industry leaders called the LTE-U Forum (**www.lteuforum.org**). The LTE-U Forum has published minimum performance and coexistence specifications for operating LTE-U base stations and consumer devices on unlicensed frequencies in the 5 GHz band. CSAT is fully complaint with the LTE-U Forum specifications.

In Rel 13, LAA, although the sharing concept is similar, there are subtle differences because of specific requirements of LBT (as defined in ETSI EN 301 893 V1.7.1). LAA senses the channel every 20 microseconds, and if free, occupies it for the next 1 - 10 milliseconds, the time can be set for dynamic utilization similar to CSAT, as illustrated in Fig. 10. If the channel is busy, it waits for a specific amount of time, based on a randomized counter (per LBT regulations), and then senses the channel again — and so on. In this manner, both LTE and Wi-Fi share the channel "fairly."

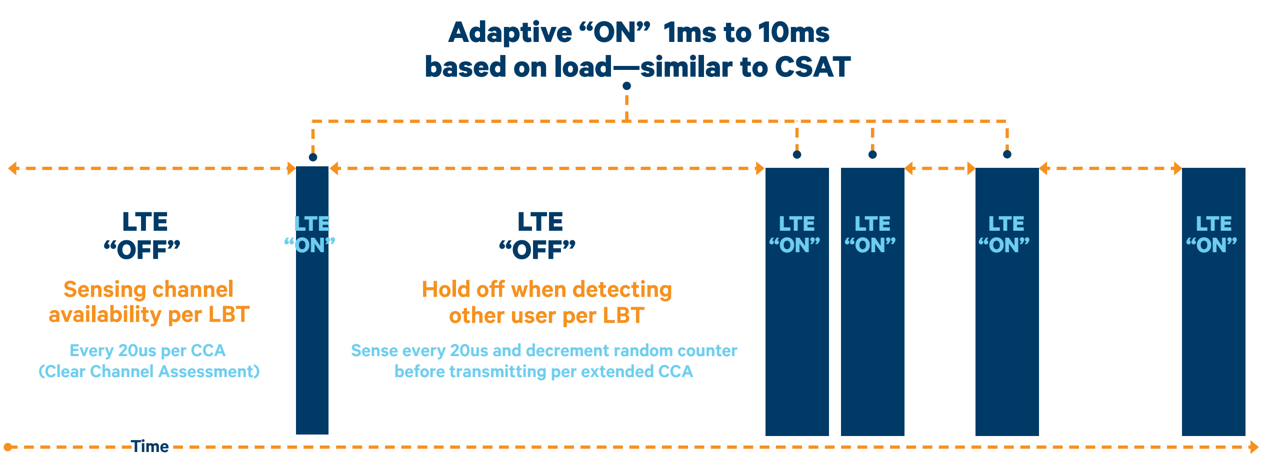

Fig. 10: Illustration of Rel 13, LAA based fair sharing supporting LBT

QTI has extensively tested both LTE-U with CSAT and Rel 13 LAA in the lab as well as in the over-the-air test network, to ensure that they work as intended in fairly sharing the unlicensed spectrum between LTE Unlicensed and Wi-Fi. Both were also demonstrated to the public at Mobile World Congress 2015 and CES 2015 (LTE-U with CSAT only).

For more technical details, please refer to this: **LTE-U/Wi-Fi fair coexistence whitepaper.**

5 Strong industry support for LTE – Wi-Fi link aggregation & LTE-U

LTE – Wi-Fi link aggregation has strong industry support. It is planned for Rel 13, supported by many industry players. We are working with operators and infrastructure vendors to bring interoperable solutions to market ahead of an approved standard, while supporting standards activities in 3GPP. One operator officially announced its demonstration of LTE – Wi-Fi link aggregation at MWC 2015. We demonstrated LTE – Wi-Fi link aggregation at MWC 2015, using our prototype set-up, as well as with a leading infrastructure vendor.

LTE Unlicensed has witnessed tremendous support from the various quarters of the mobile industry. Some operators have announced plans to trial the technology in 2015. Some infrastructure vendors have announced product plans and release dates. Many industry players conducted LTE Unlicensed demonstrations at MWC 2015 and QTI has partnered with most of them. QTI also announced the industry's first LTE-U solutions: FSM99xx SoC for small cells and RF Transceiver WTR3950 for devices, both are expected to be available in the second half of 2015 for commercial deployments in 2016. The FSM99xx solution supports LTE-U (Rel 10) with CSAT coexistence features, and is designed for enterprise and metro small cells. The WTR3950 pairs with the WTR3925, supporting 3x20 MHz carrier aggregation, including 5 GHz band. A new industry consortium, the LTE-U Forum, of which QTI is a founding member, has been formed to bring different stakeholders together and harmonize specifications. The LTE-U Forum published minimum performance and coexistence specifications in March 2015. Licensed Assisted Access (LAA) with LBT got formally approved as a work item in Rel 13 in June 2015. Extensive Industry collaboration across the Wi-Fi and mobile industries are helping to further refine coexistence specifications and test cases, to ensure that LTE Unlicensed is a good neighbor to Wi-Fi.

6 Conclusion

As operators march toward addressing the 1000x data challenge, they are looking at all available avenues to leverage more spectrum. Licensed spectrum remains the main foundation, while leveraging available unlicensed spectrum is also extremely important. Realizing this, many are already investing in Wi-Fi networks to opportunistically offload data. But interworking between LTE and Wi-Fi is a major challenge in terms of providing seamless user experience and giving mobile operators the ability to fully manage their Wi-Fi networks. Both the 3GPP and Wi-Fi communities (IEEE, WFA et. al.) are working toward a "tighter" interworking of LTE and Wi-Fi technologies. QTI is working on solutions to enable an LTE – Wi-Fi convergence, which takes their performance even higher.

FSM99xx and WTR3950 are products of Qualcomm Technologies, Inc.

Going forward, operators have two aggregation choices to best utilize unlicensed spectrum: LTE – Wi-Fi link aggregation, and LTE-U/LAA. Both will aggregate the unlicensed spectrum with an LTE anchor in the licensed spectrum and provide better performance and enhanced user experience using a unified network.

LTE – Wi-Fi link aggregation is a major step toward the convergence of these two technologies, and it is useful for mobile operators that either already have, or are planning to deploy Wi-Fi in the future. It utilizes both 2.4 GHz and 5 GHz bands. And importantly, LTE and Wi-Fi APs don't have to be collocated. On the other-hand LTE-U and LAA takes convergence to a different level, by offering and aggregating LTE on both licensed and unlicensed spectrums, specifically the 5 GHz unlicensed band. This solution is ideal for small cells. Since LTE-U and LAA uses the same technology, same network, and the same small cells, it represents the tightest possible convergence between the two spectrums, and hence offers better performance. The decision between the two options depends on the operators' existing assets and future network plans. We expect many operators to deploy both, as these solutions address different needs.

LTE Unlicensed has been designed specifically to fairly coexist with Wi-Fi, with many features and provisions that go above and beyond minimum requirements. This involves complying with regulatory requirements, adopting coexistence features such as CSAT for deploying with LTE-U (based on Rel 10/11/12) in the USA, Korea, and India, as well as adhering to Rel 13, LAA standard, in countries that have specific LBT requirements (i.e., Europe and Japan), and finally, compliance testing before commercialization, which is expected to be more rigorous than testing for today's Wi-Fi systems. And the third member of the LTE unlicensed family, MuLTEfire, promises to further broaden the deployment opportunities for LTE, especially for harder-to reach indoor locations. MuLTEfire operating solely in unlicensed will also benefit mobile operators through offload partnerships or through own deployments, for example in locations where LTE licensed spectrum is unavailable.

There is strong industry support for both LTE – Wi-Fi link aggregation and for LTE Unlicensed. LTE – Wi-Fi link aggregation is proposed to Rel 13, supported by many industry players. QTI demonstrated LTE – Wi-Fi link aggregation at MWC 2015. Looking at LTE Unlicensed, many operators and infrastructure vendors, as well as QTI, have announced trial plans, products and more. We demonstrated both LTE-U and LTE at MWC 2015 and CES 2015, highlighting its superior performance and its ability to fairly coexistence with neighboring Wi-Fi networks. A new industry consortium the LTE-U Forum, of which QTI is a founding member, has been formed to bring different stakeholders together and harmonize specifications. We are committed to making the best use of unlicensed spectrum in helping mobile operators address the 1000x data challenge.