Qualcomm Technologies, Inc.

A Quantification of 5 GHz Unlicensed Band Spectrum Needs

Rolf de Vegt
George Cherian
Gwen Barriac
Qingjiang Tian

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Qualcomm Technologies, Inc.

5775 Morehouse Drive

San Diego, CA 92121

U.S.A.

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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.

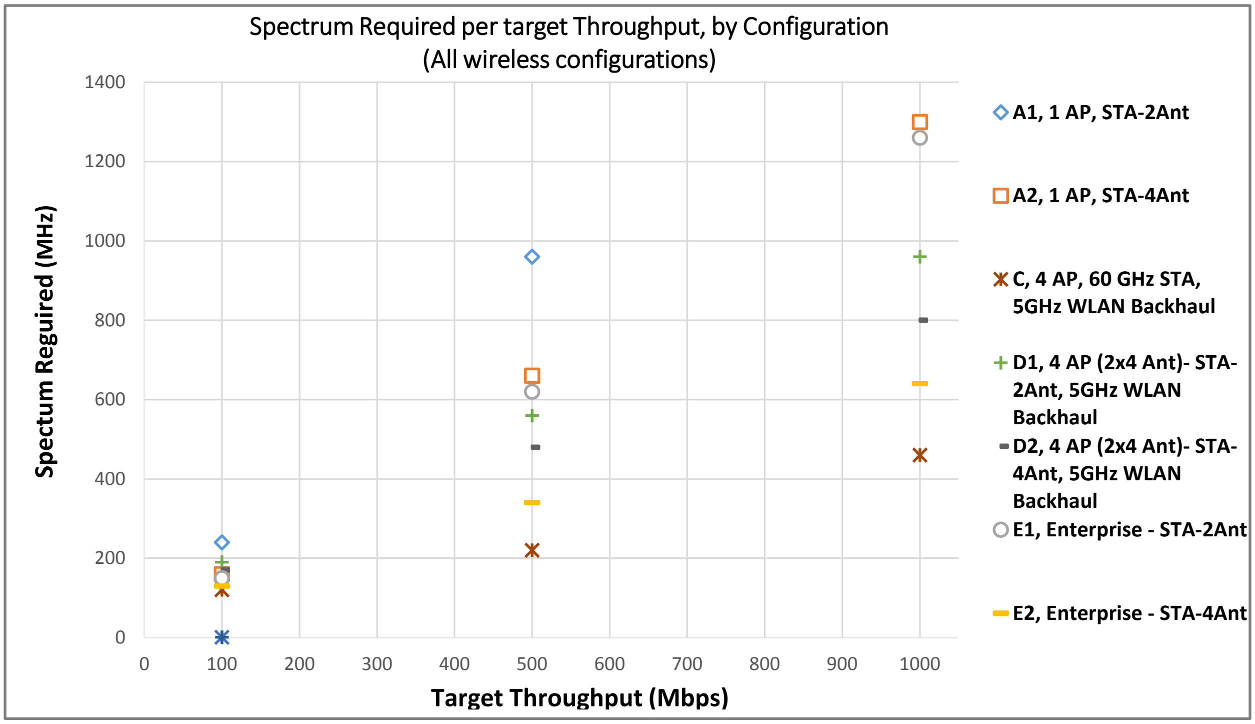

Figure 1. Overview of spectrum required by target throughput (100, 500, and 1000 Mbps) for all wireless configurations

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.

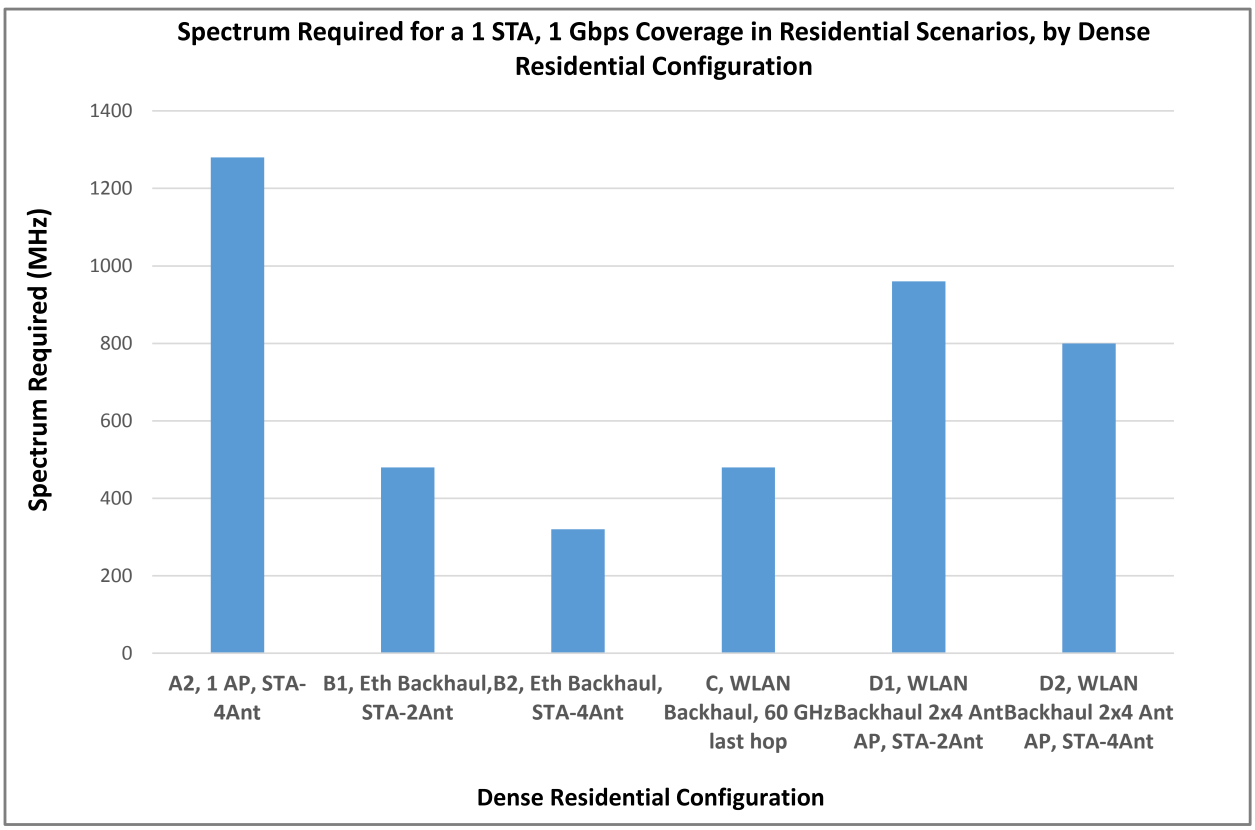

Figure 2. Spectrum required to achieve 1 Gbps coverage in a dense residential setting, by configuration

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.

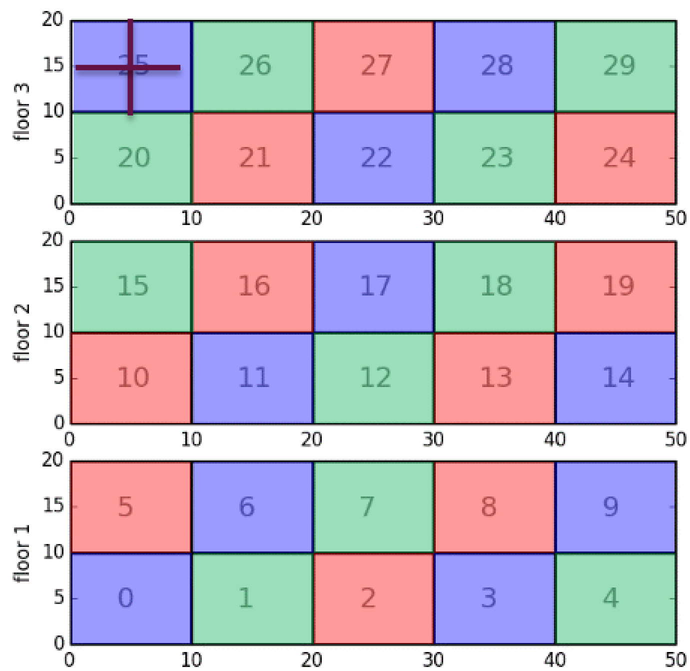

Figure 3. Layout of the IEEE dense residential simulation scenario

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.

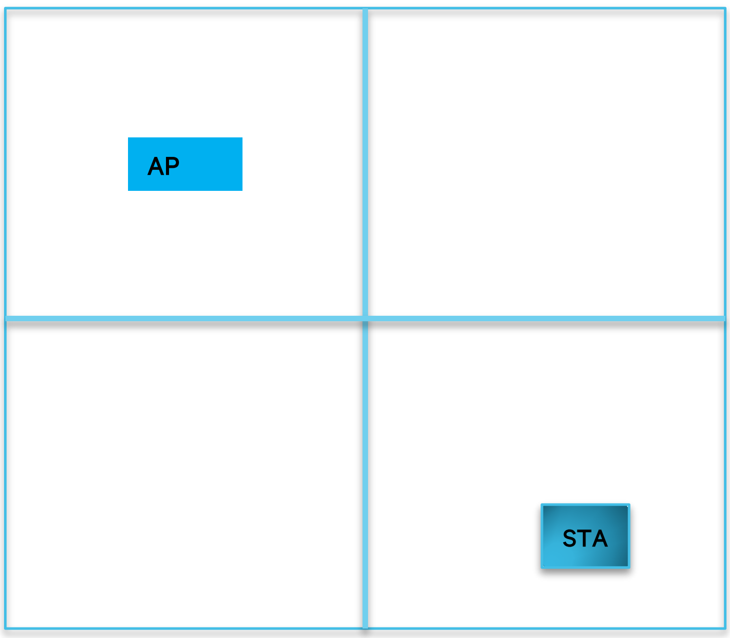

Figure 4. Configuration A, Single AP per apartment

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.

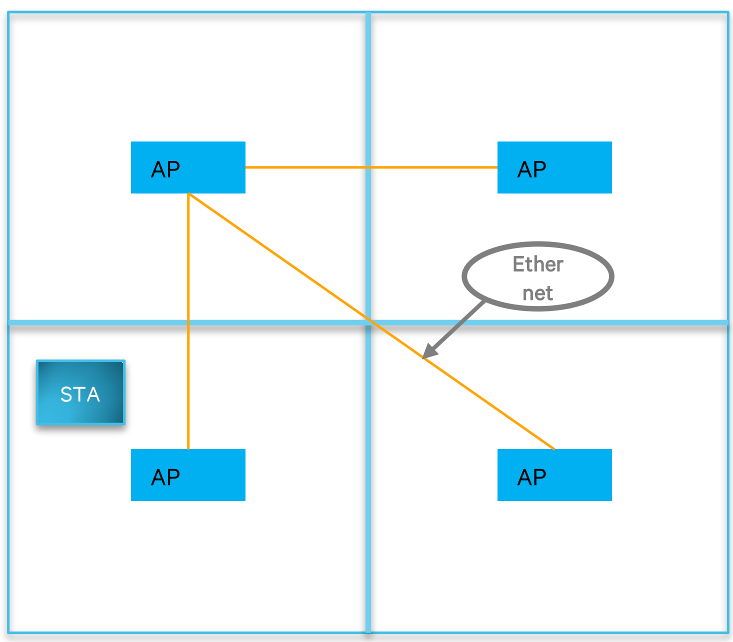

Figure 5. Configuration B, 4 APs per apartment, Ethernet connection between APs

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.

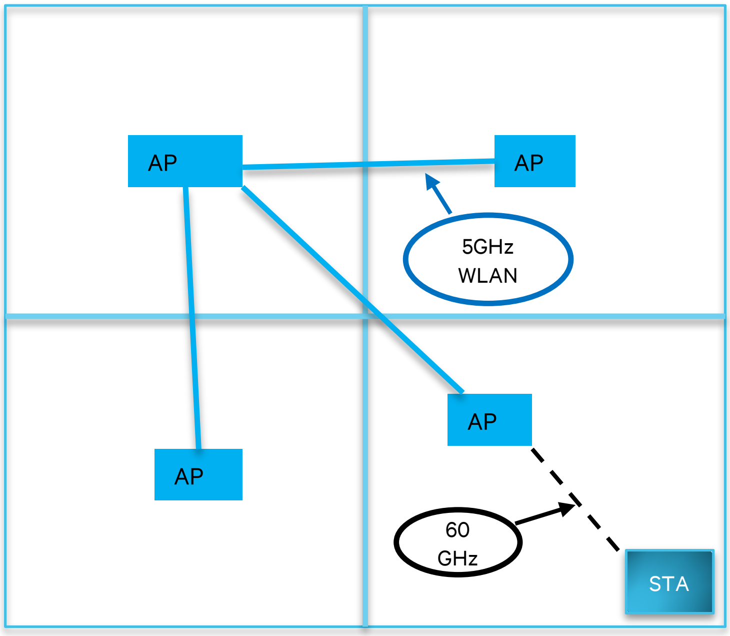

Figure 6. Configuration C, 60 GHz last hop connection between STA and AP, 4 APs per apartment, 802.11ax WLAN connection between APs

	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.

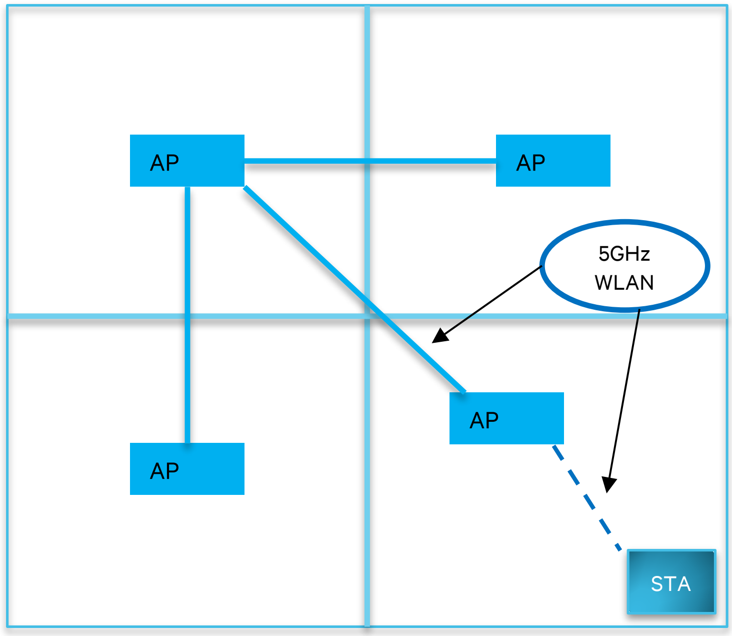

Figure 7 Configuration D, 5 GHz WLAN last hop connection between STA and AP,
4 APs per apartment, 5 GHz WLAN connection between APs

	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.

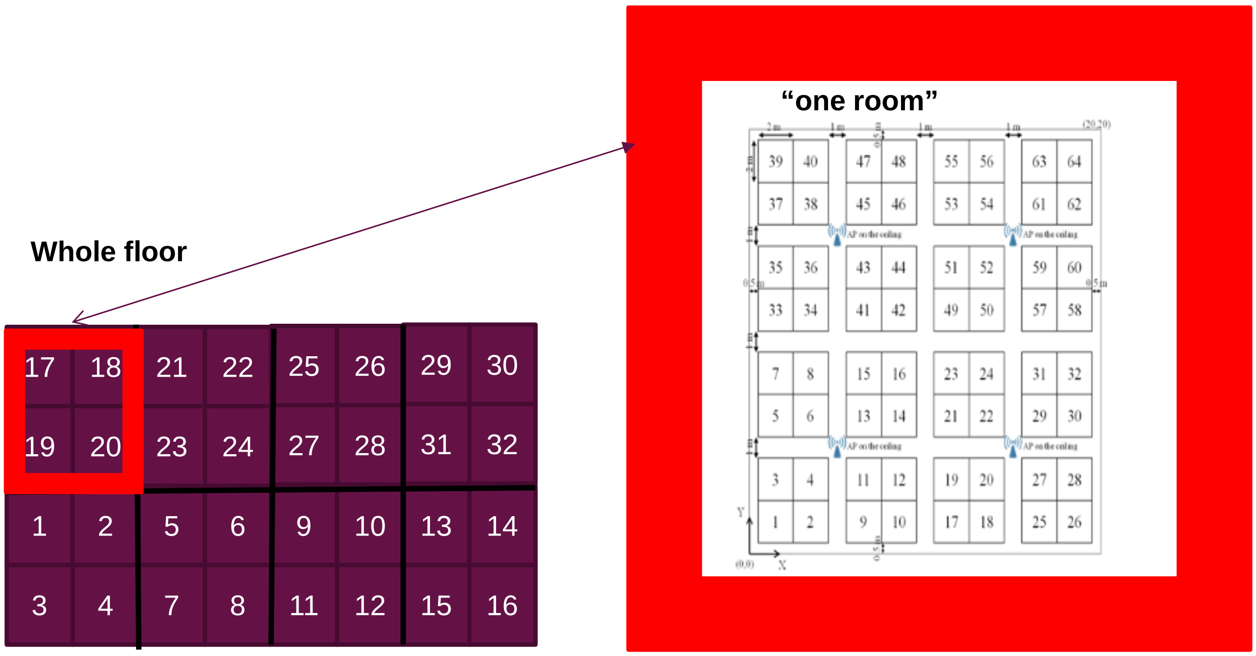

Figure 8. Configuration E, Enterprise scenario

	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.

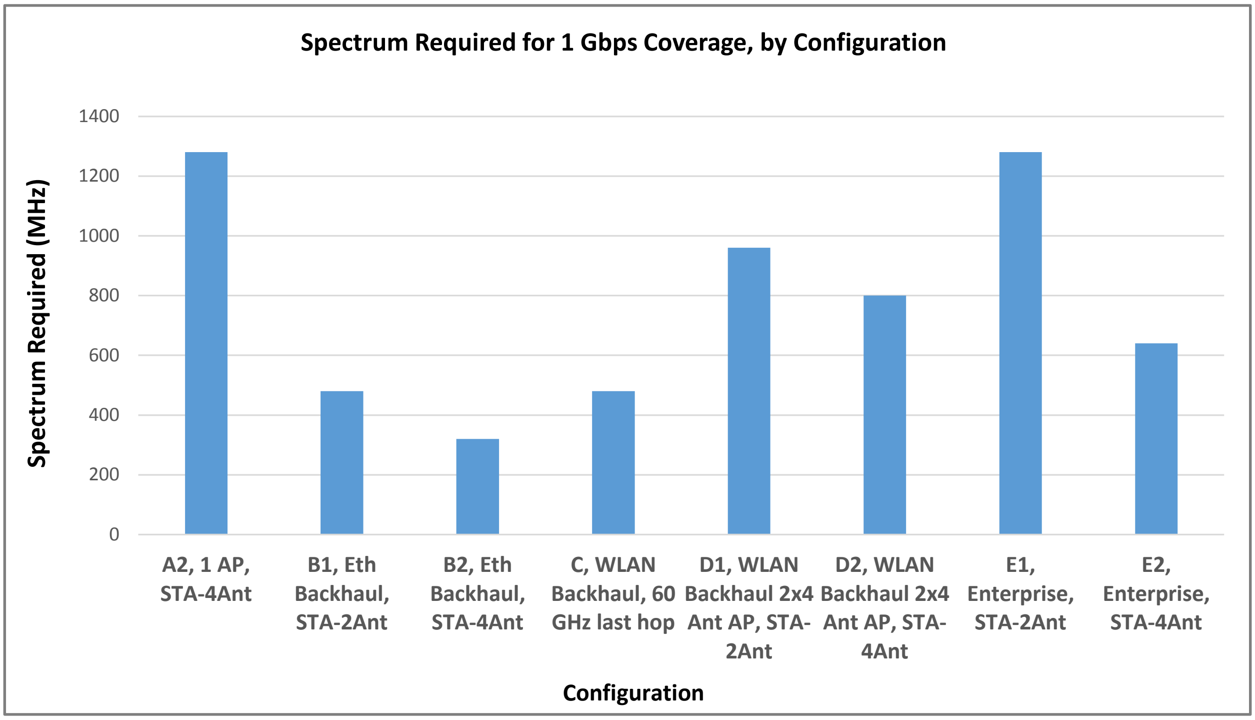

Figure 9. Spectrum required to achieve 1 Gbps coverage by configuration

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:

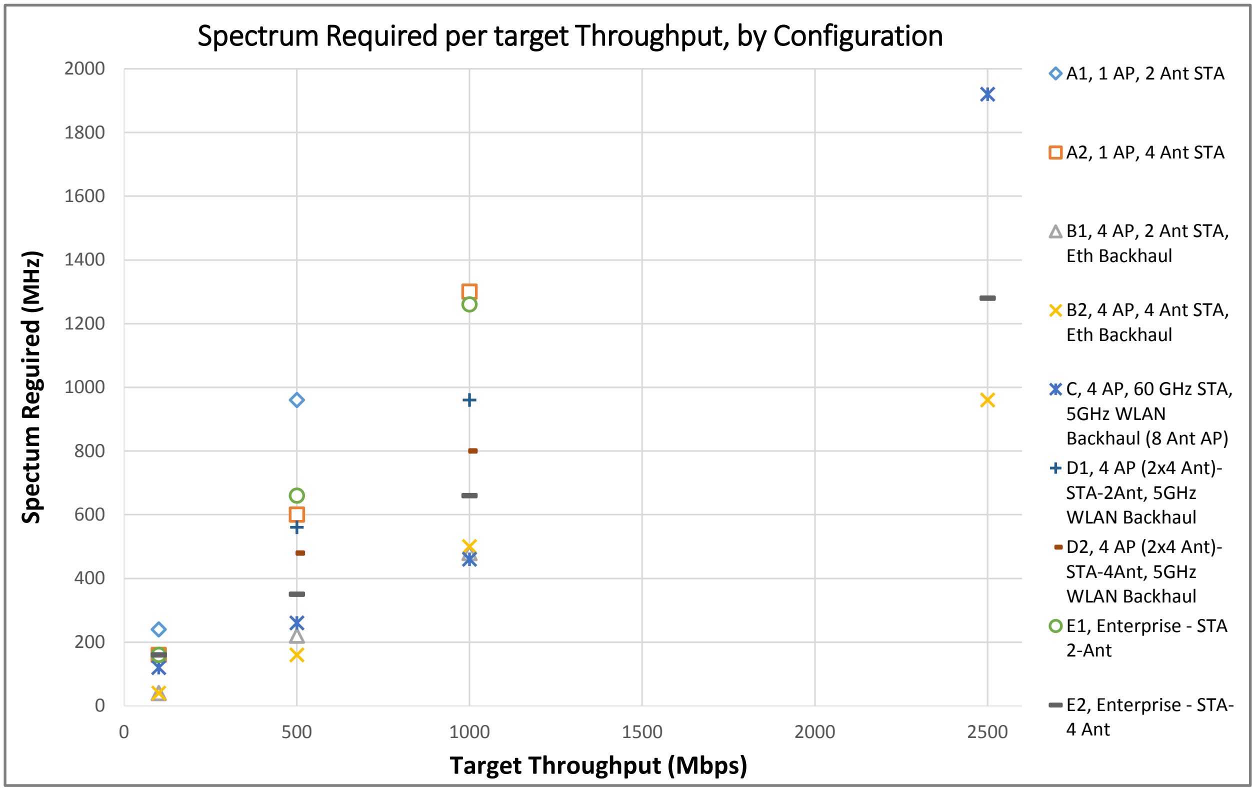

Figure 10. Overview of spectrum required by target throughput (100, 500, 1000, 2500 Mbps), all configurations

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.

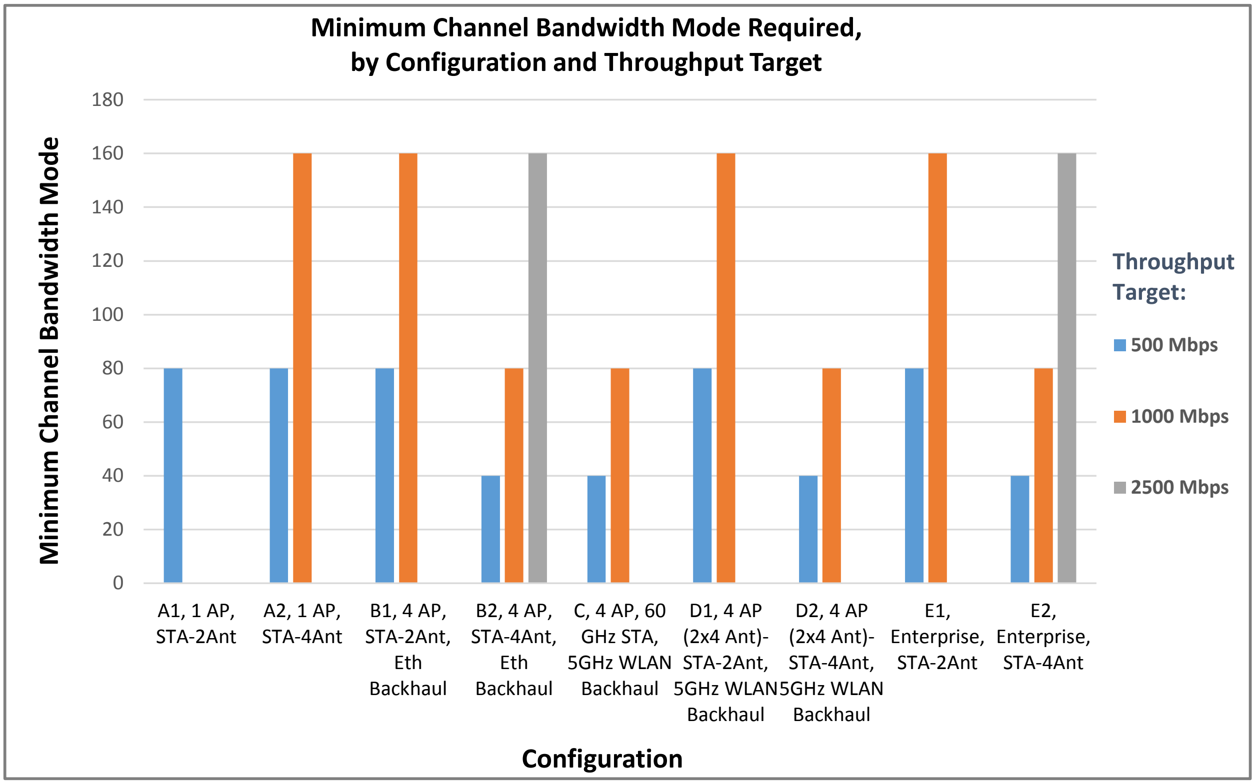

Figure 11. Minimum required bandwidth channel mode by configuration and throughput target

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.