White Paper

Next Generation Wi-Fi

Spectrum Needs of Wi-Fi 7

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Executive Summary

Availability of new spectrum resources in the 6 GHz band has provided a long-sought, much-needed boost for Wi-Fi. In some leading countries, new access to this spectrum empowers Wi-Fi 6 and the upcoming Wi-Fi 7 to take advantage of the technological advancements brought about by the standards, including the implementation of multiple 320 MHz channels, which have not previously been available. Wi-Fi 7 will be able to utilize large 320 MHz channels to allow users to benefit from new and emerging applications that extend well beyond traditional Internet connectivity. These applications have stringent requirements, some of which were not readily attainable with previous generations of Wi-Fi.

In this paper, the impact of spectrum availability on the performance of demanding Wi-Fi deployment scenarios is analyzed by assessing Key Performance Indicators (KPI) as the number of available 320 MHz channels is varied from one to three. The KPIs assess latency and reliability for emerging applications such as Augmented Reality/Virtual Reality (AR/VR) in various environments including in enterprise and industrial settings. Through extensive simulations of numerous scenarios, it is demonstrated that in moderate to high traffic load environments, e.g., enterprises, industrial plants, homes, hotspots, the availability of a single 320 MHz channel is insufficient to meet the KPIs of these emerging applications. In particular, the latency performance goals cannot be met while maintaining the required reliability target. It is also shown that only when three non-overlapping 320 MHz channels are available can the latency performance and reliability be kept at acceptable levels, including for highly loaded scenarios.

Based on this extensive study, it is concluded that the needs of licensed emerging and future wireless applications and services require access to three non-overlapping 320 MHz channels. Practically, this can only be achieved if the entire 6 GHz band (5925 MHz – 7125 MHz) is authorized for unlicensed (a.k.a. license-exempt) operation. The study indicated another important conclusion: that if regulators only authorize the lower 500 MHz of the band (5925 MHz - 6425 MHz), meaning that only a single 320 MHz or three 160 MHz channels would ever be available, a significant number of moderate to demanding future applications will not function as intended and therefore residential, enterpirse, gov't and industrial IoT users will not benefit from these applications.

Introduction

More users, more devices per user, increasing data demand for existing applications, and new bandwidth-hungry applications in both consumer and enterprise segments are expected to generate significantly higher amounts of data traffic and drive the need for sufficient license-exempt spectrum in the coming years. In addition to higher throughput, which has been stretching the capabilities of Wi-Fi 6 in the 5 GHz band to the limit, some of these new and emerging applications come with stringent latency and reliability requirements. In the meantime, the introduction of Wi-Fi 6E in support of upcoming deployments in the 6 GHz band in certain geographies has opened a much-needed door to a new environment where the most recent advancements in technology can find a place to flourish.

When Wi-Fi operation is limited to the 2.4 GHz and the 5 GHz bands, there is insufficient bandwidth to accommodate the growth in demand with the expected Quality of Service (QoS) of the current applications (video streaming, gaming, voice, etc.) and, at the same time, to enable new innovative services and usage scenarios that make use of the Wi-Fi network. Therefore, user experience is compromised due to channel congestion. Allocation of the 1200 MHz of contiguous spectrum in the 6 GHz band to unlicensed operation provides sufficient bandwidth such that Wi-Fi 6E and the next generation of Wi-Fi, namely Wi-Fi 7[1], can benefit from the cleaner, non-overlapping performance of larger channel bandwidths up to 320 MHz.

This paper underlines the expected performance and significant importance of the availability of three non-overlapping 320 MHz channels for the developments and future deployments of Wi-Fi 7 by analyzing the behavior of a fast-emerging. time-sensitive application, namely AR/VR, which has been moving away from mere entertainment and finding its place in many emerging enterprise and industrial segments.

Wi-Fi 7 Applications and Deployment Scenarios

Building on the success of Wi-Fi 6 (based on IEEE 802.11ax), Wi-Fi 7 (based on IEEE 802.11be) will boast physical layer throughput speeds up to 23 Gbit/s through the use of 320 MHz-wide channels, higher-order modulations (4096-QAM), and eight spatial streams, and will operate in license-exempt frequencies up to 7.125 GHz. Wi-Fi 7 will reduce transmission latency and jitter and increase transmission reliability to meet QoS requirements of time-sensitive applications such as AR/VR.

More specifically, video traffic will continue to be the dominant traffic in many Wi-Fi deployments. With the emergence of 4k and 8k video (uncompressed rate of 20 Gbps), we are experiencing these applications' ever-increasing throughput and bandwidth requirements.

Demand for new high-throughput, low-latency applications, such as AR/VR, remote office, cloud computing, and gaming is rapidly increasing. These applications, which are envisaged to be used in a variety of environments, including homes, enterprise, and industrial plants, require enhanced throughput and reliability, reduced latency (e.g., latency lower than 5 ms for real-time gaming) and jitter, and improved power efficiency in Wi-Fi networks.[2] Advanced AR/VR applications require 4k-8k video, minimum throughput of 400-2350 Mbit/s and a maximum streaming/interactive latency on the order of 10 ms. (See Appendix 3 for a list of requirements in industrial settings.)

Wi-Fi 7 will also define mechanisms that can enable deterministic operation by introducing features that provide predictable latency and jitter. Improved integration with Time Sensitive Networks (TSN) to support applications over heterogeneous Ethernet and Wireless LANs is targeted in Wi-Fi 7. IEEE 802.11be aims at further improvement of aggregate throughput and latency over these networks in the coming years.[3] Wi-Fi 7 also provides enhanced support for existing indoor/outdoor residential and enterprise deployments while enabling vertical and industrial IoT applications that require an advanced level of determinism and reliability performance.

Analysis of Key Performance Indicators (KPI)

A KPI refers to a system parameter heavily influenced by, and important for, the design of the system. KPI values are indicative of how well the system performs at several levels and are often used in comparison with similar technologies or previous generations of the same technology.

Major KPI categories of Wi-Fi 7 are depicted in Figure 1.

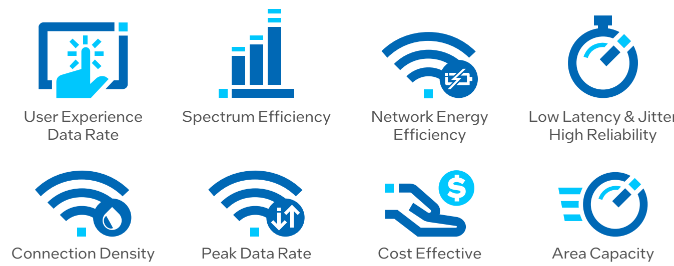


Figure 1. Major KPI categories of Wi-Fi 7

While all KPI categories shown in Figure 1 are important to support various use cases and applications, some of them have direct implications on spectrum requirements (e.g., channel sizes and number of contiguous channels) of Wi-Fi 7. Among those, peak data rate, spectrum efficiency, and low bounded latency are the most important KPIs in enabling new applications.

Spectrum Implications of KPIs

In designing future wireless systems, system architects are usually faced with two important considerations in mind:

1. designing based on the foreseen demand of anticipated usages and applications (e.g., a "killer app"), and
2. designing towards enabling certain KPIs in given deployment scenarios.

First, it is noted that trying to plan and design based on predicting the so-called "killer app" of the future is often futile. Much better results are achieved by adding innovative new capabilities to current applications. An example is sensing/gesture recognition capabilities currently being added to various wireless devices. By creating the capability to distinguish small objects' movements, a door is opened to an array of new applications, including touch-free control of machines, which has gained traction given health issues related to touching public surfaces like elevator buttons, mall directories, etc.

KPIs, along with certain other system design elements, directly or indirectly impact spectrum and regulations. In enabling capabilities, one needs to pay attention to the KPIs of a future system. Continuing with the touch-free example, one important KPI is the range resolution. A range resolution on the order of a meter has very different system implications than one of 1 cm. This is from an implementation point of view but related to the applications it can enable. These two resolutions enable potentially very different applications, e.g., presence detection vs. hand/finger gesture recognition. The target KPI has a direct impact on how much spectrum is needed to enable this capability. In this example, while a resolution of 1 meter could be achieved with a couple of hundred MHz of spectrum, going down to 1 cm would increase the required bandwidth to more than 10 GHz.[4]

The trade-off between throughput and latency/determinism requirements can also impact spectrum needs. Emerging applications need lower latency with determinism/reliability as well as high throughput. To provide strict latency guarantees, there is a need to reserve resources for some applications, which may lead to inefficiencies and fewer resources available for other applications. The competition for resources between applications and neighboring networks is a major cause of variable and typical high worst-case latencies in current Wi-Fi deployments. Future applications will need both high throughput and latency guarantees, which would be very hard to meet under resource limitation constraints.

Spectrum Needs

Continuing with the methods described above, we now turn our attention to latency, reliability, and determinism, which have been improved considerably in Wi-Fi 7, along with throughput, to enable time-sensitive applications such as AR/VR, industrial IoT, and high-end gaming.

Emerging applications such as AR/VR, industry 4.0, mobile and collaborative robotics require ultra-reliable low latency communications. Leading to the IEEE 802.11be (Wi-Fi 7) project kick-off, the IEEE 802.11 working group published a study of real-time applications (RTA) and their requirements.[5] The IEEE 802.11 RTA report described time-sensitive applications that need lower latency with determinism or very high-reliability guarantees, and in some cases, also have extremely high throughput requirements. For instance, according to the report, AR/VR applications generally require end-to-end latencies of under **10 ms** with **99.9%** reliability and single-stream throughput of around **100 Mbit/s**. Such time-sensitive requirements mean that the Wi-Fi 7 induced latency must be as low as possible, stable and preferably bounded with very high probability. (See Appendix 3 for details.)

Vision-based perception and control of collaborative robots in industrial and enterprises is another example application that requires both low latency and high throughput. Provisioning resources with exclusivity is the fundamental tool to guarantee deterministic latency and reliability in any network shared by a range of applications, which is the expected scenario for Wi-Fi 7 networks. Competition for resources between networks and applications is a major issue that causes variable and typically high worst-case latencies observed in existing Wi-Fi deployments. Future applications and Wi-Fi 7 networks will need to address the trade-off between extremely high throughput and deterministic low latency guarantees, which would be very hard to meet simultaneously if there are constrained spectrum resources. Some of the limitations of the existing spectrum resource models are illustrated in the next section.

Simulation Setup

To arrive at Wi-Fi 7 spectrum needs based on supported KPIs, it is required to analyze the performance of the most demanding applications running on the largest bandwidth supported by the standard, i.e., 320 MHz. Simulations were performed for various deployment scenarios with one to three Access Points (AP) and several client devices communicating with the APs, supporting a mix of traffic, including typical Wi-Fi connectivity and AR/VR streams. Figure 2 depicts the deployment scenarios being analyzed.

The four scenarios in Figure 2 are chosen to evaluate the impact of 1) the number of 320 MHz channels and 2) the overlap among those 320 MHz channels on the performance of the Wi-Fi 7 system in support of the expected latency as the target KPI.

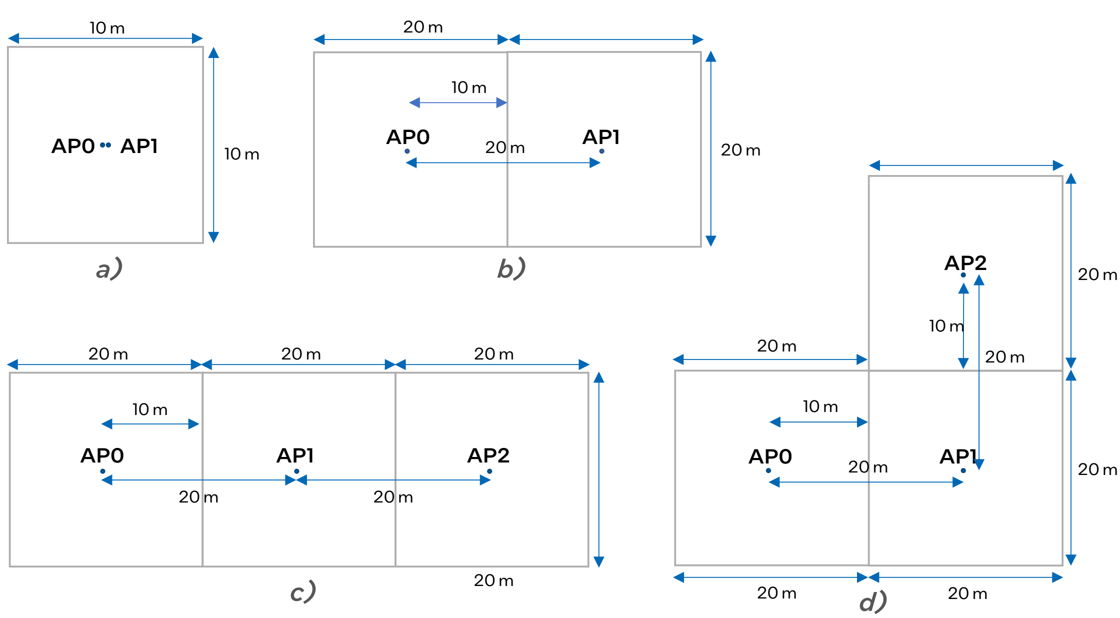


Figure 2. Wi-Fi 7 deployment scenarios analyzed to assess conformance with KPIs – a) single room with one or two APs, b) two APs in two adjacent rooms, c) three APs in three co-linear adjacent rooms, d) three APs in three L-shaped adjacent rooms

Figure 3 shows the 6 GHz channelization based on IEEE 802.11ax[6] (Wi-Fi 6E) and 802.11be[7] (Wi-Fi 7) global operating classes.

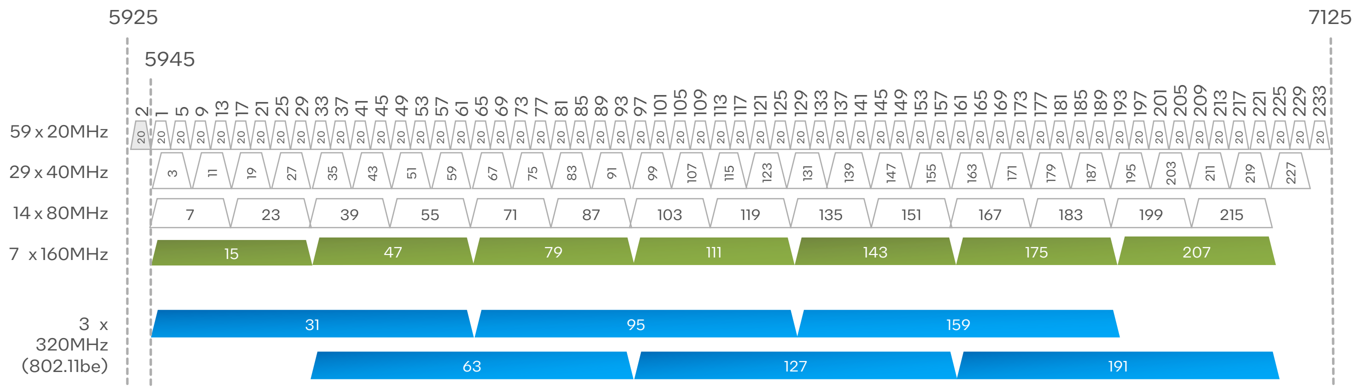


Figure 3. Global 6 GHz band (5,925 MHz – 7,125 MHz) channelization from IEEE 802.11ax (Wi-Fi 6E) and 802.11be Draft 1.0 (Wi-Fi 7)

Channelization configurations analyzed in the simulations are depicted in Figure 4.

In **Configuration 1**, there is only a single 320 MHz channel available due to limited spectrum availability.

This single channel is simulated to be used by a single BSS or shared between two or three BSSs. The 160 MHz channel option is also implemented with this configuration for comparative analysis.

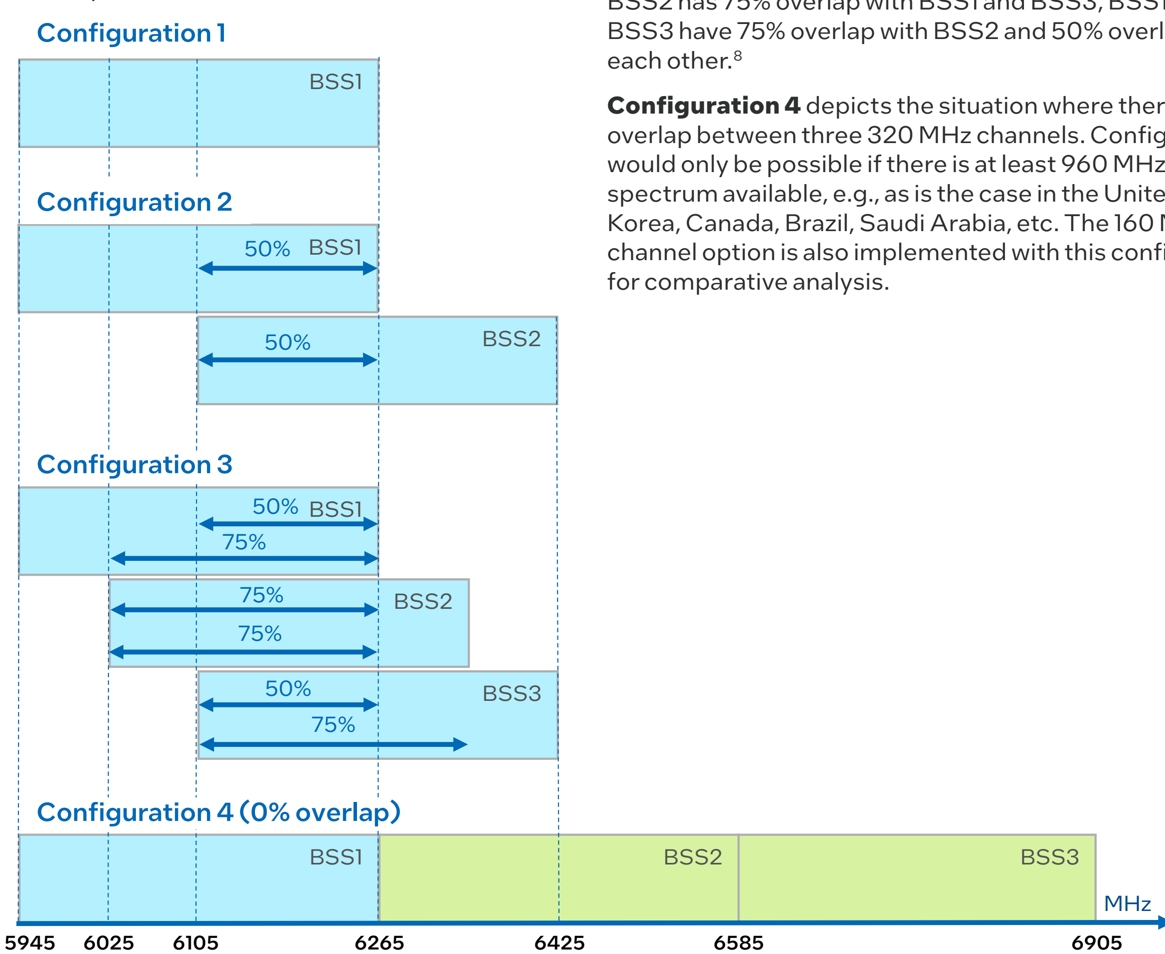


Figure 4. Various configurations of the 320 MHz channels considered in the simulations

In **Configuration 2**, there are two 320 MHz channels, still each of the 320 MHz channels used by BSS1 and BSS2 has a 50% overlap due to the limited amount of spectrum, e.g., as is the case in current CEPT regulations with a total 480 MHz of spectrum designated as license-exempt.

Configuration 3 represents the case where three 320 MHz channels are used in an overlapping manner within the same amount of spectrum (480 MHz). In this configuration, while BSS2 has 75% overlap with BSS1 and BSS3, BSS1 and BSS3 have 75% overlap with BSS2 and 50% overlap with each other.[8]

Configuration 4 depicts the situation where there is 0% overlap between three 320 MHz channels. Configuration 4 would only be possible if there is at least 960 MHz of spectrum available, e.g., as is the case in the United States, Korea, Canada, Brazil, Saudi Arabia, etc. The 160 MHz channel option is also implemented with this configuration for comparative analysis.

To assess the impact of the size of allocated spectrum on end-to-end latency of downlink AR/VR streams, various deployment scenarios and channel configurations were analyzed. For each deployment scenario/channel configuration (SC) pair below, statistics of delay for each stream were derived from simulations. For comparison purposes, SC pairs (a1) and (c4) are also simulated, assuming 160 MHz channels to represent scenarios with a smaller available spectrum (480 MHz instead of 1200 MHz).

Deployment Scenario	Channel Configuration	SC Pair
a	1	(a1)
a	1 (160 MHz)	(a1-160)
a	2	(a2)
b	2	(b2)
c	3	(c3)
c	4	(c4)
c	4 (160 MHz)	(c4-160)
d	3	(d3)

Table 1. Analyzed deployment scenarios paired with channel configuration.

In simulations related to Configurations 2 and 3,the primary channel of at least one AP is overlapping with another AP's channel. Furthermore, in all configurations, each BSS is assumed to serve eight randomly dropped devices (STA), each with a different TCP-based application stream with a mix of uplink and downlink traffic, including web browsing, email, video, and voice, generating a stream of ~30 Mbit/s (MCS10) for each STA. In addition, up to twenty AR/VR stations downloading content from the APs are being dropped. AR/VR is modeled as a video stream with 16 ms inter-arrival time and 208 kB frame size at the application level resulting in ~100Mbps data streams. A full list of other simulation assumptions is contained in Table A-1 in Appendix 1.

It should be noted that in a managed network, e.g., enterprise, a network design with non-overlapping primary channels among APs may be implemented to avoid excess performance impact in non-collocated APs. However, there are no guarantees for an interference-free primary channel in an unmanaged network, such as an apartment complex.

Analysis and Results

The distribution of delay for AR/VR streams running on one, two, or three APs in the deployment scenarios a), b), c), and d) and configurations relevant to each deployment scenario are analyzed. Specifically, the impact of the number of overlapping 320 MHz channels corresponding with the amount of available spectrum is analyzed.

The CDF of delay measured in the downlink direction at each AR/VR client associated with its AP is created to extract the maximum number of AR/VR streams that could be supported while maintaining end-to-end delay for AR/VR streams below 10 ms for 99.9% of the time. CDF plots of delay for all the analyzed cases (SC pairs) are included in Appendix 2, and results are summarized in Table 2 below.

Overall Observations

Various channel configurations were tried in four different deployment scenarios. The deployment scenarios were chosen to represent typical conditions for applications of Wi-Fi 7 in a variety of environments, including home, enterprise, and industrial settings. The channel configurations studied here represent the two current regulatory situations in the 6 GHz band in countries/regions where unlicensed services are allowed, namely 1) availability of 500 MHz in the lower part of the band and 2) availability of the entire 1200 MHz from 5925 MHz to 7125 MHz.

To assess the impact of available spectrum on major system KPIs, end-to-end latency in the downlink for AR/VR streams to clients was analyzed in various deployment scenarios and channel configurations. For each deployment scenario/channel configuration (SC) pair, statistics of delay for each stream were derived from simulations. Table 2 provides a summary of findings.

Delay (ms) for worst AR/VR stream per AP for the config. With MAX supported streams over AR/VR frames														
Scenario	Channel config	Max AR/VR streams per AP	AP0				AP1				AP2			
			Max	98%	99%	99.9%	Max	98%	99%	99.9%	Max	98%	99%	99.9%
A	1, 1 AP	7	13.5	4.1	4.6	6.6	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	1, 2 AP	1/1	13.4	5.9	6.7	8.6	14.2	5.7	6.4	9.6	n/a	n/a	n/a	n/a
	1, 3 AP	0/0/0	18.5	8.6	10.3	17.6	22.4	10.0	11.6	17.8	18.4	12.8	14.0	17.8
A (160 MHz)	1, 1 AP	3	13.9	4.7	5.1	7.3	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	1, 2 AP	0/0	17.4	8.2	9.1	13.8	19.3	8.1	9.6	13.2	n/a	n/a	n/a	n/a
	1, 3 AP	0/0/0	38.9	13.6	18.4	26.4	38.4	14.8	18.8	27.9	32.7	15.0	16.8	26.4
A	2	0/0	22.8	8.9	10.6	16.4	25.3	10.8	12.5	19.7	n/a	n/a	n/a	n/a
B	2	1/0	14.5	5.9	7.0	9.9	59.2	24.9	29.3	43.4	n/a	n/a	n/a	n/a
C	3	1/0/0	18.6	4.7	5.2	7.3	61.2	33.1	37.9	55.5	51.1	24.5	28.2	43.0
	4	7/7/7	12.8	5.3	6.5	8.7	16.7	5.3	5.9	8.2	12.5	5.0	5.9	9.3
C (160 MHz)	4	3/3/3	17.3	3.9	4.3	5.8	6.4	3.9	4.2	5.4	12.7	4.1	4.5	6.5
d	3	0/0/0	17.0	7.0	8.0	12.3	95.8	40.2	49.5	76.9	99.5	69.9	79.5	95.2

Table 2. Summary results

For each SC pair, Table 2 reports:

- Maximum number of traffic streams per AP supporting 99.9-percentile delay below 10 ms
- Statistics of end-to-end delay for the worst AR/VR stream in the form of maximum, 98-percentile, 99-percentile, and 99.9-percentile values.

This data shows that baseline SC pair (a1) can support up to 7 AR/VR streams with 99.9-percentile delay below 10 ms. However, in any other configuration involving more than one AP, the end-to-end delay is significantly impacted by the addition of clients/APs with the exception of SC pair c4. Availability of three non-overlapping 320 MHz channels in SC pair (c4) brings the performance for all clients/APs back to a level similar to the baseline case per room. Using 160 MHz channels in SC pairs (a1) and (c4) reduces the number of supported streams with delays below 10 ms to 3 and 3/3/3, respectively.

Conclusions

Network performance for emerging delay-sensitive residential, enterprise, and industrial applications of Wi-Fi 7, such as AR/VR and industrial IoT, is impacted by the amount of available spectrum. In isolated and lightly loaded scenarios with a single 320 MHz channel, the end-to-end delay of AR/VR packets can stay below the target level of 10 ms for 99.9% of the time. However, in environments characterized with moderate to high traffic load, e.g., enterprises, homes, hotspots, it is demonstrated that a single 320 MHz channel would not be able to maintain the end-to-end delay and reliability requirement of AR/VR applications. Only the availability of three non-overlapping 320 MHz channels would be able to cope with the increase in demand and keep the performance at acceptable levels even for highly loaded scenarios.

Wi-Fi 7 will need access to three non-overlapping 320 MHz channels in order to meet the demand of emerging applications. As shown here, this goal can only be achieved if the entire 6 GHz band (5925 MHz – 7125 MHz) is made available for unlicensed operation.

Appendix 1 – Traffic Assumptions

Table A-1 below lists other assumptions made for the simulations.

Source	Sink	Description	Traffic pattern			Protocol Type	User Priority (UP)
			Load/pattern	On	Off		
STA1/AP	AP/STA1	Web email DL/UL	~2 Mbit/s, 1.5 kB every 6 ms bidirectional	Always on	-	TCP	BE
AP	STA2	Web browsing, DL web page	~6 Mbit/s, 1.5 kB every 2 ms	On for 3 seconds	Off for uniform(1,5) seconds after ON period	TCP	BE
STA3	AP	File Sync to the cloud	~1.5 Mbit/s, 1.5 kB every 8 ms	Always on	-	TCP	BE
STA4/AP	AP/STA4	Cloud Office	~3 Mbit/s, 512 B every 1.4 ms	Always on	-	TCP	BE
STA5	AP	File download	75 Mbit/s, 1.5 kB every 0.16 ms	On for 5 seconds	Off for uniform(30, 50) seconds after ON period	TCP	BE
AP/STA6	STA6/AP	Voice call	64 kbit/s, 160 B every 20 ms, bidirectional	Always on	-	UDP	VO
STA7	AP	Screen Sharing	~1.5 Mbit/s, 512 B every 3 ms	Always on	-	UDP	VI
AP	STA8	YouTube video download	3 Mbit/s, 1.5 kB every 4 ms	Always on	-	UDP	VI

Table A-1. Simulation assumptions for non-AR/VR traffic

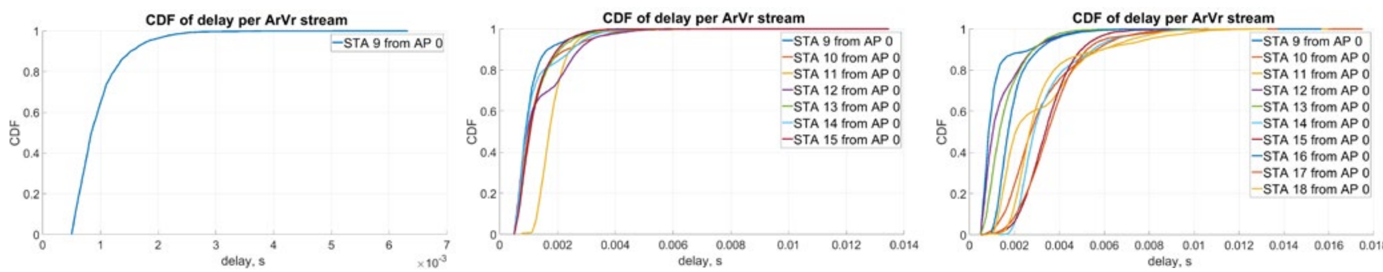
Appendix 2 – Analysis Details and Results

B.1 Deployment Scenario a)

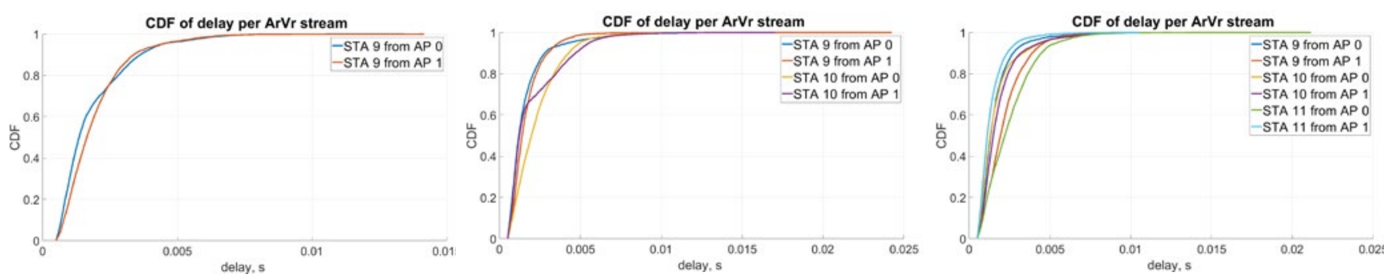
SC pair (a1), in which a single 320 MHz channel is shared among all users, i.e., 100% overlap, of one AP in a single room with 10 m x 10 m x 3 m dimensions, serves as a baseline for comparison with other deployment scenarios. In addition, in this deployment scenario, the presence of additional APs is also simulated. Each AP has an identical number of AR/VR and non-AR/VR clients. In a single room with these dimensions, the network is expected to experience no hidden nodes, i.e., every device can sense every other device's transmissions.

The following graphs compare CDF of delay measured in downlink direction at each AR/VR client associated with its respective AP.

One AP in a single 320 MHz channel (Baseline)
CDF of delay with 1, 7 and 10 streams



Two APs sharing a single 320 MHz channel
CDF of delay with 2,4 and 6streams



Three APs sharing a single 320 MHz channel
CDF of delay with 3, 6 and 9 streams

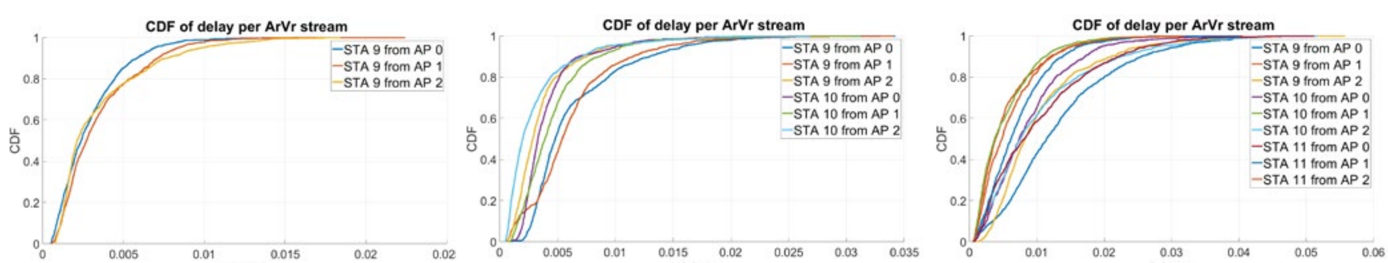


Figure B-1. Statistics of delay for SC pair (a1) with one, two, or three APs sharing a single 320 MHz channel

As can be seen in Figure B-1, with a single 320 MHz channel, a single isolated AP can serve up to 7 AR/VR streams while maintaining end-to-end delay for AR/VR streams below 10 ms for 99.9% of the time. This number drops to 1 and 0 streams per AP when 2 or 3 APs share the same single 320 MHz channel, respectively.

Deployment scenario a) with configuration 2, or SC pair (a2), is also of interest since it allows utilization of the entire 480 MHz of spectrum from 5945 MHz to 6425 MHz with two 320 MHz channels deployed with 50% overlap. To simulate this case, two APs are placed within a single room with dimensions 10 m x 10 m x 3 m. With this topology, the network has no hidden nodes, i.e., every device is able to sense every other device's transmissions. Figure B-2 compares CDFs of end-to-end delay measured in downlink direction at each AR/VR client associated with its respective AP.

Two AP with 50% overlap – SC pair (a2)
CDF of delay for 2, 4 and 6 streams

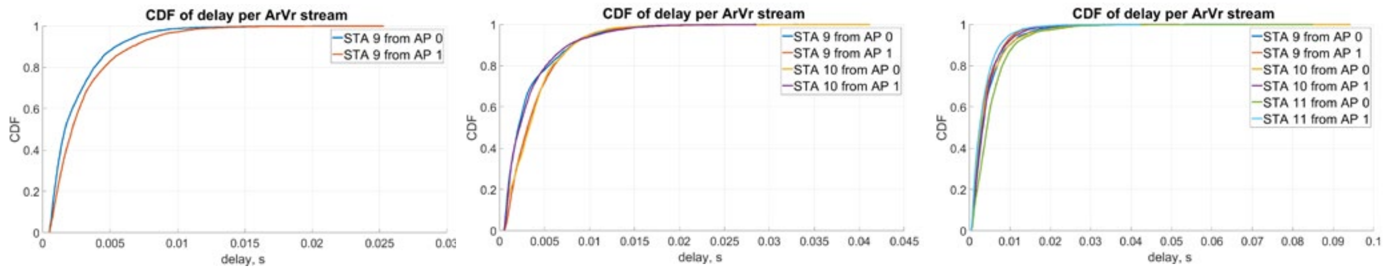


Figure B-2. Statistics of delay for SC pair (a2) with two APs sharing a single 320 MHz channel with 50% spectral overlap

Before interpreting Figure 5, let's also consider configuration 2 under deployment scenario b).

B.2 Deployment Scenario b)

In this scenario, two APs are placed in the middle of two adjacent rooms, each with 20 m x 20 m x 3 m size, to create SC pair (b2). The distance between APs is, therefore, 20 meters. With this topology, the network could have hidden nodes within either BSS, typically at the edge of the BSS.

Figure B-3 compares CDFs of delay measured in downlink direction at each AR/VR client associated with its respective AP.

Two AP with 50% overlap – SC pair (b2)
CDF of delay for the case with 2, 4 and 6 streams

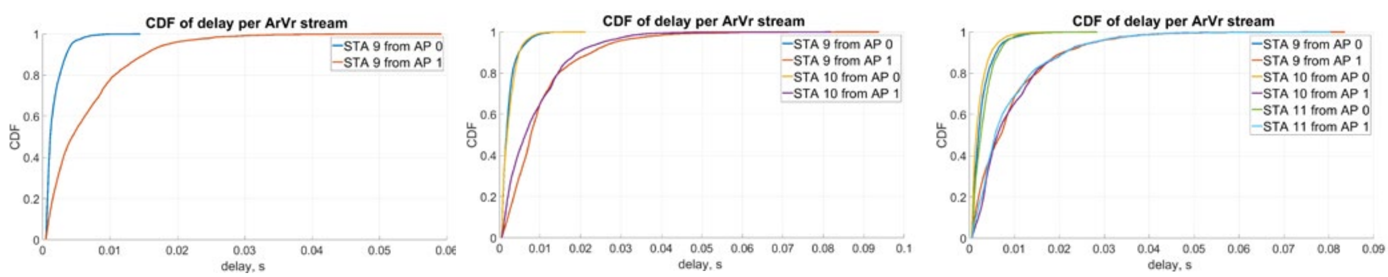


Figure B-3. Statistics of delay for SC pair (b2) with two APs sharing a single 320 MHz channel with 50% spectral overlap

It is clear from Figures B-2 and B-3 that the 50% overlap leads to significant additional delay in AR/VR DL streams. As can be seen in these figures, unlike in the baseline case, a 50% overlap of two 320 MHz channels significantly affects each BSS operation. The number of AR/VR streams with 99.9th-percentile delay below 10 ms drops to 0 streams per AP in scenario a), namely one-room topology AP, and in scenario, b), namely two-rooms topology, one AP still can serve one stream. Still, the other cannot serve even one AR/VR stream while maintaining 99.9th-percentile delay below 10 ms.

B.3 Deployment Scenarios c) and d)

In deployment scenarios c) and d), three APs are deployed in three adjacent rooms, each with dimensions 20 m x 20 m x 3 m, placed linearly or in an L-shaped topology, respectively. With these topologies, similar to scenario b), the network could have hidden nodes within each BSS, typically at the edge of the BSS. In these deployment scenarios, channelization configuration 3 is being simulated with three overlapping 320 MHz channels, all within the 480 MHz spectrum from 5945 MHz to 6425 MHz.

Figure B-4 compares CDFs of delay measured in downlink direction at each AR/VR client associated with its respective AP.

Three APs with 75% overlap – SC pair (c3), linear topology
CDF of delay with 3, 6 and 9 streams

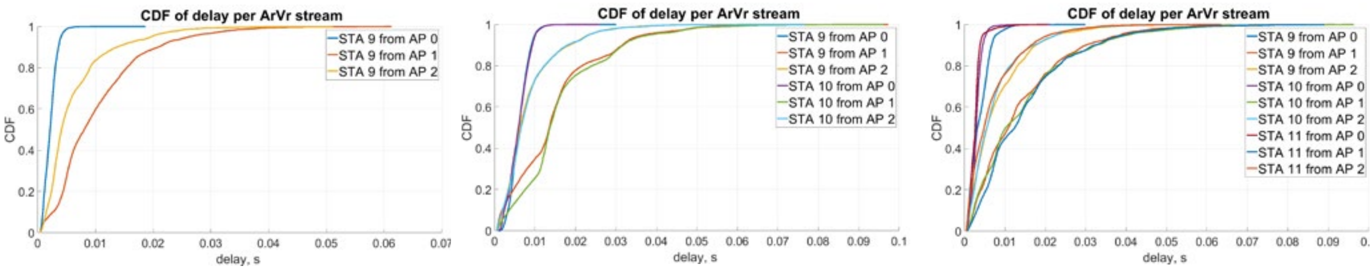


Figure B-4. Statistics of delay for SC pair (c3) with three APs sharing a single 320 MHz channel with 50% and 75% spectral overlap

Furthermore, to simulate deployment scenario d), three APs are placed in three adjacent rooms, with 20 m x 20 m x 3 m size, in an L-shape topology. In this deployment scenario, channelization configuration 3 is being simulated with three overlapping 320 MHz channels, all within the 480 MHz spectrum from 5945 MHz to 6425 MHz.

Figure B-5 compares CDFs of delay measured in downlink direction at each AR/VR client associated with its respective AP.

Three APs with 75% overlap – SC pair (d3), L-shape topology
CDF of delay with 3, 6 and 9 streams

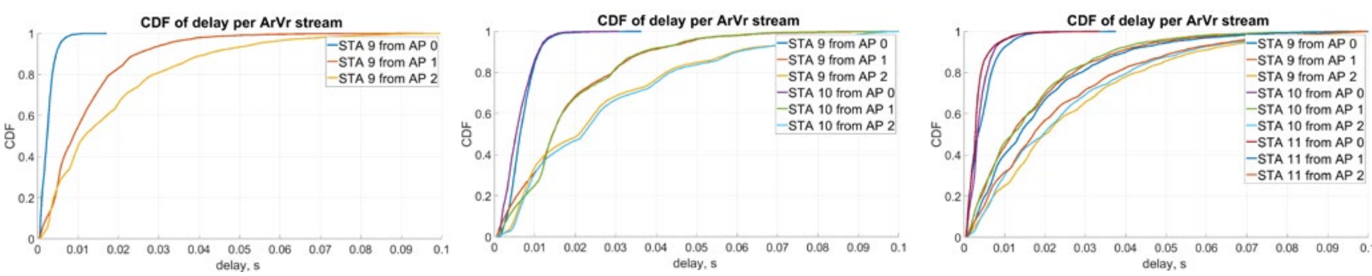


Figure B-5. Statistics of delay for SC pair (d3) with three APs sharing a single 320 MHz channel with 50% and 75% spectral overlap

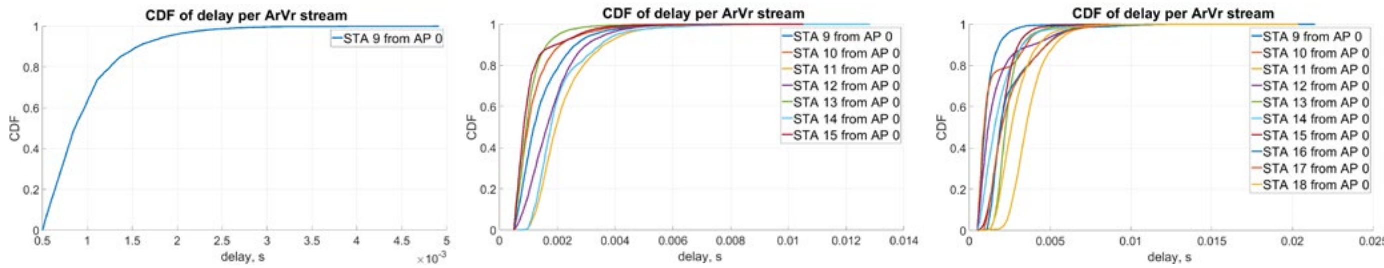
As can be seen from the provided graphs, unlike in the baseline case, a 75% overlap of three 320 MHz channels significantly affects each BSS operation. The number of AR/VR streams with 99.9-percentile delay below 10 ms drops to one stream and can only be maintained in BSS of AP0 placed in room 1. AP1 and AP2 cannot provide a sufficient level of service even for a single AR/VR client maintaining 99.9-percentile delay below 10ms.

B.4 Deployment with Three Non-Overlapping Channels

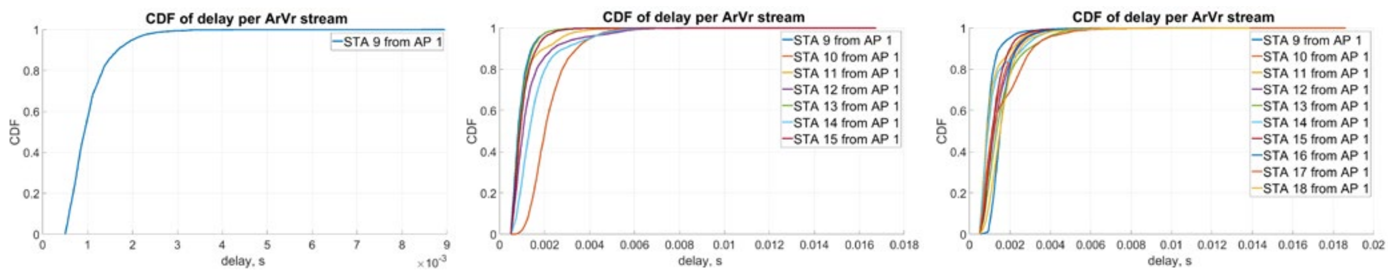
In this section, we consider deployments in countries such as the United States, Korea, Canada, Brazil, Saudi Arabia, etc., where the entire 1200 MHz (5925-7125 MHz) is available to unlicensed operation. The availability of 1200 MHz of the spectrum makes it possible to deploy three non-overlapping 320 MHz carriers in the band. In this case, due to minimal out-of-band interference, it is reasonable to consider that performance of each of the three non-overlapping 320 MHz channels resembles that of the single 320 MHz channel analyzed in the baseline case, namely Configuration 1 in deployment scenario a), as described in Figure B-1, with the added benefit of significant increase in the overall capacity delivered by the deployment.

Concerning other deployment scenarios featuring the hidden nodes problem, Configuration 4 was tried in combination with deployment scenario c), namely three adjacent rooms arranged linearly, with each of three APs (one in each room) running one of the three non-overlapping 320 MHz channels (SC pair (c4)).

Three APs in three non-overlapping 320 MHz channels
CDF of delay with 1, 7 and 10 streams per AP0



Three AP in three non-overlapping 320 MHz channels
CDF of delay with 1, 7 and 10 streams per AP1



Three AP in three non-overlapping 320 MHz channels
CDF of delay with 1, 7 and 10 streams per AP2

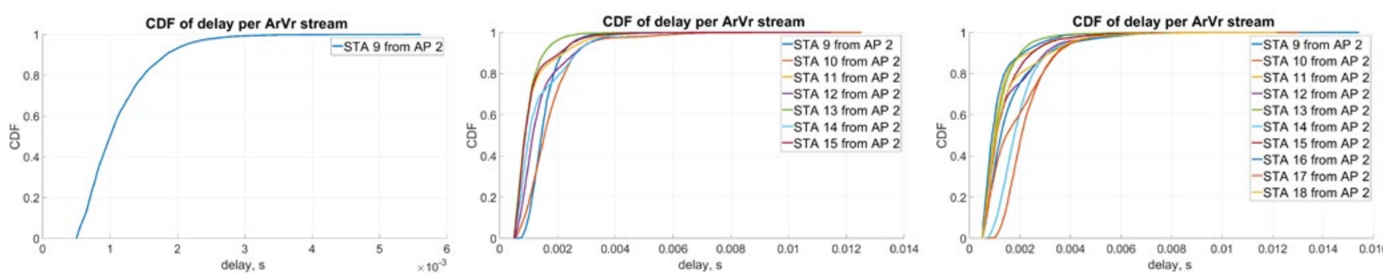


Figure B-6. Statistics of delay for SC pair (c4) with three APs placed in three adjacent rooms, each using one of the three non-overlapping 320 MHz channels

As can be seen in Figure B-6, with the availability of three non-overlapping 320 MHz channels, each AP operates in an isolated channel and can serve up to seven AR/VR streams while maintaining 99.9th-percentile end-to-end delay for AR/VR streams below 10 ms. Collectively, for the three APs, this number adds up to 21 AR/VR streams/clients served simultaneously.

Appendix 3 – Industrial Automation KPIs

The table below[9] summarizes use cases and requirements grouped in three classes of services in industrial systems. The latency bound is defined as the worst-case, one-way latency measured at the application layer. Reliability is defined as the percentage of packets expected to be received within the latency bound.

Applications and Requirements	Class A	Class B	Class C
Applications	Interactive video, soft-real-time control, mobile robotics, Automated Guided Vehicles (AGV)	AR/VR, remote HMI, hard-real-time cyclic control, machine tools, production lines	Hard-real-time isochronous control, motion control, printing, packaging
Time synchronization	10-1µs	~1 µs	~1 µs
Latency bound	50 -10 ms	10 – 1 ms	1ms – 250 µs
Reliability	99% - 99.9%	99.9% - 99.99%	>99.999%
Throughput	High (video) Low (control, robotics, AGVs)	High (VR) Moderate-Low (controls/ automation/AR)	Moderate-Low

Table B-7. Factory automation use cases summary

[1] 2024 target based on IEEE 802.11be completion timeline.
[2] IEEE P802.11be Project Authorization Request (PAR), 21-Mar-2019.
[3] Ibid.
[4] "The need for enabling touchless technologies", Claudio Da Silva, Reza Arefi, Carlos Cordeiro, Intel Corporation, October 2020. https://www.intel.com/content/dam/www/public/us/en/documents/pdf/the-need-for-enabling-touchless-technologies-whitepaper.pdf
[5] https://mentor.ieee.org/802.11/dcn/18/11-18-2009-06-0rta-rta-report-draft.docx
[6] EEE Std 802.11ax™ 2021, IEEE Standard for Information Technology—Telecommunications and Information Exchange between Systems Local and Metropolitan Area Networks— Specific Requirements, Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications, Amendment 1: Enhancements for High-Efficiency WLAN, February 2021.
[7] IEEE P802.11be™/D1.01, IEEE P802.11be™/D1.01, Draft Standard for Information technology— Telecommunications and information exchange between systems Local and metropolitan area networks—Specific requirements, Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications, Amendment 8: Enhancements for extremely high throughput (EHT), June 2021.
[8] This configuration is not currently supported in 802.11be but added here for reference.
[9] https://mentor.ieee.org/802.11/dcn/18/11-18-2009-06-0rta-rta-report-draft.docx