CableLabs/Meta Joint QoE Assessment

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Impacts of WMM on Wi-Fi

Study of Real-Time Communication Quality and Wi-Fi Multimedia

Prepared by
Lili Hervieu, Principal Architect, CableLabs Wireless R&D | l.hervieu@cablelabs.com
Shafayet Khan, Lead Software Engineer, CableLabs Wireless R&D | s.khan@cablelabs.com
Efren C. Torres, Wi-Fi Engineer, CableLabs Wireless R&D | e.torres@cablelabs.com
Olivier Mayor, Network Engineer, Network Infrastructure Services, Meta | omayor@meta.com
Sundeep Signatwaria, Full Stack Systems, Network Infrastructure, Meta | sunsing@meta.com
Luther Smith, Director/Distinguished Technologist, CableLabs Wireless R&D | l.smith@cablelabs.com

Additional Contributors
John Bahr, Principal Architect, CableLabs Advanced Technologies Group | j.bahr@cablelabs.com
Josh Redmore, Principal Architect, CableLabs Wireless R&D | j.redmore@cablelabs.com
Greg White, Distinguished Technologist, CableLabs Next Generation Systems | g.white@cablelabs.com
Justin Cardones, Infrastructure Connectivity Systems Engineering, Meta | justincardones@meta.com
Sanjay Patel, Senior Director Strategy, Cable Labs | s.patel@cablelabs.com
Sandeep Kohli, Networks Ecosystems Engineering Lead, Meta | sandeepkohli@meta.com

Executive Summary

Aligning In-Home Wi-Fi Operational Features with Consumer Experience Expectations

Wi-Fi consumption and devices have both evolved to the point where in-home wireless contention can impact the end user experience, especially in real-time communication (RTC) use cases. Latency and jitter are known factors in RTC performance, and latency under load is becoming a benchmark among competing industry, consumer, and regulatory evaluations. Many Wi-Fi topologies do not leverage existing quality assurance standards such as IEEE (802.11e), Wi-Fi Alliance (WMM), and related Wireless Broadband Alliance extensions.

Informed by previous home traffic modeling research, the purpose of this study is to characterize latency under a variety of loading conditions and apply downlink Wi-Fi Multimedia (WMM) quality of service (QoS) to mitigate the impact on RTC applications (VoIP, video calling, etc.).

Differentiating services through WMM QoS is well established in enterprise environments and is fundamental to RTC implementations, where end-user quality of experience (QoE) underload is important. When deployed correctly, non-RTC traffic will not be perceptibly affected by less time-sensitive processing. Exercising these standards can sort and manage traffic according to the type of service (TOS).

Test Approach—Induce Latency Under Load, Measure Efficacy of Downlink Traffic Classification

Testing isolates Wi-Fi, independent from WAN contributions such as DOCSIS technology, PONs, and core networks. The RTC application under test is run on a device dedicated to the task (i.e., is not simultaneously generating other traffic loads). As a result, the predominant source of latency/jitter introduced in this study comes from airtime contention between competing stations. Transient effects of access point (AP) and station (STA) queuing and bufferbloat are not studied deeply, but they are deemed relevant for future work.

This study involved the creation of an emulated home WLAN topology, complete with multiple devices and application workloads modeled after real-world deployments. In this environment, a single Wi-Fi-connected RTC application endpoint was used to test the impact that downlink WMM prioritization has on QoE and QoS metrics for that application.

Within WMM are four priority levels or “access categories” (ACs) for traffic: background (AC_BK), best effort (AC_BE), video (AC_VI), and voice (AC_VO) (listed in increasing priority order). This study examines the effect of classifying the RTC downlink traffic as AC_BE vs. AC_VI vs. AC_VO. The RTC uplink traffic is always set to AC_BE because it is under the control of the client, not the network operators, and most clients set their traffic to AC_BE.

The study combines the following to correlate RTC QoE across a variety of in-home traffic and usage scenarios:

- home emulation topology that is repeatable, emulating WAN effect (80 ms delay) and distances to AP (RSSI sweep);
- point-to-point RTC video calls over Wi-Fi, with concurrent in-home traffic models based on residential studies;
- custom instrumentation (latency/jitter monitor);
- RTC application and device layer metrics (transport, video, audio) which reflect end user QoE; and
- airtime utilization as a key indicator of in-home and neighboring contention.

The testing framework references P99 latency and P99 jitter metrics when possible, instead of average or median (P50) values. The 99th percentile packet latency, when measured over short time intervals (i.e., less than 10 seconds), is believed to be the most salient latency metric for predicting RTC quality of experience.[1,2] When measured over longer time intervals, P99 captures transient effects that can temporarily impact experience, even if the average experience during the call may be acceptable. This approach is in line with consumer desire for consistent, predictable performance.

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[1] “Latency Explained,” January 2022, Broadband Internet Technical Advisory Group (BITAG)
[2] “A Single Common Metric to Characterize Varying Packet Delay,” B. Briscoe, G. White, V. Goel, K. De Schepper, Internet Advisory Board Workshop on Measuring Network Quality for End-Users, September 14–16, 2021, virtual

Result Highlights and Collective Insight

In total, 132 test cases were executed. In all cases, concurrent loading impacted RTC metrics when compared to baseline; there is a direct correlation between latency and loading. These effects were also influenced by distance and coverage. WMM prioritization reduces RTC latency and jitter, as well as distance and coverage sensitivities. In some cases, RTC voice classification performance under load approached unloaded baseline targets. Results also showed where WMM is beneficial even though RTC is theoretically disadvantaged.

5 GHz Downlink Observations

Testing was able to compare baseline (no contention) unloaded RTC performance with the effects of latency under load. When the WLAN is idle, there is very little difference in latency performance between AC_VO, AC_VI, and AC_BE—all reflected small standard deviations. These results serve as the “best possible” reference performance.

When the channel is congested, significant latency reduction is observed when the downlink RTC traffic uses AC_VO compared to AC_BE. Use of AC_VI provides latency reduction as well but to a lesser extent. For example, with a 5 GHz Wi-Fi channel congested at 85%, we observe a P99 downlink latency reduction from 409 ms (AC_BE) to 277 ms (AC_VI) to 100 ms (AC_VO) for a client far from the access point (AP) (e.g., -82 dBm). Results include a fixed 80-ms delay to emulate the remainder of the service delivery chain.

5 GHz Uplink Observations

For each test, uplink RTC traffic was classified as best effort (BE) only achieving parity at best and frequently disadvantaged. When RTC downlink traffic is set to AC_VO, we observe either no change or an increase in uplink latency as compared to the case where RTC downlink uses AC_BE. This result is expected because of preferential access to the channel being given to downlink RTC traffic. It also illustrates the collateral damage caused by elevating the priority of a subset of traffic. In the example listed above, the uplink P99 latency for the far client was 141 ms for AC_BE, 157 ms for AC_VI, and 178 ms for AC_VO. Despite the increase in uplink latency when the higher priority access categories were used, it was outweighed by the reduction in downlink latency. Additionally, the overall user experience is still much better with AC_VO based on client metrics. The RTC Audio Jitter KPI decreases from 32 ms for AC_BE to 4 ms for AC_VO.

Loss Plan (Distance/Coverage Proxy) Influence on Performance

When DL RTC is set to AC_VO, the impact of RSSI (received signal strength indicator) on latency is significantly reduced. The link signal strength (e.g., the distance from the AP) impacts the latency when the RTC traffic is set to AC_BE. This effect is greater on the uplink because STA TX (transmit) power is much lower than AP TX power. For example, in congested networks, the DL P99 for AC_BE is 345 ms for a near client and 409 ms for a far client, and the same for AC_VO is 97 ms for a near client and 100 ms for a far client. Also, RSSI sweeps do not seem to materially impact traffic when WMM is engaged. As RTC is only BE on all uplink flows, this scenario is the only time that graphs show distance sensitivity to RSSI sweeps.

Possible Solutions and Justifications

This report documents significant improvements in RTC QoE that can be achieved by leveraging downlink WMM prioritization in residential Wi-Fi deployments. However, further study on some additional aspects is needed to operationalize these benefits.

One aspect that bears further study is the extent to which the QoE benefits are retained when multiple applications are given high priority in the WLAN. This study is limited to a single WMM-prioritized RTC call and a set of relatively low-bandwidth background streams that are also given priority. Enabling the use of WMM by additional applications raises the possibility that many applications will begin to take advantage of it, potentially overusing the VO (and/or VI) access category and thus degrading its performance.

Another aspect not included here that needs to be better understood is the impact that prioritization has on applications that are not given priority. Prioritization of low-data rate applications may intuitively not have much impact on the QoE of non-prioritized applications, but yet to be determined is the point at which the impact on non-prioritized traffic becomes objectionable as the amount of prioritized traffic increases.

Both of these aspects hint at the potential need for QoS policy management in which access to prioritization is limited to selected applications only. QoS policy management involves both setting policies (selecting the applications that are allowed/denied access to prioritization) and identifying application flows that correspond to the selected policies.

A study of QoS policy management mechanisms as well as solutions to classify and map traffic at production scale are beyond the scope of this paper. A variety of commercial and MSO-developed solutions do exist for application identification, ranging from device-oriented solutions to classification policies based on deep packet inspection (DPI). However, frameworks to create rational policies for controlling access to prioritization—ideally considering both the upside potential improvements to QoE for the allowed applications and the downside “collateral damage” that such prioritization has on the denied applications—are not well established.

Users generally expect all of their applications to “just work” and that the network will do what is needed to facilitate them. This perspective is not likely to change, so operators should be motivated to deploy network technologies that satisfy these expectations. The findings of this study point to traffic prioritization for RTC applications as a potential component of the overall solution to address consumer expectations in residential Wi-Fi.

Contents

Introduction

Even though the use of various applications on mobile devices over Wi-Fi has increased, users continue to expect a high quality of experience (QoE). Because Wi-Fi is often the first link between the user and the Internet, Wi-Fi is perceived to be the Internet and plays a critical role in QoE. This paper explores the impact on this experience while using Wi-Fi Multimedia (WMM) to prioritize data types and reduce latency. By testing different combinations of Wi-Fi traffic marking in conjunction with WMM, key performance indicators (KPIs) are collected and latency measurements with analysis of QoE impacts are shown.

1. Testing Objective

The testing objective is to assess the impact of WMM on the QoE experienced by the RTC user. The tests are conducted with the RTC traffic set to either best effort (BE), video (VI), or voice (VO). During the tests, the RTC application and the RTC server capture KPIs that are the most representative of the user experience, such as the bitrate, the video quality score, and the audio packet loss. The downlink and uplink Wi-Fi latencies are also captured, as latency is a key metric for real-time applications. Different Wi-Fi testing scenarios are evaluated, including positioning the RTC client at varying distances from the AP in the presence of diverse overlapping traffic loads.

Wi-Fi access categories (ACs) enable clients to access the medium by using a predefined contention window range. Table 1 lists the main parameters of each AC category. These parameters are aligned by traffic type with latency and bandwidth sensitivities: background traffic is delay insensitive, best effort is general purpose and not as sensitive to loss or delay, video is more critical and perceptively impacted by delay, and voice is most critical and highly impacted by delay.

Table 1. Wi-Fi Access Category Parameters

CW, contention window; AIFS, arbitration interframe space; TXOP, transmit opportunity; DCF, Distributed Coordination Function

AC Type	CW_{min}	CW_{max}	AIFS	$TXOP_{max}$
0: background	15	1023	7	0
1: best effort	15	1023	3	0
2: video	7	15	2	3.008 ms
3: voice	3	7	2	1.504 ms
DCF	15	1023	2	0

The objective of this study is to evaluate the QoE and QoS (quality of service) benefits of classifying an RTC application's downlink traffic as either AC_VI or AC_VO as compared to the default AC_BE treatment. This study does not examine the impact of prioritizing the RTC uplink traffic. *Accordingly, the RTC uplink traffic is sent as best effort (AC_BE) in all test cases.* The intention of this report is to give guidance to network operators who manage Wi-Fi APs. Network operators could have the ability to control the downlink traffic usage of different ACs, whereas the uplink traffic AC is under the control of the client.

1.1. Test Plan

The tests emulate the various Wi-Fi conditions at 5 GHz and 2.4 GHz typically found in single family unit (SFU) settings. Figure 1 gives a logical view of the test setup. The detailed implementation of the test setup with the Candela platform is given in Section 1.4. The logical test setup includes the following.

- An Android phone that runs an RTC video call (station under test, STAUT) to another phone on the same subnet.
  - The calling phone is connected to the AP with Wi-Fi.
  - The receiving phone is connected to the AP with Ethernet.

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- A set of home devices connected to the AP with Wi-Fi, emulating typical home traffic.
  - Various home devices are emulated thanks to the Candela setup.
  - Three levels of path loss are established between the AP and the emulated home devices.
- An AP under test (APUT) that connects Wi-Fi clients and the Ethernet RTC receiver (phone) to the LAN and the WAN (local and wide area network, respectively).
  - A Calnex Paragon WAN emulator is used to add a fixed delay of 80 ms in both uplink and downlink directions between the AP and the receiver phone (Ethernet) to emulate a typical 160 ms WAN round-trip time between the United States and India.
  - The AP has WMM support turned on.

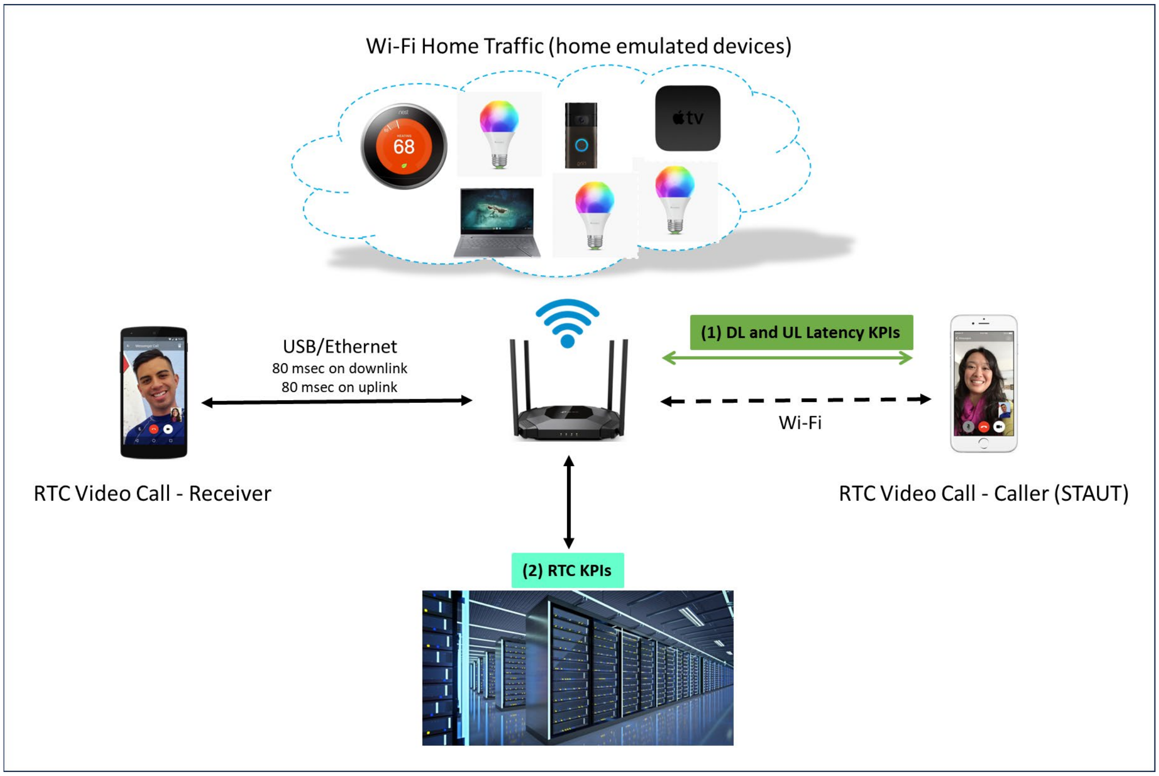

Figure 1. Test Setup—Logical View

Two different sets of KPIs are recorded during the tests to assess the quality of the call and the quality of the Wi-Fi links:

1. *Latency*—The uplink and downlink one-way latencies are measured over Wi-Fi between the caller phone (STAUT) and the AP. A specific setup is implemented to record one-way latencies as detailed in section 2.2.
   - A latency report including the P0, P99, P99.5, P99.9, and average latencies is generated for each direction.
2. *RTC Vendor Call KPIs*—During an RTC video call, many KPIs are recorded on the caller and receiver phones and are made available to the RTC vendor server. The most significant KPIs are analyzed; they are detailed in section 2.1. Most KPIs are recorded every second, and a few KPIs can give the overall call quality.

Different Wi-Fi scenarios are tested to represent different home configurations and traffic types. Tests are conducted on 5 GHz with 80 MHz bandwidth (Section 1.2) and on 2.4 GHz with 20 MHz bandwidth (Section 1.3).

1.2. 5 GHz Tests

Different Wi-Fi scenarios are tested to represent different home configurations and traffic types at 5 GHz with an 80 MHz bandwidth. The following parameters are changed (Figure 2).

- The contention traffic from the home devices is emulated with the Candela virtual clients. Four levels of contention traffic (Level 0, Level1, Level 2, Level 3) are implemented and are characterized by a different number of emulated home clients, their respective RSSIs, and their traffic profile.
    - Level 0 tests are baseline tests with no home traffic; only the RTC call is active.
    - Level 1 tests implement emulated home traffic (EHT) with (simple) constant bitrate traffic models.
    - Level 2 tests include more complex EHT that emulates file downloads and various video streaming applications.
    - Level 3 tests are similar to the Level 2 tests and introduce a large variability in the traffic contention.
- For each level of home traffic, the caller phone is tested for three RSSIs representing a client located at a near, mid, or far distance from the AP. An additional test, named “airtime sweep,” is conducted in which the RSSI (path loss, PL) is changed during the test.
- The WMM ACs of the emulated clients’ traffic and the RTC’s traffic are set to different ACs to analyze the effect of the WMM AC on RTC call quality.

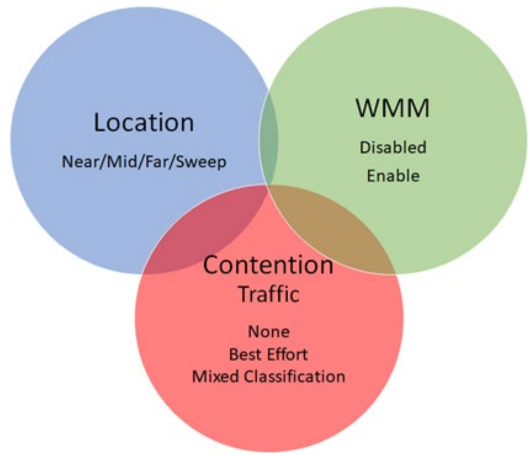

Figure 2. Key Parameters of the Tests

1.2.1. Level 0 Tests

Level 0 tests are baseline tests in which the RTC vendor KPIs and one-way latencies are recorded when no home traffic is present. The caller phone (STAUT) is the only client connected to the AP over Wi-Fi. For each test configuration, three runs of 3 minutes each are performed.

Level 0 tests (Table 2) are conducted for the following parameters.

- Three RSSIs corresponding to a near, mid, and far position of the STAUT to the AP are tested. A fourth sweep test case emulates a person moving away from an AP then toward an AP. In this test, the attenuation between the STAUT and the AP is changed every 20 seconds with the following patten: 0 dB, 10 dB, 20 dB, 30 dB, 40 dB, 30 dB, 30 dB, 20 dB, 10 dB, 0 dB.
- Two ACs are tested for the RTC downlink traffic: best effort (BE) and voice (VO). The RTC uplink traffic is set to AC_BE throughout all tests.

Table 2. 5 GHz Level 0 Test Cases

Emulated Home Traffic	Emulated Home Traffic AC (Downlink and Uplink)	RTC Traffic AC (Downlink Only)	Chamber Attenuation and RSSI on STAUT
Level 0 / no traffic	N/A	BE or VO	Near (0 dB) / -49 dBm
Level 0 / no traffic	N/A	BE or VO	Medium (15 dB) / -65 dBm
Level 0 / no traffic	N/A	BE or VO	Far (30 dB) / -82 dBm
Level 0 / no traffic	N/A	BE or VO	Sweep

1.2.2. Level 1 Tests

Level 1 tests assess the performance of the RTC QoE in the presence of home traffic for different ACs. Table 3 lists the emulated home devices and their traffic profiles. Each emulated home device implements UDP or TCP traffic with a constant bitrate detailed in the table. Seven emulated home devices are placed near the AP with an RSSI of approx. -49 dBm (0 dB PL in the chamber), five emulated devices are placed at mid-distance with an RSSI of approx. 65 dBm (15 dB PL), and three emulated devices are placed far from the AP with an RSSI of approx. -82 dBm (30 dB PL in the chamber).

Table 3. 5 GHz Level 1 Tests—Emulated Home Traffic

Device Type	Capability	EHT Location	Traffic Uplink	Traffic Downlink	IP Transport Protocol	WMM Uplink/Downlink AC/AX
Camera	11ax 2x2	Near	3.8 Mbps	9.6 Kbps	UDP	VI/BE
Laptop	11ax 2x2	Near	1.5 Mbps	1.5 Mbps	TCP	VO/VO
Phone	11ax 2x2	Near	1.5 Mbps	1.5 Mbps	TCP	VO/VO
TV-1	11ax 2x2	Near	128 Kbps	6 Mbps	TCP	BE/VI
Thermostat	11ax 2x2	Near	9.6 Kbps	None	UDP	BE/BE
Speaker x2	11ac 2x2	Near	9.6 Kbps	380 Kbps	UDP	BE/VO
Camera	11ax 2x2	Mid	3.8 Mbps	9.6 Kbps	UDP	VI/BE
Laptop	11ax 2x2	Mid	1.5 Mbps	1.5 Mbps	TCP	VO/VO
Phone	11ax 2x2	Mid	1.5 Mbps	1.5 Mbps	TCP	VO/VO
Speaker	11ac 2x2	Mid	9.6 Kbps	380 Kbps	UDP	BE/VO
Speaker	11ax 2x2	Mid	9.6 Kbps	380 Kbps	UDP	BE/VO
Camera x2	11ax 2x2	Far	3.8 Mbps	9.6 Kbps	UDP	VI/BE
TV-2	11ax 2x2	Far	128 Kbps	6 Mbps	TCP	BE/VI

Level 1 tests (Table 4) are conducted for the following parameters.

- Three RSSIs corresponding to a near, mid, and far position of the STAUT to the AP are tested. A fourth sweep test case emulates a person moving away from an AP then toward an AP. In this test, the attenuation between the STAUT and the AP is changed every 20 seconds with the following patten: 0 dB, 10 dB, 20 dB, 30 dB, 40 dB, 30 dB, 30 dB, 20 dB, 10 dB, 0 dB.
- Three ACs are tested for the RTC downlink traffic: best effort (BE), video (VI), and voice (VO). The RTC uplink traffic is set to AC_BE throughout all tests.
- Two AC configurations are used for the home emulated traffic. Downlink and uplink emulated home traffic are set to either AC_BE or the WMM uplink/downlink AC listed in Table 3.

For each test configuration in Table 4, three runs of 3 minutes each are performed.

Table 4. 5 GHz Level 1 Test Cases

Emulated Home Traffic	Emulated Home Traffic AC (Downlink and Uplink)*	RTC Traffic AC (Downlink Only)	Chamber Attenuation and RSSI on STAUT
Level 1 traffic	BE or WMM	BE or VI or VO	Near (0 dB) / -49 dBm
Level 1 traffic	BE or WMM	BE or VI or VO	Medium (15 dB) / -65 dBm
Level 1 traffic	BE or WMM	BE or VI or VO	Far (30 dB) / -82 dBm
Level 1 traffic	BE or WMM	BE or VI or VO	Sweep

* See Table 3.

1.2.3. Level 2 Tests

The key difference between Level 1 and Level 2 tests is the addition of file transfer and video streaming applications using traffic models that emulate real traffic. These models (Section 1.6) generate non-constant bitrate traffic that best represents the behavior of real applications. Table 5 lists the emulated home devices and their traffic profiles. Some emulated home devices implement UDP or TCP traffic with a constant bitrate, and some generate file download and video streaming traffic. Six emulated home devices are placed near the AP with an RSSI of approx. -49 dBm (0 dB PL in the chamber), six emulated devices are placed at mid-distance with an RSSI of approx. 65 dBm (15 dB PL), and six emulated devices are placed far from the AP with an RSSI of approx. -82 dBm (30 dB PL in the chamber).

The video streaming has_model is set to a maximum bitrate of 15.6 Mbps. The file_transfer model is set to 1.5 Mbps downlink and 1.5 Mbps uplink. The file_transfer model generates traffic with randomized patterns and file sizes.

Table 5. 5 GHz Level 2 Tests—Emulated Home Traffic

Device Type	Capability	EHT Location	Traffic Uplink	Traffic Downlink	IP Transport Protocol	WMM Uplink/Downlink AC/AX
TV	11ax 2x2	Near	None	has_model	UDP	BE/VI
TV	11ac 2x2	Near	None	has_model	TCP	BE/VI
Laptop	11ax 2x2	Near	file_transfer	file_transfer	TCP	BE/BE
Camera	11ac 2x2	Near	1 mbps	1 Kbps	UDP	BE/VI
Speaker	11ax 2x2	Near	None	135 Kbps	UDP	BE/BE
Thermostat	11ac 2x2	Near	180 Kbps	180 Kbps	UDP	BE/VO
TV	11ac 2x2	Mid	None	has_model*	TCP	BE/VI
TV	11ax 2x2	Mid	None	has_model	TCP	BE/VI
Laptop	11ax 2x2	Mid	file_transfer	file_transfer	TCP	BE/BE
Camera	11ac 2x2	Mid	1 mbps	1 Kbps	UDP	VO/VO
Speaker	11ax 2x2	Mid	None	135 Kbps	UDP	BE/VO
Thermostat	11ax 2x2	Mid	180 Kbps	180 Kbps	UDP	BE/VO
TV	11ax 2x2	Far	None	has_model	TCP	BE/VI
TV	11ac 2x2	Far	None	has_model	TCP	BE/VI
Laptop	11ax 2x2	Far	file_transfer	file_transfer	TCP	BE/BE
Camera	11ac 2x2	Far	1 mbps	1 Kbps	UDP	BE/VI
Speaker	11ax 2x2	Far	None	135 Kbps	UDP	BE/BE
Thermostat	11ax 2x2	Far	180 Kbps	180 Kbps	UDP	BE/BE

*Maximum bitrate: 17 Mbps

Level 2 tests (Table 6) are conducted for the following parameters (similar to those for level 1 tests).

- Three RSSIs corresponding to a near, mid, and far position of the STAUT to the AP are tested. A fourth sweep test case emulates a person moving away from an AP then toward an AP. In this test, the attenuation between the STAUT and the AP is changed every 20 seconds with the following patten: 0 dB, 10 dB, 20 dB, 30 dB, 40 dB, 30 dB, 30 dB, 20 dB, 10 dB, 0 dB.
- Three ACs are tested for the RTC downlink traffic: best effort (BE), video (VI), and voice (VO). The RTC uplink traffic is set to AC_BE throughout all tests.
- Two AC configurations are used for the home emulated traffic. Downlink and uplink emulated home traffic are set to either AC_BE or the WMM uplink/downlink AC listed in Table 5.

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For each test configuration in Table 6, three runs of 3 minutes each are performed.

Table 6. 5 GHz Level 2 Test Cases

Emulated Home Traffic	Emulated Home Traffic AC (Downlink and Uplink)*	RTC Traffic AC (Downlink Only)	Chamber Attenuation and RSSI on STAUT
Level 2 traffic	BE or WMM	BE or VI or VO	Near (0 dB) / -49 dBm
Level 2 traffic	BE or WMM	BE or VI or VO	Medium (15 dB) / -65 dBm
Level 2 traffic	BE or WMM	BE or VI or VO	Far (30 dB) / -82 dBm
Level 2 traffic	BE or WMM	BE or VI or VO	Sweep

* See Table 5.

1.2.4. Level 3 Tests

Level 3 tests assess the impact of Wi-Fi airtime utilization on the performance of the RTC QoE in the presence of home traffic for different ACs. The emulated home traffic varies during each test to emulate clients downloading files at different rates. Table 7 lists the emulated home devices and their traffic profiles. Each emulated home device implements UDP or TCP traffic with a constant bitrate. Two home devices, one at a near distance to the AP and one at a mid-distance to the AP, generate non-constant bitrate traffic corresponding to file downloads with different bitrates. The traffic is called “airtime sweep” and has the following pattern:

- no download traffic for 2 minutes,
- file download traffic at 100 Mbps downlink and 12.5 Mbps uplink for 2 minutes,
- file download traffic at 400 Mbps downlink and 50 Mbps uplink for 2 minutes,
- file download traffic at 100 Mbps downlink and 12.5 Mbps uplink for 2 minutes, then
- no download traffic for 2 minutes.

The file download model generates traffic with randomized patterns and file sizes. Eight emulated home devices are placed near the AP with an RSSI of approx. -49 dBm (0 dB PL in the chamber), and five emulated devices are placed at mid-distance with an RSSI of approx. 65 dBm (15 dB PL).

Table 7. 5 GHz Level 3 Tests—Emulated Home Traffic

Device Type	Capability	EHT Location	Traffic Uplink	Traffic Downlink	IP Transport Protocol	WMM Uplink/Downlink AC/AX
Camera	11ax 2x2	Near	3.8 Mbps	9.6 Kbps	UDP	VI/BE
Laptop	11ax 2x2	Near	1.5 Mbps	1.5 Mbps	TCP	VO/VO
Phone	11ax 2x2	Near	1.5 Mbps	1.5 Mbps	TCP	VO/VO
TV-1	11ax 2x2	Near	128 Kbps	6 Mbps	TCP	BE/VI
Thermostat	11ax 2x2	Near	9.6 Kbps	None	UDP	BE/BE
Speaker x2	11ac 2x2	Near	9.6 Kbps	380 Kbps	UDP	BE/VO
Laptop (file DL)	11ax 2x2	Near	Airtime sweep	Airtime sweep	TCP	BE/BE
Camera	11ax 2x2	Mid	3.8 Mbps	9.6 Kbps	UDP	VI/BE
Laptop	11ax 2x2	Mid	1.5 Mbps	1.5 Mbps	TCP	VO/VO
Phone	11ax 2x2	Mid	1.5 Mbps	1.5 Mbps	TCP	VO/VO
Speaker	11ac 2x2	Mid	9.6 Kbps	380 Kbps	UDP	BE/VO
Laptop (file DL)	11ax 2x2	Mid	Airtime sweep	Airtime sweep	TCP	BE/BE

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Level 3 tests (Table 8) are conducted for the following parameters.

- The STAUT is placed at mid-distance to the AP.
- Two ACs are tested for the RTC downlink traffic: best effort (BE) and voice (VO). The RTC uplink traffic is set to AC_BE throughout all tests.

For each test configuration in Table 8, three runs of 3 minutes each are performed.

Table 8. 5 GHz Level 3 Test Cases

Emulated Home Traffic	Emulated Home Traffic AC (Downlink and Uplink)	RTC Traffic AC (Downlink Only)	Chamber Attenuation and RSSI on STAUT
Level 3 traffic	BE	BE	Medium (15 dB) / -65 dBm
Level 3 traffic	BE	VO	Medium (15 dB) / -65 dBm

1.3. 2.4 GHz Tests

Following the 5 Ghz methodology, three Wi-Fi scenarios are tested to represent different home configuration and traffic types at 2.4 GHz with a 20 MHz bandwidth. The following parameters are changed.

- The contention traffic from the home devices is emulated with the Candela virtual clients. Three levels of contention traffic (Level 0, Level 1, and Level 2) are implemented and are characterized by a different number of emulated home clients, their respective RSSIs, and their traffic profile.
  - Level 0 tests are baseline tests with no home traffic; only the RTC call is active.
  - Level 1 tests implement emulated home traffic (EHT) with (simple) constant bitrate traffic models.
  - Level 2 tests include more complex EHT that emulates file downloads and various video streaming applications.
- For each level of home traffic, the caller phone is tested for three RSSIs representing a client located at a near, mid, or far distance from the AP. An additional test, named “airtime sweep,” is conducted in which the RSSIs (path loss, PL) is changed during the test.
- The WMM ACs of the emulated clients’ traffic and the RTC traffic are set to different ACs to analyze the effect of the WMM AC on the RTC call quality.

Note: It is assumed that that in a modern dwelling deploying a dual-band AP, most devices/STAs would prefer the 5 GHz band to the 2.4 GHz band when the SNR (signal-to-noise ratio) is high enough. Only legacy or IoT devices and dual-band STAs far from the AP would connect to the 2.4 GHz band. The traffic models or contention profiles for these tests were built with this in mind.

1.3.1. Level 0 Tests

Similarly to the 5 GHz Level 0 tests (Section 1.2.1), Level 0 tests are baseline tests in which the RTC vendor KPIs and one-way latencies are recorded when no other home traffic is present. The caller phone is the only client connected to the AP over Wi-Fi. For each test configuration, three runs of 3 minutes each are performed.

Level 0 tests (Table 9) are conducted for the following parameters.

- Three RSSIs corresponding to a near, mid, and far position of the RTC caller phone to the AP are tested. A fourth sweep test case model a person moving away from an AP then toward an AP. In this test, the attenuation between the caller phone and the AP is changed every 30 seconds with the following patten: 0dB, 10 dB, 20 dB, 30 dB, 40 dB, 30 dB, 30 dB, 20 dB, 10 dB, 0 dB.
- The best effort AC is tested for the RTC downlink traffic. The RTC uplink traffic is set to AC_BE throughout all tests.

Table 9. 2.4 GHz Level 0 Test Cases

Emulated Home Traffic	Emulated Home Traffic AC (Downlink and Uplink)	RTC Traffic AC (Downlink Only)	Chamber Attenuation and RSSI on Caller Phone
Level 0 / no traffic	N/A	BE	Near (0 dB) / -30 dBm
Level 0 / no traffic	N/A	BE	Medium (15 dB) / -47 dBm
Level 0 / no traffic	N/A	BE	Far (30 dB) / -62 dBm
Level 0 / no traffic	N/A	BE	Sweep

1.3.2. Level 1 Tests

Level 1 tests assess the performance of the RTC QoE in the presence of home traffic for different ACs. Table 10 lists the emulated home devices and their traffic profiles. Each emulated home device implements UDP or TCP traffic with a constant bitrate detailed in the table. Three emulated home devices are placed near the AP (0 dB PL), two emulated devices are placed at mid-distance (15 dB PL), and six emulated devices are placed far from the AP (30 dB PL).

Table 10. 2.4 GHz Level 1 Tests—Emulated Home Traffic

Device Type	Capability	EHT Location	Traffic Uplink	Traffic Downlink	IP Transport Protocol	WMM Uplink/Downlink AC
IoT/Sensor	11ax 2x2	Near	9.6 Kbps	None	UDP	BE/BE
IoT/Sensor	11ax 2x2	Near	9.6 Kbps	None	UDP	BE/BE
TV-1	11ax 2x2	Near	128 Kbps	6 Mbps	TCP	BE/VI
IoT/Sensor	11ax 2x2	Mid	9.6 Kbps	None	UDP	BE/BE
IoT/Sensor	11ax 2x2	Mid	9.6 Kbps	None	UDP	BE/BE
Phone	11ax 2x2	Far	1.5 Mbps	1.5 Mbps	TCP	VO/VO
Speaker x2	11ax 2x2	Far	9.6 Kbps	380 Kbps	UDP	BE/VO
Camera	11ax 2x2	Far	3.8 Mbps	9.6 Kbps	UDP	VI/BE
Camera	11ax 2x2	Far	3.8 Mbps	9.6 Kbps	UDP	VI/BE
TV-2	11ax 2x2	Far	128 Kbps	6 Mbps	TCP	BE/VI

Level 1 tests (Table 11) are conducted for the following parameters.

- Three RSSIs corresponding to a near, mid, and far position of the caller phone to the AP are tested. A fourth sweep test case model a person moving away from an AP then toward an AP. In this case, the attenuation between the caller phone and the AP is changed every 30 seconds with the following patten: 0dB, 10 dB, 20 dB, 30 dB, 40 dB, 30 dB, 30 dB, 20 dB, 10 dB, 0 dB.
- Two ACs are tested for the RTC downlink traffic: best effort (BE) and voice (VO). The RTC uplink traffic is set to AC_BE throughout all tests.
- Two AC configurations are used for the home emulated traffic. Downlink and uplink emulated home traffic are set to either AC_BE or the WMM uplink/downlink AC listed in Table 10.

For each test configuration in Table 11, three runs of 3 minutes each are performed.

Table 11. 2.4 GHz Level 1 Test Cases

Emulated Home Traffic	Emulated Home Traffic AC (Downlink and Uplink)*	Messenger Traffic AC (Downlink Only)	Chamber Attenuation and RSSI on Caller Phone
Level 1 traffic	BE or WMM AC	BE or VO	Near (0 dB) / -31 dBm
Level 1 traffic	BE or WMM AC	BE or VO	Medium (15 dB) / -47 dBm
Level 1 traffic	BE or WMM AC	BE or VO	Far (30 dB) / -60 dBm
Level 1 traffic	BE or WMM AC	BE or VO	Sweep

* See Table 10.

1.3.3. Level 2 Tests

Level 2 tests assess the performance of the RTC QoE in the presence of home traffic for different ACs. The key difference between Level 1 and Level 2 tests is the addition of video streaming applications using traffic models that emulate real traffic. These models (Section 1.6) generate non-constant bitrate traffic that best represent the behavior of real applications. Table 12 lists the emulated home devices and their traffic profiles. Some emulated home devices implement UDP or TCP traffic with a constant bitrate, and some emulated devices generate file download and video streaming traffic. Three emulated home devices are placed near the AP (0 dB PL), two emulated devices are placed at mid-distance (15 dB PL), and six emulated devices are placed far from the AP (30 dB PL).

The video streaming has_model is set to a maximum bitrate of 15.6 Mbps.

Table 12. 2.4 GHz Level 2 Tests—Emulated Home Traffic

Device Type	Capability	EHT Location	Traffic Uplink	Traffic Downlink	IP Transport Protocol	WMM Uplink/Downlink AC
IoT/Sensor	11n 2x2	Near	9.6 Kbps	None	UDP	BE/BE
IoT/Sensor	11n 2x2	Near	9.6 Kbps	None	UDP	BE/BE
TV-1	11ax 2x2	Near	has_model	has_model	TCP	BE/VI
IoT/Sensor	11n 2x2	Mid	9.6 Kbps	None	UDP	BE/BE
IoT/Sensor	11n 2x2	Mid	9.6 Kbps	None	UDP	BE/BE
Phone	11ax 2x2	Far	1.5 Mbps	1.5 Mbps	TCP	VO/VO
Speaker	11n 2x2	Far	9.6 Kbps	380 Kbps	UDP	BE/VO
Speaker	11n 2x2	Far	9.6 Kbps	380 Kbps	UDP	BE/VO
Camera	11n 2x2	Far	3.8 Mbps	9.6 Kbps	UDP	VI/BE
Camera	11n 2x2	Far	3.8 Mbps	9.6 Kbps	UDP	VI/BE
TV-2	11ax 2x2	Far	has_model	has_model	TCP	BE/VI

Level 2 tests (Table 13) are conducted for the following parameters (similar to those for level 1 tests).

- Three RSSIs corresponding to a near, mid, and far position of the STAUT to the AP are tested. A fourth sweep test case emulates a person moving away from an AP then toward an AP. In this test, the attenuation between the Caller phone and the AP is changed every 30 seconds with the following patten: 0 dB, 10 dB, 20 dB, 30 dB, 40 dB, 30 dB, 30 dB, 20 dB, 10 dB, 0 dB.
- Two ACs are tested for the RTC downlink traffic: best effort (BE) and voice (VO). The uplink traffic is set to AC_BE throughout all tests.
- Two AC configurations are used for the home emulated traffic. Downlink and uplink emulated home traffic are set to either AC_BE or the WMM uplink/downlink AC listed in Table 12.

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For each test configuration in Table 13, three runs of 3 minutes each are performed.

Table 13. 2.4 GHz Level 2 Test Cases

Emulated Home Traffic	Emulated Home Traffic AC (Downlink and Uplink)*	RTCMessenger Traffic AC (Downlink Only)	Chamber Attenuation and RSSI on Client
Level 2 traffic	BE or WMM AC	BE or VO	Near (0 dB) / -33 dBm
Level 2 traffic	BE or WMM AC	BE or VO	Medium (15 dB) / -48 dBm
Level 2 traffic	BE or WMM AC	BE or VO	Far (30 dB) / -61 dBm
Level 2 traffic	BE or WMM AC	BE or VO	Sweep

* See Table 12.

1.4. Test Platform

To test RTC application performance when connected via Wi-Fi, we modeled the home in three parts: near, mid, and far ranges (Figure 3). These ranges are often referred to as vantage points. An additional vantage point, sweep, captures the RTC application experience for a device that is moving within the home. The LANforge at near, mid, and far ranges generates concurrent traffic to emulate a residential Wi-Fi environment.

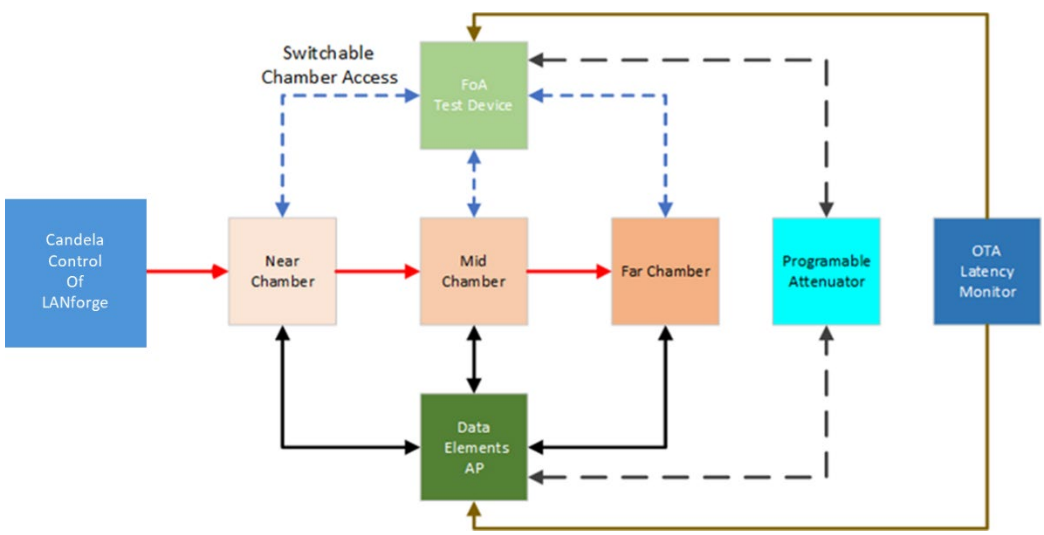

Figure 3. Model Layout of Wi-Fi QoE: Home in a Box

For each of the defined test cases, the RTC application calling tests are performed at four different vantage points (or attenuation profiles): near, mid, far, and sweep. For the near, mid, and far test cases, it is assumed that the RTC device is at that vantage point and does not move. For the sweep test case, it is assumed that the user starts the call at the near Wi-Fi range, goes to the far Wi-Fi range, and returns to the near Wi-Fi range. Each of the three fixed vantage points is modeled by using a fixed RF attenuator. For the sweep test case, the desired RF behavior at that vantage point is captured by changing the value of a programmable attenuator.

The network diagram for the test setup is captured in Figure 4. The RTC application calling for all test runs are peer-to-peer calls between a Wi-Fi device in-chamber and a wired/Ethernet device, enabled through the Wi-Fi AP's LAN bridge. This prevents any variations in WAN latency from skewing the interpretation of test results. A fixed 80-ms latency is introduced with the Calnex WAN emulator to reach latency typical for a call made over a WAN. This return trip time (RTT) number closely models the average WAN latency numbers collected from a large sample of RTC application call data.

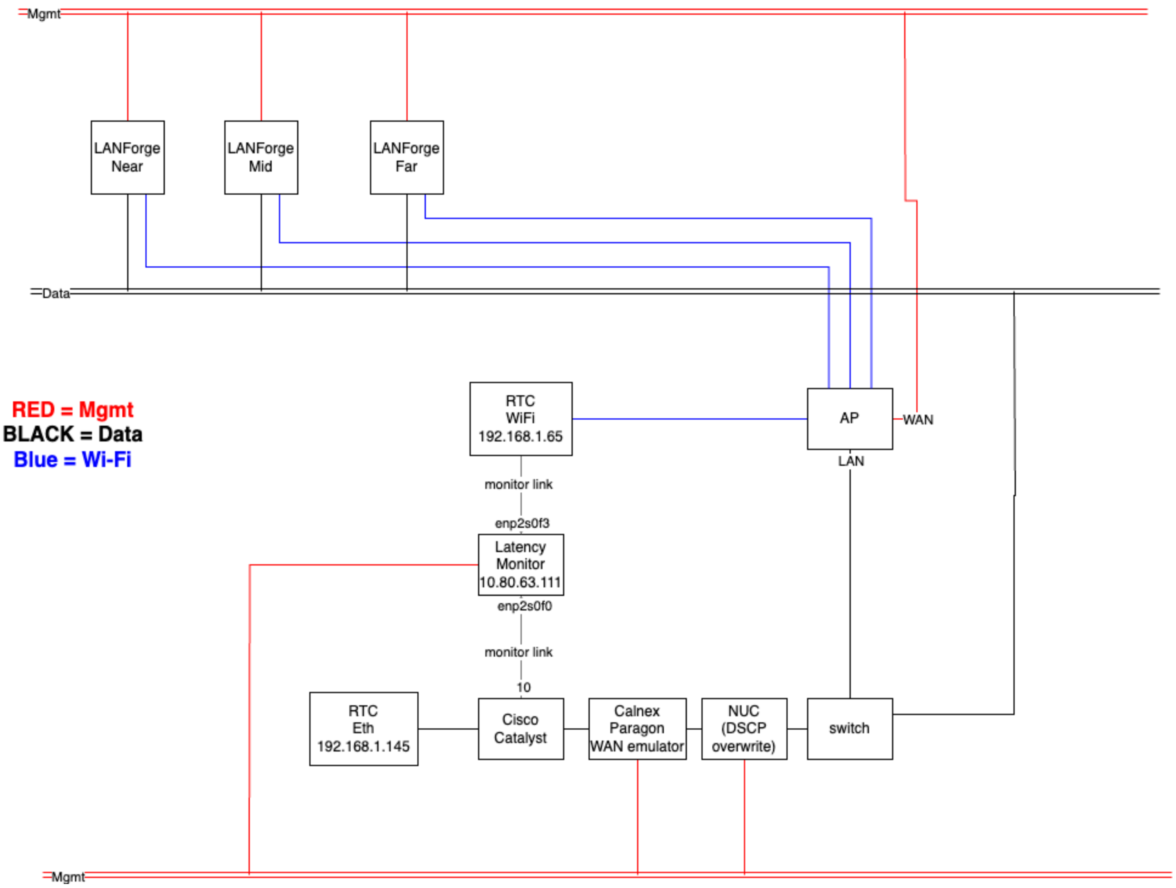

Figure 4. Network Topology of Wi-Fi QoE: Home in a Box

1.4.1. Candela System

Figure 5 shows the physical layout of the setup. The three large chambers representing the three vantage points house actual Wi-Fi client devices. The three small chambers representing the three vantage points house emulated Wi-Fi client devices. These two sets of chambers generate the concurrent traffic for the tests. The fourth large chamber houses the Wi-Fi AP, and the fourth small chamber houses the device on which the RTC is executed. The fourth small chamber is connected to a programmable attenuator.

Figure 5. Physical Layout of Wi-Fi QoE: Home in a Box

1.4.2. LANforge

Concurrent traffic is emulated by using the CandelaTech LANforge system. The LANforge traffic generator, in its deployed configuration, allows for the programing and operation of hundreds of Wi-Fi devices through up to ten unique Wi-Fi radios. Each radio can be enabled to support 802.11 capabilities ranging from legacy 802.11abgn to more recent 802.11ac and 802.11ax in the 2.4 GHz and 5 GHz bands. A variety of traffic patterns, resembling typical residential devices, can then be programmed for each radio (as described in Section 1.6). A unique LANforge instance is deployed at each vantage point (near, mid, and far). The LANforge systems are further clustered together, allowing for single pane of glass operation. In addition, the LANforge is used to control the programmable attenuator used to emulate distance between the AP and the device under test running the RTC.

Figure 6. CandelaTech LANforge Wi-Fi Client Emulator

1.4.3. Latency Monitor Platform

The latency monitor captures and analyzes the application traffic exchanged between the two vantage points at the two RTC endpoints. The first vantage point is created by a port mirroring switch in the network path near the Ethernet-connected RTC endpoint, and the second vantage point is produced by the RTC Wi-Fi device by internally mirroring all traffic sent/received on its Wi-Fi interface to a USB-Ethernet dongle. Between these two vantage points lies the Wi-Fi network. The latency monitor captures each endpoints' traffic data simultaneously.

The process of mirroring Wi-Fi traffic in the device involves configuring special features in the Android (Linux) operating system. These features help control how packets move in and out of the available network interfaces. By using Traffic Control and Queue Discipline modules in Linux, the incoming and outgoing packets on the wireless interface are duplicated onto the Ethernet interface through a USB-Ethernet dongle, which is connected to the latency monitor platform for measurement.

Mirrored traffic from these two vantage points is captured by the latency monitor via a single, dual-port Ethernet NIC card that supports hardware timestamps. The timestamps on the two interfaces are synchronized to a common clock. By simultaneously capturing on both interfaces and timestamping with a common clock, the analysis software can identify, on a packet-by-packet basis, the time that each packet crosses the first vantage point and the time that it crosses the second vantage point. It can then calculate the latency between those two crossings, as well as identify any packets dropped by the network.

The latency monitor analysis software plots per-packet latency for each identified "flow" (i.e., 5-tuple) as well as the flow's data rate (on 100-ms intervals) over time.

1.4.4. Hardware Configuration

The test environment was set up to emulate a typical Wi-Fi deployment of a U.S. residential unit (apartment/detached home) with an average area of 2,000–2,500 square feet. To enable this emulation, multiple wireless testing chambers, splitters, attenuators, and latency injectors were used to simulate different rooms in a house and to characterize the behavior of RTC endpoint locations. The hardware used consists of 1 AP chamber, 1 RTC device chamber (mobile phone connected via Wi-Fi to AP 5 Ghz CH149 BW 80 MHz), 3 LANforge chambers (near, mid, far), and 3 LANforge emulators. In conjunction with the chambers, an RTC endpoint with an Ethernet connection on the LAN side of the AP was used to mirror the called endpoint.

A test call consists of an RTC calling endpoint connected via Wi-Fi to the APUT (RTC Chamber) to the called RTC connected on the LAN ethernet. To simulate the audio and video component of the call, another pair of phones streaming a 1080p video clip were positioned adjacent to the RTC endpoint devices. Audio/Video calling on the Client devices (RTC Wi-Fi and RTC Ethernet) is assumed as the Video/audio call will be peer-2-peer. The RTC device on Wi-Fi (chamber phone) makes use of a programmable attenuation to simulate use at different vantage points (near, mid, far) within the home.

1.5. Test Applications

Over-the-top RTC applications have become fairly resilient to network performance variations through coding efficiencies and other optimizations. In spite of this, these applications have latency and bandwidth requirements for minimally viable operation, and latency under load conditions can exceed application thresholds.

The RTC application for the tests has a peak bandwidth requirement of 3 Mbps to deliver an HD video for a peer-to-peer call. The latency requirement using excessive one-way delay (eOWD), the difference between one-way latency and the minimum one-way latency, as a proxy for this RTC application is 170 ms. The control traffic for this RTCP (Real-Time Transport Control Protocol) uses RTP (Real-Time Protocol), the data transport protocol used by this RTC application.

The Candela LANforge traffic generator is the source of concurrent traffic for the testbed. The LANforge does not emulate the control and data protocol that each of the applications running on a device within a home would use, but it does emulate the volume of traffic typical within a residential environment. This capability meets the concurrent traffic requirement for the testbed.

1.6. Traffic Model

Three traffic models were used in the testing. The baseline model creates traffic designed to emulate different kinds of traffic while making use of all available bandwidth of the WLAN, .i.e., a fully loaded WLAN. The application model is designed to mirror expected application traffic in the home setting in a static state. The application sweep model is a variant of the application model that dynamically changes the traffic characteristics to further mirror expected changes in real-time traffic in the home setting, altering channel utilization.

1.6.1. Baseline Model

The baseline model emulates different traffic that could be seen in a typical home. The traffic, while having the following characteristics, is sent at a rate that utilizes the maximum airtime available.

Table 14 Baseline Model Data Characteristics

Device Type	Capability	EHT Location	Traffic Uplink	Traffic Downlink	IP Transport Protocol	WMM Uplink/Downlink AC/AX
Camera	11ax 2x2	Near	3.8 Mbps	9.6 Kbps	UDP	VI/BE
Laptop	11ax 2x2	Near	1.5 Mbps	1.5 Mbps	TCP	VO/VO
Phone	11ax 2x2	Near	1.5 Mbps	1.5 Mbps	TCP	VO/VO
TV-1	11ax 2x2	Near	128 Kbps	6 Mbps	TCP	BE/VI
Thermostat	11ax 2x2	Near	9.6 Kbps	None	UDP	BE/BE
Speaker x2	11ac 2x2	Near	9.6 Kbps	380 Kbps	UDP	BE/VO
Camera	11ax 2x2	Mid	3.8 Mbps	9.6 Kbps	UDP	VI/BE

Device Type	Capability	EHT Location	Traffic Uplink	Traffic Downlink	IP Transport Protocol	WMM Uplink/Downlink AC/AX
Laptop	11ax 2x2	Mid	1.5 Mbps	1.5 Mbps	TCP	VO/VO
Phone	11ax 2x2	Mid	1.5 Mbps	1.5 Mbps	TCP	VO/VO
Speaker	11ac 2x2	Mid	9.6 Kbps	380 Kbps	UDP	BE/VO
Speaker	11ax 2x2	Mid	9.6 Kbps	380 Kbps	UDP	BE/VO
Camera x2	11ax 2x2	Far	3.8 Mbps	9.6 Kbps	UDP	VI/BE
TV-2	11ax 2x2	Far	128 Kbps	6 Mbps	TCP	BE/VI

1.6.2. Application Model

Background traffic is generated to create load in the WLAN intended to model a typical residential Wi-Fi environment. Three application types were modeled: video streaming, file transfer, and IoT. The traffic characteristics are shown in Table 15.

Table 15. Application Model Data Characteristics

Traffic Type	Emulated Traffic	Traffic Characteristics	Model
Netflix	Adaptive bitrate (ABR video streaming)	Target bitrate from 0.2 Mbps to 15.6 Mbps	has_model
Hulu	Adaptive bitrate (ABR video streaming)	Target bitrate from 0.2 Mbps to 15.6 Mbps	has_model
File transfer	File uploading	Target data rate (up/dl) is 50% of TCP capacity (50% airtime); to be calculated per device/MCS	file_traffic model
WebCam (security)	High resolution High motion Video	1 Mbps UL TCP 1500 B packets Peak data rate: 2 Mbps 1 kbps DL TCP 1500 B	IoT model
Internet speaker	Streaming audio	135 kbps DL (packet size 1276 B) (UL traffic is mainly TCP ack)	IoT model
Thermostat	Periodic reporting	DL 180 kbps (packet size 350 B) UL 180 kbps (packet size 350 B)	IoT model

The video streaming model (has_model) mimics a typical HTTP adaptive streaming video session in steady-state operation. It results in a video chunk being downloaded once every 6 seconds. The video streaming rate is adapted based on the throughput that it achieved in the immediately previous download, with the highest available streaming rate less than 80% of the achieved throughput selected. The available streaming rates are: 235 kbps, 375 kbps, 560 kbps, 750 kbps, 1.05 Mbps, 1.75 Mbps, 2.35 Mbps, 3 Mbps, 4.5 Mbps, 6 Mbps, 10 Mbps, 12 Mbps, 15.6 Mbps.

The file transfer model (file_traffic) mimics a range of file transfer workloads (web browsing, email, social media, cloud sync, cloud backup, etc.). It generates a configurable amount of TCP file transfer traffic in both upstream and downstream directions, consisting of a series of file transfers with randomized file sizes (drawn from a log-normal distribution with mean 500 kB, median 100 kB). File transfers are initiated via a Poisson process with a mean transfer initiation rate calculated based on the configured rate.

The IoT model mimics the traffic produced by several IoT devices: a streaming camera, an Internet speaker, and a thermostat. This model consists of typical upstream and downstream traffic that is present continuously on the Wi-Fi network. Other IoT devices were reviewed and not included because their traffic was bursty or is represented by one of the other two models. This model was built on layer 3 traffic generation.

2. Data Collected

Data from the RTC application and network latency were collected to assess the impacts WMM had on QoE. The data were collected during each of the differing WMM data marking and concurrent traffic in use. Though extended data were collected, only those that clearly show the impacts are included in this paper. Application Data

The RTC application used for the tests is based on the webRTC stack. It collects a comprehensive set of metrics to analyze each test. For the test runs, metrics were collected from the application stack in three categories:

- transport (e.g., transport bitrates, encoding/decoding rates, bytes sent/received, available bandwidth),
- video (e.g., send/receive bitrate, packets lost, huge frame sent, frames per second, video quality score), and
- audio (e.g., send/receive bitrate, packets lost, jitter).

These metrics provide sufficient information to examine the QoE for the RTC application during each of the tests.

2.1. Network Latency Data

In addition to the internal metrics (KPIs) collected by the application, the network latency for the RTC application traffic is measured directly using the latency monitor platform described in Section 1.4.3. The latency monitor provides per-packet, one-way latency measurements and groups packets that share a common 5-tuple into a “flow.”

To compare against the application metrics, the per-packet latency data for the RTC flow are time aligned with the application’s call record and then transformed into a time-series format of 1-second intervals to align with the time-series format of the application data. Within each 1-second interval, the average per-packet latency and 99th percentile per-packet latency are calculated.

Synchronization is key because it allows for a direct correlation between the network latency measurements and the application KPIs.

3. Data Analysis

Through the collection of data, it is possible to see how WMM in combination with aligned traffic marking can impact the user’s experience. Analyzed data come from RTC-collected information, measured latency, and information found within on-the-air pcap files. The collected data show the downlink (DL) and uplink (UL) latency, audio jitter, video RTT, and air-time utilization. The impacts or improvements on the user’s experience can be realized through these KPIs. Data are presented in various formats based on the type of data collected—tables show averages, and graphs show time-based data.

3.1. Application Data—5 GHz and 2.4 GHz

The data collected from the application were first compared through the summary metrics for each test run. The summary metric allows us to examine the QoE with data from transport, audio, and video metrics. Some of the important application metrics that affect QoE are audio jitter and video quality score. These metrics are compared for the tests with and without WMM. Acceptable levels are audio jitter of 30 ms and video latency of 180 ms. A 24-per-second frame rate for video transmission will deliver 1080p video quality.

3.1.1. Level 1 Testing

The 5 GHz and 2.4 GHz Level 1 tests compare the video received quality score in frames per second on the Y-axis. For 5 GHz with AC_BE for the RTC, the video quality remains over 25 frames per second for the entire duration of the call. For 2.4 GHz, the video quality remains low (below 25 frames per second) for 99 samples of quality metric with AC_BE for the RTC compared to 27 samples with AC_VO.

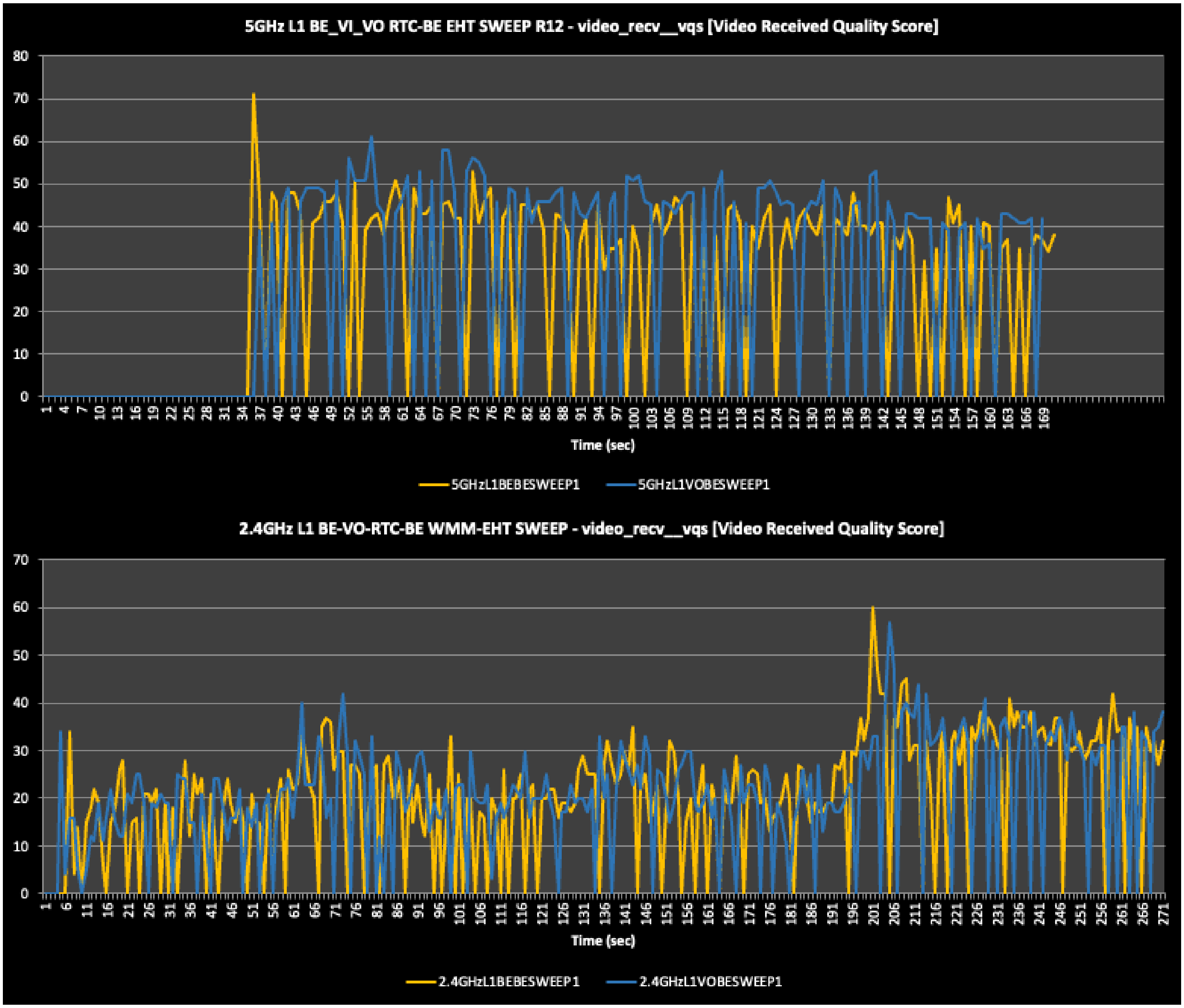

Figure 7. 5 GHz and 2.4 GHz Level 1 Testing Results of Video Performance

Impacts of WMM on Wi-Fi

The 5 GHz and 2.4 GHz Level 1 tests compare the audio jitter in milliseconds on the Y-axis. For 5 GHz, the audio jitter peaks to 56 ms with AC_BE for the RTC compared to 15 ms with AC_VO. The peak audio jitter is almost twice as high as the acceptable jitter for the RTC. For 2.4 GHz, the peak value of audio jitter during the test is 26 ms with AC_BE for the RTC compared to 23 ms with AC_VO.

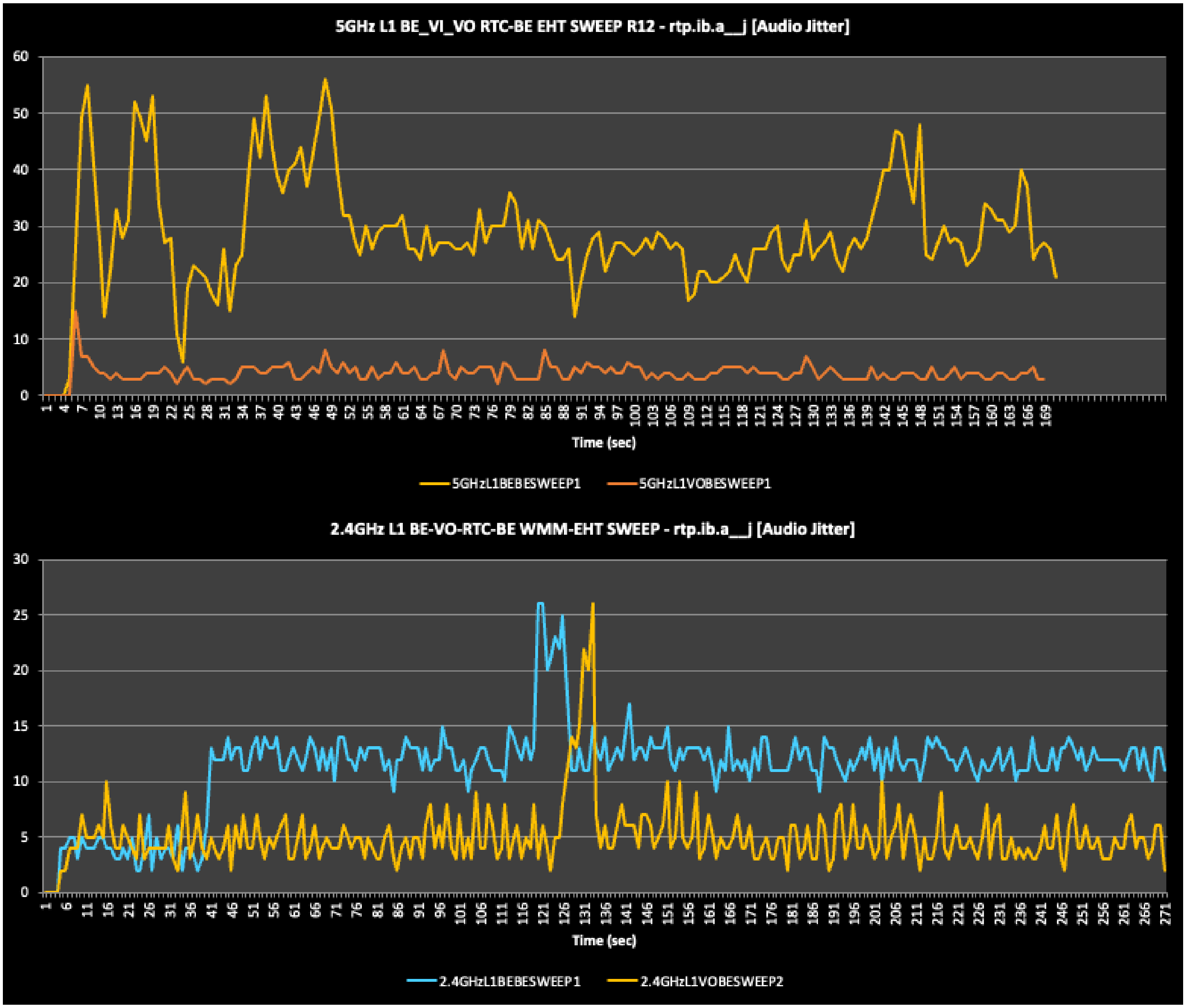

Figure 8. 5 GHz and 2.4 GHz Level 1 Testing Results of Audio Performance

3.1.2. Level 2 Testing

The 5 GHz Level 2 tests compare the video received quality score, with and without WMM, in frames per second on the Y-axis. With AC_BE for the RTC and also with AC_VO, the video quality remains good (above 25 frames per second) for the entire duration of the call.

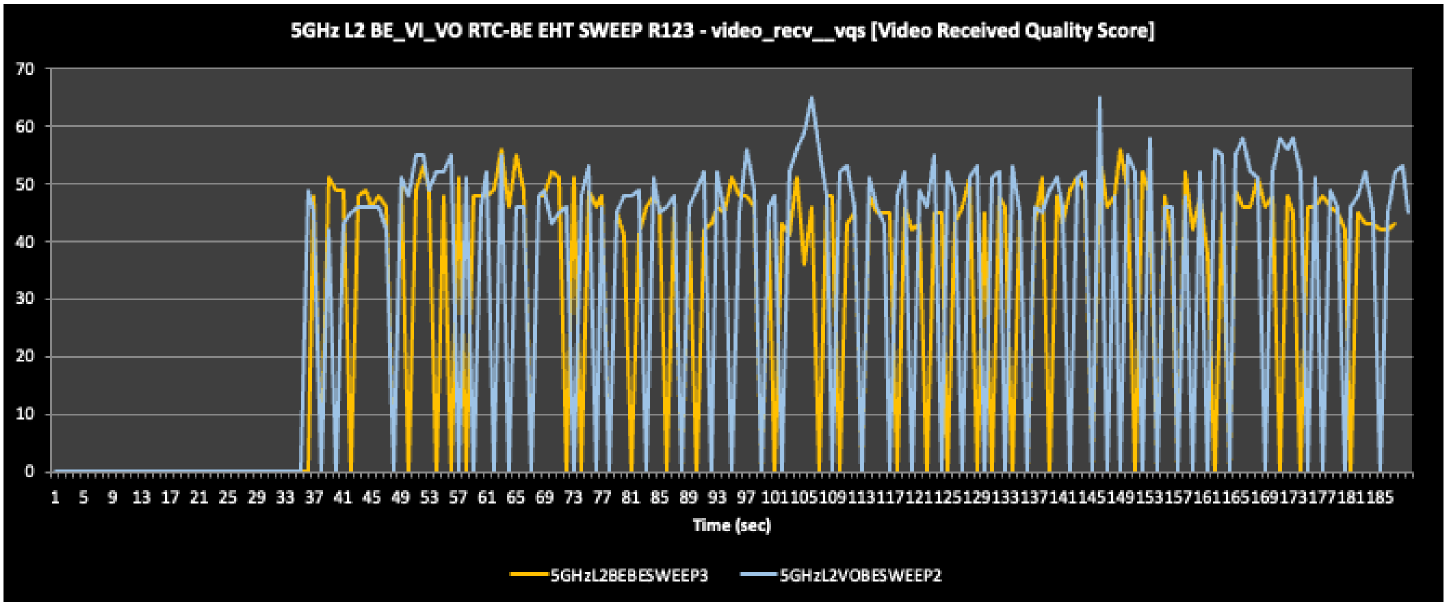

Figure 9. 5 GHz Level 2 Testing Results of Video Performance

The 5 GHz Level 2 tests compare the audio jitter, with and without WMM, in milliseconds on the Y-axis. The audio jitter peaks to 25 ms with AC_BE for the RTC compared to 7 ms with AC_VO. Both peaks, with and without WMM, are within the acceptable range for a good quality audio RTC call.

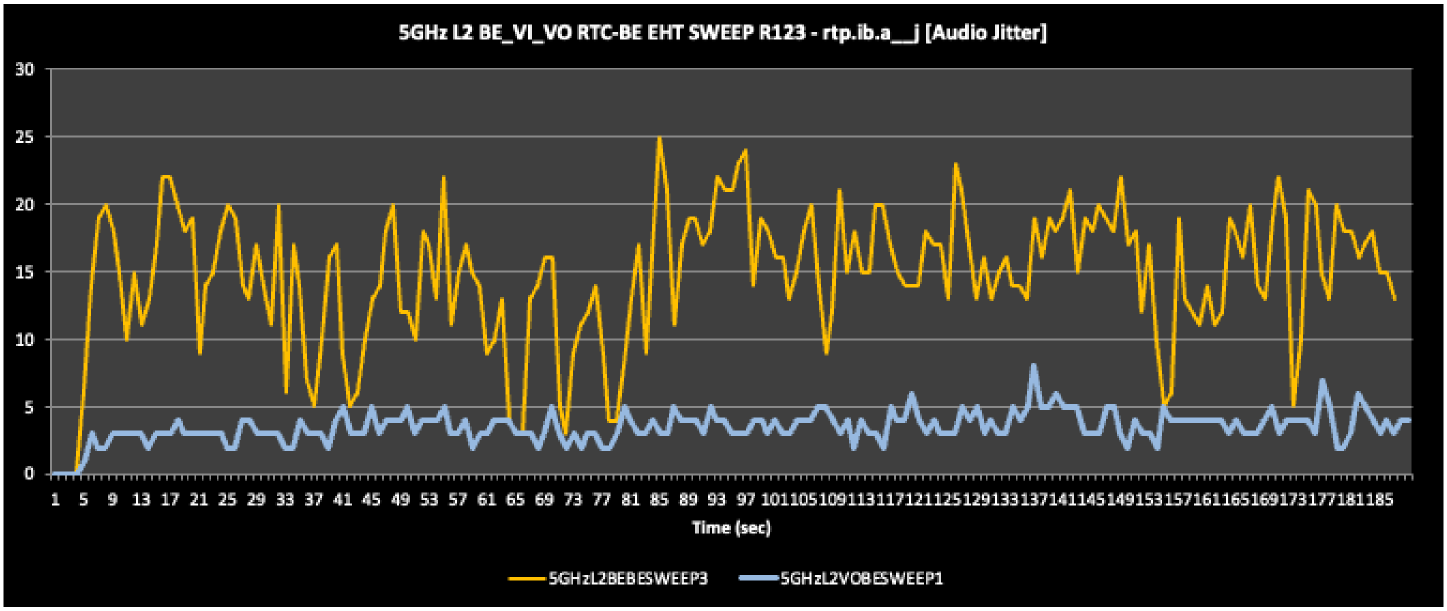

Figure 10. 5 GHz Level 2 Testing Results of Audio Performance

3.1.3. Level 3 Testing

The 5 GHz Level 3 tests compare the video received quality score, with and without WMM, in frames per second on the Y-axis. With AC_BE for the RTC and also with AC_VO, the video quality remains good (above 25 frames per second) for the entire duration of the call.

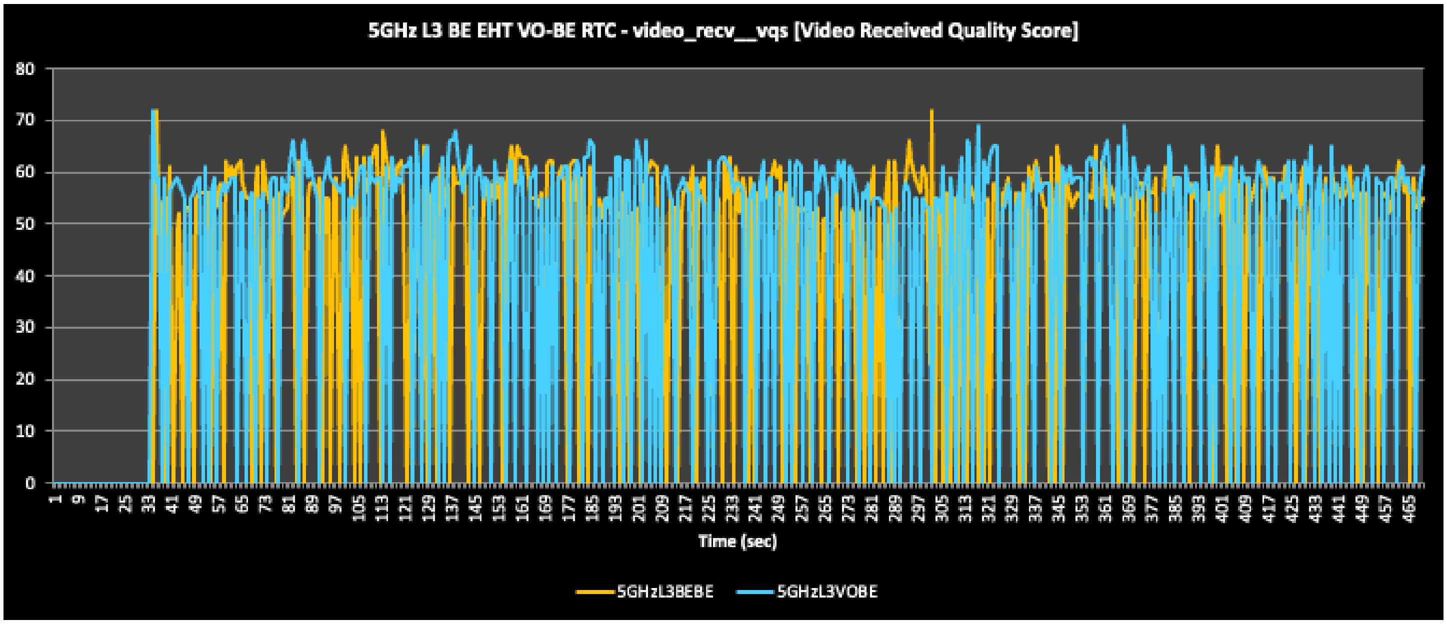

Figure 11. 5 GHz Level 3 Testing Results of Video Performance

The 5 GHz Level 3 tests compare the audio jitter, with and without WMM, in milliseconds on the Y-axis. The audio jitter peaks to 67 ms with AC_BE for the RTC compared to 7 ms with AC_VO.

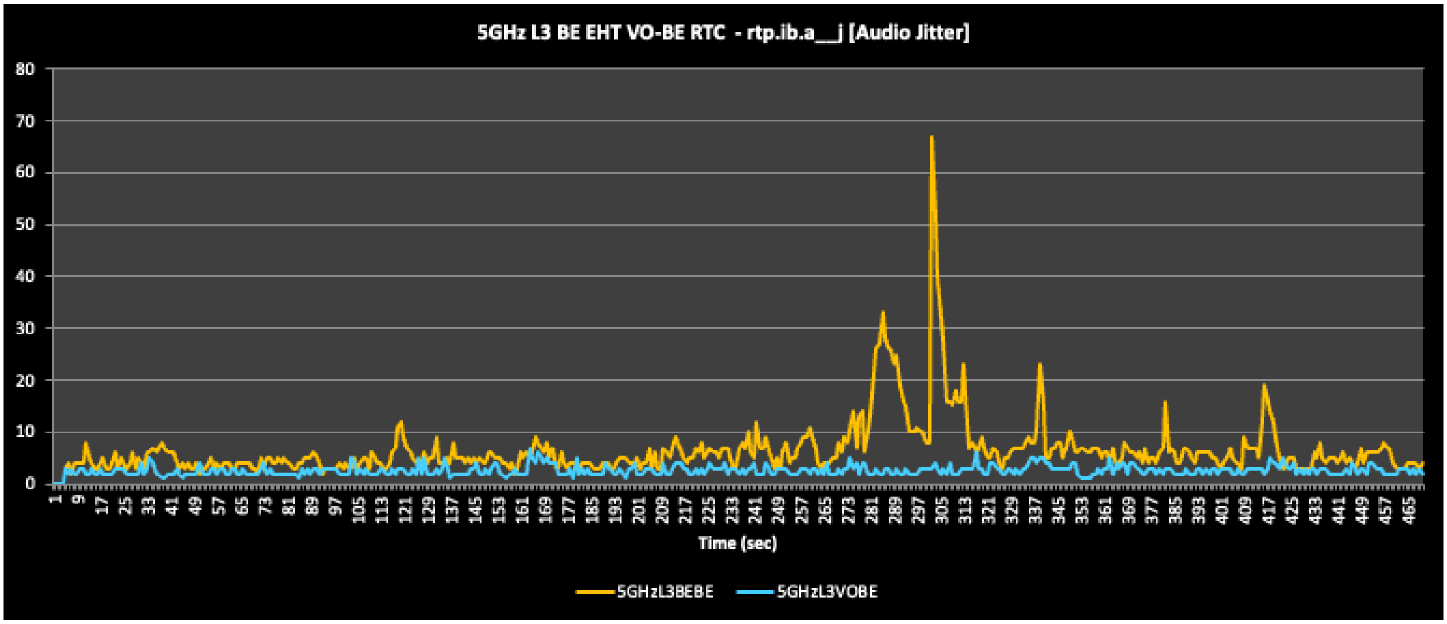

Figure 12. 5 GHz Level 3 Testing Results of Audio Performance

3.2. Latency Data—5 GHz and 2.4 GHz

This section analyzes the impact of RSSI and AC on the uplink and downlink latencies. The downlink and uplink latency statistics results in the tables below report the average across three runs of the same test case. The latency statistics include the following:

- average latency;
- standard deviation latency (Std Dev);
- P0, the minimum latency observed during the test;
- P90, the 90th percentile;
- P99, the 99th percentile, and its packet delay variation (99 PDV = P99 - P0);
- P99.9, the 99.9th percentile, and its packet delay variation (99.9 PDV = P99.9 - P0);
- audio jitter average (RTC KPI); and
- transport RTT average (RTC KPI).

For P99.9, note that about 20,000 packets are exchanged during a 3-minute RTC call; therefore, P99.9 represents about 2 packets and is not representative of the overall latency.

The figures shown in this section graph some of the test runs to illustrate the latency trends and patterns observed between different test runs or test cases. No (timeline) point-to-point comparison should be made, except for the downlink and uplink latency of the same test run.

> **Note:** The RTC uplink traffic is set to AC_BE throughout all tests. The RTC ACs referenced in this section—BE, VI, or VO—refer only to downlink traffic.

3.2.1. 5 GHz Level 0 Testing

Level 0 tests are conducted without Wi-Fi contention (no EHT traffic), and the only client connected to the AP is the RTC device. The test cases include AC_BE and AC_VO at near (approx. -49 dBm), mid (approx. -65 dBm), and far (approx. -82 dBm) distances from the AP.

The downlink and uplink latencies are reported in Table 16 and Table 17. All test cases show similar downlink and uplink latency results with P99 downlink at approx. 90 ms (about 9 ms PDV) and P99 uplink at approx. 92 ms (about 11 ms PDV).

Table 16. 5 GHz Level 0 Downlink Latency Statistics (in milliseconds)

EHT AC	RTC AC	RSSI	Lat Avg	Lat Std Dev	Lat P0	Lat P90	Lat P99	Lat P99.9	Lat P99 PDV	Lat P99.9 PDV	Audio Jitter Avg	Transport RTT Avg
NA	BE	Near	83	2	81	85	90	98	9	17	3	173
NA	BE	Mid	83	2	81	85	90	97	9	16	3	168
NA	BE	Far	83	2	81	85	91	97	9	16	3	171
NA	BE	Sweep	83	2	81	84	90	97	9	16	3	166
NA	VO	Near	83	2	81	84	90	97	9	16	3	166
NA	VO	Mid	83	2	81	85	90	97	9	16	3	167
NA	VO	Far	83	2	81	85	90	97	9	16	3	167
NA	VO	Sweep	83	2	81	85	90	97	9	16	3	165

Table 17. 5 GHz Level 0 Uplink Latency Statistics (in milliseconds)

EHT AC	RTC AC	RSSI	Lat Avg	Lat Std Dev	Lat P0	Lat P90	Lat P99	Lat P99.9	Lat P99 PDV	Lat P99.9 PDV	Audio Jitter Avg	Transport RTT Avg
NA	BE	Near	83	2	80	84	91	98	11	18	3	173
NA	BE	Mid	83	2	80	84	91	97	11	18	3	168
NA	BE	Far	83	2	79	84	91	98	13	19	3	171
NA	BE	Sweep	82	2	80	84	92	99	12	20	3	166
NA	VO	Near	82	2	80	84	91	98	11	18	3	166
NA	VO	Mid	82	2	79	84	92	100	13	21	3	167
NA	VO	Mid	83	2	80	84	92	100	13	20	3	167
NA	VO	Mid	82	2	78	84	92	100	14	21	3	165

Figure 13 shows the P99 downlink and uplink latency recorded for a test run when the RTC client is far from the AP and its traffic is set to AC_BE.

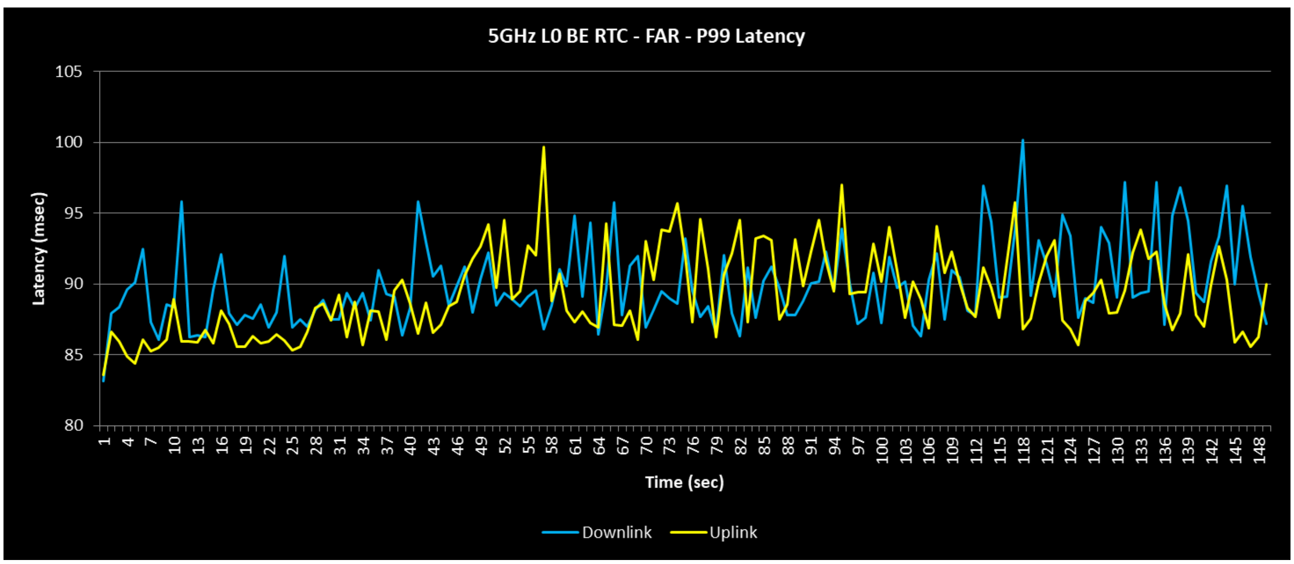

Figure 13. 5 GHz Level 0 P99 Latency (AC_BE, Far Client)—Comparison of Downlink and Uplink

3.2.2. 5 GHz Level 1 Testing

Level 1 tests are conducted with contention traffic (EHT) that includes 15 clients generating constant UDP or TCP flows and an airtime utilization at approx. 88%. EHT traffic is set to either AC_BE in downlink and uplink or the WMM AC. RTC downlink traffic is set to AC_BE, AC_VI, or AC_VO. RTC uplink traffic is always set to AC_BE.

Impacts of WMM on Wi-Fi

Figure 14 shows the EHT airtime utilization for one test run.

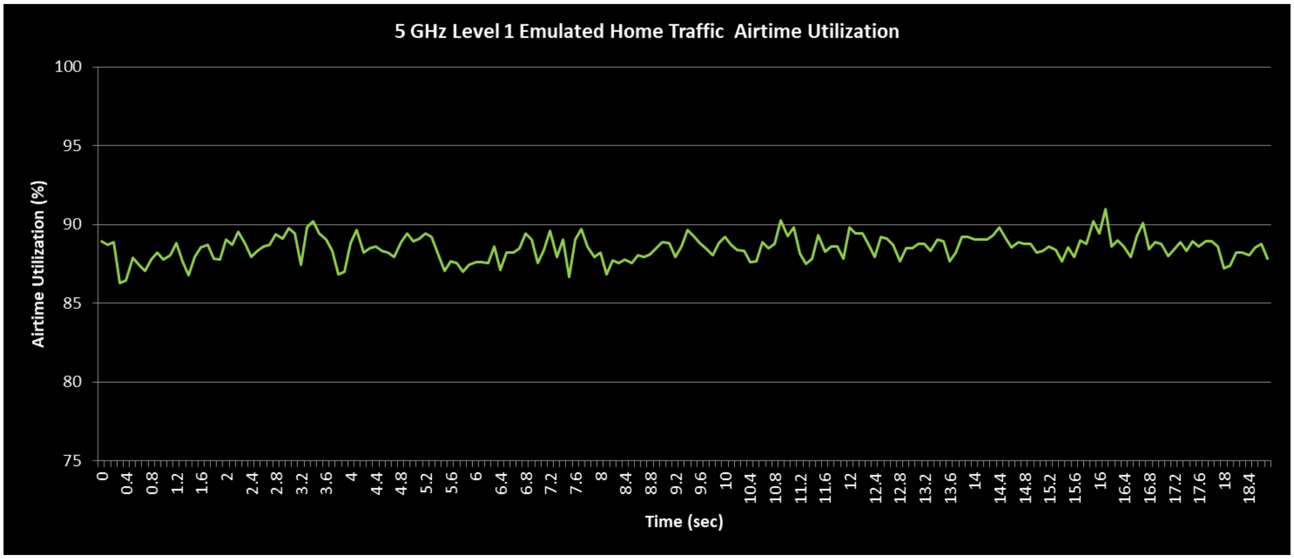

Figure 14. 5 GHz Level 1 Emulated Home Traffic Airtime Utilization

Table 18 and Table 19 give the downlink and uplink statistics. With EHT traffic set to AC_BE, the average downlink latency is higher than 147 ms with AC_BE for the RTC, lower than 118 ms with AC_VI, and lower than 87 ms with AC_VO. This observation applies to all RSSIs including the sweep test case. The P99 downlink latency is further reduced from greater than 345 ms for AC_BE to lower than 100 ms for AC_VO. There is no improvement of uplink latency with AC_VO for the RTC downlink traffic because the RTC uplink traffic is always set to AC_BE. In some cases, the P99 uplink latency increases. Overall, the average audio jitter and transport RTT are greatly improved. Similar observations are made when the EHT traffic is set to WMM.

Table 18. 5 GHz Level 1 Downlink Statistics (in milliseconds)

EHT AC	RTC AC	RSSI	Lat Avg	Lat Std Dev	Lat P0	Lat P90	Lat P99	Lat P99.9	Lat P99 PDV	Lat P99.9 PDV	Audio Jitter Avg	Transport RTT Avg
BE	BE	Near	147	53	82	210	345	500	264	419	28	231
BE	BE	Mid	158	59	82	225	379	584	297	502	30	240
BE	BE	Far	160	63	82	232	409	535	327	453	32	246
BE	BE	Sweep	154	56	82	220	361	481	279	399	29	241
BE	VI	Near	118	42	82	160	286	489	204	408	22	206
BE	VI	Mid	114	35	81	152	253	381	172	300	20	201
BE	VI	Far	118	40	81	158	277	475	196	394	21	211
BE	VI	Sweep	117	39	82	158	279	408	197	327	21	208
BE	VO	Near	86	4	81	89	97	123	16	42	4	172
BE	VO	Mid	86	4	81	89	97	128	16	46	4	175
BE	VO	Far	87	4	81	91	100	123	19	42	4	176
BE	VO	Sweep	86	4	81	90	98	120	17	39	4	179
WMM	BE	Near	124	35	82	164	266	371	184	289	22	212
WMM	BE	Mid	131	43	82	179	305	420	222	338	24	213

EHT AC	RTC AC	RSSI	Lat Avg	Lat Std Dev	Lat P0	Lat P90	Lat P99	Lat P99.9	Lat P99 PDV	Lat P99.9 PDV	Audio Jitter Avg	Transport RTT Avg
WMM	BE	Far	137	45	83	190	307	433	225	351	25	230
WMM	BE	Sweep	132	41	82	182	288	377	205	295	25	230
WMM	VI	Near	99	30	81	129	234	352	152	271	12	185
WMM	VI	Mid	124	46	82	172	298	559	216	477	24	215
WMM	VI	Far	111	37	82	146	252	504	170	422	18	209
WMM	VI	Sweep	113	38	81	152	259	503	178	421	18	208
WMM	VO	Near	87	16	81	91	113	343	32	262	5	175
WMM	VO	Mid	88	20	81	93	124	388	42	307	6	182
WMM	VO	Far	86	16	81	90	103	375	22	294	4	176
WMM	VO	Sweep	87	7	81	92	115	171	34	90	5	183

Table 19. 5 GHz Level 1 Uplink Latency Statistics (in milliseconds)

EHT AC	RTC AC	RSSI	Lat Avg	Lat Std Dev	Lat P0	Lat P90	Lat P99	Lat P99.9	Lat P99 PDV	Lat P99.9 PDV	Audio Jitter Avg	Transport RTT Avg
BE	BE	Near	90	6	81	98	113	128	31	47	28	231
BE	BE	Mid	91	7	80	100	117	141	37	62	30	240
BE	BE	Far	97	14	81	112	141	237	60	156	32	246
BE	BE	Sweep	99	27	81	115	227	348	146	267	29	241
BE	VI	Near	90	7	81	98	113	130	32	49	22	206
BE	VI	Mid	91	8	81	102	120	139	39	59	20	201
BE	VI	Far	99	17	81	119	157	241	76	160	21	211
BE	VI	Sweep	98	26	81	113	227	368	146	287	21	208
BE	VO	Near	91	14	81	101	157	225	76	144	4	172
BE	VO	Mid	92	16	81	103	159	293	79	213	4	175
BE	VO	Far	96	18	81	112	178	246	97	165	4	176
BE	VO	Sweep	96	25	80	111	204	385	124	305	4	179
WMM	BE	Near	92	9	81	104	125	146	44	65	22	212
WMM	BE	Mid	93	11	81	106	135	168	54	87	24	213
WMM	BE	Far	101	18	81	122	169	257	87	176	25	230
WMM	BE	Sweep	103	46	80	121	302	686	223	607	25	230
WMM	IVI	Near	92	15	81	102	152	245	71	164	12	185
WMM	VI	Mid	94	11	81	107	131	167	50	86	24	215
WMM	VI	Far	102	18	81	124	162	224	81	143	18	209
WMM	VI	Sweep	102	46	81	116	297	677	216	596	18	208
WMM	VO	Near	94	21	81	107	183	336	102	255	5	175
WMM	VO	Mid	98	28	81	114	229	391	149	310	6	182

EHT AC	RTC AC	RSSI	Lat Avg	Lat Std Dev	Lat P0	Lat P90	Lat P99	Lat P99.9	Lat P99 PDV	Lat P99.9 PDV	Audio Jitter Avg	Transport RTT Avg
WMM	VO	Far	98	19	81	118	171	262	90	182	4	176
WMM	VO	Sweep	103	40	81	125	306	458	225	377	5	183

Figure 15 compares the P99 downlink latencies for an RTC client near the AP (top figure) and far from the AP (bottom figure). The P99 downlink latency for the near client is 415 ms for AC_BE, 245 ms for AC_VI, and 99 ms for AC_VO. As expected, these results show the clear benefit of setting RTC to AC_VO or, to a lesser extent, AC_VI.

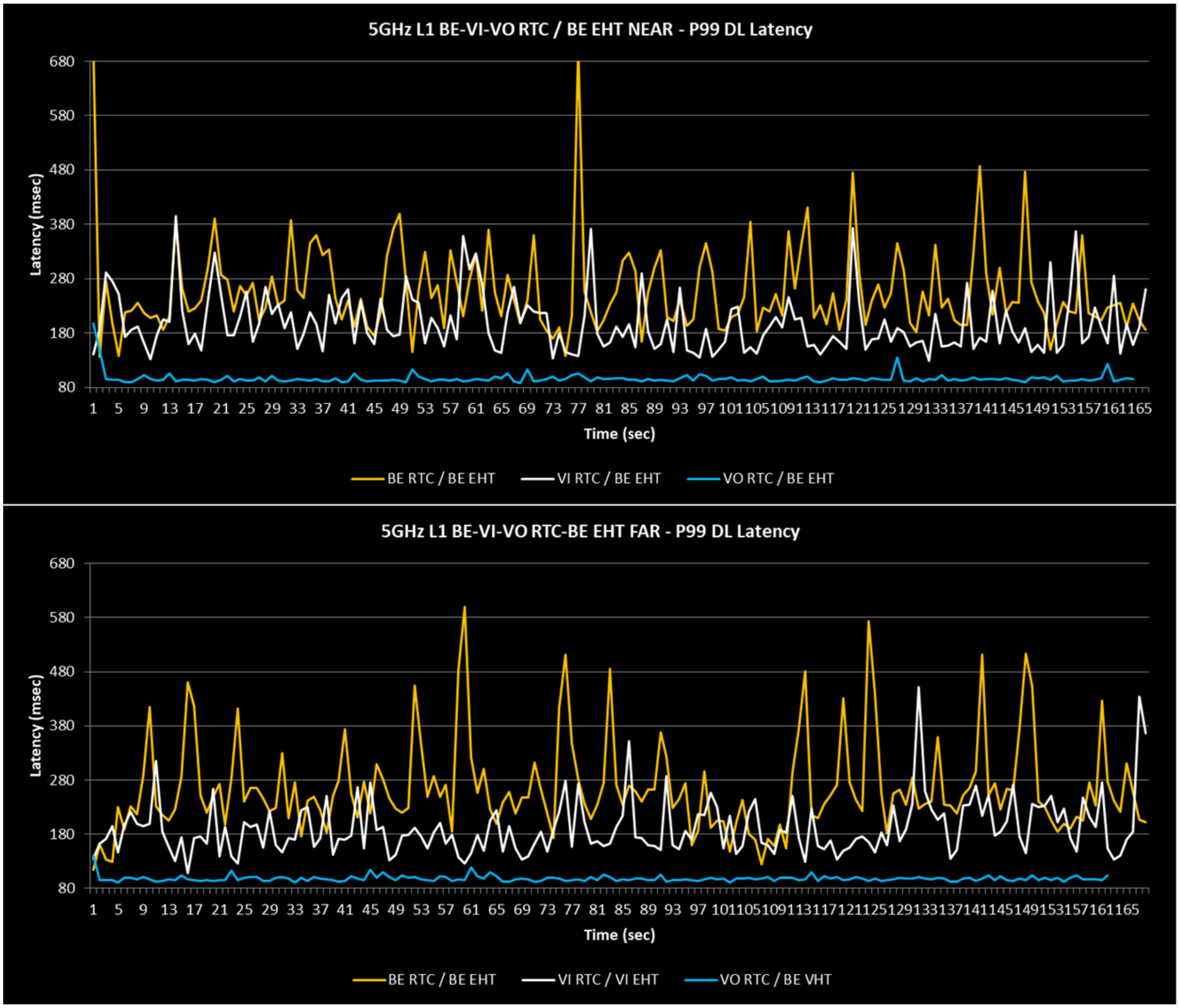

Figure 15. 5 GHz Level 1 P99 Downlink Latency (AC_BE EHT)—
Comparison of AC_BE, AC_VI, and AC_VO for a Near Client (top) and Far Client (bottom)

Figure 16 shows, for one test run, the P99 uplink latency for an RTC client near the AP (top figure) and far from the AP (bottom figure). It shows that RTC uplink latency can degrade when the downlink RTC client is set to AC_VI or AC_VO. The P99 uplink latency for the near and far client is, respectively, 115 ms and 134 ms for AC_BE, 113 ms and 150 ms for AC_VI, and 159 ms and 176 ms for AC_VO. The degradation is more pronounced as the client moves farther away from the AP.

Though the uplink latency increases when RTC downlink traffic is set to AC_VI or AC_VO, the round-trip time (RTT) experienced by the RTC application is better than when RTC downlink traffic is set to AC_BE (Figure 17).

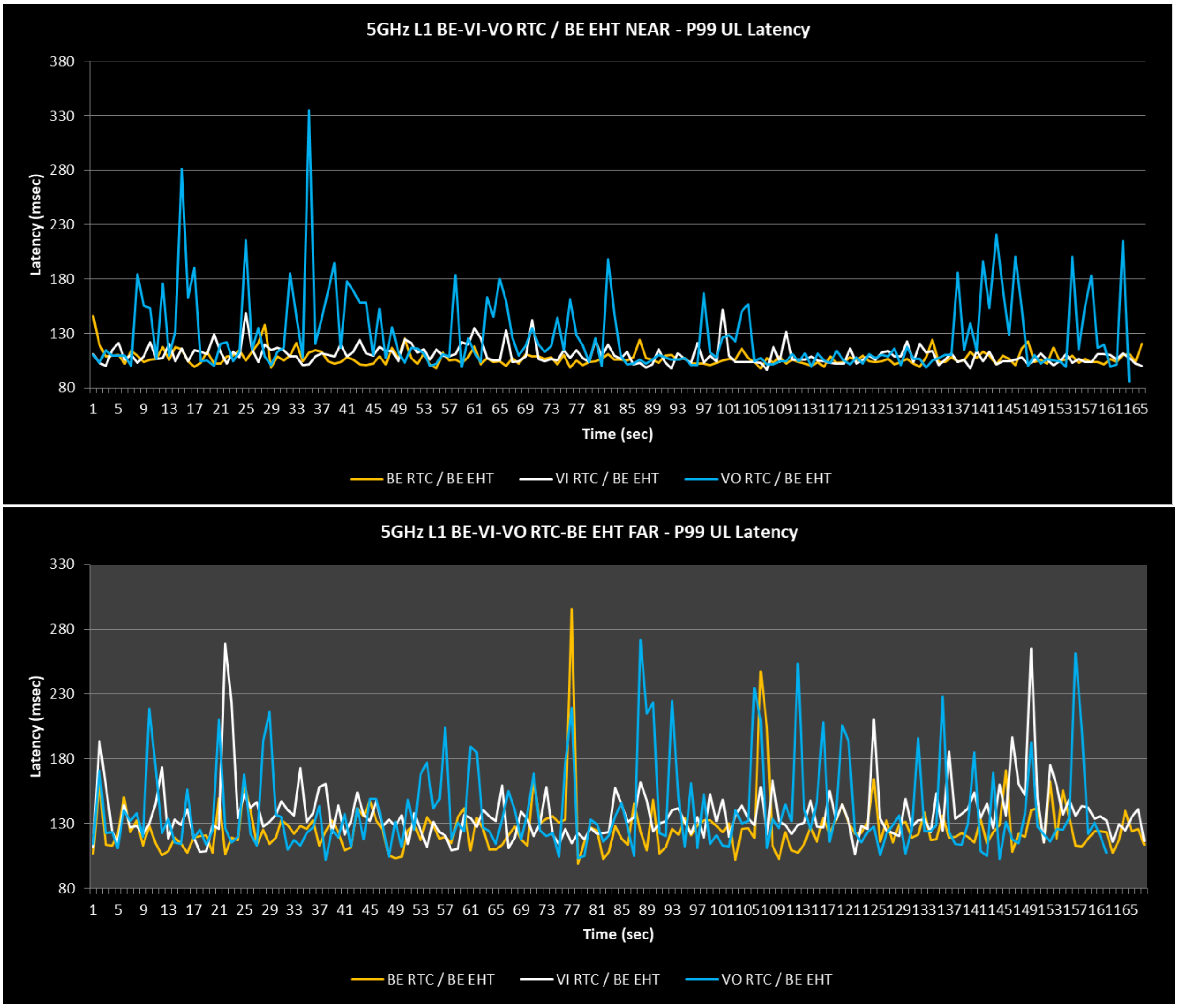

Figure 16. 5 GHz Level 1 P99 Uplink Latency (AC_BE EHT)—
Comparison of AC_BE, AC_VI, and AC_VO for a Near Client (top) and Far Client (bottom)

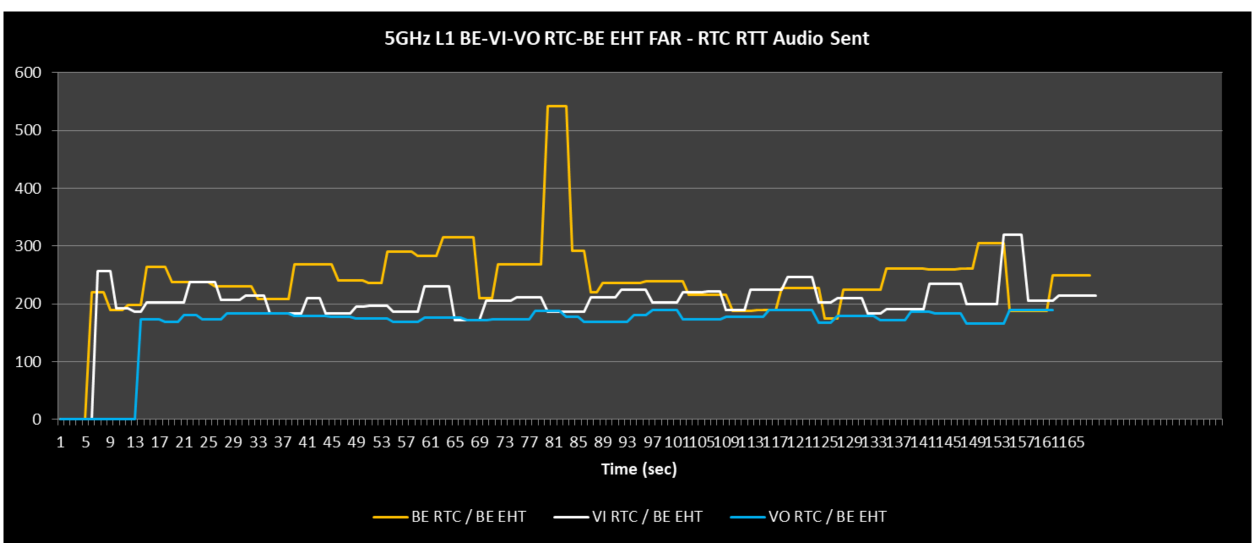

Figure 17. 5 GHz Level 1 RTT Audio (AC_BE EHT, Far Client)—Comparison of AC_BE, AC_VI, and AC_VO

Increasing the attenuation between the client and the AP has a higher impact on the uplink latency than the downlink latency. This behavior is expected as APs have a higher transmit power than the client (e.g., a mobile phone). Figure 18 shows the P99 downlink latency (top diagram) and uplink latency (bottom diagram) for AC_BE and AC_VO when the client RSSI (attenuation) is changed (sweep). The downlink latency when the RTC traffic is set to AC_VO is lower than when it is set to AC_BE.

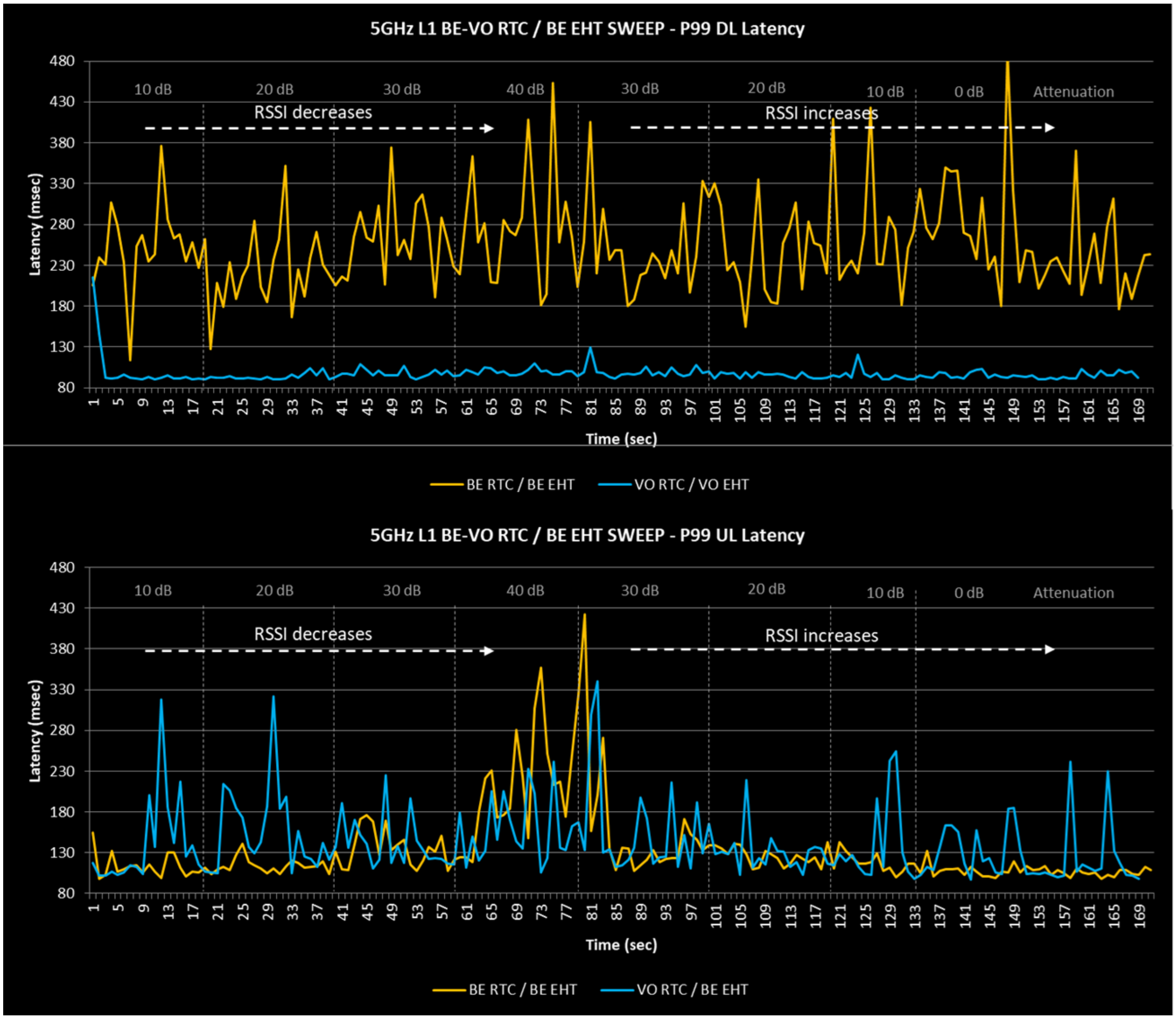

Figure 18. 5 GHz Level 1 P99 Latency (AC_BE EHT)—Comparison of AC_BE and AC_VO for Downlink (top) and Uplink (bottom) When the Client RSSI (Attenuation) Changes (Sweep)

3.2.3. 5 GHz Level 2 Testing

Level 2 tests are conducted with contention traffic (EHT) that includes 16 clients running various applications including video streaming and file download. The EHT traffic varies over time as file download and video streaming models exhibit non-constant bitrate behavior. EHT traffic is set to either AC_BE or WMM (Table 6) in downlink and uplink. RTC downlink traffic is set to AC_BE, AC_VI, or AC_VO, and the RTC uplink traffic is always set to AC_BE.

Figure 19 shows the airtime utilization of Level 2 EHT traffic for one test run. The airtime utilization varies from 40 to 85% because of the presence of file download and video streaming traffic.

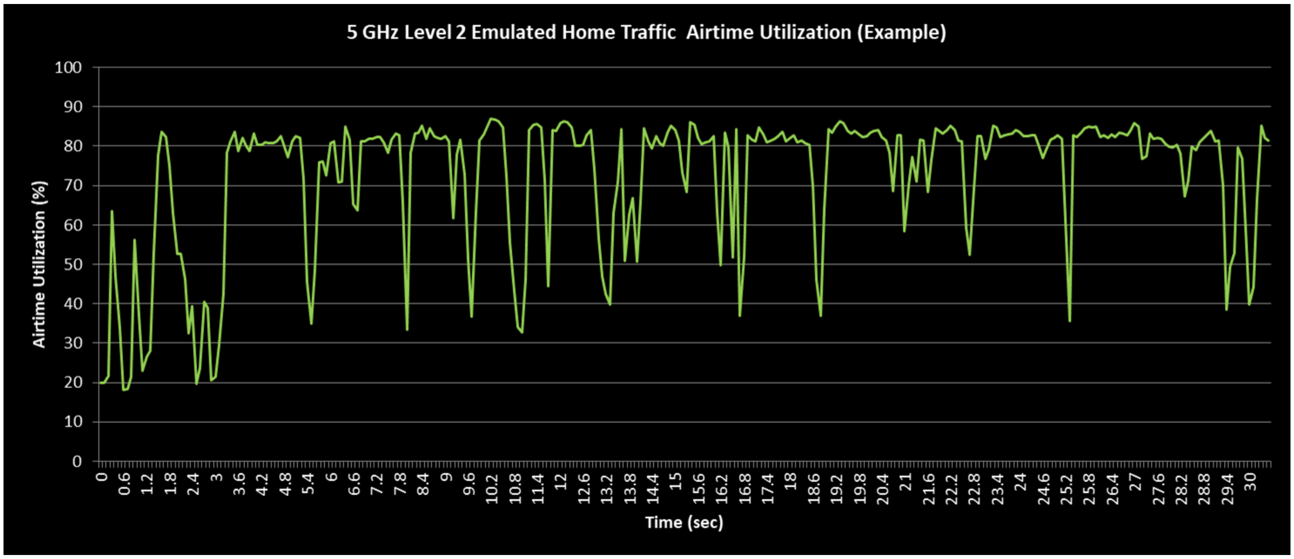

Figure 19. 5 GHz Level 2 Emulated Home Traffic Airtime Utilization

Table 20 and Table 21 give the downlink and uplink statistics. Similarly to Level 1 tests, with EHT traffic set to AC_BE, the P90 downlink latency with AC_VI or AC_VO for the RTC is reduced significantly from the downlink latency with AC_BE, at approx. 30 ms and approx. 40 ms, respectively. The P90 downlink latency is approx. 130 ms for AC_BE, approx. 100 ms for AC_VI, and approx. 88 ms for AC_VO. The uplink latency is similar at best and sometimes worse when downlink RTC is set to AC_VO compared to AC_BE.

Table 20. 5 GHz Level 2 Downlink Latency Statistics (in milliseconds)

EHT AC	RTC AC	RSSI	Lat Avg	Lat Std Dev	Lat P0	Lat P90	Lat P99	Lat P99.9	Lat P99 PDV	Lat P99.9 PDV	Audio Jitter Avg	Transport RTT Avg
BE	BE	Near	108	20	81	133	172	220	91	138	14	196
BE	BE	Mid	107	20	81	132	173	213	91	132	13	197
BE	BE	Far	113	22	81	142	184	238	103	156	15	206
BE	BE	Sweep	113	25	81	142	192	332	111	250	15	203
BE	VI	Near	87	5	81	93	105	120	23	39	4	177
BE	VI	Mid	89	14	81	97	117	322	36	241	5	182
BE	VI	Far	92	15	81	105	133	305	52	224	7	189
BE	VI	Sweep	92	21	81	104	145	345	64	264	7	186
BE	VO	Near	85	3	81	88	94	103	13	22	3	173
BE	VO	Mid	85	3	81	88	96	106	15	25	3	181
BE	VO	Far	86	12	81	89	98	308	17	227	4	184
BE	VO	Sweep	86	17	81	88	98	386	17	305	4	181
WMM	BE	Near	184	272	42	290	1601	3047	1559	3006	23	269
WMM	BE	Mid	213	300	19	432	1609	2836	1590	2817	25	289

EHT AC	RTC AC	RSSI	Lat Avg	Lat Std Dev	Lat P0	Lat P90	Lat P99	Lat P99.9	Lat P99 PDV	Lat P99.9 PDV	Audio Jitter Avg	Transport RTT Avg
WMM	BE	Far	281	418	64	644	2362	3435	2299	3371	31	406
WMM	BE	Sweep	255	382	81	540	1996	3880	1915	3798	39	337
WMM	VI	Near	84	2	81	86	91	98	10	17	3	175
WMM	VI	Mid	98	20	54	114	151	396	97	342	11	197
WMM	VI	Far	97	31	81	111	174	573	93	491	10	209
WMM	VI	Sweep	96	30	81	109	153	586	72	504	8	206
WMM	VO	Near	85	3	81	88	94	102	13	20	3	181
WMM	VO	Mid	86	12	81	89	98	265	17	184	4	185
WMM	VO	Far	87	26	81	89	106	545	25	464	4	207
WMM	VO	Sweep	88	32	81	89	105	652	24	571	4	198

Table 21. 5 GHz Level 2 Uplink Latency Statistics (in milliseconds)

EHT AC	RTC AC	RSSI	Lat Avg	Lat Std Dev	Lat P0	Lat P90	Lat P99	Lat P99.9	Lat P99 PDV	Lat P99.9 PDV	Audio Jitter Avg	Transport RTT Avg
BE	BE	Near	89	11	81	97	136	208	55	127	14	196
BE	BE	Mid	91	12	80	101	146	204	66	124	13	197
BE	BE	Far	95	19	80	112	183	268	102	188	15	206
BE	BE	Sweep	95	24	81	109	188	399	107	318	15	203
BE	VI	Near	90	15	78	99	159	234	81	156	4	177
BE	VI	Mid	91	18	81	103	177	261	96	181	5	182
BE	VI	Far	98	32	81	123	249	405	169	324	7	189
BE	VI	Sweep	95	27	80	113	220	347	141	268	7	186
BE	VO	Near	89	12	80	98	147	203	67	123	3	173
BE	VO	Mid	92	18	81	107	177	247	96	167	3	181
BE	VO	Far	98	33	79	123	252	375	173	296	4	184
BE	VO	Sweep	95	27	81	114	219	346	138	265	4	181
WMM	BE	Near	94	19	81	107	173	301	93	220	23	269
WMM	BE	Mid	101	39	81	126	287	469	206	388	25	289
WMM	BE	Far	127	84	68	208	503	793	435	724	31	406
WMM	BE	Sweep	102	40	81	123	270	595	190	514	39	337
WMM	VI	Near	87	11	80	93	140	196	60	116	3	175
WMM	VI	Mid	99	34	81	118	251	496	170	415	11	197
WMM	VI	Far	113	62	81	162	399	675	318	594	10	209
WMM	VI	Sweep	110	59	80	150	395	643	315	563	8	206
WMM	VO	Near	97	29	79	117	234	360	154	281	3	181
WMM	VO	Mid	99	30	81	120	243	368	162	287	4	185

EHT AC	RTC AC	RSSI	Lat Avg	Lat Std Dev	Lat P0	Lat P90	Lat P99	Lat P99.9	Lat P99 PDV	Lat P99.9 PDV	Audio Jitter Avg	Transport RTT Avg
WMM	VO	Far	120	69	73	190	426	627	352	553	4	207
WMM	VO	Sweep	109	55	79	154	352	641	273	561	4	198

Figure 20. compares the P99 downlink latency when the RTC downlink traffic is set to AC_BE (3 test runs) or AC_VO (3 test runs). It shows the benefit of setting the RTC traffic to AC_VO. Similar figures are observed when the RTC client is placed far from the AP.

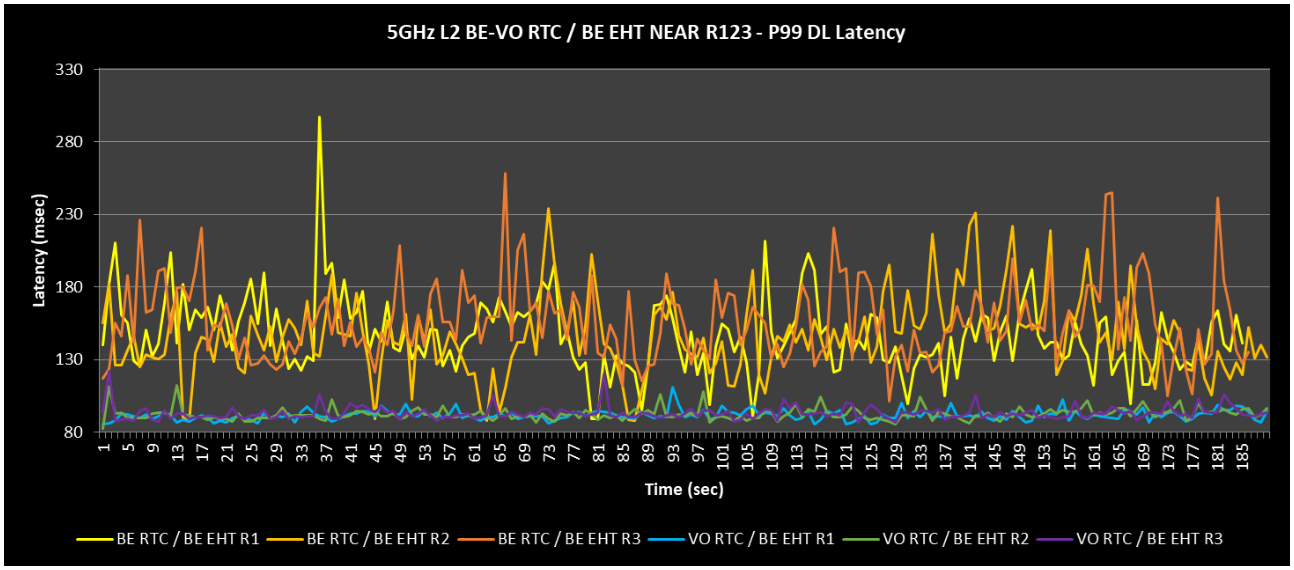

Figure 20. 5 GHz Level 2 P99 Downlink Latency (AC_BE EHT, Near Client)— Comparison of AC_BE RTC (3 Runs) and AC_VO RTC (3 Runs)

The downlink latency observed when the RTC traffic is set to AC_VI is between the same with AC_BE and AC_VO. This result is expected because the Wi-Fi contention window for AC_VI is lower than the window for AC_BE and higher than the window for AC_VO. Figure 21 compares the P99 downlink latency for the 3 ACs when the client is near the AP.

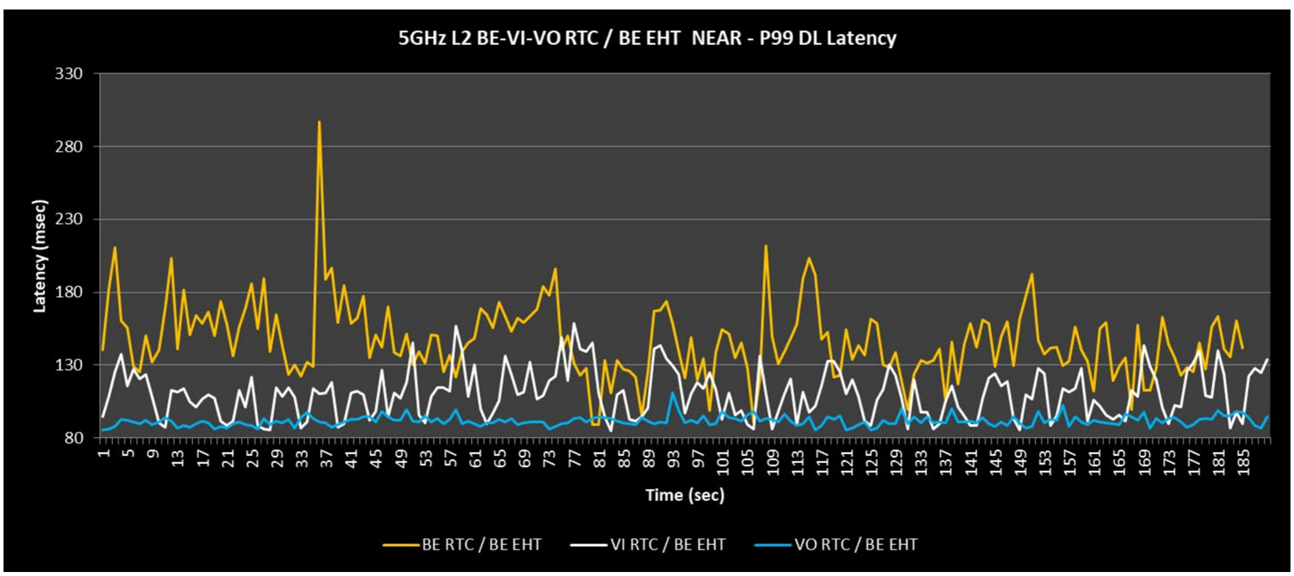

Figure 21. 5 GHz Level 2 P99 Downlink Latency (AC_BE EHT, Near Client)— Comparison of AC_BE, AC_VI, and AC_VO for RTC

As the RTC client is placed farther away from the AP, the uplink latency (e.g., P99) increases, especially when the downlink RTC client is set to AC_VO. Figure 22 compares the P99 downlink latency (top figure) and uplink latency (bottom figure) with AC_VO and AC_BE for an RTC client placed far from the AP.

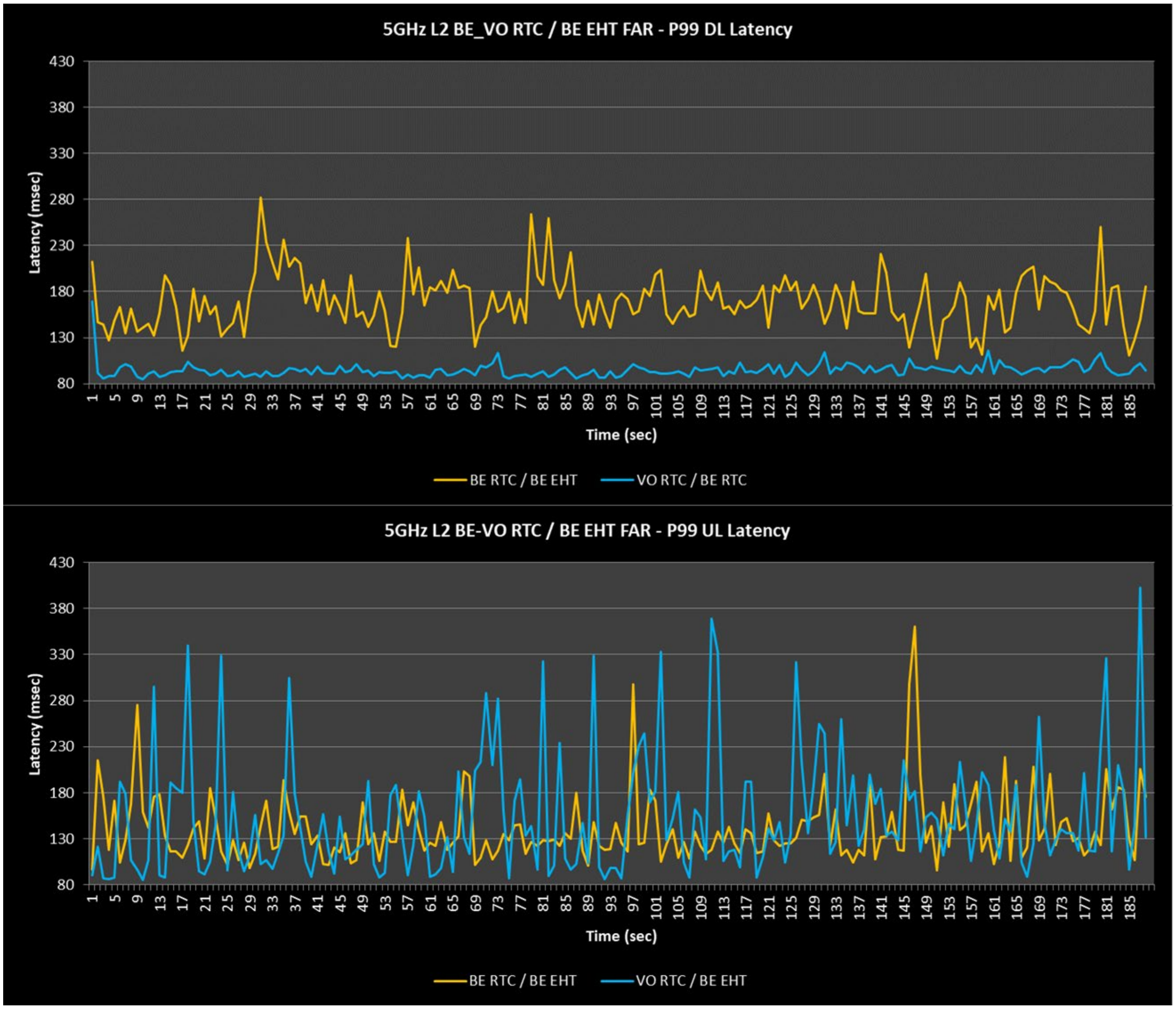

Figure 22. 5 GHz Level 2 P99 Latency (AC_BE EHT, Far Client)—
Comparison of AC_BE and AC_VO for Downlink (top) and Uplink (bottom)

Figure 23 compares the downlink latency for four scenarios in which the EHT is set to AC_BE or WMM and the RTC traffic is set to AC_BE or AC_VO. There is a clear benefit to setting the downlink RTC traffic to AC_VO regardless of the EHT AC used, but the benefit is higher when the EHT traffic is set to WMM. When the RTC traffic is set to AC_VO, the P99 downlink latencies for EHT set to AC_BE (red line) and WMM (white line) are similar. When the RTC traffic is set to AC_BE, however, the latency increases significantly if the emulated home traffic is set to WMM (orange line) compared to AC_BE (blue line).

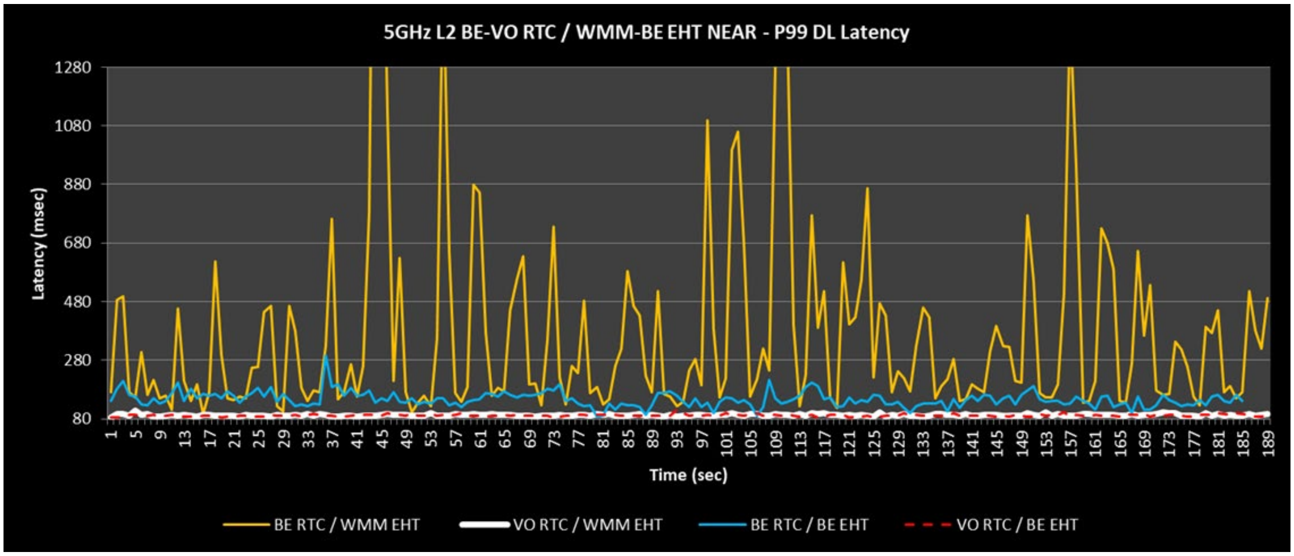

Figure 23. 5 GHz Level 2 Downlink Latency (Near Client)—Comparison of EHT on AC_BE or WMM and RTC on AC_BE or AC_VO

3.2.4. 5 GHz Level 3 Testing

5 GHz Level 3 tests are conducted with contention traffic (EHT) that includes 12 clients running constant bitrate UDP or TCP traffic and 2 clients running file downloads whose bitrate increases (from 0 to 400 Mbps) and decreases (from 400 to 0 Mbps) during the tests. The airtime during the tests varies significantly even for a given file download target bitrate because of the presence of file downloads. The client is set to a mid-distance RSSI, the EHT traffic is set to AC_BE, and the RTC traffic is set to AC_BE or AC_VO. Figure 24 graphs the airtime utilization for a client with RTC traffic set to AC_BE.

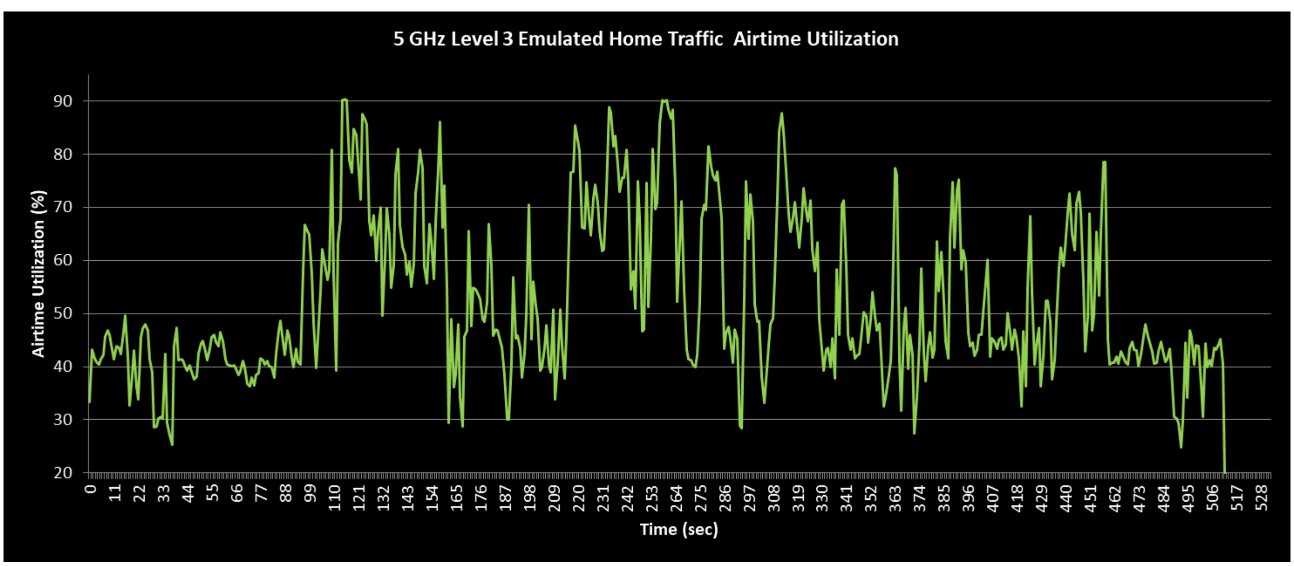

Figure 24. 5 GHz Level 3 Emulated Home Traffic Airtime Utilization (AC_BE RTC, Mid Client)

Table 22 and Table 23 give the downlink and uplink statistics for each RTC AC test run: 3 with AC_BE and 3 with AC_VO. The presence of file download traffic with a high bitrate introduces variability between runs, making it challenging to draw clear and definitive conclusions.

Table 22. 5 GHz Level 3 Downlink Statistics for Each Test Run (in milliseconds)

EHT AC	RTC AC	RSSI	Lat Avg	Lat Std Dev	Lat P0	Lat P90	Lat P99	Lat P99.9	Lat P99 PDV	Lat P99.9 PDV	Audio Jitter Avg	Transport RTT Avg
BE	BE	Mid R1	86	7	81	93	117	141	36	60	4	175
BE	BE	Mid R2	90	25	81	102	152	405	71	324	6	178
BE	BE	Mid R3	84	2	81	86	91	100	10	18	3	172
BE	VO	Mid R1	84	2	81	86	91	98	10	17	3	173
BE	VO	Mid R2	84	2	81	86	92	99	10	18	3	172
BE	VO	Mid R3	84	2	81	86	92	101	11	20	3	174

Table 23. 5 GHz Level 3 Uplink Statistics for Each Test Run (in milliseconds)

EHT AC	RTC AC	RSSI	Lat Avg	Lat Std Dev	Lat P0	Lat P90	Lat P99	Lat P99.9	Lat P99 PDV	Lat P99.9 PDV	Audio Jitter Avg	Transport RTT Avg
BE	BE	Mid R1	89	15	80	95	122	313	41	233	4	175
BE	BE	Mid R2	89	13	81	96	121	305	40	225	6	178
BE	BE	Mid R3	89	14	78	95	127	304	49	226	3	172
BE	VO	Mid R1	89	11	81	96	127	247	47	166	3	173
BE	VO	Mid R2	88	13	80	95	123	287	43	207	3	172
BE	VO	Mid R3	91	10	80	103	132	161	51	80	3	174

Figure 25 shows the P99 downlink and uplink latency and the airtime utilization of 3 test runs with AC_VO for the RTC. When traffic leads to very high variability in airtime utilization, the latency analysis becomes more complex and data with finer granularity must be captured.

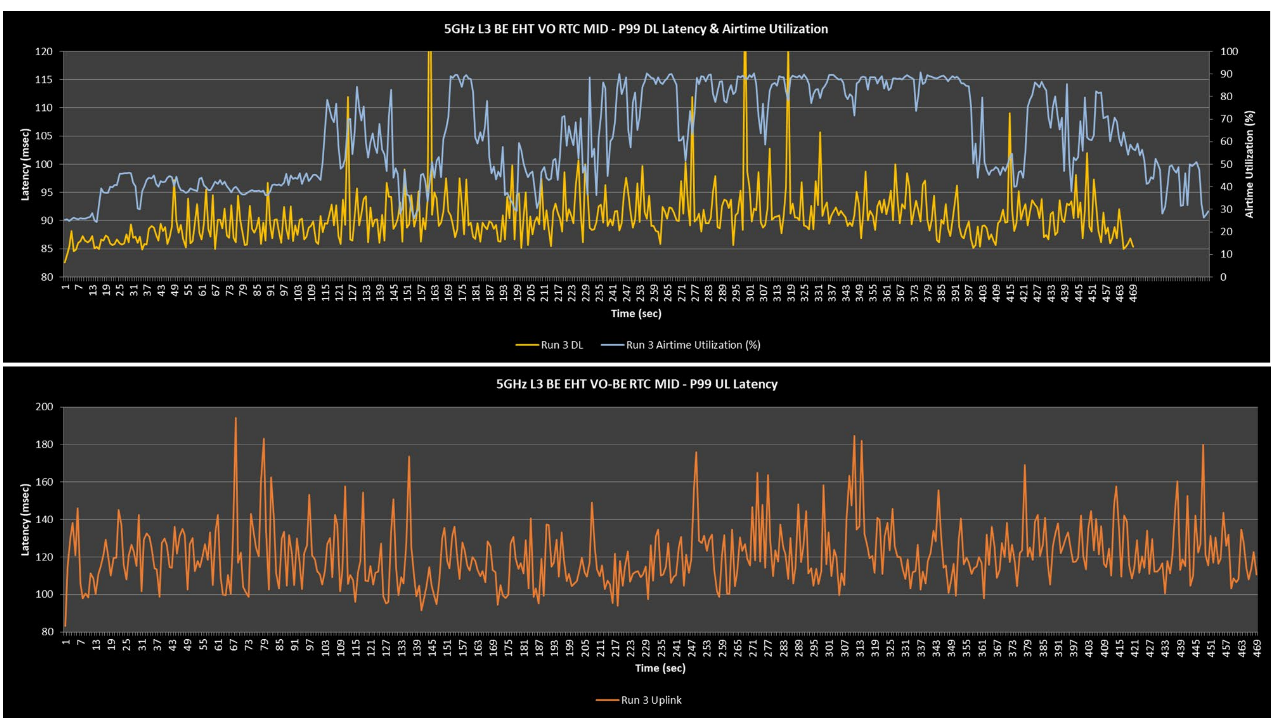

Figure 25. 5 GHz Level 3 Downlink (top) and Uplink (bottom) Latency and Airtime Utilization (top) for Run 3 of AC_VO RTC Test (AC_BE EHT, Mid Client)

3.2.5. 2.4 GHz Level 0 Testing

The 2.4 GHz Level 0 tests are conducted without EHT traffic and are used as a baseline. The RTC client is set to AC_BE, and the tests are conducted at near, mid, and far distances from the AP and with an RSSI sweep. The downlink and uplink latencies are reported in Table 24 and Table 25. The P99 downlink latency varies from 111 to 129 ms and the uplink latency from 105 to 125 ms.

Table 24. 2.4 GHz Level 0 Downlink Latency Statistics (in milliseconds)

EHT AC	RTC AC	RSSI	Lat Avg	Lat Std Dev	Lat P0	Lat P90	Lat P99	Lat P99.9	Lat P99 PDV	Lat P99.9 PDV	Audio Jitter Avg	Transport RTT Avg
BE	BE	Near	85	8	81	96	116	119	35	39	13	179
BE	BE	Mid	83	5	81	84	111	117	30	36	5	168
BE	BE	Far	86	8	81	96	114	120	34	40	10	177
BE	BE	Sweep	90	15	81	110	129	237	49	157	14	186

Table 25. 2.4 GHz Level 0 Uplink Latency Statistics (in milliseconds)

EHT AC	RTC AC	RSSI	Lat Avg	Lat Std Dev	Lat P0	Lat P90	Lat P99	Lat P99.9	Lat P99 PDV	Lat P99.9 PDV	Audio Jitter Avg	Transport RTT Avg
BE	BE	Near	82			90	110	112	35	38	6	167
BE	BE	Mid	81			81	105	111	31	37	3	163
BE	BE	Far	84			93	109	114	34	40	8	169
BE	BE	Sweep	87			104	125	248	51	173	13	178

3.2.6. 2.4 GHz Level 1 Testing

The 2.4 GHz Level 1 tests are conducted with contention traffic (EHT) that includes 11 clients generating constant UDP or TCP flows. EHT traffic is set to either AC_BE in downlink and uplink or the WMM AC (Table 10). RTC downlink traffic is set to AC_BE or AC_VO. RTC uplink traffic is always set to BE AC.

Figure 26 graphs the airtime utilization for a near client and far client. The average airtimes are similar at approx. 50% with some higher spikes for the far client. This result is considered a congested medium, though it is not highly congested as seen in 5 GHz Level 1 tests.

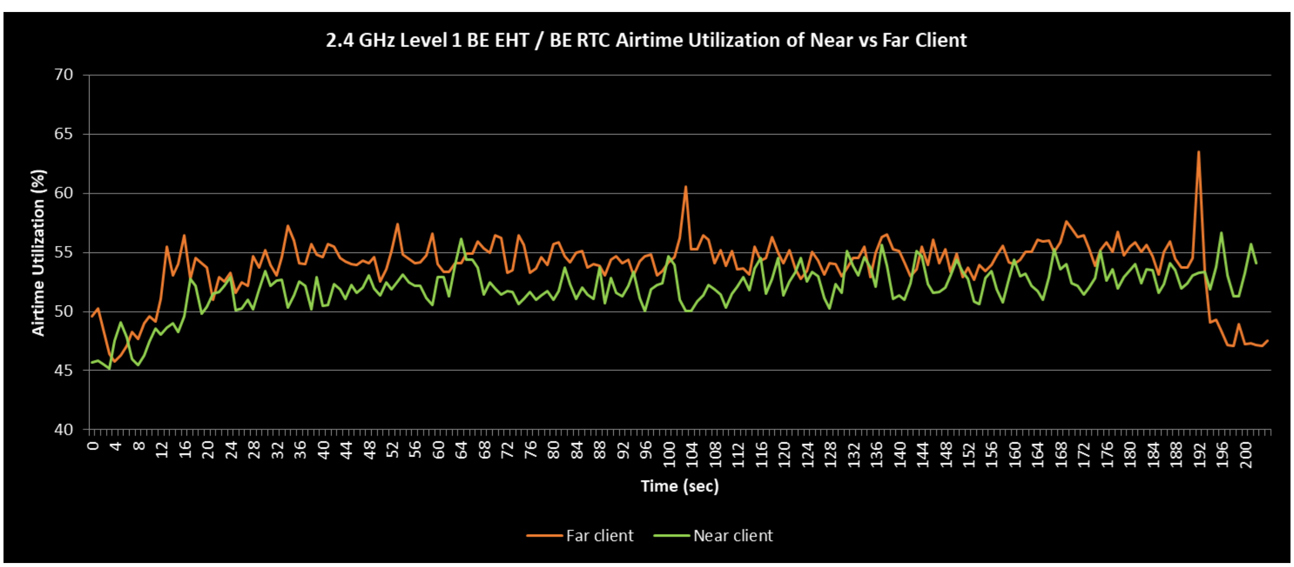

Figure 26. 2.4 GHz Level 1 Airtime Utilization (AC_BE EHT, AC_BE RTC)—Comparison of a Near Client and a Far Client

Impacts of WMM on Wi-Fi

Table 26 and Table 27 give the downlink and uplink statistics. With EHT traffic set to AC_BE and RTC traffic set to AC_VO (for a mid client), the P99 downlink latency is about 6 ms less than when RTC traffic is set to AC_BE (118 ms compared to 124 ms). For the uplink traffic, the latency is similar or increased for AC_VO compared to AC_BE. The latency variations and trends between AC_BE and AC_VO are smaller for the 2.4 GHz tests than for the 5 GHz tests, most likely because of the lower airtime utilization: about 88% for 5 GHz versus about 50% for 2.4 GHz.

Table 26. 2.4 GHz Level 1 Downlink Latency Statistics (in milliseconds)

EHT AC	RTC AC	RSSI	Lat Avg	Lat Std Dev	Lat P0	Lat P90	Lat P99	Lat P99.9	Lat P99 PDV	Lat P99.9 PDV	Audio Jitter Avg	Transport RTT Avg
BE	BE	Near	87	10	81	101	122	137	42	56	8	173
BE	BE	Mid	87	10	81	102	124	148	44	67	8	172
BE	BE	Far	85	8	81	94	120	138	39	58	5	168
BE	BE	Sweep	85	11	81	93	127	209	46	128	5	169
BE	VO	Near	84	7	81	89	115	121	35	40	5	166
BE	VO	Mid	87	10	81	105	118	124	37	43	9	172
BE	VO	Far	84	7	81	88	115	122	35	41	5	167
BE	VO	Sweep	87	12	81	98	133	221	52	140	8	172
WMM	BE	Near	87	14	81	101	152	185	72	104	7	176
WMM	BE	Mid	92	21	81	111	195	236	115	155	10	183
WMM	BE	Far	87	11	81	103	129	151	48	70	7	173
WMM	BE	Sweep	91	15	81	108	154	189	73	108	11	179
WMM	VO	Near	86	8	81	95	115	122	35	41	7	169
WMM	VO	Mid	85	8	81	95	115	123	35	43	6	168
WMM	VO	Far	83	5	81	85	113	121	33	41	3	166
WMM	VO	Sweep	84	7	81	91	114	122	33	41	5	169

Table 27. 2.4 GHz Level 1 Uplink Latency Statistics (in milliseconds)

EHT AC	RTC AC	RSSI	Lat Avg	Lat Std Dev	Lat P0	Lat P90	Lat P99	Lat P99.9	Lat P99 PDV	Lat P99.9 PDV	Audio Jitter Avg	Transport RTT Avg
BE	BE	Near	84	8	75	95	112	122	36	47	8	173
BE	BE	Mid	85	8	69	97	115	127	46	58	8	172
BE	BE	Far	84	7	73	91	113	129	40	56	5	168
BE	BE	Sweep	84	12	74	90	122	235	48	161	5	169
BE	VO	Near	83	7	75	90	111	122	37	47	5	166
BE	VO	Mid	86	10	73	102	117	133	44	60	9	172
BE	VO	Far	84	8	74	94	116	137	42	63	5	167
BE	VO	Sweep	87	16	71	99	139	316	68	245	8	172
WMM	BE	Near	86	12	75	98	145	176	70	101	7	176
WMM	BE	Mid	89	19	75	106	187	229	112	154	10	183

EHT AC	RTC AC	RSSI	Lat Avg	Lat Std Dev	Lat P0	Lat P90	Lat P99	Lat P99.9	Lat P99 PDV	Lat P99.9 PDV	Audio Jitter Avg	Transport RTT Avg
WMM	BE	Far	85	9	75	98	122	144	48	69	7	173
WMM	BE	Sweep	89	15	74	103	149	211	76	138	11	179
WMM	VO	Near	85	9	74	97	117	133	42	59	7	169
WMM	VO	Mid	86	9	74	99	121	140	47	66	6	168
WMM	VO	Far	84	8	70	93	121	141	51	70	3	166
WMM	VO	Sweep	85	10	74	95	121	192	47	117	5	169

Figure 27 shows the P99 downlink and uplink latency for a test run when the EHT traffic is set to AC_BE and the RTC traffic is set to AC_BE or AC_VO. The P99 downlink latency for is approx. 125 ms for AC_VO and approx. 115 ms for AC_BE. The P99 uplink latencies are similar.

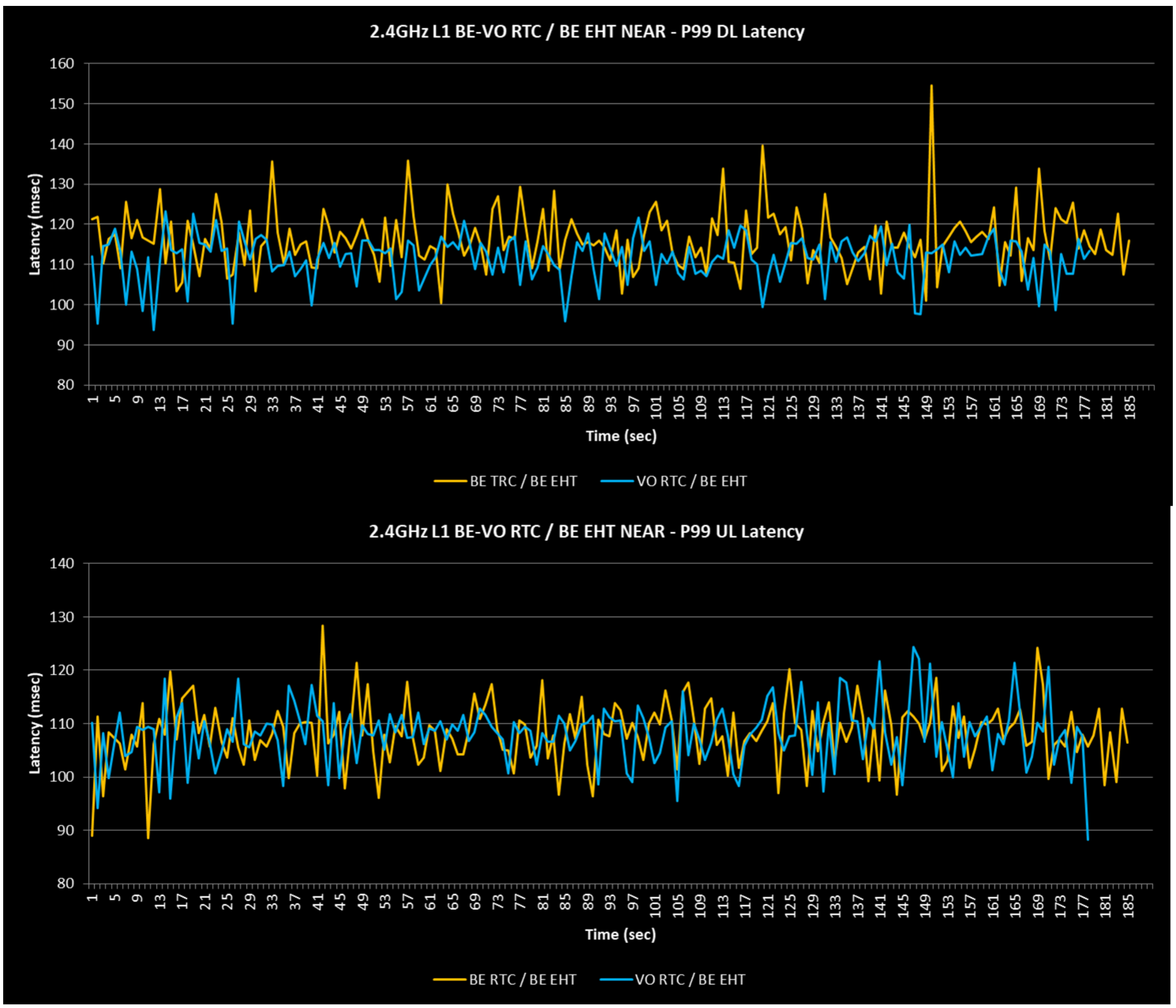

Figure 27. 2.4 GHz Level 1 P99 Latency (AC_BE EHT, Near Client)—
Comparison of AC_BE and AC_VO for Downlink (top) and Uplink (bottom)

Impacts of WMM on Wi-Fi

Many factors play a role in the latency experienced over Wi-Fi networks. Figure 28 graphs the P99 downlink and uplink latencies of an RTC client that experiences a path loss increase from 0 to 40 dB and a path decrease from 40 dB to 0 dB. As the client moves farther away from the AP, the airtime utilization increases by up to 10%. The downlink and uplink latencies are strongly correlated to those moves because of higher airtime utilization, higher percent of retries, and/or disconnection.

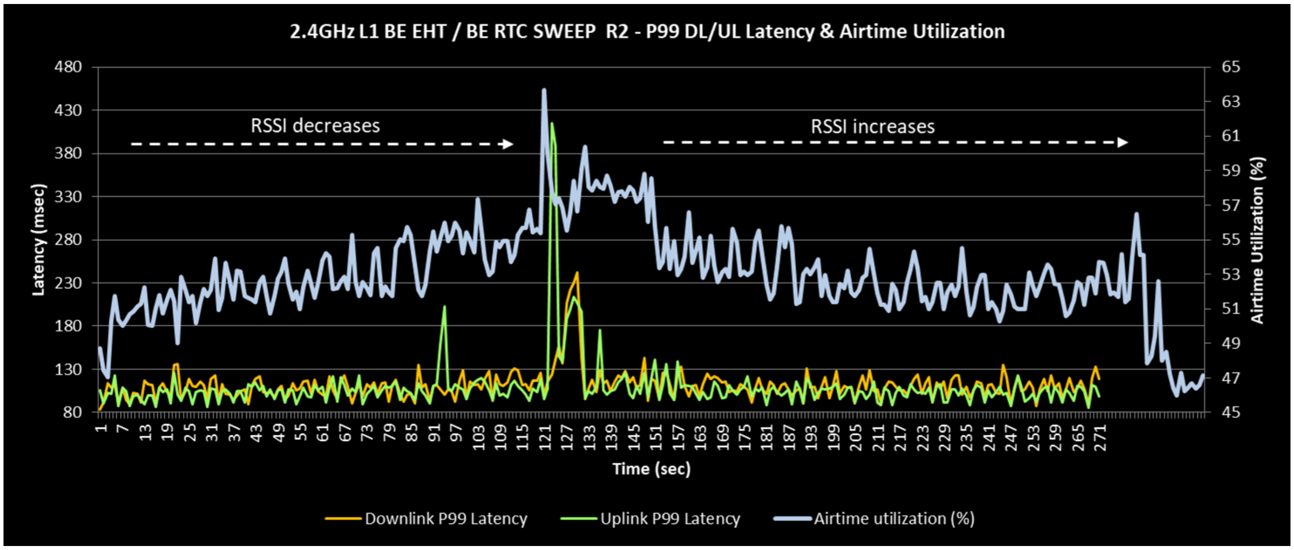

Figure 28. 2.4 GHz Level 1 P99 Latency (AC_BE EHT, AC_BE RTC)—Comparison of Downlink, Uplink, and Airtime Utilization When the Client RSSI (Attenuation) Changes (Sweep)

3.2.7. 2.4 GHz Level 2 Testing

The 2.4 GHz Level 2 tests are conducted with contention traffic (EHT) that includes 9 clients running constant UDP or TCP low, constant bitrate flows and 2 clients running video streaming applications. EHT traffic is set to either AC_BE or WMM (Table 13) in downlink and uplink. RTC downlink traffic is set to AC_BE or AC_VO, and the RTC uplink traffic is always set to AC_BE. Figure 29 graphs the airtime utilization of a far client when both EHT and RTC traffic are set to AC_BE. The average airtime utilization is about 40 %.

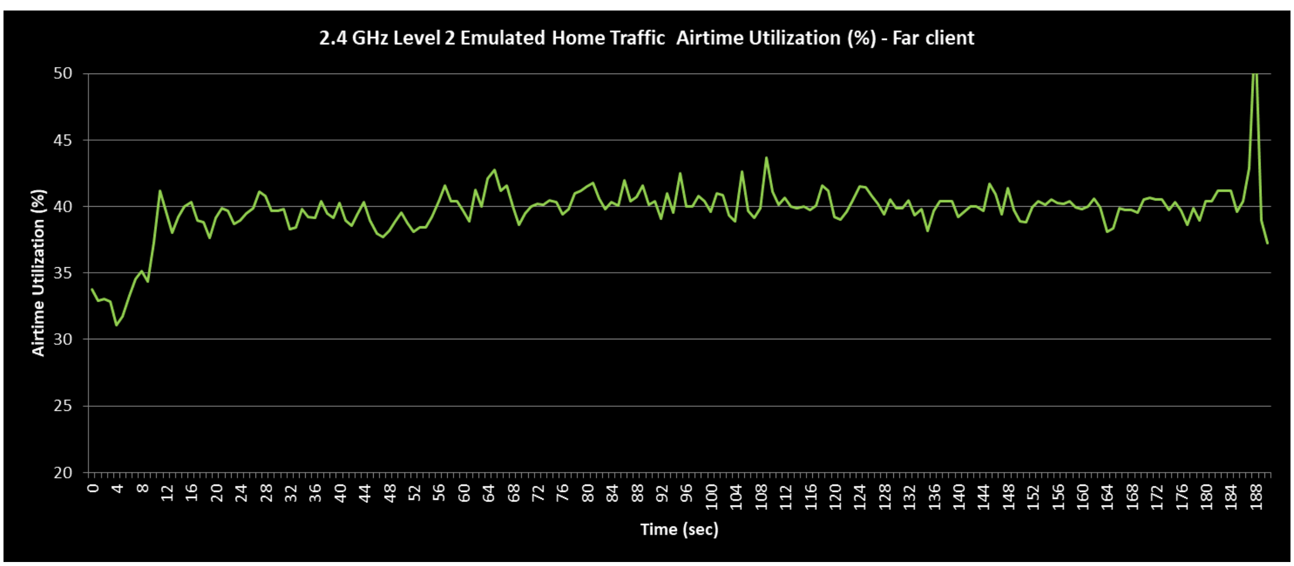

Figure 29. 2.4 GHz Level 2 Airtime Utilization (AC_BE EHT, AC_BE RTC, Far Client)

Impacts of WMM on Wi-Fi

Table 28 and Table 29 give the downlink and uplink latency statistics. The downlink latencies are similar or better when the RTC client is set to AC_VO compared to AC_BE. For example, with EHT traffic set to AC_BE, the P99 downlink latency for a far client is 164 ms when RTC traffic is set to AC_VO and 184 ms when it is set to AC_BE. When the EHT traffic is set to WMM, setting the RTC traffic to AC_VO reduces significantly the downlink and uplink latencies compared to setting it to AC_BE. For example, the P99 downlink latency for a far client is 111 ms when RTC traffic is set to AC_VO and 197 ms when it is set to AC_BE.

Table 28. 2.4 GHz Level 2 Downlink Latency Statistics (in milliseconds)

EHT AC	RTC AC	RSSI	Lat Avg	Lat Std Dev	Lat P0	Lat P90	Lat P99	Lat P99.9	Lat P99 PDV	Lat P99.9 PDV	Audio Jitter Avg	Transport RTT Avg
BE	BE	Near	88	18	81	101	186	215	106	135	6	171
BE	BE	Mid	89	19	81	108	191	217	110	136	8	177
BE	BE	Far	86	17	81	90	184	216	103	135	5	174
BE	BE	Sweep	86	16	81	89	181	231	101	150	5	170
BE	VO	Near	86	16	81	87	181	213	101	132	5	171
BE	VO	Mid	92	19	81	112	188	215	108	135	12	184
BE	VO	Far	85	14	81	85	164	212	83	131	4	169
BE	VO	Sweep	87	17	81	100	181	215	100	134	7	174
WMM	BE	Near	88	17	81	103	177	215	96	134	8	175
WMM	BE	Mid	88	19	81	103	191	226	110	145	7	172
WMM	BE	Far	89	20	81	105	197	238	116	157	8	180
WMM	BE	Sweep	88	18	81	103	185	233	104	152	7	174
WMM	VO	Near										
WMM	VO	Mid	83	5	81	85	112	120	31	39	4	165
WMM	VO	Far	83	5	81	85	111	119	31	38	4	165
WMM	VO	Sweep	87	10	81	105	117	124	37	44	9	172

Table 29. 2.4 GHz Level 2 Uplink Latency Statistics (in milliseconds)

EHT AC	RTC AC	RSSI	Lat Avg	Lat Std Dev	Lat P0	Lat P90	Lat P99	Lat P99.9	Lat P99 PDV	Lat P99.9 PDV	Audio Jitter Avg	Transport RTT Avg
BE	BE	Near	85	17	75	93	180	210	105	135	6	171
BE	BE	Mid	87	17	77	103	177	216	101	139	8	177
BE	BE	Far	85	16	75	90	183	210	107	134	5	174
BE	BE	Sweep	85	16	74	88	181	224	107	150	5	170
BE	VO	Near	84	15	70	86	176	207	106	137	5	171
BE	VO	Mid	90	18	75	108	183	218	109	144	12	184
BE	VO	Far	84	13	76	89	163	208	87	131	4	169
BE	VO	Sweep	86	17	75	97	180	218	105	143	7	174
WMM	BE	Near	85	15	74	98	174	213	99	139	8	175
WMM	BE	Mid	86	16	75	95	178	211	102	135	7	172
WMM	BE	Far	87	18	76	99	186	222	110	146	8	180

EHT AC	RTC AC	RSSI	Lat Avg	Lat Std Dev	Lat P0	Lat P90	Lat P99	Lat P99.9	Lat P99 PDV	Lat P99.9 PDV	Audio Jitter Avg	Transport RTT Avg
WMM	BE	Sweep	85	17	74	93	181	238	106	163	7	174
WMM	VO	Near										
WMM	VO	Mid	82	6	76	86	110	120	34	45	4	165
WMM	VO	Far	83	7	74	88	113	128	39	53	4	165
WMM	VO	Sweep	86	11	74	104	120	149	45	75	9	172

4. Conclusion

Enabling WMM and correct traffic marking yielded a positive impact on QoE. Improvements included lower latency of critical traffic, which reduces audio and video lag and increases audio and video quality. As shown in the test results, movement of the RTC device from near the AP to the edge has less of an impact on QoE. The QoE improvements can be analytically supported by KPI data. The use of both application KPIs and network KPIs can give operators and application vendors insights to the user's QoE and allow them to make proactive adjustments to assist with maintaining it. Operators can reduce service calls and increase subscriber satisfaction, and application vendors can provide a quality experience to their users.