Work-in-Progress: An Empirical Study of the Joint Effects of WiFi Coverage and Channel Congestion on Quality of Experience in 5 GHz Band

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***Abstract*—Ever-increasing multimedia application usage brings stricter network requirements every day for wireless networks. WiFi is the commonly used wireless technology for in-home and public networks. Existing literature focuses mainly on video streaming QoE over WiFi against channel congestion. None of the studies investigates the joint effects of coverage and congestion issues on the QoE of different multimedia applications with different network requirements and adoption rates. In this study, first time in the literature, QoE of video conferencing, YouTube video streaming, cloud gaming, and VR streaming applications are investigated under different congestion and coverage scenarios in the 5 GHz WiFi band, taking into account the different adoption rates of the applications. The results show that high congestion can prevent a single user from streaming a 4K video, even when the user is in a medium coverage region. On the other hand, the QoE of cloud gaming, and especially VR streaming, are more to the congestion and coverage issues. For better user experience in multimedia applications with more demands, e.g., VR streaming, the new 6 GHz WiFi band could be a solution in near future.**

***Index Terms*—WiFi, Congestion, Coverage, Quality of Experience, Video Conferencing, YouTube, Cloud Gaming, VR Streaming**

I. Introduction

Multimedia applications with significant network requirements, such as on-demand video streaming and live video conferencing, have already been commonly adopted today; whereas the ones with even more strict network demands, such as cloud gaming and Virtual Reality (VR) streaming, are expected to proliferate in the near future. Video streaming constituted 60.6% of all internet download traffic in 2020 [1]. Cloud gaming holds an 8% share of total internet download traffic [1]; and the number of cloud gaming providers, e.g., Microsoft XCloud [2] and NVIDIA Geforce-Now [3], are increasing every day. Although only two commercially available VR platforms offer early access for cloud VR gaming, e.g., PlutoSphere [4] and Shadow [5], today, the market size of the VR and Augmented Reality (AR) ecosystem is expected to reach $80 billion, according to Goldman Sachs [6].

Satisfying the network requirements of multimedia applications, so the end-user Quality of Experience (QoE), is a challenging and never-ending task for wireless communications. WiFi, a.k.a. IEEE 802.11 standard, is commonly adopted wireless technology for home internet access. With advancing multi-user access techniques in each WiFi generation [7]–[9] and OpenRoaming protocol [10], WiFi is rapidly becoming the first choice for internet access in public areas, e.g., shopping malls, stadiums, and concert halls, as well. Therefore, a comprehensive study for WiFi adequacy to satisfy multimedia QoE becomes crucial.

The current literature contains empirical and simulated works on video-streaming QoE in 2.4 and 5 GHz WiFi bands [11]–[18]. However, these works do not consider the usage trends and different requirements of the different multimedia applications. A study on multimedia QoE over WiFi, considering the different adoption rates of the applications today and in the future, would be helpful for service providers to decide on new technologies, e.g., deployment of Customer Premises Equipment (CPE) supporting 6 GHz band.

Existing literature studies the impact of WiFi channel congestion on multimedia QoE [13], [15]; however, do not evaluate the joint impact of WiFi coverage and congestion. In real-life scenarios, the multimedia QoE is affected by both WiFi congestion and coverage status [17]. For instance, a family of five could simultaneously stream video content over the internet in different rooms of an apartment; or multiple people may try to stream a live video of a concert in a huge open area.

In this paper, a comprehensive empirical study is conducted regarding the joint effect of WiFi coverage and channel congestion on the multi-media QoE in the 5 GHz band. The QoE of video conferencing, YouTube video streaming, cloud gaming, and VR streaming are analyzed over Iperf throughput, Ping delay, and YouTube streaming performance measurements under various coverage and congestion scenarios. This analysis enlightens the severity of WiFi congestion and coverage issues of today. We, then, discuss the need and emergency of the adoption of the new 6 GHz WiFi band according to the adequacy of the 5 GHz band to support today's and future's multimedia applications.

The rest of the paper is organized as follows. Section II re-

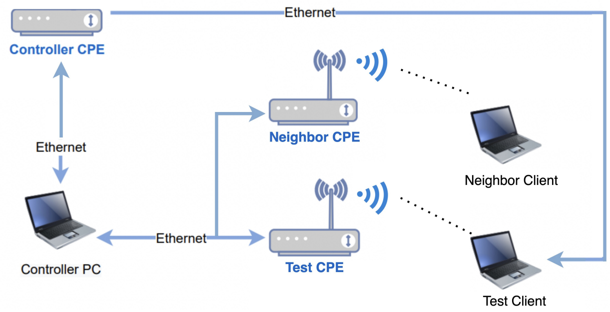

Fig. 1. Measurement Setup.

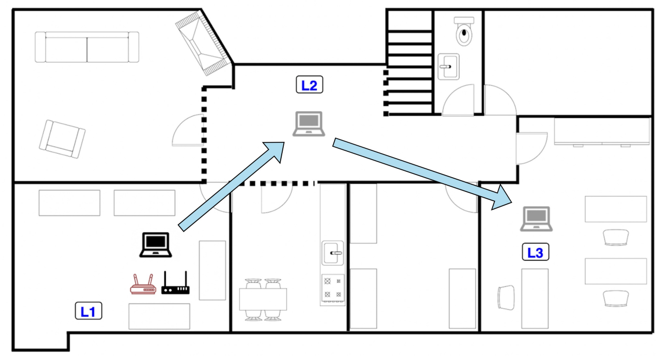

Fig. 2. In-home test cases.

views the literature for related studies. Section III and Section IV provide the measurement setup and results, respectively. Section V discusses the measurement results together with the network requirements of each multi-media application and determines the limiting congestion and coverage issue severity levels on the QoE. Finally, Section VI concludes the paper.

II. Related Work

WiFi performance is commonly evaluated for video streaming applications in NS-2 or NS-3 simulation environments [11], [12], [17]. [11] conducts a QoE analysis on two audio and video clips in the 2.4 GHz WiFi band. [12] studies service fairness of non-deterministic resource allocation methods in medium access for simultaneous High Definition (HD) video transmission in the 5 GHz WiFi band. [14] investigates the QoE of different adaptive video streaming protocols over WiFi. [17] proposes a congestion prediction algorithm by utilizing frame aggregation for adaptive video streaming over WiFi to reduce video stalling and buffer time. In these works, observations from real-life experiments are missing.

Existing empirical studies on the WiFi QoE mainly focus on the channel congestion impact on the performance of video streaming applications [13], [15], [16]. [13] empirically analyzes the congestion effect on the Quality of Service (QoS) of simultaneous live 4K video transmissions at the 5 GHz WiFi band. [15] analyzes cross-layer congestion control mechanisms for uplink real-time video transmission over WiFi regarding application QoS via simulations and experiments. [16] conducts experiments measuring the coefficient of throughput variation for YouTube 360-videos streamed over a WiFi channel to evaluate the QoE at different video resolutions. [18] compares different congestion control algorithms for real-time video streaming application QoE over heterogeneous networks, including WiFi. None of these studies investigate the congestion impact on the QoE, considering different applications, especially more demanding ones such as VR and cloud gaming. Furthermore, the joint effect of WiFi coverage and channel congestion on the application QoE has not been studied in the literature for the 5 GHz WiFi band.

III. Measurement Setup

This section explains the measurement setup, procedure, and data for WiFi QoE tests. Iperf throughput, ping delay, and YouTube video streaming performances are measured at different CPE-to-client distances under gradually increasing congestion levels to observe the combined effect of congestion and coverage on WiFi QoE.

Fig. 1 shows the measurement setup in a home environment with fiber broadband with a downlink speed of 100Mbps. A test client, with Ubuntu operating system and 2x2 11ax WiFi interface, is connected to a commercially available, standard compliant test CPE featuring Broadcom 4x4 11ax chipset at maximum transmit power, via WiFi. Iperf, Ping, and YouTube tests are performed over the test CPE and test client. Another Ubuntu client with 2x2 11ac capability is connected to a CPE featuring Broadcom 4x4 11ac chipset via WiFi. This additional pair, called neighbor CPE and client, is located close to the test CPE and are used to control air congestion levels during tests. A control network is established to reliably convey the signaling messages to start/stop the tests and collect test logs from all clients and CPEs. A desktop PC is utilized as the automation controller of the measurements and connected to all CPEs via Cat6 ethernet cables. The controller CPE connects the clients to the controller PC. All WiFi connections are at Channel 36 with 80 MHz bandwidth in the 5 GHz WiFi band.

Fig. 2 depicts three different locations at which the test client is located to represent three different Coverage Scenarios (CSs) as follows:

- **Good CS:** The test client is located in a good coverage region (L1), where the Received Signal Strength Indicator (RSSI) $\in$ (-48, -43) dBm interval.
- **Mid CS:** The test client is located in a mid coverage region (L2), where the RSSI $\in$ (-68, -63) dBm interval.
- **Poor CS:** The test client is located in a poor coverage region (L3), where the RSSI $\in$ (-82, -78) dBm interval.

During the tests, air congestion is artificially created via download Iperf TCP traffic from the neighbor CPE to the neighbor client at different rates to simulate different congestion levels. Overlapping Basic Service Set (OBSS) is utilized to indicate congestion level, which is the ratio of airtime occupied by the neighbors at the same channel. Note that in theory, each of the two neighboring CPE occupies at most half the airtime due to the fairness concern of the WiFi channel access. However, in practice, some commercial CPEs occupy the airtime even more, since they have different hardware and sensitivity. Therefore, we choose our neighboring CPE accordingly, to simulate the higher rates of congestion.

We repeat the following measurement procedure at different congestion levels in each CS. The measurements start with Iperf tests. Iperf TCP traffic is generated over 10 parallel streams, from the test CPE to the test client for 60s, and then, in reverse direction again during 60s to represent download and upload traffic, respectively. Iperf throughput is sampled every second as an indicator of maximum WiFi speed. The measurements continue with the Ping test, for which the test client pings the test CPE during 60s. Ping delay and packet loss are collected every second. Ping delay is calculated as the total Round Trip Time (RTT) from the test client to the test CPE to indicate WiFi latency. The measurements end with YouTube tests. The tests are conducted over three YouTube videos with a total duration of 1200s. A YouTube video starts with a 4K quality and later alters its quality automatically according to the network conditions. Video streaming performance indicators, such as buffer health, buffering, stalling events, quality change events, and video download throughput, are acquired every 10 seconds via YouTube IFrame Player API. During all tests, wireless driver parameters, such as RSSI and OBSS values, representing WiFi coverage and congestion severity, are collected from the test CPE in 1s intervals.

IV. Measurement Results

The results of the Iperf, Ping, and YouTube tests acquired via the aforementioned test setup are discussed in this section.

Fig. 3 demonstrates the download and upload Iperf throughputs measured at varying congestion levels and coverage locations. Mean download [upload] throughput is decreased by 76.3%, 88.3% and 99.6% [53.6%, 72.4% and 95.8%] with the increasing congestion level at good, mid and poor CSs, respectively. Similarly, minimum download [upload] throughput is decreased down to 70 [234] Mbps at a good CS, and 26 [67] Mbps at a mid CS, as the congestion level increases. At the poor CS, mean upload throughput almost diminishes after 47.5% congestion; whereas minimum throughput is almost always zero. Notice that, upload throughput is measured higher than download, for a given setup, since the test CPE has more limited airtime access than the client because it is closer to the congestion source, and the client's receiver sensitivity is lower than of the CPE, causing more packet loss in download. Also notice, the throughput values are not monotonically decreasing with the increased congestion, since the tests are not conducted in an isolated environment, and the Iperf tool do not always provide a steady traffic.

Fig. 4 provides mean ping delay and packet loss rate. The packet loss rate is the ratio of the lost packets with respect to the total packets transmitted/received in a given congestion level. Mean ping delay is higher than 20 ms after 91%,

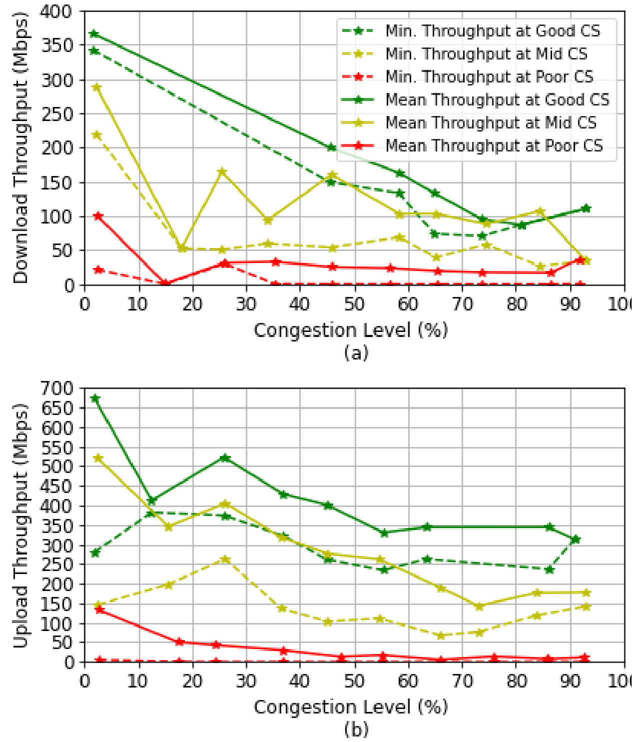

Fig. 3. Iperf TCP Throughput Results: a) Download b) Upload

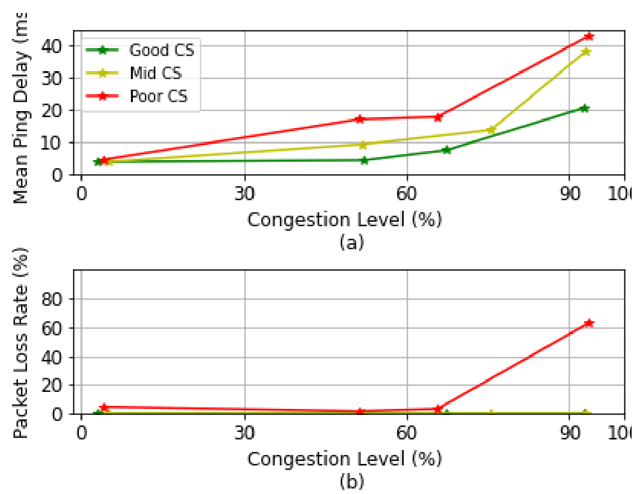

Fig. 4. Ping Test Results: a) Mean Ping Delay b) Packet Loss Rate

TABLE I
PING DELAYS AND THEIR FIRST OBSERVED CONGESTION INTERVALS

Coverage Scenarios	First Appearence of Ping Delays under Congestion (%)					
	10ms	20ms	30ms	40ms	50ms	100ms
Good CS	>90	>90	>90	>90	NA	NA
Mid CS	>50	>60	>85	>90	>90	NA
Poor CS	>50	>50	>50	>65	>90	NA

80%, 68% mean congestion for good, mid and poor CSs, respectively. Although there is no packet loss in good and

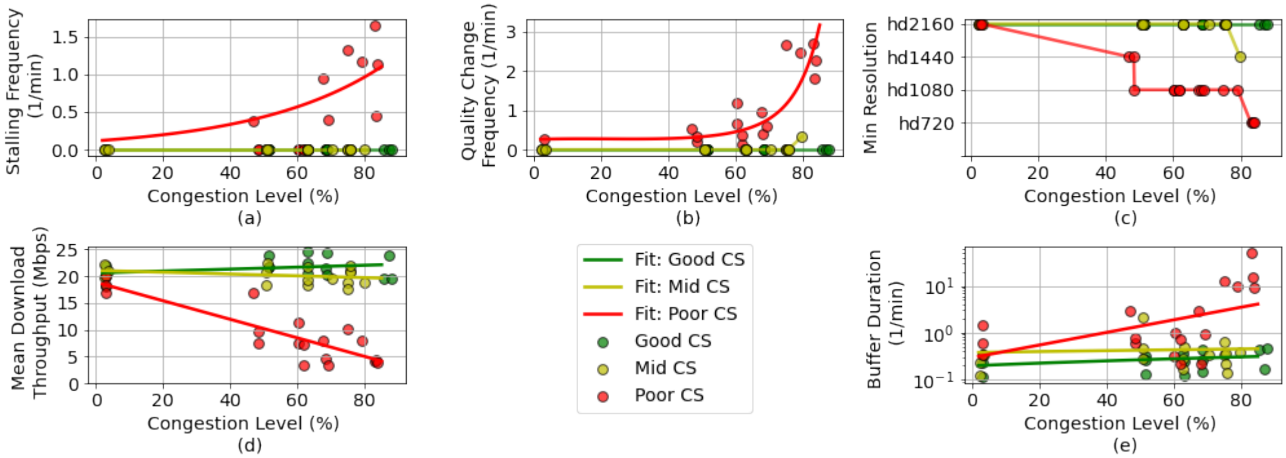

Fig. 5. YouTube Test Results: a) Number of stalling events per minute b) Number of quality change events per minute c) Minimum video resolution of a video streaming test d) Mean download throughput of a video streaming test e) Buffer duration per minute, at various congestion levels and coverage scenarios.

mid CS, the packet loss rate increases up to 63% in poor CS under high congestion.

Table I presents the congestion level at which the given ping delay values appeared for the first time in good, mid, and poor CSs. As the client moves from poor to good coverage location, the same ping delay appears at the higher congestion levels. For instance, 20 ms ping delay is observed with >90% congestion at good CS, >60% congestion at mid CS, and >50% congestion at poor CS. The maximum ping delay remains lower than 100ms even in the worst-case coverage and congestion scenarios, i.e., >90% congestion in poor CS.

Fig. 5 shows YouTube video streaming results in terms of stalling frequency, quality change frequency, minimum resolution, mean download throughput, and total buffer duration per minute recorded for each video, conducted at various coverage locations and congestion levels. Stalling/quality change frequency is calculated as the total number of stalling/quality change events per minute. In good and mid CSs, stalling frequency, quality change frequency, and buffer duration per minute are zero, while the mean download throughput values are steady at around 20 Mbps. One exception is that at a mid CS, quality change frequency increased to 0.33 min^{-1} and the quality reduced to *hd1440* after 80% congestion. On the other hand, at the poor CS, at least one stalling or quality change event is observed, after 68% and 60% congestion, respectively. Buffer duration per minute increases above 10 seconds when the congestion level is higher than 75%. Mean download throughput halves after 50% congestion, and reduces down to 3.35 Mbps after 80% congestion. As a consequence, minimum video resolution drops to *hd1080* and *hd720* at 50% and 83% congestion, respectively.

V. Application Quality of Experience

Video conferencing, YouTube video streaming, cloud gaming, and VR streaming applications have different network requirements to satisfy a certain QoS level, provided in Tables II-VI. First, separate analyses are conducted on the QoE of each application by evaluating the application network requirements together with the test results discussed in the previous section. Later, an overall discussion is conducted by considering different coverage and congestion conditions to demonstrate how sufficient the 5 GHz band is to satisfy multimedia QoE requirements. Note that, we evaluate the QoE as good, if all network QoS requirements of an application, provided in the tables, are satisfied, or poor, otherwise. The exception is Cloud Gaming, for which Table IV provides more detailed QoE categorization. We treat the QoE levels in Table IV as an upper bound for the application QoE, given the latency.

In general, this section aims to provide an upper bound for the QoE of different applications. More accurate QoE evaluation requires testing with multiple clients equipped with different chipsets, and various test scenarios, and must be repeated for each different application, since each application show different data traffic characteristics. On the other hand, Iperf tool measures the best possible TCP throughput in a given setting. Also, latency measurements utilizing the ICMP ping packets provide the best possible latency in a given setting. Hence, the conducted QoE analysis in this section can provide an upper bound for the QoE of different applications, rather than the exact QoE evaluation.

A. Video Conferencing

Video conferencing has network requirements in terms of worst-case throughput, latency, and packet loss, which are provided in Table II. According to the minimum throughput in the Iperf tests, as in Fig. 3, video conferencing at poor CS (RSSI $\approx$ -80 dBm) results often in a poor QoE in general, since the throughput diminishes at all congestion levels. However, video conferencing at good and mid CSs always results in a good QoE since all network requirements are satisfied at all congestion levels.

TABLE II
VIDEO CONFERENCING NETWORK REQUIREMENTS

Application	Resolution	Throughput	Latency	Packet Loss
Video Conferencing [19], [20]	720p	2.6 Mbps	200 ms	2%
	480p	1.5 Mbps		
	360p	1 Mbps		
	240p	0.5 Mbps		

TABLE III
YOUTUBE NETWORK REQUIREMENTS

Application	Resolution	Sustained Throughput
YouTube [21]	4K 2160p	20 Mbps
	HD 1080p	5 Mbps
	HD 720p	2.5 Mbps
	SD 480p	1.1 Mbps
	SD 360p	0.7 Mbps

TABLE IV
CLOUD GAMING LATENCY REQUIREMENTS

Application	QoE	Latency
Cloud Gaming [22]	Great	20 ms
	Good	50 ms
	Fair	100 ms
	Poor	300 ms
	Unplayable	> 300 ms

TABLE V
CLOUD GAMING THROUGHPUT REQUIREMENTS

Application	Resolution	Throughput
Cloud Gaming [23]	720p at 60 FPS	15 Mbps
	1080p at 60 FPS	25 Mbps
	2560x1440p at 120 FPS, 2560x1600p at 120 FPS, 1920x1080 at 240 FPS	35 Mbps
	3840x2160p at 120 FPS	45 Mbps

B. YouTube Video Streaming

The throughput requirements of YouTube for different video resolutions are provided in Table III. YouTube only has one requirement from the network, which is sustained throughput, since it is not a live video streaming application. In the evaluation of YouTube streaming QoE, mean Iperf downlink throughput measurement results are investigated together with the sustained throughput requirements. Stalling, buffering, and quality change events are the resulting effects when the sustained throughput requirement cannot be met. YouTube tests demonstrate a 4K video streaming experience for a single user. According to the test results, in a good CS, YouTube provides a good QoE at all congestion levels. In a mid CS, QoE decreases as video resolution drops from 4K to 2K (*hd1440*) at 80% congestion. Lastly, in a poor CS, stalling and buffering events become frequent after 50% congestion and cause poor QoE. The video resolution further drops to *hd1080* at 48% congestion and to *hd720* at 83% congestion, for a single video streaming. Considering a case of multiple video streaming, at most two simultaneous 4K video streaming is possible with a good QoE, when the congestion level is lower than 75% at a mid CS. On the other hand, up to three simultaneous 4K video streaming on YouTube is possible with a good QoE, considering the worst-case download throughput measured, which is 70 Mbps at a good CS.

C. Cloud Gaming

Cloud gaming has different worst-case latency and throughput requirements from the network to provide different resolutions and QoE levels, provided in Tables IV and V. It suffers from poor QoE at poor CSs at all congestion levels since the worst-case throughput requirement is not satisfied for any video resolution. In a mid CS, great QoE is possible for the highest resolution, up to 60% congestion. When the resolution is one step down, a great QoE is still possible, up to 80% congestion. Beyond 90% congestion, only fair QoE is possible with a video resolution of 1080p at 60 FPS. Regarding cloud gaming at a good CS, a great QoE can be observed with the highest video resolution, up to 90% congestion.

D. VR Streaming

VR Streaming has the most strict latency and the highest throughput requirements, provided in Table VI. Good QoE is not possible for advanced and extreme VR under any circumstances due to their ultrahigh throughput requirements. For entry level VR, we can observe good QoE up to 14% congestion at a mid CS, and 60% congestion at a good CS. On the other hand, early stage VR can satisfy good QoE up to 90% congestion at good and mid CSs.

E. Overall Discussion

The comparative analysis is conducted over a discussion on the general effects of the congestion and coverage issues on the 5 GHz WiFi QoS, and then their projection on the application QoE. The analysis shows that all four multimedia applications suffer from poor QoE when the client is at a poor CS regardless of congestion level. Channel congestion, independent from the coverage, causes poor QoE for future multimedia applications such as VR and cloud gaming. However, good QoE can still be available for today's applications, such as on-demand video streaming or video conferencing, when the client is located in a good coverage region.

A more detailed analysis indicating the joint impact of coverage and congestion issues is as follows. Video conferencing is the least affected application by the congestion, considering all CSs. In good and mid CSs, YouTube video streaming has a high tolerance against congestion in case of a single video streaming event. When multiple YouTube videos are streamed simultaneously, QoE tolerance against the congestion decreases, especially for high-resolution videos. Cloud gaming has less tolerance against congestion compared to YouTube streaming; however, good QoE is still possible for cloud gaming at low congestion levels for good and mid CSs. Lastly, in VR streaming, only early stage and entry level VR can be utilized over the 5 GHz WiFi band. Entry level VR

TABLE VI
VR STREAMING NETWORK REQUIREMENTS

Application	Technology Level	Throughput	Latency
VR Streaming [24]	Early Stage VR (Current)	25 Mbps	40 ms
	Entry Level VR	100 Mbps	30 ms
	Advanced VR	400 Mbps	20 ms
	Extreme VR (smooth play)	1 Gbps	10 ms
	Extreme VR (interactive)	2.35 Gbps	10 ms

streaming has extremely low tolerance against congestion in a mid CS.

To support the QoE requirements of advanced VR streaming and similar future multimedia applications, higher channel bandwidth available up to 360 MHz in the 6 GHz WiFi band can be exploited, with the introduction of 802.11be. Further, the new 6 GHz band can improve QoE by providing channels with less traffic so lower congestion.

VI. CONCLUSION

This paper aims to investigate the QoE of different multimedia applications, such as the ones commonly adopted today (e.g., video conferencing, YouTube video streaming) and the ones that will be dominant in the future (e.g., cloud gaming and VR streaming), under different congestion and coverage scenarios in the 5 GHz WiFi band. The study is conducted by evaluating the application requirements with the empirical data collected over various Iperf, Ping, and YouTube tests conducted at different channel congestion levels and coverage locations.

In conclusion, all multimedia applications suffer form poor QoE under poor WiFi coverage conditions. The coverage issues can be addressed by utilizing additional access points in the area. The channel congestion in the 5 GHz WiFi band will be a limiting factor on the application QoE, as it has been for a while for the 2.4 GHz band. Therefore, more intelligent congestion management algorithms are required for the 5 GHz band. Furthermore, the use of the 6 GHz band must be promoted against the legacy devices, considering the future applications, especially VR streaming. On the other hand, the 5 GHz band can provide tolerable performance for today's applications in a general case.

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