RESEARCH ARTICLE

AR/VR Spectrum Requirement for Wi-Fi 6E and Beyond

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ABSTRACT Wi-Fi spectrum scarcity is a challenge for popular wireless applications that require a high data rate, low latency, and high reliability in different environments. AR/VR applications for e-education in a school is a good example of a challenging scenario where a large number of AR/VR devices have high data rate and latency-sensitive traffic, and require reliable wireless connectivity. In order to accommodate such emerging applications, several leading countries including the USA, South-Korea, Brazil and Canada released 1200 MHz of the spectrum in the 6 GHz band for the unlicensed use cases. Other countries, including European Union member states, only released the lower 500 MHz of the 6 GHz band and have yet to decide on the future use of the upper 6 GHz band. In this paper, we quantify the impact of spectrum scarcity on the feasibility of the AR/VR applications for e-education. Practically, we compare the maximum number of AR/VR devices supported in each classroom of a given school, depending on whether 500 MHz or 1200 MHz are available for unlicensed use cases.

INDEX TERMS AR/VR, 6 GHz unlicensed band, Wi-Fi.

I. INTRODUCTION

The daily usage of wireless devices and the uptake of new high-demand applications running on these devices increases the need for higher data rates wireless connectivity and as a result, the demand for more spectrum. To tackle the spectrum scarcity issue, the FCC has released 1200 MHz of unlicensed spectrum in the 6 GHz band [1]. Several other countries including South-Korea, Brazil and Canada also opened the full 1200 MHz to unlicensed devices. IEEE 802.11 standard body enabled the usage of the 6 GHz spectrum in 802.11ax specification (aka Wi-Fi 6E [2]) and 802.11be (aka Wi-Fi 7 [3]). However, some countries, including European Union Member States released only 500 MHz of the lower 6 GHz band [4] and are yet to decide on the future use of the upper 6 GHz band.

Several papers studied the performance of Wi-Fi on the dense deployment and some of them with similar scope as this paper are discussed here. In [5], the effect of interference in dense deployment in 5 GHz is discussed and a transmit power control solution is proposed to improve the throughput

performance. In [6], the effect of beacon collisions in a dense deployment scenario at 5 GHz that may cause client disassociation is discussed; solutions from IEEE 802.11ax standard are evaluated to overcome the issue. The effect of spatial reuse and transmit power control which is proposed in IEEE 802.11ax standard is investigated in a dense indoor residential deployment [7]; the study considers different number of channels at 5 GHz band. The paper shows that by using these techniques the total network performance improvement is negligible compared with the legacy standard in the dense deployment, and also neighbor legacy devices observe performance degradation.

There are some papers on the impact of the 6 GHz band on the Wi-Fi network performance in residential and low to high congested environments. The simulation study in [8] shows that for a single-family house, there is a significant Wi-Fi performance improvement; the multiple dwelling units scenario can also benefit from the 6 GHz spectrum, but the potential concern is the co-channel interference (CCI) from the neighboring units due to basic service set (BSS) density in a multiple overlaid network. Here, depending on the level of interference, the channel switch or rate adaptation (lower MCS selection due to lower SINR) can tackle the issue.

In [9], single room and multi rooms scenarios are simulated with 320 MHz bandwidth; the analysis of the latency performance shows that only the availability of three non-overlapping 320 MHz channels, i.e., the whole 6 GHz band, can meet the performance requirements of the time-sensitive applications in the highly loaded scenario.

There is no study on the Wi-Fi network performance with low latency traffic requirement (AR/VR applications) using the 6 GHz band spectrum in a large-scale dense deployment scenarios, e.g., school scenario. In this paper, the impact of the amount of 6 GHz spectrum on the performance of the AR/VR headsets which are used by the students for e-education in a school scenario is evaluated. This paper determines the maximum number of AR/VR headsets that can be supported when 1200 MHz or 500 MHz of spectrum is available to show if it meets the headsets used by the minimum number of students per classroom. E-education application using VR headsets in the school is considered a challenging scenario as the school is a highly congested environment and the VR application has a high QoS requirements compared with traditional non-VR applications. Our study uses the 802.11ax protocol enhancements [2] such as larger symbol duration and higher modulations (1024QAM), new PHY preamble processing, high MCSs (MCS11), larger block-ack (BA) window size (256), and 6 GHz unlicensed band channels, without using the advanced features like multi-user operation (e.g., multi-user MIMO (MU-MIMO) and/or orthogonal frequency division multiple access (OFDMA)) in 802.11ax. The availability of larger spectrum in the 6 GHz band can help these advanced features to unfold extra performance gain. However, the focus of this paper is to study the impact of the 6 GHz spectrum band independent of these advanced features and show how the baseline 802.11ax perform when a smaller spectrum is available. This is justified by the requirement to keep the cost of devices manageable in a school environment.

The rest of this article is organized as follows. Section II explains the school scenario and simulation setup. Section III describes the analysis methodology and QoS requirements in VR applications. Section IV presents the analysis and benchmarking results. Section V illustrates the simulation results. Section VI presents a summary and discussion of the results. Section VII discusses the further considerations of the study, and section VIII presents the conclusions.

II. SCHOOL SCENARIO AND SIMULATION SETUP

The school scenario is a three-story building as shown in Fig. 1. Each story has 14 classrooms, and the classrooms are in two rows which are separated by a hallway, as shown in Fig. 2. The size of each classroom is $10m \times 10m$, and the hallway is $6m$ wide. The material of the inner walls is thick brick, and the material of the floors is reinforced concrete. There is one AP in each classroom serving 20 to 30 students (STAs), where each student wears a VR headset for e-education.
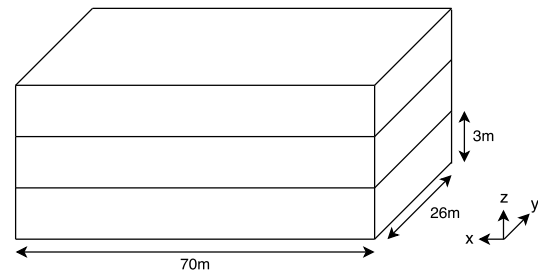

FIGURE 1. Three story building of school scenario.

In our simulation, we assume each classroom is a BSS, consisting of 1 Access Point (AP) and N Stations (STAs, N VR headsets); the AP is at the center of the classroom at the height of $3m$ attached to the ceiling, and the STAs are randomly located in a $10m \times 10m$ classroom (x-y plane) at the height of $1.25m$ as shown in Fig. 3. In our study, the intended classroom may observe CCI from neighbor classrooms with the same channel or adjacent channel interference (ACI) from the neighbor classrooms with adjacent channels (small frequency separation). There is no link adaptation algorithm for MCS selection in our study, and MCS is fixed for all the APs and STAs.

IEEE 802.11ax standard is used in our simulation study. Each BSS is assigned to a 160 MHz channel where the channel allocation is based on the availability of the spectrum (500 MHz vs. 1200 MHz). We choose 160 MHz channels because it has enough capacity to meet the per classroom VR application requirements and also result in better frequency planning compared to 320 MHz (only three 320 MHz channels are available for the whole 1200 MHz spectrum, which introduces higher CCI and ACI). All the STAs and APs are assumed to be low power indoor (LPI) devices. Per FCC rule, the AP max TX power is 27 dBm and STA max TX power is 21 dBm at 160 MHz bandwidth [1]. There are N traffic streams from each AP to its N associated STAs in a classroom with the rate of DL = 50Mbps. Table 1 summarizes the simulation parameters we used in our simulation study; these are the common parameters used for all the simulations in this paper unless specified otherwise.

In this simulation, the frame exchange sequence for data frame transmission is as follows: RTS/CTS/Data/BA. Data frame contains an A-MPDU which is the aggregation of the multiple MPDUs; the maximum number of MPDUs per A-MPDU depends on the BA window size, maximum A-MPDU length, and the maximum PPDU duration as defined in the IEEE 802.11ax. Each MPDU contains a single A-MSDU which, in this work, is the aggregation of 2 MSDUs in the MAC sublayer.
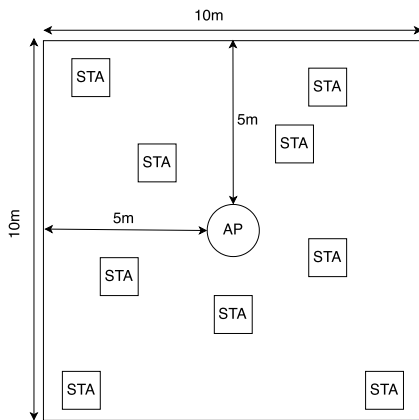
III. SIMULATION METHODOLOGY AND QoS REQUIREMENTS FOR AR/VR
A. METHODOLOGY
With the preliminary analysis in the next section, we limit the study to obtain a key understanding of the performance

FIGURE 2. 2D floor plan of one story of the school building.

* AP is attached to ceiling at the height of 3m.
* STAs are at the height of 1.25m and randomly located in the classroom.

FIGURE 3. AP and STAs orientations in a classroom.

TABLE 1. Simulation parameters.

Parameter	Value
160 MHz Channel Numbers at 6 GHz	15/47/79/111/143/175/207
Bandwidth	160 MHz
AP TX Power	27 dBm
STA TX Power	21 dBm
Traffic Type	UDP, DL best effort (BE)
Traffic Load per DL streams	50Mbps, constant bit rate
MCS/NSS/nTx/nRx	11/2/2/2
Guard Interval	0.8 μs
HE-LTF Size	1xHE-LTF
Payload Size	1472 Bytes
BA Window	256
Number of MSDUs per AMSDU	2
RTS/CTS	Enabled

of 500 MHz vs. 1200 MHz spectrum availability. Given each selected area composed of one or more classrooms, we sweep the number of STAs per classroom and identify the "maximum number of STAs that can support our QoS requirement", i.e, capacity. We repeat this for the 3-channels case (500 MHz spectrum) and the 7-channels case (1200 MHz spectrum) and compare their respective capacity.

The main factors in our preliminary analysis are:

- Link budget: determine the achieved minimum SNR within one classroom, as well as the impact of interference from other floors. Note that all the link budget analysis are deterministic assuming mean of the path loss variation.
- Co-channel interference effect: identify classrooms that are subject to co-channel interference based on their distance and channel allocation.
- Adjacent channel interference effect: the signal strength leaked into adjacent channels may cause interference to neighbor classrooms.

Due to the limited number of channels, two classrooms next to each other or separated by a hallway or other classrooms may have to share the same channel or operate on

adjacent channels. Based on the IEEE 802.11 spectral mask definition, our analysis in the next section shows that the transmission in one channel can cause non-negligible interference to the BSS operating on the adjacent 160 MHz channel. The co-channel and adjacent channel interferences degrade network performance due to CSMA/CA, energy detection (ED), degraded SINR, and hidden terminal; all these factors are captured by the simulator.

B. QoS REQUIREMENT

There are multiple factors that play a role in the VR QoS requirements, such as architectures of the VR devices in which they offload computation partially or completely to another device, how interactive the application (e.g., gaming is highly interactive when compared with virtual meetings) is, display size and resolution, and power consumption. In VR use cases, latency is especially important as high latency causes motion sickness [10]. Motion-to-photon latency (time from the movement of the head and the corresponding reaction that is displayed on the VR device) is an important metric that is considered in a lot of studies. There are multiple references proposing different latency requirements. For example, [11] states that for a good VR experience, the motion-to-photon latency should be below 50ms and latency above 63ms causes significant motion sickness. Another

paper reports that high jitter in motion-to-photon latency causes motion sickness [12]. This means that the tail of the latency histogram (X-percentile latency) is also critical in the user's experience.

Latency of the wireless links, such as that of Wi-Fi, is one part of the overall motion-to-photon latency. Standard bodies discussed the QoS requirements proposed for different VR use cases [13], [14]. In [13], the QoS requirements in WLAN based on the data rate, latency, and jitter for the gaming and real-time video application are discussed. In [14], the QoS requirements in 5G networks for the high data rate and low latency services such as Cloud/Edge/Split Rendering, Gaming or Interactive Data Exchanging, and Consumption of VR content via tethered VR headset are presented; the requirements in [14] are stricter compared to [13], e.g. for one use case the requirement is 100Mbps to 1Gbps data rate with 10ms end to end latency and 99.99% reliability.

The school scenario with the e-education VR use case has lower QoS requirements per VR STA. We choose the QoS requirements of 50Mbps DL per-stream traffic (between the AP and each STA) with 20ms latency at 90% (P90) to reflect our expectation that educational application would be less visually dynamic. The traffic-rate can be calculated as $W \times H \times 2 \times Co \times Cr \times S$, where $W \times H$ is the resolution of the display per eye where it is multiplied by 2 for the two displays, Co is the color depth (number of bits per pixel), Cr is the compression ratio, and S is the screen refresh rate; in a typical example case, the resolution of display is 1832×1920, color depth is 12, compression ratio is 1/150, and display refresh rate is 90 Hz, which gives the traffic-rate of around 50 Mbps [15]. On the other hand, the e-education VR use case involves a higher number of users, leading to a challenging environment. The latency is measured at the transmitter. Latency is defined as the time from the packet being queued into the MAC layer until the time where either the packet acknowledgment is received or the retry limit is reached. This includes queuing delay, medium contention, (re-)transmission time, and the time to receive the acknowledgment.

IV. ANALYSIS AND BENCHMARKING
In this section, we will do some preliminary analysis to:
- calculate minimum SNR and find the suitable MCS,
- analyze the impact of CCI,
- analyze the impact of ACI,
- and analyze the multi-floor interference to see the impact from other floors.

A. MINIMUM SNR CALCULATION IN A CLASSROOM AND BENCHMARK PERFORMANCE
If the STA is at the corner of the classroom, the maximum distance from AP to STA in the classroom is $d = \sqrt{5^2 + 5^2 + (3-1.25)^2} = 7.28m$. The minimum SNR inside the classroom is calculated as:

$$SNR_{min} = P_{TX,AP} - PL_{Friis}(d) - NP \qquad (1)$$

where $P_{TX,AP} = 27$ dBm, $PL_{Friis}(d)$ is the free space pathloss (Friis) which is 65.3 dB at distance d and frequency of 6025 MHz (center frequency for the first 160 MHz channel in 6 GHz band), and NP is the noise power for 160 MHz channel bandwidth which is -89 dBm (considering 3 dB noise figure). So, the minimum SNR is:

$$SNR_{min} = 27dBm - 65.3dB - (-89dBm) = 50.7dB. \qquad (2)$$

The minimum SNR for the VR headsets inside one classroom is high enough to support up to MCS11 (for MCS11, the SNR value between 31-33 dB is required to achieve less than 10% PER [16]).

We simulate the single classroom scenario for different MCSs and sweep the number of STAs in the classroom to establish the benchmark per-user performance in a single classroom when there is no interference from other classrooms (CCI and ACI). Fig. 4 shows the per-user DL throughput and P90 latency performance for MCS7, MCS9, and MCS11, which is compared to the throughput and latency requirement that is discussed in QoS requirement section III-B (i.e., 50Mbps throughout with 20ms P90 latency). From Fig. 4, MCS11 curve shows that at most 25 STAs in a classroom can meet both throughput and latency requirements and MCS9 curves show at most 22 students. MCS9 and MCS11 are the best choice of MCS for the school scenario as they can meet the minimum of 20 students per classroom threshold in our scenario (20-30 students per classroom). When we introduce more classrooms to our scenario, it is expected that the number of STAs that can be supported per classroom with MCS9 and MCS11 decreases due to ACI and CCI from other classrooms; so, for the rest of this paper, we only consider MCS11 as it has better performance and we hope with MCS11 to support more than 20 students per classroom.

The reason we choose the bandwidth 160 MHz in this study is that the max number of STAs in a classroom that meet the requirement with bandwidth 160 MHz is 25 in the best case (no interference from neighboring classrooms), so if we consider a lower bandwidth like 80 MHz, the max number of STA decreases to half which is much lower than the 20 students per classroom.

B. SAME FLOOR CO-CHANNEL INTERFERENCE ANALYSIS
In this section, we study the effect of the co-channel interference caused by the neighbor classrooms in the same floor. For the link budget calculation, we use the room-to-room pathloss model, which is derived from the measurements in a school building with the corridor between the classrooms [17]; the school building structure, plan, material, and frequency band in the paper are very close to the scenario that is considered in this work. The measurements in [17] are performed at 5.2 GHz; vertically polarized halfwave dipole (2 dBi) antenna was used for the measurement of this pathloss model. The measured pathloss is fitted with a logarithmic model as
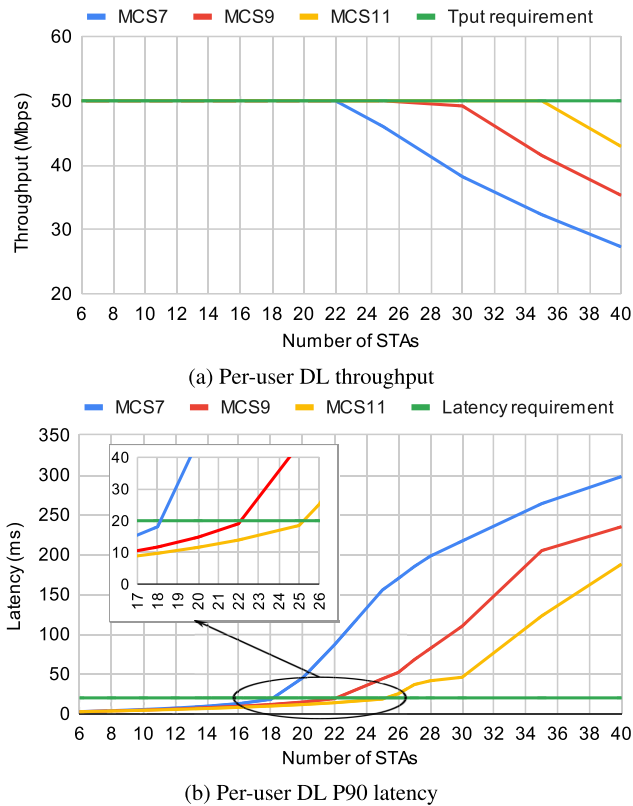
(a) Per-user DL throughput

(b) Per-user DL P90 latency

FIGURE 4. The per-user performance in single classroom without any interference.

below:

$$PL_{cr}(d) = 11.3 + 70 \times \log_{10}(d) + S_{\sigma_c}, \qquad (3)$$

where d is the distance between the TX and RX endpoints, and S_{σ_c} is a log-normal random variable with zero mean and standard deviation of 3.9 dB.

Fig. 5a illustrates the channel allocation in 3-channels case (i.e., channel 15, 47, and 79 are considered in this case) and Fig. 5b illustrates the channel allocation in 7-channels case (i.e., channels 15, 47, 79, 111, 143, 175, and 207 are considered in this case; numbers in the box is the channel numbers for each classroom which are the channels at 6 GHz band per 802.11ax specification [2]). Channel allocation strategy is:

- assign different channels to neighboring classrooms as much (different) as possible,
- and assign the same channel to classrooms with maximum distance to reduce CCI,
- and assign adjacent channels to classrooms with maximum distance to reduce the ACI.

In Fig. 5a, classroom B, C, and D with the same channel 15 which are highlighted with red circles have the dominant interference to classroom A which is highlighted with green circle. The interference from the co-channel classrooms B, C, and D to classroom A is:

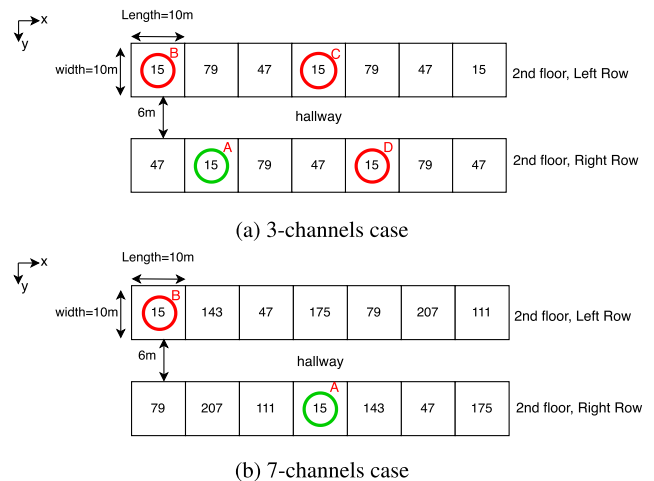$$Int_{B,3} = 27dBm - (PL_{cr}(18.86)) = -73.6dBm,$$

(a) 3-channels case

(b) 7-channels case

FIGURE 5. Frequency planning and interferer classrooms.

$$Int_{C,3} = 27dBm - (PL_{cr}(25.6)) = -82.9dBm,$$
$$Int_{D,3} = 27dBm - (PL_{cr}(30)) = -87.7dBm, \qquad (4)$$

where the distance is the Euclidean distance from the interferer APs to the center of the classroom A. Classroom D, which is in the same row as classroom A, has the lowest interference to classroom A, and classroom B has the largest interference to classroom A. Interference from classroom C, and D is low, and the calculation inside the classroom shows that minimum SNR of 50.7 dB inside the classroom is high enough so that the interference doesn't affect the performance of higher MCSs like MCS11. The dominant interferer is classroom B, so in the next subsection, the two classrooms scenario for the 3-channels case in which only classrooms A and B in Fig. 5a are present is simulated to study the effect of the CCI.

Fig. 5b illustrates the channel allocation in 7-channels case. In this figure, classroom B with the same channel 15 has the dominant interference to classroom A (classroom B is highlighted with red circle and classroom A is highlighted with green circle). So, interference from classroom B to A is:

$$Int_{B,7} = 27dBm - (PL_{cr}(34)) = -91.5dBm. \qquad (5)$$

The interference level is quite low for this scenario compared to the 3-channels case. In fact, it is less than the noise floor. In the next subsection, the two classrooms scenario for the 7-channels case in which only classrooms A and B in Fig. 5b are present is simulated to study the effect of CCI.

C. CO-CHANNEL INTERFERENCE SIMULATION RESULTS
In this section, we illustrate the simulation results for the CCI effect for the 3-channels case and the 7-channels case. The 2-Classrooms scenario is compared with the baseline single-classroom; the two classrooms are the classroom A and classroom B in Fig. 5a and Fig. 5b for 3-channels case and 7-channels case, respectively. The simulation parameters are identical to Table 1. In the 3-channels case for BE traffic,

as shown in Fig. 6, only up to 12 STA can meet the throughput and latency requirements which is below the minimum number of students per classroom (note that in Fig. 6a all 4 curves are on top of each other). In the 7-channels case for BE traffic, as shown in Fig. 7 (the throughput meets the 50Mbps requirement in the whole range of sweep; it is not plotted for the brevity), up to 23 STAs can meet the throughput and latency requirement, which is more than the minimum number of 20 students per classroom threshold.

The AR/VR applications could have any type of traffic and VI traffic is one of the typical traffic types, so this is simulated in this section to analyze the effect and comparison with the BE traffic. For the VI traffic, the contention window parameters are smaller which causes higher collision in presence of neighbor co-channel classroom within the sensing range compared with the BE traffic; in 3-channels case, the co-channel classrooms are closer which causes higher collision and worst latency performance compared with the BE traffic; in 7-channels case, the co-channel classrooms are further away from each other which causes lower collision and lower latency compared with the BE traffic. So, as expected the VI traffic in a dense deployment in which less spectrum is available shows a worse performance. For the rest of this paper, we only consider the BE traffic for brevity.

In this simulation results that only consider the CCI effect from another classroom, the 3-channels case cannot meet the requirement while the 7-channels case meets the requirement. In the next section, we extend the study to multi classrooms scenario, which includes the CCI and ACI effects from multiple classrooms.

D. SAME FLOOR ADJACENT CHANNEL INTERFERENCE ANALYSIS

In this section, we analyze the impact of the adjacent channel interference given the neighbor classrooms has an adjacent channel, e.g., channels 15 and 47, as shown in Fig. 8. The TX spectral mask in our simulation follows the IEEE spectral mask that is defined for 160 MHz [2]. On the receive side, we assume we use the ideal lowpass filter, which is 1 in passband and zero in stopband in the frequency domain. Considering the IEEE spectral mask, the transmitted signal leakage from channel 15 to the adjacent channel 47 is 24.9 dB lower than the TX power of the signal on channel 15 (without considering other factors, like pathloss between TX/RX endpoints, the RX gain, etc.) which is non-negligible.

Fig. 9 illustrates the simulation results for the two neighbor classrooms scenario with the ACI channel and compared with no ACI in a single-classroom scenario (the throughput meets the 50Mbps requirement in the whole range of sweep; corresponding plot is not included for concision). The simulation parameters are identical to Table 1. While the throughput performance can meet the throughput requirement for the whole range, the ACI effect causes latency performance degradation. The P90 latency of more than 6 STAs in each classroom cannot meet the latency requirement. The ACI effect is worse than the CCI in previous subsection. One
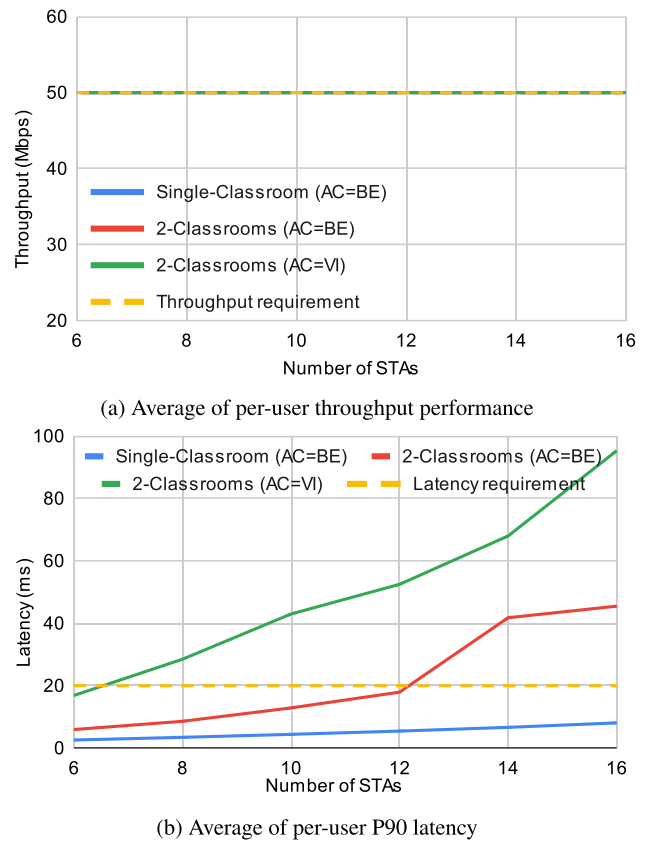

(a) Average of per-user throughput performance

(b) Average of per-user P90 latency

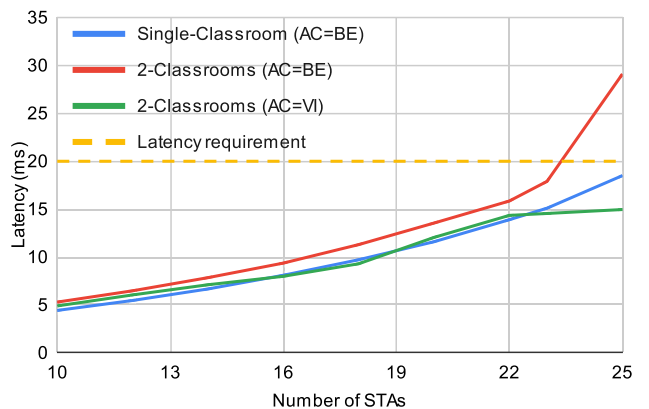**FIGURE 6.** The performance of a classroom when there is a OBSS network in 3-channels case.

FIGURE 7. The performance of a classroom when there is a OBSS network in 7-channels case; P90 latency.

contributing factor is that ACI occurs between adjacently located classrooms, whereas CCI occurs between classrooms that are located further away from each other.

E. MULTI-FLOOR INTERFERENCE ANALYSIS

In this section, we calculate the interference from one floor to another floor to see the impact of the interferer classroom. We analyze the interference impact for 3-channels case considering channel allocation illustrated in Fig. 10. Then,
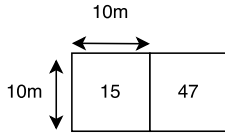
FIGURE 8. Two classrooms with adjacent channel for studying the ACI effect.
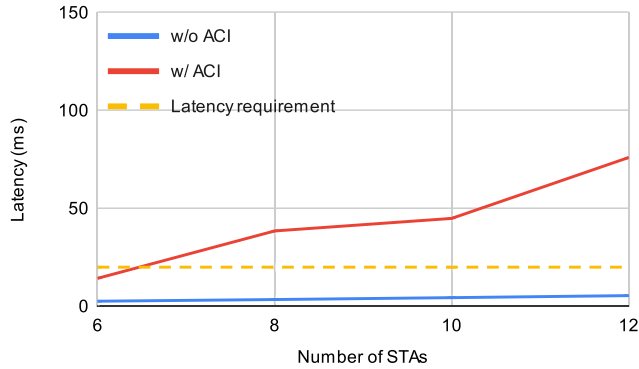

FIGURE 9. The ACI simulation results; Average of per-user P90 latency.

by comparison we conclude that for 7-channels case the interference effect is even lower.

The Keenan-Motley [18] pathloss model is considered for link budget analysis; this model is formulated based on the number of walls and floors between the TX and RX endpoints and their corresponding losses:

$$PL_{km}(d) = PL_{Friis}(d) + n_w \times L_w + n_f \times L_f, \qquad (6)$$

where L_{Friis} is the Friis pathloss model, n_w is the number of walls between the TX and RX, L_w is the loss of the wall, n_f is the number of floors between the TX and RX, and L_f is the loss of floor.

Fig. 10a is the 2D x-y plane of the 2nd floor, and Fig. 10b is 2D x-z plane of the "Right Row". The blue dashed line highlights the same classrooms in Fig. 10a and 10b. Considering classroom A in Fig. 10b, the CCI is from the diagonal room on the other floor, which is classroom B. Using the Keenan-Motley pathloss model, the signal is going through one floor and one wall between classrooms A and B. The material between the walls is thick brick, where the average loss is 27 dB for 6-7 GHz [19] and the material between the floors is reinforced concrete, where the average loss is 65 dB for 6-7 GHz. So, the received interference in classroom A is:

$$Int_{CCI} = P_{TX,AP} - PL_{km}(d), \qquad (7)$$

where in Keenan-Motley path loss model, $n_w = 1$, $n_f = 1$, $L_w = 27$ dB, $L_f = 65$ dB, d is the average distance of the AP in 1st floor (at the ceiling) to the STA on the 2nd floor which is equal to $d = 11.5m$ (10m for length of the class and 1.5m for the z-direction distance between the AP and STA considering the thickness of the floor as 0.25m), and the Friis pathloss is $PL_{Friis}(11.5) = 69.2$ dB. So, interference is calculated as:

$$Int_{CCI} = 27dBm - (69.2dB + 27dB + 65dB) = -134.2 \ dBm.$$
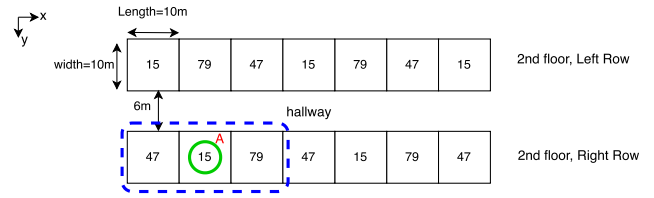
(a) The channel allocation to illustrate the interferer in single floor
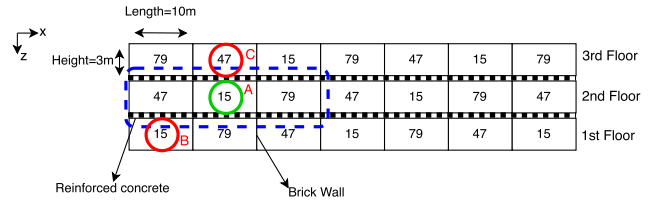
(b) The channel allocation in multi-story building considering the top

FIGURE 10. Effect of co-channel interference.

$$(8)$$

So, for the 3-channels case, the level of CCI is very low compared to the error floor, which is around -89 dBm (-89 dBm is the error floor for 160 MHz channel considering the 3 dB noise figure).

In Fig. 10b, classroom C is the closest neighbor to classroom A with the adjacent channel. The ACI from classroom C to A is calculated as:

$$\begin{aligned} Int_{ACI} &= P_{TX,AP} - (PL_{km}(d) + L) \\ &= 27dBm - ((62dB + 65dB) + 24.9dB) \\ &= -124.9 \ dBm, \end{aligned} \qquad (9)$$

where in Keenan-Motley pathloss model there is only one floor between classrooms A and C, i.e., $l_w = 0$ and $l_f = 1$, Friis pathloss is $PL_{Friis}(5) = 62$ dB ($d = 5$ is calculated based on the minimum distance of the interferer AP in classroom C to a STA at the center of classroom A), and L is the loss due to leakage from channel 47 to channel 15 which is 24.9 dB lower than the transmitted signal. So, the nearest ACI interferer classroom causes very low interference of -124.9 dBm to classroom A which is way below the noise floor.

From the analysis for the 3-channels case, the ACI and CCI interferences from other floors are very low. The distance between the co-channel interferer and adjacent channel interferer in the 7-channels case is larger than the 3-channels case, so the interference from the other floors is even smaller. This calculation helps us to narrow down the simulation for 3-channels and 7-channels cases to be on the 2D x-y plane.

V. SIMULATION RESULTS

The ns-3 network simulator is used for this study [20]. Some of the aspects that are captured in the simulators are preamble processing, SNR/PER for payload reception, the frame and packet (MPDU) level collision in a frame sequence, the effect of CCI and ACI from neighbor classrooms (BSSs), spectral mask which affect the level of ACI, CSMA/CA channel
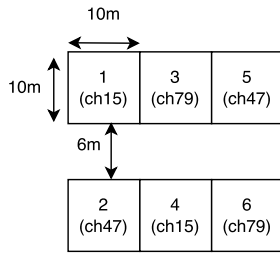
FIGURE 11. 6 classrooms scenario for 3-channels case simulation study.

FIGURE 12. Average of per-user P90 latency in 3-channels case for each classroom number.

TABLE 2. Summary of 3-channels case capacity.

# of classrooms	Capacity	Tput Req	Latency Req
1	25	yes	yes
1	26	yes	no
2	23	yes	yes
2	24	yes	no
4	4	yes	yes
4	6	yes	no
6	4	yes	no

access, hidden node problem, and application level per stream traffic processing. These aspects have cross effects on the other ones and since they are not orthogonal, they can be captured through simulation. In this section, different scenarios are simulated to find out the maximum number of STAs that meets the QoS requirement (Capacity). We increase the number of classrooms as well as the number of STAs (students) per classrooms to see where it starts to fail to meet the QoS requirements.

A. 3-CHANNELS CASE

This section illustrates the simulation results when 3 channels are available. As fewer channels are available in this case, the adjacent channels are assigned to some of the neighbor classrooms, so we expect a higher ACI and worse performance. Also, as we observed in the previous section, the CCI has a worse effect in the 3-channel case due to the closer distance between classrooms operating on the same channels. Fig. 11 illustrates the frequency planning for the 3-channels case considering only 6 classrooms are available per floor; the number in the first row indicates the classroom number, and the second row indicates the channel numbers in the 6 GHz band (lower 500 MHz spectrum).

Fig. 12 illustrates the P90 latency when there are 4 or 6 classrooms per floor; each classroom has 4 or 6 STAs. The throughput performance in all these cases meets the throughput requirement. In the 4 classrooms scenario, classroom #4 has the highest latency as it is impacted by a higher ACI compared to others, i.e., classroom #4 sees ACI from neighbor classroom #2, and it has the CCI from classroom #1; other classrooms do not have a very close ACI interferer. In the 4 classrooms scenario, when there are 6 STAs per classroom, the latency increases and cannot meet the requirement. In the 6 classrooms scenario, classrooms #3 and #4 have the highest latency as they observe a higher ACI from their neighbor classrooms compared to others. Even with only 4 STAs per classroom, this scenario cannot meet the latency requirement.

Table 2 summarizes all the simulation results conducted for the 3-channels case to illustrate the capacity (number of STAs) that can be supported in each scenario. The results show that the two classrooms with 23 STAs can support the QoS requirement, which is above our 20 students per classroom threshold; when we go beyond 2 class-
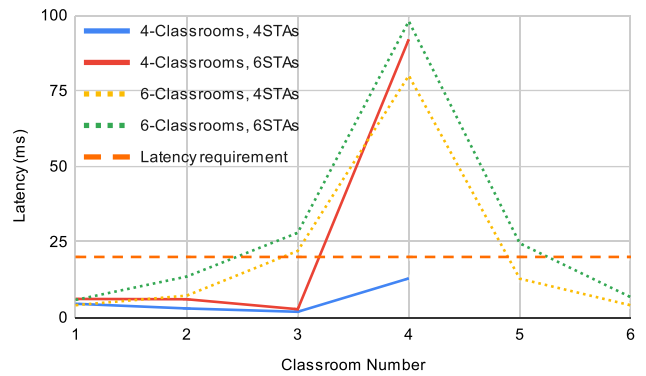
rooms, the number of STAs that can meet the QoS requirements decreases below 20 students per classroom. The 6 classrooms scenario cannot even support 4 STAs per classroom.

B. 7-CHANNELS CASE

Fig. 13 illustrates the frequency planning for the 7-channels case considering 14 classrooms per floor. It should be noted that all seven channels are used in each floor, and therefore the scenario could conceivably be extended for a larger number of classrooms within the same floor plan through "wrap-around" of the channel allocation pattern simulated here, without a significant increase of the interference level. In the 7-channels case scenario, as there are more channels, the classrooms with co-channel and adjacent channels have a larger separation distance and we expect a lower ACI and CCI effect.

Fig. 14 illustrates the P90 latency when there are 8 and 14 classrooms per floor. The throughput performance meets the throughput requirement in all cases. In the 8 classrooms scenario, at most 23 STAs per classroom can meet the latency requirement. In the 14 classrooms scenario, at most 22 STAs per classroom can meet the latency requirement. Due to the larger separation distance of co-channels and adjacent channels in the 7-channels case, the effect of interference is not observable in the curves.

Table 3 summarizes all the simulation results conducted for the 7-channels case to illustrate the capacity that can be supported in each scenario. In scenarios involving up to 4 classrooms, since there are neither ACI nor CCI classroom
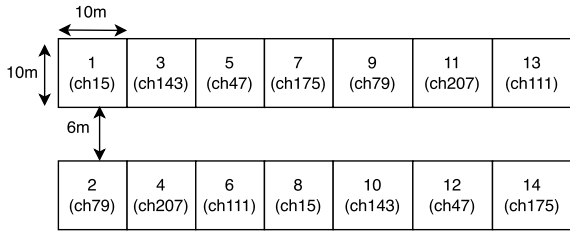
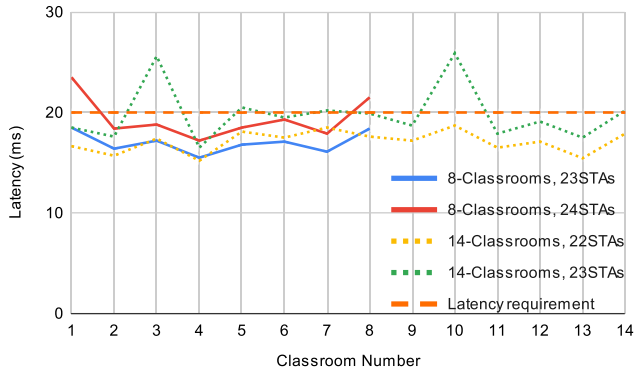**FIGURE 13.** 14 classrooms scenario for 7-channels case simulation study.

FIGURE 14. Average of per-user P90 latency in 7-channels case for each classroom number.

TABLE 3. Summary of 7-channel case capacity.

# of classrooms	Capacity	Meet Tput Req	Meet Latency Req
1	25	yes	yes
1	26	yes	no
2	25	yes	yes
2	26	yes	no
4	25	yes	yes
4	26	yes	no
8	23	yes	yes
8	24	yes	no
14	22	yes	yes
14	23	yes	no

interferers, up to 25 STAs per classroom meet the QoS requirement (no degradation from the single classroom case). However, in scenarios with more than 4 classrooms, the ACI and CCI effects appear. In the 14 classrooms scenario, the capacity decreases to 22 STAs.

Fig. 15 compares the 3-channels case and 7-channels case. In the 3-channels case, as the number of classrooms increases, the capacity decreases very rapidly. In the 7-channels case, the capacity remains above 20 students per classroom threshold, when increasing the number of classrooms up to 14 classrooms per floor. As mentioned before, the number of classrooms per floor can be extended beyond 14 within the same floor plan without adverse effect on the per class capacity because adding more classrooms does not cause significant increase of the interference level. The results show that access to 7 channels (1200 MHz of spectrum) is required to enable our modelled AR/VR e-education school. Conversely, such school could not operate under the current EU spectrum regulatory framework.
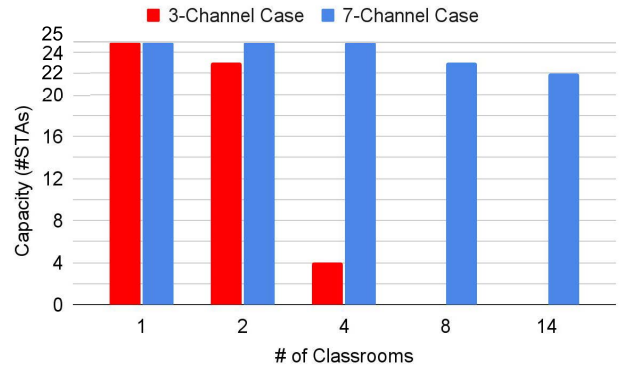

FIGURE 15. Comparing 3-channels case and 7-channels case.

C. IMPACT OF EU TX POWER

In the European Union, only 500 MHz spectrum of the 6 GHz band is released (3 channels of 160 MHz) and the maximum TX power limit is 23 dBm [21] which is different from the power limit enforced by FCC. We modified the study presented in section V-A and V-B to analyze the impact of this TX power change. This improves our understanding of the impact of limited spectrum availability when considering the TX power limits applicable in Europe. The simulation results indicate that the effect of ACI and CCI is similar to the initial study using the TX power limit of FCC. This makes sense since our simulation scenarios include sufficient SNR margin for MCS11. Decreasing the TX power by 4 dB does not affect the performance.

D. IMPACT OF LOWER TX POWER

In order to improve our understanding of the impact of TX power change and how different level of interference from neighboring classrooms affects the performance, the 2 classrooms scenario where the BSSs operate on the same channel similar to section IV-C for the 3-channels case is studied. The TX power is swept from 15 dBm to 27 dBm to see what the maximum number of STAs is that meet the throughput and P90 latency requirements. Table 4 summarizes the maximum number of STAs for each TX power that meets the requirements. When the TX power is high, the APs of two classrooms can hear each other and coexist. However, when the TX power is lower, the APs may not hear each other and thus concurrently transmit frames to their associated STAs which increases the probability of collision; as a result, the performance degrades as shown in the table. The performance at 23 dBm and 27 dBm are almost identical as it is shown in previous subsection.

VI. SUMMARY AND DISCUSSION OF THE RESULTS

The results show that with 500 MHz of spectrum availability, the capacity is 4 students per classroom with 4 classrooms per floor. When 1200 MHz of spectrum is available, up to 22 students per classroom can concurrently use the VR headsets in 14 classrooms per floor (whole school). The number

TABLE 4. Impact of TX power.

TX Power (dBm)	Max Number of STAs
15	4
18	6
21	10
23	12
27	12

of classrooms can be extended beyond 14 per floor without affecting the capacity of each classroom. The results highlight the significance of 1200 MHz spectrum availability for supporting AR/VR applications in high-density large-scale scenarios and 500 MHz of spectrum is not enough to support AR/VR applications.

By changing the TX power, the capacity decreases when the TX power is below 23dBm. Considering the maximum TX power of 23dBm in European Union, the results remain unchanged, and the same conclusion as previous paragraph can be derived.

VII. FURTHER CONSIDERATIONS

In this section, we discuss potential performance effects of some of the features. In this study, only DL traffic is present. Therefore the only contentions are from APs in different classrooms. Due to the absence of UL traffic, UL OFDM is not relevant. In addition, for the scenarios that the total DL traffic rate is high compared with the Wi-Fi physical layer data rate (this is the case for most of the scenarios in this paper), DL OFDMA is not expected to provide significant gains compared to single-user transmission because all STAs are capable of transmitting and receiving on 160 MHz bandwidth, which is the same as the AP's operating channel bandwidth.

With respect to MU-MIMO, performance gain in MU-MIMO depends on multiple factors such as: 1) Orthogonality of the MU-MIMO channels in which the interference among the spatial streams of different STAs should be negligible; 2) Client mobility, environmental change, and precoding error (due to channel state information feedback compression/quantization) may degrade the performance significantly; 3) The extra beamforming overhead decreases the efficiency in MU-MIMO. Let's consider a typical example scenario for the MU-MIMO: a 4×4 AP with the 2×2 STAs associated with it. It is known that in a 4×4 AP MU-MIMO with two streams to each of the two 2×2 STAs (concurrent transmission to 2 STAs at a time), it is hard to get sufficient diversity gain. This is especially true in a single classroom where it may not be possible to have orthogonal channels for all the STAs. By using DL MU-MIMO, at the best case, the AP may concurrently serve two STAs (with each having 2 spatial-streams) and double the capacity in some ideal/limited cases. So, for the 3-channels case (500 MHz of spectrum) when there are 4 classrooms, the AP can support at most 8 STAs (2 times the number of STAs shown in Fig. 15 which is single user transmission) which is still way below the

20 students per classroom requirement. In the same scenario, when there are 8 classrooms and beyond, the AP cannot support up to 20 students per classroom either. So, by using the MU-MIMO in 500 MHz spectrum scenario, the Wi-Fi system cannot support up to 20 students per classroom. The full 1200 MHz spectrum is needed to meet the latency and throughput requirement.

In the simulations, the highest MCS, MCS11 in IEEE 802.11ax standard, is used with enough SNR margin within the BSS (also RTS/CTS is enabled to prevent long frame collision) so the rate adaptation cannot help to improve the performance within the classroom. Complex rate adaptation algorithms which consider the inter BSS interference and possibly using spatial reuse might help to enable the concurrent transmission with the neighbor BSSs (coexistence of the neighbor classrooms), but at the cost of operating at a lower MCS, which decreases the capacity per classroom. For example, by using MCS7, the maximum capacity in a single classroom is 18 as shown in Fig. 4 which is below 20 students per classroom.

VIII. CONCLUSION

In this paper, the performance of the VR headsets used by students for e-education in a school scenario is studied. The goal was to highlight the impact of spectrum availability (either 500 or 1200 MHz) on the number of students that can simultaneously use VR headsets in each class. The following steps are performed to conduct the study: 1) VR application performance requirements (50 Mbps, 20ms P90 latency) is selected to reflect the likely limited requirements of educational VR (compared with other VR application such as gaming); 2) The benchmark simulation analysis is conducted to select the MCS required to meet the QoS requirements of our VR application; 3) The ACI and CCI analysis is performed with two classrooms to study the effect of each type of interference on the neighbor classrooms; 4) In order to simplify the scenario involving the whole school, an initial analysis considering the school floor plan, classroom structures, and school building material is performed to untangle the simulation of the multi-story school to a single-story scenario in which the performance of one floor is independent of the performance on the other floors; 5) Finally, different scenarios for the 3-channels case (500 MHz spectrum availability) and 7-channels case (1200 MHz spectrum availability) are simulated to compare the performance. The results illustrate that 500 MHz is not enough to support AR/VR applications in a school scenario, while 1200 MHz provides enough capacity for this use case.

REFERENCES

[1] *Unlicensed use of the 6 GHz band; expanding flexible use in mid-band spectrum between 3.7 and 24 GHz*, document ET Docket No. 18–295, FCC, Apr. 2020.

[2] *Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications—Amendment 1: Enhancements for High Efficiency WLAN*, Standard IEEE 802.11ax/D8.0, 802.11 Working Group, Oct. 2020.

[3] *Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications—Amendment 8: Enhancements for Extremely High Throughput (EHT)*, Standard IEEE 802.11be/D1.5, 802.11 Working Group, Mar. 2022.

[4] *Commission Implementing Decision of 17.6.2021 on the Harmonised use of Radio Spectrum in the 5945–6425 MHz Frequency Band for the Implementation of Wireless Access Systems Including Radio Local Area Networks (WAS/RLANs)*, Eur. Commission, Directorate-Gen. Commun. Netw., Content Technol., C(2021) 4240 Final, Eur. Commissions, Brussels, Belgium, Jun. 2021.

[5] F. S. Chaves, A. M. Cavalcante, E. P. L. Almeida, F. M. Abinader, R. D. Vieira, S. Choudhury, and K. Doppler, "Adaptive transmit power for Wi-Fi dense deployments," in *Proc. IEEE 80th Veh. Technol. Conf. (VTC-Fall)*, Sep. 2014, pp. 1–6.

[6] D. Bankov, E. Khorov, A. Lyakhov, and S. Schelstraete, "Beacons in dense Wi-Fi networks: How to befriend with neighbors in the 5G world?" in *Proc. IEEE 17th Int. Symp. A World Wireless, Mobile Multimedia Netw. (WoWMoM)*, Jun. 2016, pp. 1–6.

[7] A. M. Voicu, F. Giorgi, L. Simic, and M. Petrova, "Wi-Fi evolution for future dense networks: Does sensing threshold adaptation help?" in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Apr. 2018, pp. 1–6.

[8] J. Flesch, C. Cheevers, and K. Lumbatis, "The promise of WiFi in the 6 GHz band," Technical Forum SCTE/ISBE, NCTA, Cable-Labs, Fall, 2019. [Online]. Available: https://www.nctatechnicalpapers.com/Paper/2019/2019-the-promise-of-wifi-in-the-6-ghz-band

[9] D. Akhmetov, R. Arefi, H. Yaghoobi, C. Cordeiro, and D. Cavalcanti, "6 GHz spectrum needs for Wi-Fi 7," *IEEE Commun. Standards Mag.*, vol. 6, no. 1, pp. 5–7, Mar. 2022.

[10] M. E. McCauley and T. J. Sharkey, "Cybersickness: Perception of self-motion in virtual environments," *Presence, Teleoperators Virtual Environ.*, vol. 1, no. 3, pp. 311–318, 1992.

[11] P. Caserman, M. Martinussen and S. Göbel, "Effects of end-to-end latency on user experience and performance in immersive virtual reality applications," in *Proc. Joint Int. Conf. Entertainment Comput. Serious Games*. Springer, 2019, pp. 57–69.

[12] J.-P. Stauffert, F. Niebling, and M. E. Latoschik, "Effects of latency jitter on simulator sickness in a search task," in *Proc. IEEE Conf. Virtual Reality 3D User Interfaces (VR)*, Mar. 2018, pp. 121–127.

[13] K. Meng, A. Jones, and D. Cavalcanti, "RTA TIG summary and recommendations," IEEE 802.11 RTA TIG, Tech. Rep. 11-19-0065v6, Mar. 2019.

[14] *3GPP Technical Specification*, document TS 22.261 V18.5.0, 3GPP, Dec. 2021.

[15] *Oculus Quest 2*. Accessed: Sep. 2022. [Online]. Available: https://en.wikipedia.org/wiki/Oculus_Quest_2

[16] A. Akbilek, F. Pfeiffer, M. Fuenfer, F. Langer, and B. Napholz, "Analysis of IEEE 802.11ax high efficiency WLANs for in-vehicle use," in *Proc. 15th Wireless Congr., Syst. Appl.*, Munich, Germany, Nov. 2018, pp. 1–9.

[17] J. Medbo and J.-E. Berg, "Simple and accurate path loss modeling at 5 GHz in indoor environments with corridors," in *Proc. 52nd Veh. Technol. Conf. (IEEE-VTS Fall VTC)*, vol. 1, Sep. 2000, pp. 30–36.

[18] J. M. Keenan and A. J. Motley, "Radio coverage in buildings," *Bell Syst. Tech. J.*, vol. 8, pp. 19–24, Jan. 1990.

[19] W. C. Stone, "NIST construction automation program report, no. 3 electromagnetic signal attenuation in construction materials," in *Proc. NISTIR*, Oct. 1997, pp. 1–185.

[20] *Ns-3 Simulator*. Accessed: Sep. 2022. [Online]. Available: https://www.nsnam.org

[21] *ANNEX to the Commission Implementing Decision of 17.6.2021 on the Harmonised use of Radio Spectrum in the 5945–6425 MHz Frequency Band for the Implementation of Wireless Access Systems Including Radio Local Area Networks (WAS/RLANs)*, Eur. Commission, Directorate-Gen. Commun. Netw., Content Technol., C(2021) 4240 Final, Eur. Commission, Brussels, Belgium, Jun. 2021.

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