What's Behind 'Sorry, I Lagged': Correlating Wi-Fi Metrics with Online Gaming Latency

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***Abstract*—Online gaming is one of the most popular services via Wi-Fi at home, requiring stable, low latency to ensure responsive gameplay. Although recent versions of Wi-Fi offer maximum theoretical bitrates up to 9.6 Gbps, far exceeding throughput requirements for online games, players still experience frustrating moments due to poor Wi-Fi connections during the game. Among other challenges, Wi-Fi is particularly sensitive to its radio environment due to its unlicensed spectrum. In addition to interferences from neighboring Wi-Fi networks in crowded areas, other radio technologies such as Bluetooth, Thread and microwave ovens that share the same frequency as Wi-Fi can also have non-desirable effect for Wi-Fi services. In this paper, we focus on how Wi-Fi coverage and neighboring interference can impact the gaming experience of a well-known multiplayer online game, Counter-Strike: Global Offensive. We conducted gaming experiments and collected metrics from a Wi-Fi access point and gaming device in a controlled and automated Wi-Fi testbed with different attenuation values and available airtime on the 2.4 GHz and 5 GHz frequency bands. Our analysis identifies strong correlations between in-game latency and specific Wi-Fi metrics for each frequency band. This study helps better understand the impact of Wi-Fi quality on in-game latency, and could guide Internet Service Providers and telecommunication operators on diagnostics and future network design.**

***Index Terms*—online gaming; Wi-Fi; network latency; network impairment**

I. Introduction

Online video games, and especially competitive online video games, have been on the rise for the past two decades. *League of Legends*, one of the most popular online video games had over 20 M daily players in 2019 [1]. As this highly interactive application connects distant players over the Internet, network quality degradations can significantly impact competitive performance and player satisfaction. Wi-Fi networks are widespread in domestic networks due to their convenience and flexibility. However, these unlicensed wireless networks are vulnerable to environmental factors. Interference from other wireless technologies or neighboring Wi-Fi networks, as well as signal weakening due to physical obstructions or distance, can cause performance deterioration, thus negatively affecting Quality of Experience (QoE) on different services.

QoE models have been standardized for some services, such as ITU-T P.1203 [2] for HTTP Adaptive Streaming (HAS) or ITU-T P.863 [3] for voice communications, using metrics from end-users' applications. However, network operators cannot easily access application-level metrics to enhance their diagnosis and recommend suitable solutions for their customers. Meanwhile, end-to-end (E2E) network latency has been recognized as a critical factor influencing the quality of online gaming experiences [4], [5]. Among the various sources of network delay, Wi-Fi connections often contribute the most to overall network latency [6]. In this paper, we investigate the impact of Wi-Fi quality degradations on the network latency measured in the online first-person shooter (FPS) *Counter-Strike: Global Offensive*. We conducted tests in Wi-Fi coverage and neighboring interference scenarios by changing signal strength between the player's station and Access Point (AP), and available airtime by generating traffic in a neighboring Wi-Fi network operating on the same channel, since users in dense areas are affected by nearby networks operating on the same channel. We then identified multiple Wi-Fi performance metrics correlated with in-game latency, and analyzed the 99^{th} percentile (P99) in-game latency across Received Signal Strength Indicator (RSSI) and available airtime ranges, with the aim of identifying network conditions that may lead to poor user experience, and to provide a base for further user experience studies.

The rest of the paper is organized as follows. Section II describes related literature. Section III presents our data collection method, experimental setup, and scenarios. Section IV presents our process for transforming data collected in the game and from the AP, as well as our findings from a correlation analysis between in-game latency and Wi-Fi metrics. Finally, Section V provides a conclusion and directions for future work.

II. Related Work

A clear understanding of the impact of network factors on QoE could help network operators better design and manage their network to meet users QoE requirements. Recent industry initiatives, such as the Telecom Infra Project's Metaverse Ready Network Project Group, have highlighted the importance of understanding the relationship between network-level Quality of Service (QoS) and end-user level QoE, publishing a framework [7] to guide this mapping.

Previous studies have examined how Wi-Fi quality affects QoE for services like web browsing, video streaming, and audio and video conferencing, identifying metrics such as RSSI and channel utilization as important factors [8], [9]. While Tan et al. [10] developed a QoE model making its prediction based

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on 5G network metrics for *Apex Legends* players, the impact of Wi-Fi performance metrics on QoE in online gaming remains underexplored. Studies have shown through subjective tests that network factors such as latency and jitter significantly affect player experience in online games. Claypool [11] found that latency has a greater impact on short or precise player actions in multiplayer games. In a study on a First-Person Shooter (FPS) game, Amin et al. [12] observed that high jitter, over 100 ms or 250 ms depending on the game server's network conditions, can reduce QoE to unacceptable levels. Recent work has shown that OFDMA in Wi-Fi 6 can reduce latency in multi-user scenarios, but interfering networks on the same channel can still cause high latency and packet loss, especially with smaller channel bandwidths and high network load [13]. Another study [14] found that channel utilization, the number of online devices and Signal-to-Noise Ratio (SNR) are informative indicators for Wi-Fi latency. However, in this study, Wi-Fi latency was estimated with pings, which can differ from real service latency due to the characteristics of ping traffic may not accurately reflect the latency experienced by real-time applications such as online games, due to the distinct characteristics of ping traffic. Several studies [15], [16], [17] have focused on the capability of Wi-Fi 3 to Wi-Fi 5 networks to support online games. Their results show that background traffic is the primary factor that can degrade online games performance, leading to increased latency and packet loss.

Building on these findings, we investigate how quality degradations in a Wi-Fi 6 (802.11ax) network, through signal attenuation and background traffic test scenarios, affect network latency in the FPS *Counter-Strike: Global Offensive (CS:GO)*. We focus on network latency as a key indicator of game performance, given its significant impact on FPS players' performance and satisfaction [4], [5]. Packet loss can impact player performance and QoE, however, previous work suggests its impact is limited in FPS featuring client-side prediction, such as CS:GO [18], so it will not be studied in this paper.

III. Experimental Setup

A. *Gaming server and metric collection*

The FPS game Counter-Strike: Global Offensive (CS:GO) is chosen in our study [19], as FPS games are considered among the most sensitive to latency and its variation. Thanks to an open source project [20] for CS:GO, we can access game process memory and collect various performance metrics during gameplay for our study of gaming quality. The collected gaming performance metrics include Round Trip Time (RTT) latency between the game client and server, uplink and downlink throughput, and packet loss percentage. Our developed plugin reads the performance metrics in the game process memory every 250 ms. Among all the metrics collected in the game, latency was prioritized in our study, as online gaming typically requires very little throughput (generally $\leq$ 500Kbps), which is well below the theoretical maximum data rates of Wi-Fi 6 (around 9.6 Gbps). To eliminate network fluctuations unrelated to the Wi-Fi network, a locally hosted game server is connected directly to the AP via Ethernet. The chosen game mode was team deathmatch, where the goal of the player is to score as many points as possible, usually by killing players of the opposite team. All tests were conducted on the Dust II map with 10 AI-controlled bots, using the same game mode, player count, and at least 50 minutes of gameplay was captured for each condition to ensure consistency across experiments. Additionally, we automated the gaming actions to repeat test sessions and create realistic gaming traffic in our lab. We developed a script that controls the local player, automatically aiming and shooting at visible enemies or walking to the nearest enemy if none are visible.

B. *Wi-Fi metrics collection from AP*

We use Orange Livebox 6 [21] and 7 [22] as Wi-Fi 6E (802.11ax) access points. These APs can operate on 2.4 GHz frequency band with 3x3 spatial streams, and on 5 GHz and 6 GHz frequency bands with 4x4 spatial streams. Experiments are run on two widely used bands: 2.4 GHz with a 20 MHz channel and 5 GHz with a 80 MHz channel, reflecting common real-world deployments.

Network performance metrics are collected from Wi-Fi chipset driver every 3 seconds. The collected metrics include:

1) Wireless link statistics: RSSI, physical rate, SNR, Modulation Coding Scheme (MCS), channel width, etc.
2) Transmission statistics: number of retransmissions, errors, downlink and uplink frames sent, etc.
3) Air channel utilization statistics: available airtime, time occupied by other Basic Service Set (BSS), signals that could not be decoded as Wi-Fi.
4) AP queue statistics: downlink queue depth, drops, retransmissions.

The game traffic was assigned default priority and was placed in the Best Effort (BE) queue of the AP. To be

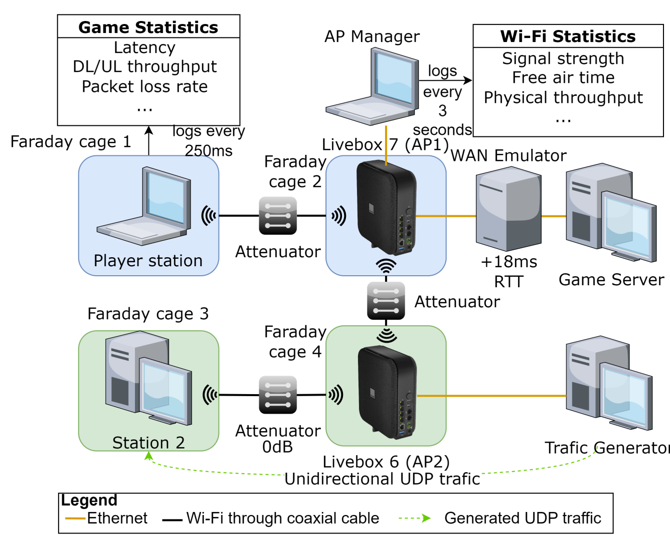


Fig. 1: Schematic of the testbed. Player Wi-Fi network in blue, neighboring interferer network in green.

representative of typical default deployments, we did not modify the AP queue configuration in this paper.

C. Testbed description

Figure 1 shows the setup. Experiments are performed in a controlled environment testbed with four Wi-Fi-suitable Faraday cages linked by coaxial cables carrying the analog Wi-Fi signal. Programmable attenuators [23] between cages allow us to control signal strength. Inside cages, Wi-Fi antennas [24] retransmit signals from coaxial cables or capture wireless signals within the cages.

Two Wi-Fi networks coexist to emulate neighbor interference. In the main network, a player laptop (HP ZBook Studio 16-inch G10) with an Intel AX211 Wi-Fi 6E card in cage 1 connects over Wi-Fi to AP1 in cage 2 and the game server is connected to AP1 via Ethernet. A Raspberry Pi 5 between AP1 and the server emulates a wide-area network (WAN), adding 9 ms one-way delay via Linux tc [25] (18 ms added to RTT) to match typical delay experienced in same-country online matches. In the second network, station 2 with an Intel AX210 Wi-Fi 6E card in cage 3 connects over Wi-Fi to AP2 in cage 4, a traffic generator wired to AP2 uses iPerf3 [26] to generate unidirectional User Datagram Protocol (UDP) traffic to station 2, creating a controlled level of interference with stable airtime occupation.

D. Test scenarios

Within our enclosed environment testbed, we emulated degraded Wi-Fi conditions due to coverage and neighbor interference by changing two key variables: signal strength (through attenuation) and available airtime. The range of RSSI and available airtime values across test scenarios are listed in Table I. The maximum RSSI value for 5 GHz band is limited due to attenuation caused by the transportation of the signal between cages without additional applied attenuation. The minimum RSSI value is obtained by applying attenuation until the station lost connection to the AP or the player was unable to join the server due to a high loading time exceeding the maximum value tolerated by the game.

To emulate different levels of airtime occupation for AP 1, we varied the throughput of UDP traffic generated in the second Wi-Fi network operating on the same channel. Since both APs are operating on the same channel, they share the same airtime resources. We used a finer granularity for available airtime values below 20% as we hypothesized that more degradations occur in this range.

Each gaming session lasts 10 minutes starting from the moment the player joins the game. For each Wi-Fi condition, the gaming session is repeated at least 5 times.

IV. Analysis and Results

A. Preliminary data transformation

Prior to analysis, all metrics related to dates, such as timestamps or connection durations, were removed from the dataset to prevent identification of test sessions during analysis, which could introduce bias into the results.

Game metrics were collected every 250 ms from the player station and every 3 seconds from AP 1. The 3-second interval for Wi-Fi metrics balances data precision and processing load on the AP, while the player station's superior processing capabilities allowed for finer sampling. Rather than interpolating the sparser Wi-Fi measurements to match the higher-frequency game data, which could introduce artificial patterns, game measurements were aggregated to match the 3-second intervals of the Wi-Fi data. For each 3-second window, the mean and maximum are computed for all game performance metrics. As the time frame of the window is relatively short, the mean provides an overall view, while the maximum captures any extreme values. Finally, aggregated game and AP data were merged into a single table for analysis.

B. Correlation analysis

Correlation between Wi-Fi performance metrics and mean in-game latency over the 3-second time windows was investigated to identify the most significant metrics related to in-game latency.

We used Spearman's rank correlation coefficient [27] to capture monotonic relationships. Table III presents Wi-Fi performance metrics with Spearman's correlation coefficient absolute value greater or equal to 0.5. Available airtime is strongly negatively correlated with latency in both frequency bands (2.4 GHz: -0.83, 5 GHz: -0.77), showing that lower available airtime is consistently associated with higher latency, regardless of the frequency band and channel width. When the channel is occupied, a station has to back off and wait until the channel is clear to transmit. This not only increases overall latency, but also introduces variability in transmission timing which might result in latency variations, negatively impacting player experience. In our test scenarios, the only concurrent traffic was generated on a neighboring Wi-Fi network. This is why the correlation coefficient of Radio.ReceiveOther is very close to the correlation coefficient of Radio.AvailableAirTime. Other strong correlations common across both bands include:

- Radio.PHY_Glitches (2.4 GHz: 0.60, 5 GHz: 0.61), suggesting that physical layer errors contribute to higher latency across the spectrum
- STA.RTSFail (2.4 GHz: 0.54, 5 GHz: 0.63). Request to Send (RTS) and Clear to Send (CTS) frames are used to reserve the channel before transmission. A high number of failed RTS frames could indicate that the channel is busy and that the probability of collision is high.
- Radio.NonDecodableSignal (2.4 GHz: 0.61, 5 GHz: 0.50). We did not intentionally generate non-Wi-Fi signals in our tests, but collisions could generate this type of signal.

In the 5 GHz band, STA.ULAggregationRatio, which represents the ratio of aggregated to non-aggregated frames received by the AP from a specific station, is positively correlated (0.51) with latency. This might be due to the buffering delays caused by aggregation.

Figure 2 shows the 99^{th} percentile (P99) latency as a function of RSSI and available airtime for both frequency

Frequency band	Channel bandwidth (MHz)	RSSI range (dBm)	Radio.AvailableAirTime range (%)
2.4 GHz	20 MHz	-45 dBm to -85 dBm (-5 dBm steps)	[2, 5, 7, 10, 15, 20, 30, 40, 50, 60, 70, 80, 90]
5 GHz	80 MHz	-60 dBm to -85 dBm (-5 dBm steps)	[3, 5, 7, 10, 15, 20, 30, 40, 50, 60, 70, 80, 90]

TABLE I: RSSI and available airtime configurations used in the test scenarios.

Performance metric	Description
Radio.NonDecodableSignal	Proportion of time the channel is occupied by signals that could not be decoded as Wi-Fi
Radio.AvailableAirTime	Proportion of time the channel is free
Radio.ReceiveOther	Proportion of time the channel is used by Wi-Fi communications from neighboring networks
STA.RTSFail	Number of Request to Send frames (RTS) sent by the AP without receiving a Clear to Send (CTS) frame from the station
Radio.PHY_Glitches	Number of OFDM or BPHY (802.11b PHY) glitches
STA.ULAggregationRatio	Ratio of aggregated frames to non-aggregated frames received by the AP from a specific station

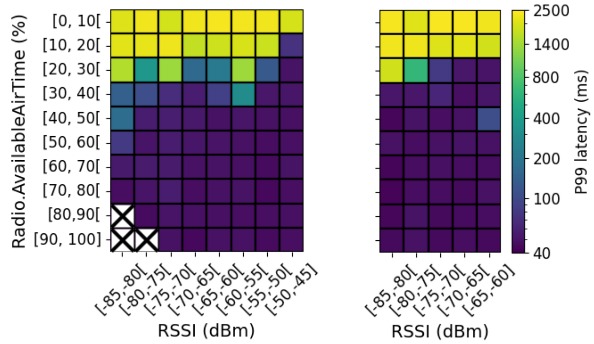
TABLE II: Description of Wi-Fi performance metrics.

Band	Performance Metric	Correlation coefficient
2.4 GHz	Radio.AvailableAirTime	-0.83
	Radio.ReceiveOther	0.80
	Radio.NonDecodableSignal	0.61
	Radio.PHY_Glitches	0.60
	STA.RTSFail	0.54
5 GHz	Radio.AvailableAirTime	-0.77
	Radio.ReceiveOther	0.76
	STA.RTSFail	0.63
	Radio.PHY_Glitches	0.61
	STA.ULAggregationRatio	0.51
	Radio.NonDecodableSignal	0.50

TABLE III: Spearman rank correlation coefficients for Wi-Fi performance metrics strongly correlated to in-game latency

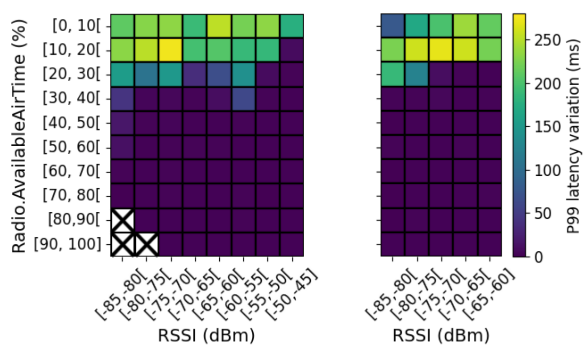
bands. In online gaming, even occasional high-latency events can negatively impact user experience. The P99 latency allows us to quantify these high-latency events, even if they are rare. Cells for high available airtime ([80-100]%) with low RSSI (below -80 dBm) on the 2.4 GHz grid are crossed out due to an insufficient number of samples. Low RSSI leads to lower physical throughput, causing the game traffic to use over 20% of the total airtime. When the amount of available airtime is below 20%, the P99 latency increases to unacceptable levels, over 1400 ms. Individually, RSSI does not seem to impact latency as long as the amount of available airtime is sufficient. However, the available airtime threshold at which latency begins to sharply increase depends on signal strength: as RSSI weakens, latency problems emerge at progressively higher available airtime values. The 2.4 GHz configuration is more sensitive as latency begins to increase at higher available airtime values compared to the 5 GHz configuration.

To estimate latency variation, for each 3-second window we compute $\Delta_i = |L_i - L_{i-1}|$ over the latency measurements L_i collected every 250 ms, and take the mean Δ_i within the window. This is similar to the Inter-Packet Delay Variation (IPDV) metric in RFC 5481 [28], except that we use in-game RTT instead of one-way per-packet delay due to measurement constraints. Figure 3 shows the P99 of this window-mean latency variation as a function of RSSI and available airtime for both frequency bands. High latency variation is observed when available airtime is below 20%, consistently across both bands. As RSSI weakens, high variation appears at progressively higher airtime values. In very degraded conditions (low RSSI and available airtime), we sometimes observe less latency variation because latency becomes steadily high, which still degrades player experience.



(a) 2.4GHz (b) 5GHz

Fig. 2: P99 in-game latency as a function of RSSI and available airtime.



(a) 2.4GHz (b) 5GHz

Fig. 3: P99 in-game latency variation as a function of RSSI and available airtime.

V. Conclusion and future work

Our work helps to better understand how Wi-Fi networks impact online gaming experience by reproducing harsh Wi-Fi conditions that mimic real-life scenarios where performance degradations occur due to signal coverage issues or neighboring interference. Our correlation analysis identified several Wi-Fi metrics that are strongly correlated with in-game latency. Airtime related metrics are the most strongly correlated to in-game latency, and other metrics such as physical layer errors count and unanswered RTS frames are also informative. Our analysis could be leveraged to develop models that predict in-game network latency only based on Wi-Fi performance metrics. However, an enclosed environment with Faraday cages does not fully replicate real-world wireless environments where phenomena such as multipath effects are present. To generalize our findings and further explore the relationship between Wi-Fi and game performance, future work should include experiments in free-space environments and all other possible scenarios (internal BSS congestion, different Multiple Input, Multiple Output (MIMO) composition, different channel configurations etc.).

Despite limitations mentioned above, our results offer valuable insights into how Wi-Fi affects the performance of online games and other latency-sensitive applications, and highlight opportunities for future research on the relationship between Wi-Fi network QoS and application performance. Our future work will include methods on the gateway to improve online gaming experience using recent Wi-Fi features such as Orthogonal Frequency-Division Multiple Access (OFDMA) as well as advanced QoS configurations and Active Queue Management (AQM).

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