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A Survey of IEEE 802.11ax WLAN Temporal Duty Cycle for the Assessment of RF Electromagnetic Exposure

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Abstract: The increasing deployment of IEEE 802.11ax (Wi-Fi 6) networks necessitates an accurate assessment of radiofrequency electromagnetic field (RF-EMF) exposure under realistic usage scenarios. This study investigates the duty cycle (DC) and corresponding exposure levels of Wi-Fi 6 in controlled laboratory conditions, focusing on bandwidth variations, multi-user scenarios, and application types. DC measurements reveal significant variability across internet services, with FTP upload exhibiting the highest mean DC (94.3%) under 20 MHz bandwidth, while YouTube 4K video streaming showed bursts with a maximum DC of 89.2%. Under poor radio conditions, DC increased by up to 5× for certain applications, emphasizing the influence of degraded signal-to-noise ratio (SNR) on retransmissions and modulation. Weighted exposure results indicate a reduction in average electric-field strength by up to 10× when incorporating DC, with maximum weighted exposure at 4.2 V/m (6.9% of ICNIRP limits) during multi-user scenarios. These findings highlight the critical role of realistic DC assessments in refining exposure evaluations, ensuring regulatory compliance, and advancing the understanding of Wi-Fi 6's EMF exposure implications.

Keywords: Wi-Fi 6; EMF exposure; duty cycle; realistic scenarios; regulatory compliance

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1. Introduction

Wireless local-area networks (WLANs) have permeated nearly every aspect of modern life. Although alternative standards such as Bluetooth and ZigBee can also be used to establish WLANs, the most widely recognized and utilized standard is IEEE 802.11, commonly known as Wi-Fi. The IEEE 802.11 standard defines Medium Access Control (MAC) and Physical (PHY) layer protocols for wireless communication and channel management. Since its introduction in 1997, IEEE 802.11 has evolved through multiple amendments, including 802.11b, 802.11n, 802.11ac [1], and the latest 802.11ax [2] and 802.11be. Wi-Fi 6 (802.11ax), ratified in 2019, enhances network efficiency, throughput, and user experience in dense environments.

By 2023, 3.8 billion users rely on Wi-Fi, with household devices growing 10–20% annually. By 2025, households are expected to own 20–30 Wi-Fi-connected devices, including smartphones, computers, and IoT devices [3]. The growth of Wi-Fi networks raises concerns about RF-EMF exposure [4,5]. Accurate assessment is needed to ensure compliance with ICNIRP [6] and IEEE standards [7].

1.1. Duty Cycle

Nevertheless, Wi-Fi signals are transmitted in bursts with high Crest Factor (CF), making real-world exposure assessment challenging. Conventional methods use spectrum analyzers (SA) in max-hold mode with Root Mean Square (RMS) detectors to measure peak power density (S_{max}) or field strength (E_{max}). These methods capture worst-case exposure but fail to reflect typical Wi-Fi transmission. Consequently, such methods tend to overestimate EMF exposure levels and are unsuitable for informing appropriate safety policies. To address this, duty cycle (DC) [8] is introduced as a calibration factor, defined as the ratio of active signal duration (T_{active}) to total observation time (T_{total}) [8,9]:

$$DC = \frac{T_{active}}{T_{total}} \times 100\ (\%)\,. \tag{1}$$

This time -domain metric can be measured using the zero-span mode of the SA [8]. The average RMS electric-field strength (E-field) E_{avg} of the Wi-Fi signal can then be calculated as the product of E_{max} and the square root of DC [8,9]:

$$E_{avg} = \sqrt{DC} \cdot E_{max}\ (\mathrm{V\,m^{-1}})\,. \tag{2}$$

This approach integrates peak transmission with active duration, yielding a more realistic EMF exposure estimate. Several studies have examined Wi-Fi DC and its impact on EMF exposure. Verloock et al. [8] investigated IEEE 802.11b/g signals, focusing on the optimization of SA parameter settings for DC and exposure measurement, including resolution bandwidth (RBW) and sweep time (SWT). The optimal SA parameters were used by them to measure Wi-Fi exposure levels and DC in a laboratory context, and the results after DC weighting were verified for compliance with the guidelines. Khalid et al. [10] measured the DC of Wi-Fi (802.11a/b/g/n) access points (APs) and laptops in six schools, finding DC ranges of 0.02–0.91% and 1.0–11.7%, respectively, which were combined with numerical dosimetry results to evaluate compliance. The authors of [11] monitored the 24 h DC variability in schools and residences, while Joseph et al. [12] conducted a comprehensive study across 178 locations, including rural, residential, urban, suburban, office, and industrial settings. They also calculated the theoretical maximum Wi-Fi (802.11a/g) DC under Carrier-Sense Multiple Access/Collision Avoidance (CSMA/CA) mode [9], and the authors measured the DC for different network applications, revealing that different network applications significantly impact the DC, e.g., file transfer had a DC of around 60%, while Skype voice calls with low traffic exhibited a DC of only 1%. They concluded that assuming a DC of 100% could overestimate Wi-Fi exposure by up to eight-fold, highlighting the crucial role of DC in accurate EMF exposure assessments. Similarly, Yang et al. [13] analyzed the theoretical maximum DC during busy periods, finding values ranging from 49.55% at 54 Mbps to 98.10% at 1 Mbps. Koprivica et al. [14] extended Joseph et al.'s work by measuring DC across different radio conditions (good, moderate, and bad) for various internet services on 802.11a/g networks, reporting a DC range of 0.21–74%. Together, these studies highlight the variability of DC and its critical importance in accurately estimating realistic Wi-Fi exposure.

Previous studies, covering theoretical, laboratory, and real-world WLAN DC measurements, highlight the importance of DC in assessing Wi-Fi network exposure. However, as Wi-Fi 6 expands and Wi-Fi 7 emerges, previous studies become less relevant. While some studies have investigated Wi-Fi 5 and 6 exposure levels, such as [15,16], which evaluated Wi-Fi 5 exposure at user devices and analyzed the impact of modulation schemes on exposure, and Chountala et al. [17], which examined Wi-Fi 6 exposure from smartphones and APs, while the authors showed that DC and power density are proportional to data rate, they did not measure DC in realistic scenarios. Fernández et al. [18] investigated the temporal and spatial variability of Wi-Fi exposure in real-world scenarios (inside a university), demonstrating significant fluctuations in exposure levels depending on environmental factors. To the best of the authors' knowledge, no existing studies have specifically investigated the DC of real-world Wi-Fi 6 network services.

1.2. Wi-Fi 6 and Objectives

Wi-Fi 6 introduces several new features, as summarized in Table 1, which compares the features of Wi-Fi 6 to Wi-Fi 5, such as orthogonal frequency-division multiple access (OFDMA), multi-user multiple-input–multiple-output (MU-MIMO), and basic-service-set (BSS) coloring, to enhance network capacity, reduce latency, and improve spectral efficiency. For multi-user support, Wi-Fi 6 leverages OFDMA, allowing for a Wi-Fi channel's subcarriers to be packaged into multiple resource units (RUs) that can be simultaneously allocated to different users, reducing collisions and competition and improving efficiency. In contrast, for OFDM, all the subcarriers in a channel can only be distributed to a single user. Wi-Fi 6 also delivers higher throughput by introducing several key improvements. First, modulation has been upgraded from 256-Quadrature Amplitude Modulation (QAM) in Wi-Fi 5 to 1024-QAM, achieving a 1.25$\times$ increase in peak data rates. Second, the number of subcarriers has increased (e.g., 160 MHz bandwidth now provides 242 usable subcarriers), and the longer symbol duration enhances time-domain efficiency and multipath robustness. Finally, while Wi-Fi 5 supports up to four spatial streams (SS) for downlink MIMO (DL MIMO), Wi-Fi 6 expands this capability to eight SS for both uplink and downlink, significantly boosting bidirectional throughput. Since the data rate is proportional to the number of SS, Wi-Fi 6 achieves a maximum throughput of up to 9.6 Gbps, marking a substantial leap compared to legacy Wi-Fi technologies. These advancements underline the fundamental differences in the time-domain distribution of Wi-Fi 6 signals compared to previous amendments, emphasizing the need for further investigation in this area. This study fills this gap by analyzing Wi-Fi 6 DC under controlled laboratory conditions. The objectives are:

1. Determining the DC of Wi-Fi 6 networks for seven commonly used internet applications under different bandwidths and different radio-quality conditions in single-user device (UD) scenarios;
2. Investigating the variations in DC in multi-UD scenarios with up to four UDs;
3. Examining the EMF exposure levels of Wi-Fi 6 devices under various configurations (e.g., bandwidth, location, and device count) and weighting with DC results to accurately evaluate compliance with international exposure guidelines.

Table 1. Wi-Fi 6 innovations compared to Wi-Fi 5.

Wi-Fi 6 [2]	Wi-Fi 5 [1]	Remarks [19–21]
OFDMA [1]	OFDM [2]	Higher throughput, high spectral efficiency
Longer PHY symbol	-	High time-domain efficiency, multipath robustness
1024-QAM [3]	256-QAM	25% data rate improvement
MU-MIMO [4]	Donwlink MIMO	Up to 8$\times$ increase in uplink throughput
Spatial reuse	-	Improved network capacity and efficiency

[1] OFDMA = orthogonal frequency-division multiple access; [2] OFDM = orthogonal frequency-division multiplex; [3] QAM = Quadrature Amplitude Modulation; [4] MU-MIMO = multi-user multiple-input–multiple-output.

The paper is organized as follows: Section 2 presents the methodology for assessing DC, the equipment with its configuration, and the experimental setup; Section 3 demonstrates and discusses the results of the measurements; Section 4 compares the results of this study with the literature to put this study into a broader context and points out the limitations of this study; finally, Section 5 summarises the results of this study and proposes guidelines for future work.

2. Materials and Methods

2.1. Experimental Setup

To comprehensively investigate the DC and EMF exposure levels of Wi-Fi 6 networks under varying scenarios, a series of controlled experiments were conducted in a laboratory environment located in the second basement of a building with minimal interference.

Network Configuration

The WLAN AP used in this study is an Asus RT AX88U wireless router, which supports Wi-Fi 6, while remaining compatible with legacy Wi-Fi. It operates on dual bands (2.4 GHz and 5 GHz) with a 4 SS MIMO antenna system. This AP supports a maximum bandwidth of 160 MHz, in addition to legacy bandwidths of 20 MHz, 40 MHz, and 80 MHz, and allows for the configuration of various features through its browser-based graphical user interface (GUI). The detailed AP configuration settings are listed in Table 2. To avoid interference and reduce congestion from other devices which operate at 2.4 GHz, the AP was configured to operate exclusively on the 5 GHz band in this study. It was set to 802.11ax mode only, enabling all Wi-Fi 6 features, including uplink/downlink OFDMA, MIMO, and beamforming. The highest modulation and coding scheme (MCS) was set up to 11, corresponding to 1024-QAM with a 5/6 code rate. These configurations were designed to fully utilize the advanced capabilities of Wi-Fi 6, ensuring optimal performance. Additionally, to evaluate the worst-case exposure scenario, the AP's dynamic transmission (TX) power was set to its maximum, i.e., an effective isotropic radiated power (EIRP) of 23 dBm.

Table 2. Access point configuration.

AP Configuration	
Band	5 GHz
Channel	36, 46, 58, or 114
Center Frequency	5.18, 5.23, 5.29, or 5.57 GHz
Bandwidth	20, 40, 80, or 160 MHz
Wireless Mode	802.11ax only
Waveform	DL/UL OFDMA + MU-MIMO
Beamforming	Enabled
Max MCS [1]	11 (1024-QAM, 5/6 code rate)
Max TX Power	23 dBm

[1] MCS = modulation and coding scheme.

The AP was connected to a maximum data rate of 1 Gbps Ethernet network in the laboratory and mounted on a stable platform at a fixed height of 1 m, simulating a typical real-world deployment scenario. This study utilized four commonly used consumer electronic devices as UD, including a laptop, a smartphone, a tablet, and a USB Wi-Fi adapter (UWiA). The detailed specifications of these devices are listed in Table 3. Notably, when the UWiA was used, the internal wireless adapter of the laptop hosting the UWiA was disabled to ensure accurate and isolated measurements for this configuration.

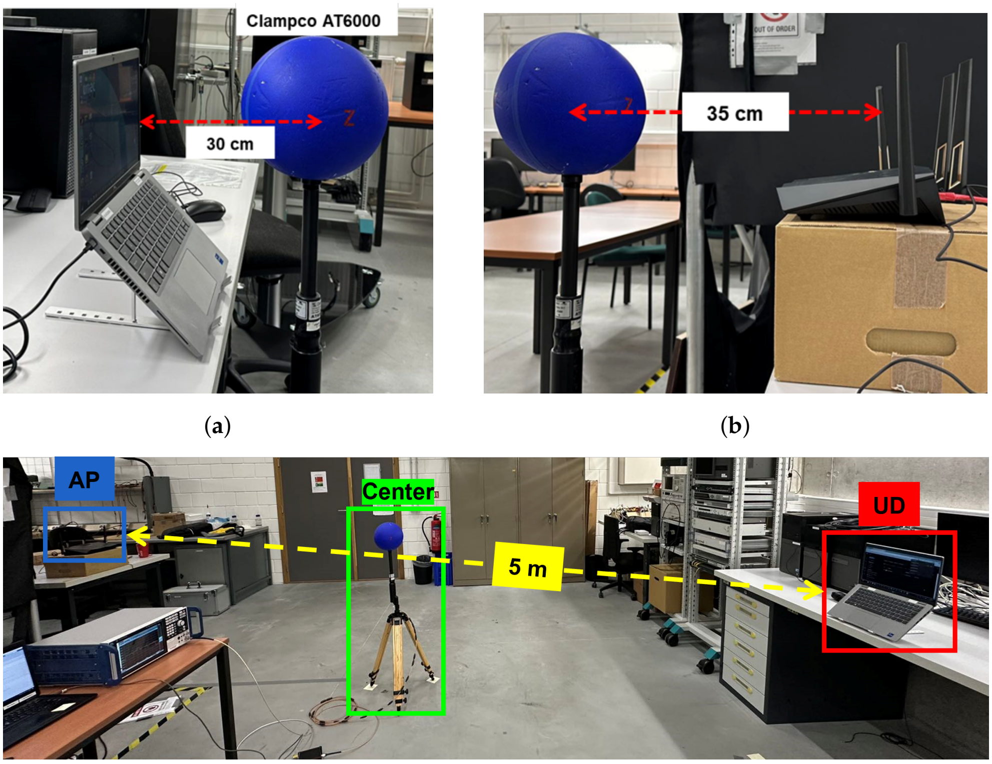
Table 3. User devices used in this work and their models.

User Device	Model
Mobile phone	iPhone 14 Pro
Tablet	Samsung Galaxy Tab S8+
Laptop	Dell Latitude 5430
USB Wi-Fi adapter	Asus USB-AX56 Dual-band

2.2. Duty Cycle Measurement

2.2.1. Equipment and Configurations

Figure 1 shows the setups for the Wi-Fi 6 exposure measurements. The DC was measured using a Rohde & Schwarz FSV3030 SA connected with a Clampco AT6000 three-axis isotropic antenna (frequency range of 400 MHz to 6 GHz, with a maximum accepted electric field strength of 300 V/m). The antenna's axis selection was achieved via an internal electronic switch controlled by the ATSA04 axis controller through a coaxial cable. The measurement system has an uncertainty of ±3 dB. The SA parameter settings were configured following the recommendations of [8] for Wi-Fi DC time-domain measurements, and the detailed parameters are listed in Table 4. The zero-span mode was used to record Wi-Fi 6 time-domain signals in spectrogram form. Since DC measurement focuses solely on the temporal distribution of signals, only the power density along a single axis was recorded.



(**a**) (**b**) (**c**)

Figure 1. The measurement setup and layout for the single-user scenario. (**a**) Three-axis antenna was placed at the UD side. (**b**) Three-axis antenna was placed at the AP side. (**c**) The overall layout of the measurement setup, and the three-axis antenna was placed at the center.

Table 4. The configuration of the spectrum analyser in time-domain and frequency-domain modes.

Parameter [1]	Time Domain	Frequency Domain
CF [GHz]	5.18, 5.23, 5.29, or 5.57	5.18, 5.23, 5.29, or 5.57
Span [MHz]	0	40, 60, 100, or 200
RBW [MHz]	20	1
VBW [MHz]	40	10
SWT [ms]	10	6.2
Points	2401	455
Detector	RMS	RMS
Trace Mode	Clear/Write	Max-hold

[1] CF = center frequency; RBW = resolution bandwidth; VBW = video bandwidth; SWT = sweep time.

2.2.2. Single-User DC Measurement

In the single-user scenario, seven commonly used internet activities were selected based on their distinct traffic patterns, covering streaming, communication, file transfer, gaming, and browsing:

1. YouTube video streaming: A single video was streamed at two resolutions, 2160p (i.e., so-called 4K video, 4096×2160 pixels) and 1080p (1920×1080 pixels);
2. WhatsApp communication: Both voice and video calls were conducted;
3. File Transfer Protocol (FTP): File download (DL) and upload (UL) were tested;
4. Online gaming: Overwatch 2 (OW2) was involved;
5. Web browsing: The Edge browser was used to randomly access MSN news (www.msn.com);
6. Audio streaming: Spotify was used for music streaming;
7. Live streaming: Twitch was used to stream video content at 1080p resolution and 30 frames per second (fps).

To measure DC during these activities, a laptop of Dell Latitude 5430 was used as the UD, featuring an Intel Wi-Fi 6E AX210 WLAN adapter module with an integrated 2×2 MIMO antenna embedded in the screen bezel. The experimental setup is shown in Figure 1, where the laptop maintained a line-of-sight (LOS) distance of 5 m from the AP with no obstructions to ensure excellent channel conditions. The three-axis isotropic antenna was positioned at the AP side, with the antenna's center located 35 cm from the AP antenna to satisfy far-field conditions (the diameter of the three-axis antenna radome is 20 cm), as shown in Figure 1b. A section of the Wi-Fi 6 signal recorded in the preliminary experiments with zero-span mode is shown in Figure 2, where three distinct signals can be identified by power density levels: the AP signal, the UD signal, and the noise. For DC estimation using Equation (1), Wi-Fi signals were defined as any signal exceeding the noise floor (-76 dBm) by 5 dB. The active time (T_{active}) was defined as the duration for which the signal exceeded this threshold. Signals stronger than -60 dBm were attributed to the AP, while remaining signals above the threshold were attributed to the UD. This allowed for the calculation of DC values for both AP and UD transmissions.

To investigate the impact of varying bandwidths on Wi-Fi 6 DC, the AP bandwidth was sequentially set to 20 MHz, 40 MHz, 80 MHz, and 160 MHz for each internet activity. The corresponding channels and their center frequencies are detailed in Tables 2 and 4, and the SA's center frequency was adjusted accordingly. Each measurement session lasted at least 6 min, consistent with the ICNIRP guidelines for estimating time-averaged exposure levels [6]. During each session, the network applications remained continuously active to ensure representative results. For data post-processing, a single DC sample was calculated for each second of recorded signal, nevertheless, for combining with the exposure values obtained from the max-hold approach to check ICNIRP limits compliance, we advise to use the mean DC during 6 min given in the results, which provides a realistic reflection of the average exposure level in the time period specified by the ICNIRP guidelines. Please bear in mind that the DC measurements in each of the other scenarios presented below were taken over 6 min and post-processed in the same way as the data unless explicitly indicated.

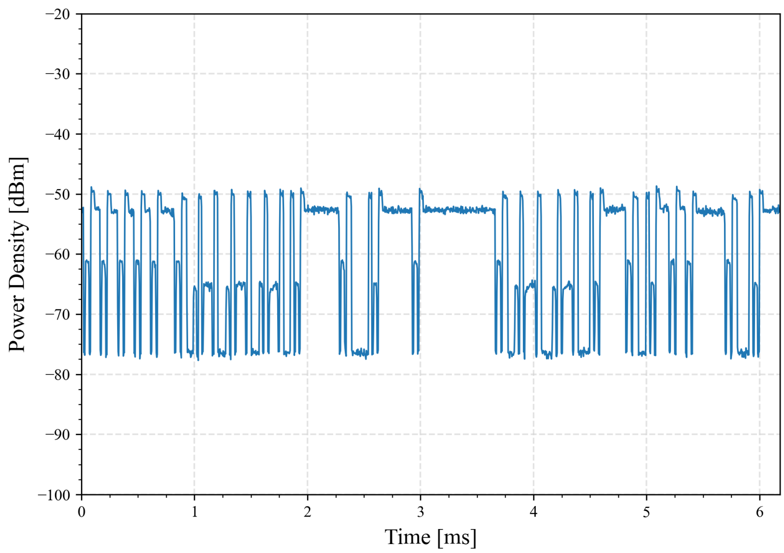


Figure 2. Wi-Fi 6 signal recorded using the SA's zero-span mode.

2.2.3. Low Radio Quality Conditions

To evaluate the DC under poor wireless communication conditions, where poor radio conditions are defined as a signal-to-noise ratio (SNR) of less than 17.5 dB, while good radio conditions constitute SNR > 44 dB [14], the same UD (laptop) used in the single-user scenario measurements was moved to a separate room with significant physical obstructions to the AP. The pyramidal EMF absorber wall was placed in front of the UD, as shown in Figure 3, to simulate extreme signal degradation. While the position of the AP and the three-axis antenna was maintained and the channel of the AP was configured to channel 58 with the bandwidth fixed at 80 MHz; for the rest of the experimental setups, all of them, as well as the Internet activities, were consistent with the measurements of the single-user scenarios—the DC was measured for each of these internet activities.

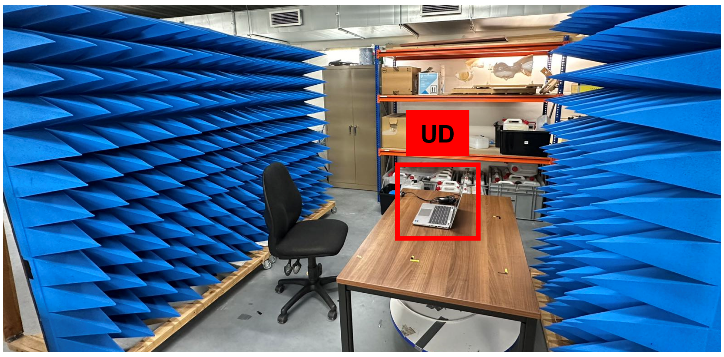


Figure 3. The setup for Wi-Fi 6 DC measurements under poor radio conditions, where UD is a laptop.

2.2.4. Multi-User DC Measurement

One of the most significant advancements in Wi-Fi 6 compared to previous generations is the enhanced multi-user support enabled by technologies such as OFDMA and MU-MIMO. Therefore, it is essential to investigate the DC under conditions where multiple users are accessing the network simultaneously. To this end, we followed the experimental setup of the single-user scenario, but the UD was increased to four laptops of the same model placed side by side, while the layout of the other measurement equipment and the AP remained unchanged (as shown in Figure 1b). The AP was fixed on channel 58 with an 80 MHz bandwidth. In order to simplify the complexity of the experiment and to highlight the focus of the study, we selected four representative internet activities: 1. YouTube 4K video streaming; 2. WhatsApp video calling; 3. FTP file downloading; 4. Web browsing of news websites. Initially, the four UDs were connected to the AP sequentially. Since measurements with only one UD would replicate the single-user scenario, we began our measurements with two UDs connected simultaneously, then incrementally increased the number of UDs to three and finally four. During each measurement session, all connected UDs used the same internet application. Thus, we repeated the measurement process four times, each time using a different application from the list above. Finally, we measured the DC when all four UDs were connected to the AP, each engaging in a different internet activity simultaneously. This allowed us to assess the DC under a mixed-application, multi-user scenario.

2.3. EMF Exposure Assessment

The EMF exposure assessment for Wi-Fi 6 in this study was conducted for both single-user and multi-user scenarios, utilizing the same measurement equipment as described for the DC evaluations. The parameters used for SA measurements in the frequency-domain mode are listed in Table 4. The accuracy of SA measurements is influenced by parameter settings. Notably, because Wi-Fi 6 employs OFDMA with a symbol duration of 12.8 μs and a minimum guard interval (GI) of 0.8 μs, the SA's SWT was set to (12.8 + 0.8 μs) $\times$ 455 = 6.2 ms, following recommendations by [8], to ensure no underestimation of exposure levels.

For single-user scenarios, the layout of the UD and AP remained consistent with the configuration detailed in Section 2.2.2 (as shown in Figure 1). The three-axis antenna was placed at three locations:

1. At the AP: The three-axis antenna's center was placed 35 cm from the AP antennas (as illustrated in Figure 1b);
2. At the UD: The three-axis antenna's center was placed 30 cm from the UD's screen or antennas (as illustrated in Figure 1a);
3. At the center: The three-axis antenna was positioned equidistantly between the AP and UD in the LOS path, as shown in Figure 1c.

Exposure levels during file transfers at AP bandwidths of 20 MHz, 40 MHz, 80 MHz, and 160 MHz were measured sequentially at each measurement position, as [9] reported that maximum exposure occurs during file transfers. Then we investigated the exposure levels for different UDs, for which the bandwidth of the AP was fixed at 80 MHz. The original UD (laptop) was replaced with a mobile phone, tablet, and UWiA respectively, with the distance between the center of the three-axis antenna and the screens or antennas of these devices remaining at 30 cm, the exposure levels of these UDs were evaluated.

For the multi-user scenario, Figure 4 shows the layout of each UD and the AP in the laboratory, with the AP set to channel 58 with a bandwidth of 80 MHz. The exposure levels at all UDs, at the center marked by the black squares in Figure 4, and at the AP were assessed. The network application used during the measurements was still file transfer.

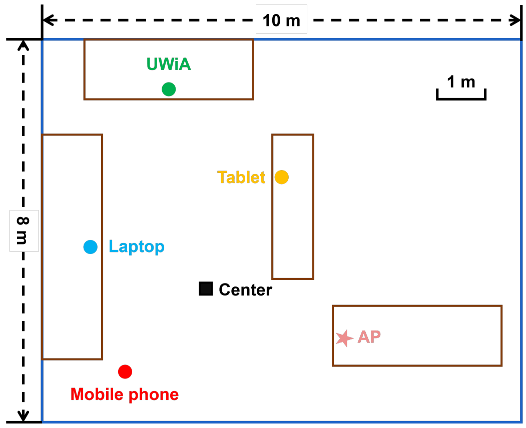


Figure 4. Layout of UDs (including a laptop, a mobile phone, a tablet and a laptop with UWiA installed), measurement points (center) and the AP for assessing the exposure level of Wi-Fi 6 in a multi-user scenario (The brown boxes show tables where devices were placed).

3. Results

3.1. Difference in DC for Internet Activities

We remind the reader again that in this work we calculated a DC sample using Wi-Fi 6 signals recorded per second, taking a total of 6 min of signal duration, which is the time specified by the ICNIRP guidelines for estimating the average exposure level. Figure 5 presents the DC versus time for four representative internet activities conducted on an 80 MHz Wi-Fi 6 network: YouTube 4K video streaming, WhatsApp video calling, FTP file downloading, and web browsing. The results demonstrate that Wi-Fi 6 DC is highly dependent on the type of internet service, as different applications exhibit significant variations in traffic demands and transmission patterns.

- YouTube 4K video streaming follows a cyclic behavior characterized by periods of preloading (buffering) and silence. As shown in Figure 5, DC peaks during buffering, reaching approximately 40%, followed by periods of minimal activity with low DC as only control frames are transmitted;
- FTP file downloading, as a high-bandwidth, continuous transmission application, exhibits the stable and highest DC, with an average of approximately 57%;
- WhatsApp video calling: This real-time interactive application requires continuous up and downlink traffic. However, since the data are transmitted in small packets (i.e., low data rate), it maintains a relatively low yet stable DC of around 6%;
- Web browsing, on the other hand, alternates between AP active and idle due to the intermittent nature of the user's activity, and DC exhibits burstiness with a CF of 12.9 dB, reflecting the sporadic nature of the traffic.

Table 5 details the statistics of DCs recorded at 20 MHz and 80 MHz for different network applications with mean, median, 95th percentile (P_{95}), maximum values (Max), and standard deviation (SD). To intuitively present the data distribution, the DC box plots at 4 bandwidths are shown in Figure 6. We remark that at 20 MHz bandwidth, high-throughput applications such as FTP upload demonstrate the highest mean DC, reaching 94.3%, which is attributed to its continuous and stable data transmission demands. A closer examination reveals that FTP upload consistently exhibits higher DC values than download across all bandwidths, primarily due to the fact that upload traffic is more concentrated, with data being sent directly from the UD to the AP and the acknowledge (ACK) frames taking up less time; in contrast, download traffic needs to switch directions frequently, and the AP needs to wait for the ACK response and buffer assembly of the data, which results in longer waiting time between frames, thus resulting in a lower DC for downloads.

Pre-buffered internet services (e.g., video and audio stream) show positively skewed DC distributions, which are manifested by short bursts of high-intensity data, as shown in Figure 5. Buffering behavior is the main contributor to the overall DC; hence, the maximum value better characterizes the impact of network bandwidth on the DC compared to the mean value for such applications. For YouTube 4K and 1080p video streaming, the mean DC values were 5.3% and 1.2%, respectively, while the maximum values reached 89.2% and 15.4%. Applications with continuous up and downlink traffic, such as WhatsApp video calls, Twitch streaming, and online gaming, showed varying mean DC values depending on their traffic demands: 5.6%, 7.8%, and 2.8%, respectively. In contrast, web browsing demonstrated bursty traffic patterns due to user-triggered activity, resulting in a positively skewed DC distribution with an average of 1.6% and a P_{95} of 6.1%.

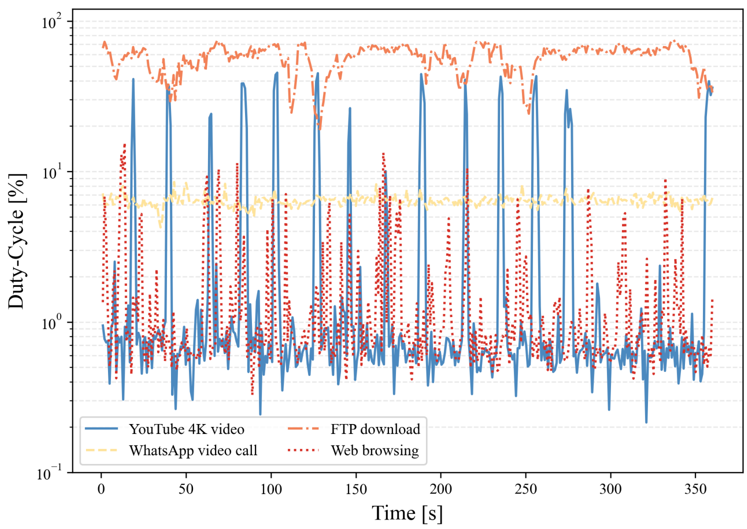
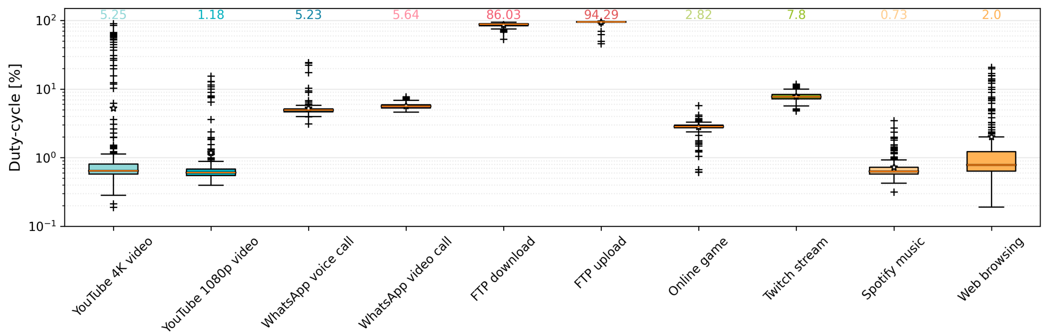


Figure 5. Wi-Fi DC versus time for different activities under 80 MHz bandwidth (YouTube 4K video, FTP download, WhatsApp video call, and web browsing).

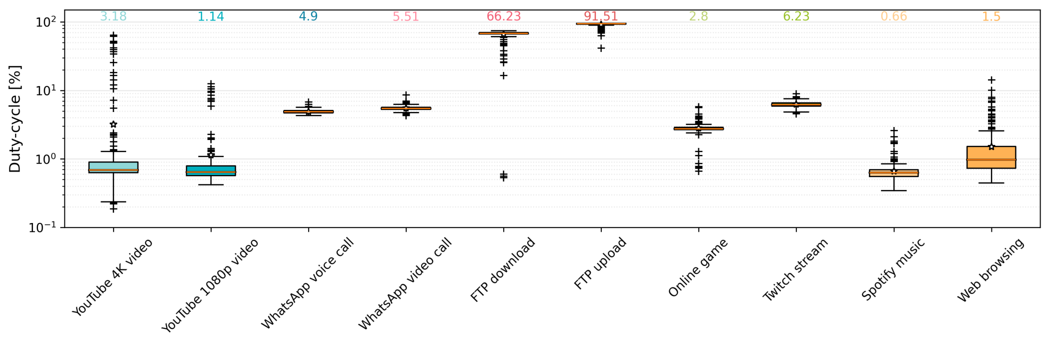
Table 5. Measured mean, median, 95th percentile (P_{95}), maximum (Max) duty cycle, and standard deviation (SD) for different activities under bandwidth (BW) of 80 MHz and 20 MHz.

Applicaiton	BW [MHz]	Mean [%]	Median [%]	P_{95} [%]	Max [%]	SD [%]
YouTube 4K video	20	5.25	0.64	45.29	89.19	14.97
YouTube 1080p video	20	1.18	0.61	5.01	15.42	2.26
WhatsApp voice call	20	5.23	4.91	5.88	24.24	2.24
WhatsApp video call	20	5.64	5.61	6.48	7.69	0.53
FTP download	20	86.03	87.53	92.42	94.20	5.55
FTP upload	20	94.29	95.10	95.68	96.17	5.27
Online game	20	2.82	2.84	3.43	5.72	0.51
Twitch stream	20	7.80	7.72	9.56	11.81	1.00
Spotify audio	20	0.73	0.63	1.37	3.44	0.35
Web browsing	20	2.00	0.78	10.22	20.65	3.45
YouTube 4K video	80	4.32	0.68	33.84	44.74	10.04
YouTube 1080p video	80	1.27	0.64	5.84	13.31	2.10
WhatsApp voice call	80	6.13	6.10	6.80	8.14	0.45
WhatsApp video call	80	6.39	6.38	7.06	8.81	0.49
FTP download	80	56.99	60.29	69.37	73.38	11.23
FTP upload	80	74.40	74.98	81.45	85.94	5.78
Online game	80	2.70	2.65	3.30	4.24	0.35
Twitch stream	80	5.47	5.47	6.46	7.47	0.63
Spotify audio	80	0.81	0.62	1.81	11.47	0.97
Web browsing	80	1.60	0.81	6.12	11.01	1.90

A declining trend in DC was observed as bandwidth increased, reflecting improvements in data transmission efficiency: at 40 MHz bandwidth, the DC for FTP downloads decreased to 66.2%, while the maximum DC for 4K video streaming and video calls dropped to 64% and 5.5%, respectively; for 80 MHz bandwidth, the DC further reduced for certain applications, with FTP download dropping to 57%, the maximum DC for 4K video streaming to 44.7%, and live streaming (Twitch) to 5.5%. However, applications like voice and video calls showed little to no DC reduction, and in some cases, DC even increased. This can be attributed to higher data demands induced by increased transmission rates, as network services dynamically adjusted parameters like video resolution and frame rate to maintain quality of service (QoS), consequently raising DC. At the highest bandwidth of 160 MHz, the DC for file transfers did not significantly decrease. This is because the WLAN throughput reached a bottleneck, limited by the wired Ethernet connection to the AP. Notably, under 40 MHz bandwidth, the theoretical maximum data rate for Wi-Fi 6 with four SS is 1147.2 Mbps [22], already exceeding the 1 Gbps Ethernet link used in this study. These DC results can be used as a reference to accurately assess the realistic EMF exposure under known Internet activities, e.g., the exposure of children in multimedia classrooms with live online courses, multi-person online meetings in a meeting room, etc.

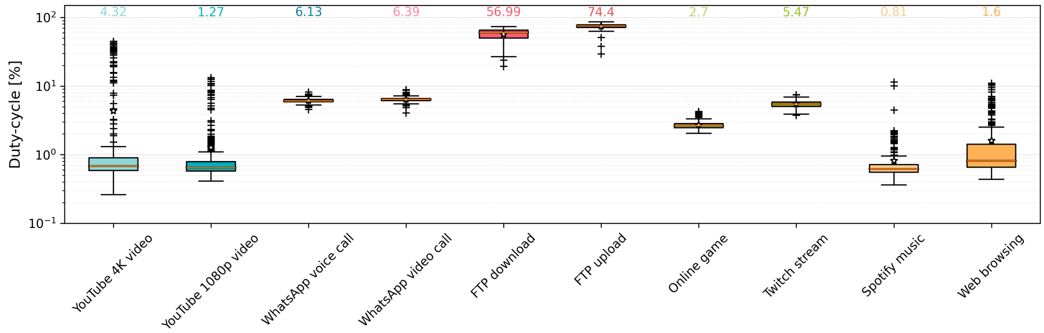


(**a**)

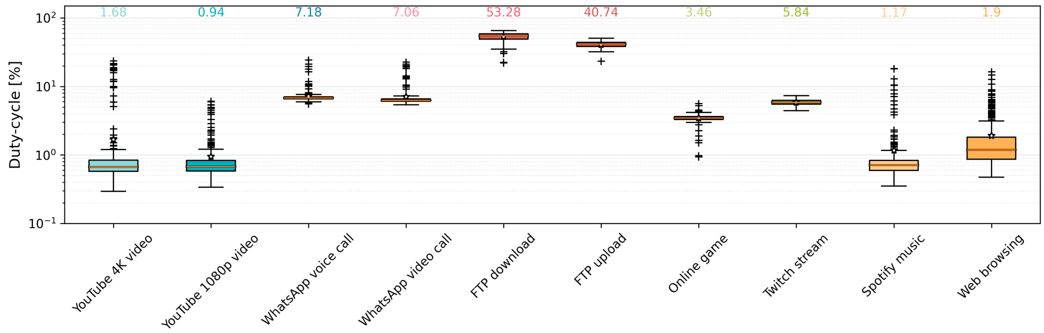


(**b**)

Figure 6. *Cont.*



(**c**)



(**d**)

Figure 6. One-second-averaged DCs as a function of Internet application per bandwidth: (**a**) 20 MHz, (**b**) 40 MHz, (**c**) 80 MHz, and (**d**) 160 MHz. The mean DC for each application over 6 min (marked with a star in the box plot) is labeled above each box.

3.2. Impact of Radio Conditions on DC

Figure 7 presents box plots comparing the DC of various internet activities under 80 MHz bandwidth for good and poor radio conditions. Table 6 provides detailed statistical data, including the mean, median, P_{95}, max, and SD for both conditions. It is important to note that under worst radio conditions, only AP signals could be captured. Thus, the DC data for good radio conditions were calculated using the method described in Section 2.2.2, extracting AP-transmitted signals based on received signal amplitudes. The results indicate a significant influence of radio conditions on DC. As expected, for most network services, except FTP upload, the mean DC increases substantially under poor radio conditions: the mean DC of 4K video streaming increased from 3.1% to 19%, with a larger interquartile range (IQR) reflecting greater transmission instability; video calling: DC rose from 3.8% to 8.8%; the change in FTP downloads was from 43.1% to 88.6%; the largest relative change was observed in the case of Spotify audio streaming, with mean DC rising from 0.72% to 11.5%. These increases are attributed to degraded channel quality, which lowers the SNR. This leads to higher error rates and retransmission demands, while devices often reduce their MCS to maintain connection stability. These factors collectively worsen transmission efficiency, resulting in elevated DC. Conversely, the DC for FTP upload decreased under poor radio conditions. This can be explained by the reduced efficiency of continuous uplink data transmission from the UD to the AP, leading to a decline in AP-side DC under such conditions. Therefore, the counterintuitive conclusion is that the increased duration of active Wi-Fi signals may lead to higher exposure levels in the presence of "weak signals".

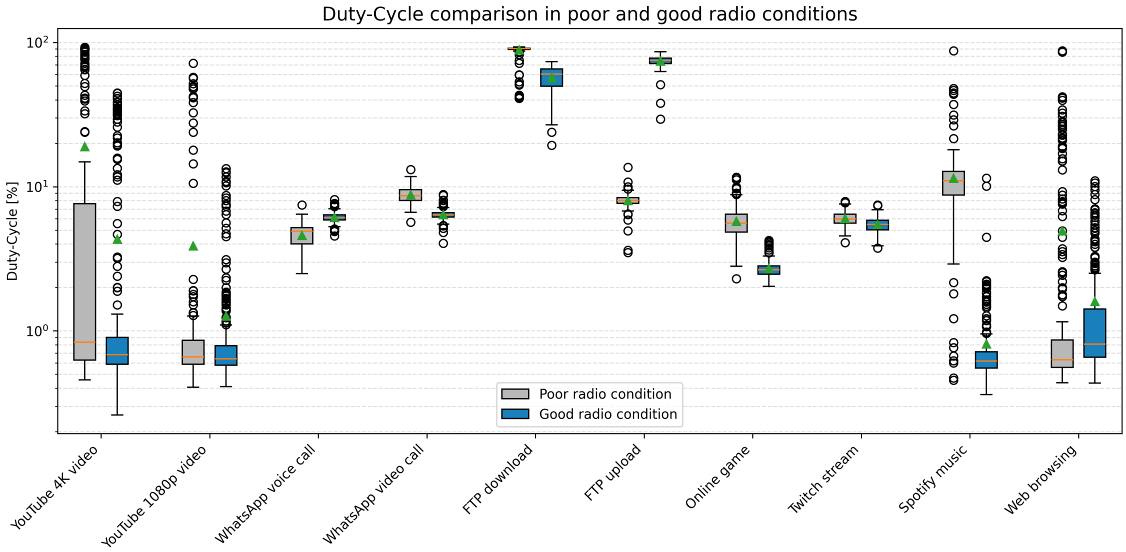


Figure 7. The comparison of Wi-Fi 6 DCs for different Internet applications under good and poor radio conditions (DC mean values are marked as green triangles).

Table 6. Measured mean, median, 95th percentile (P_{95}), maximum (Max) duty cycle, and standard deviation (SD) for different activities under radio conditions (RC) of poor and good.

Applicaiton	RC	Mean [%]	Median [%]	P_{95} [%]	Max [%]	SD [%]
YouTube 4K video	poor	18.99	0.83	90.51	92.28	33.30
YouTube 1080p video	poor	3.88	0.66	37.20	71.64	11.58
WhatsApp voice call	poor	4.59	4.90	5.67	7.45	0.94
WhatsApp video call	poor	8.80	8.65	10.63	13.12	1.06
FTP download	poor	88.59	90.50	92.10	93.12	8.41
FTP upload	poor	8.03	8.03	9.12	13.65	0.83
Online game	poor	5.75	5.57	8.72	11.62	1.43
Twitch stream	poor	6.02	5.96	7.17	7.91	0.64
Spotify audio	poor	11.47	11.00	16.70	87.54	7.50
web browsing	poor	4.94	0.63	27.65	87.38	12.92
YouTube 4K video	good	3.10	0.66	23.39	30.37	6.78
YouTube 1080p video	good	1.05	0.62	4.31	9.15	1.45
WhatsApp voice call	good	3.77	3.74	4.16	5.48	0.32
WhatsApp video call	good	3.76	3.74	4.22	5.55	0.32
FTP download	good	43.09	45.66	53.59	57.34	9.13
FTP upload	good	21.19	21.41	25.38	26.56	3.02
Online game	good	1.63	1.59	2.00	3.11	0.23
Twitch stream	good	2.96	2.93	3.55	4.26	0.37
Spotify audio	good	0.72	0.60	1.36	7.23	0.61
web browsing	good	1.17	0.71	3.84	6.85	1.14

3.3. DC in Multi-User Scenarios

Figure 8 illustrates the relationship between DC and the number of UDs for four internet applications. The results show that the mean DC over six minutes increases in multi-user scenarios compared to single-user scenarios, with distinct trends observed for different applications:

- 4K Video Streaming: The mean DC increases progressively as the number of UDs grows, ranging from 4.3% to 12.9%. Unlike other applications, the IQR significantly increases, indicating a more dispersed distribution of DC values. This is attributed to the higher frequency of buffering behaviors as more users are added, leading to more frequent bursts of data transmission. This trend is confirmed by Figure 9, which shows an increasing number of peaks in the DC versus time-series curve for video streaming as the number of users grows;

- FTP File Downloading: The mean DC stabilizes at approximately 85% after the first UD (57%) and remains consistent as additional UDs connect. The IQR remains minimal, indicating a highly stable and concentrated distribution;
- Web Browsing: The mean DC stays at around 7% once the number of UDs increases to two. While the IQR slightly increases, its variation is smaller compared to 4K video streaming. This is because web browsing generates lower total traffic demands, leading to less pronounced increases in traffic variability even as UDs are added;
- Video Calling: The mean DC increases almost linearly with the number of UDs, from 6.4% to 17.5% as the number of UDs grows from one to four. The IQR remains low, reflecting the consistent and stable uplink/downlink traffic required to meet the high QoS demands of video call.

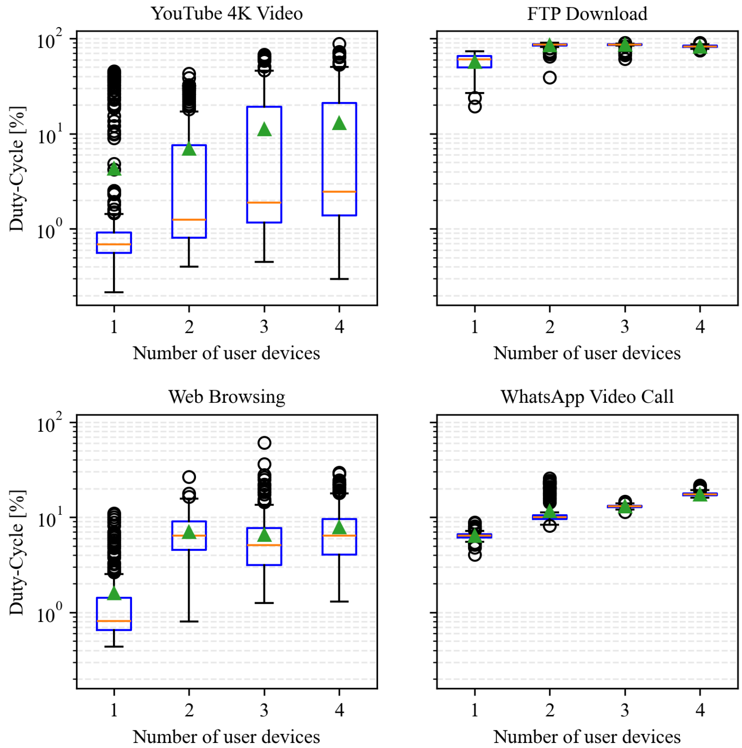


Figure 8. DC as a function of the number of UDs for four different Wi-Fi 6 network applications, including 4K video streaming, FTP downloads, web browsing, and video calls (DC mean values are marked as green triangles).

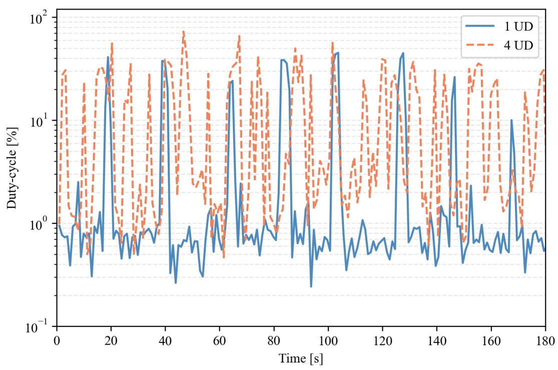


Figure 9. DC variation over time for 4K video streaming in single-user and four UDs scenarios.

Figure 10 compares DC distributions when four UDs are using different applications simultaneously versus the same application. When UDs engage in different applications, the DC distribution is very similar to that of FTP downloading, with an average DC of 81.9%, i.e., the high-traffic applications like file transfer dominate the overall DC in multi-user scenarios. In summary, multi-user scenarios exhibit higher DC compared to single-user scenarios, but the trends and data distributions vary notably depending on the application type.

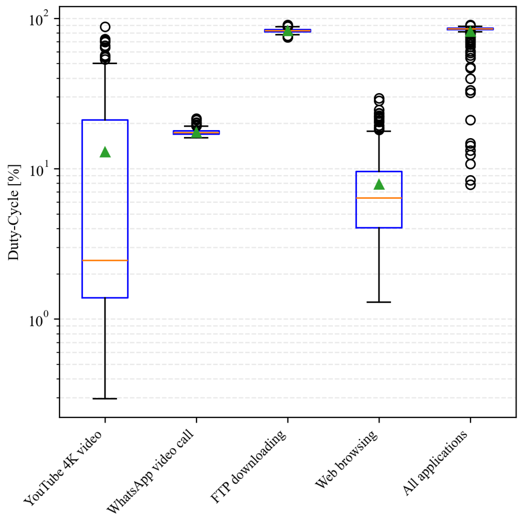


Figure 10. Comparison of DC distributions for four UDs using different applications simultaneously ("All applications") versus the same application (DC mean values are marked as green triangles).

3.4. Wi-Fi 6 EMF Exposure Assessment

Figure 11 presents the exposure levels measured in terms of E-field at the AP side, the UD side (laptop), and the center between them under bandwidths of 20 MHz, 40 MHz, 80 MHz, and 160 MHz. Figure 12 further compares the exposure levels of four different UDs under 80 MHz bandwidth. Across all bandwidths, the recorded maximum exposure levels (E_{max}) in max-hold mode were weighted using the maximum average DC (DC_{max}), minimum average DC (DC_{min}), and video-call DC according to Equation (2).

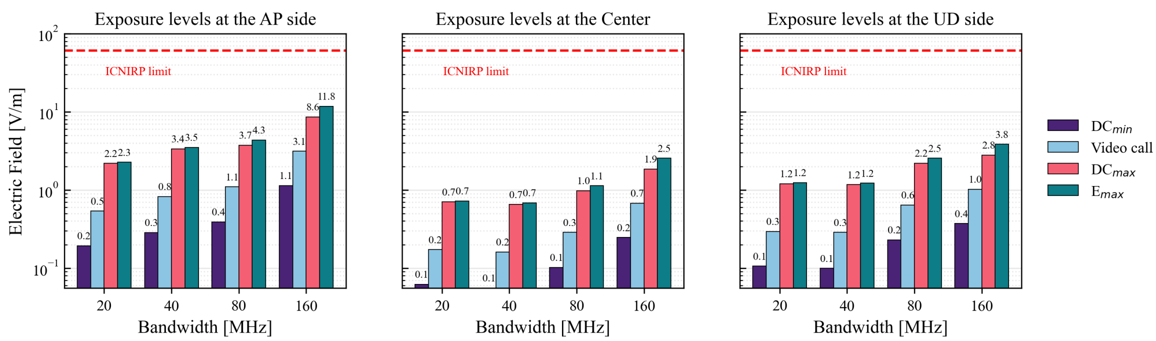


Figure 11. Measured exposure levels (weighted with different DC: DC_{min}, DC_{max}, video call, and DC = 100%) at the AP side, UD side, and the center location under varying bandwidths (20 MHz, 40 MHz, 80 MHz, and 160 MHz).

The results indicate that the EMF exposure levels at the AP side are significantly higher than those at the center and UD side, due to the greater EIRP power of the AP, with exposure increasing with bandwidth. E_{max} rose from 2.3 V/m at 20 MHz to 11.8 V/m at 160 MHz. According to the ICNIRP guidelines, the exposure limit for the general public at this frequency range is defined as 10 W/m^2 or 61 V/m. The measured maximum exposure is 19% of the ICNIRP limit, but when weighted with DC$_{min}$, the exposure reduces to 1.1 V/m (1.8% of the ICNIRP limit), a reduction by nearly a factor of 10. Weighting by the DC for video calls results in an exposure level of 3.1 V/m (5.1% of the ICNIRP limit), and weighting by DC$_{max}$ results in 8.6 V/m (14.1% of the ICNIRP limit). However, at lower bandwidths, the higher DC$_{max}$ causes the weighted exposure level to remain close to E$_{max}$.

For the center and UD side positions, the maximum E$_{max}$ values recorded were 2.5 V/m (4.1% of the ICNIRP limit) and 3.8 V/m (6.2% of the ICNIRP limit), respectively. When weighted by DC$_{min}$, the average exposure levels at these positions also decreased by approximately 10×, with the lowest level recorded being only 0.33% of the ICNIRP limit.

For different types of UDs, including laptop, mobile phone, tablet, and UWiA, the results reveal significant variations in exposure levels. The UWiA exhibited the highest exposure, with an E$_{max}$ of 4.7 V/m (7.7% of the ICNIRP limit)—comparable to the AP's exposure level at the same bandwidth. This was followed by the laptop (2.6 V/m) and the tablet (2.3 V/m), both below 4.3% of the ICNIRP limit, while the mobile phone had the lowest exposure level, with an E$_{max}$ of 1.5 V/m (2.5% of the ICNIRP limit).

These differences highlight the significant impact of antenna design and power configurations across devices on exposure levels. After weighting the exposure levels by the corresponding DC values, the average exposure for different UDs ranged between 0.23% and 6.6% of the ICNIRP limit. This is consistent with prior conclusions that assuming a 100% DC could result in an approximately ten-fold overestimation of exposure levels.

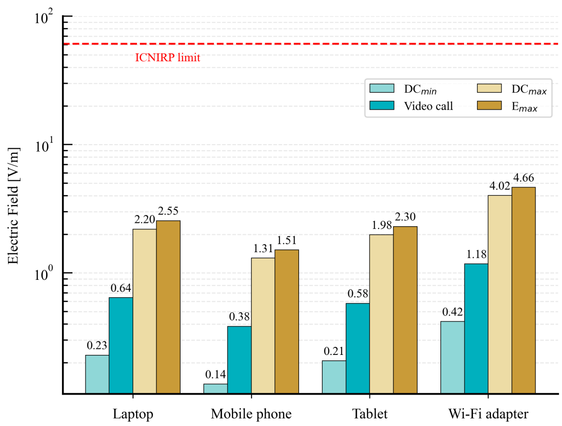


Figure 12. Measured exposure levels (weighted with different DC: DC$_{min}$, DC$_{max}$, video call and DC = 100%) for different types of UD (laptop, mobile phone, tablet and UWiA) under a bandwidth of 80 MHz.

Figure 13 illustrates the exposure levels measured under 80 MHz bandwidth in multi-user scenarios at various devices and locations, with the setup and layout shown in Figure 4. The analysis combines DC results for scenarios where four UDs simultaneously ran 4K video streaming, video calling, FTP downloading, and web browsing, as well as when the four UDs used all these applications simultaneously (denoted as "All" in the legend). E$_{max}$ still represents the exposure levels assuming a 100% DC.

The results show that the AP and UWiA exhibited the highest and comparable exposure levels, with an E$_{max}$ of up to 4.6 V/m (7.5% of the ICNIRP limit). A comparison of single-user and multi-user E$_{max}$ values (Figures 11 and 12) across all devices and locations, accounting for measurement uncertainty, indicates that the E$_{max}$ levels are largely consistent between the two scenarios. This suggests that each device's intrinsic contribution to exposure dominates, rather than being significantly influenced by the addition of more UDs. A similar trend is observed at the center location, where the E$_{max}$ values for single-user and multi-user scenarios are 1.1 V/m and 1.2 V/m (1.9% of the ICNIRP limit), respectively, showing minimal additional signal contribution from the increased number of UDs.

In contrast, when considering DC-weighted exposure levels, the elevated DC in multi-user scenarios results in generally higher average exposure levels compared to single-user scenarios, with a maximum value of 4.2 V/m (6.9% of the ICNIRP limit). Using Equation (2), the increase in Wi-Fi 6 exposure levels due to the higher DC in the four UD scenario compared to the single-user scenario can be quantified for each application: 1.7× for both 4K video streaming and video calls, 1.2× for FTP downloads, and 2.2× for web browsing. These findings highlight the impact of multi-user DC increases on average exposure levels.

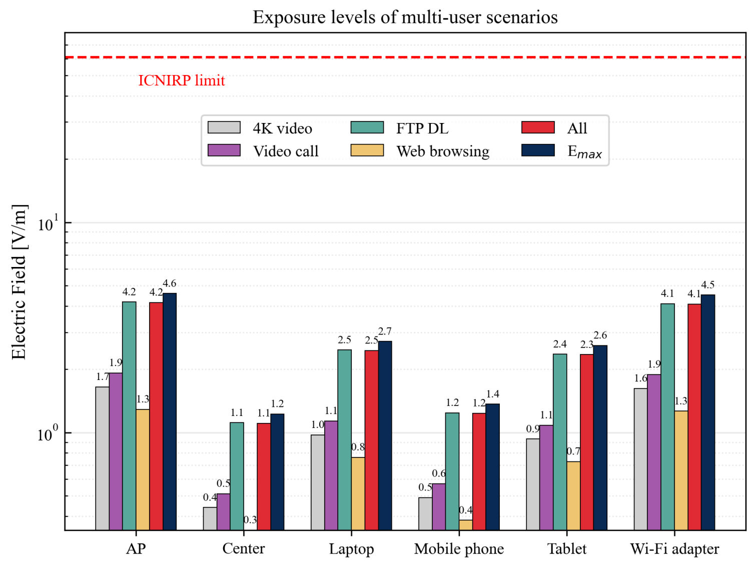


Figure 13. Exposure levels at different UDs (laptop, mobile phone, tablet, and UWiA), center, and AP measured in the multi-user scenario for different DCs (all 4 UD-scenario DCs).

4. Discussion

This study comprehensively assessed the DC and EMF exposure levels of Wi-Fi 6 networks under various scenarios, addressing the influence of bandwidth, radio conditions, user devices, and multi-user environments. The results reveal significant findings that provide valuable insights into the realistic exposure characteristics of Wi-Fi 6 and their implications for public health and regulatory compliance.

The measured DC showed a clear dependency on the application type and bandwidth. High-throughput applications like FTP file transfers exhibited stable and the highest DC (e.g., the maximum mean DC of 94.2% for FTP downloads at 20 MHz bandwidth), while pre-buffered services like YouTube video streaming demonstrated a bursty transmission pattern with positively skewed DC distributions. DC generally decreased for most applications as bandwidth increased, reflecting improved transmission efficiency. However, for certain applications such as video calls, DC either remained stable or increased due to higher traffic demands at higher data rates, emphasizing the role of QoS requirements in shaping DC behavior. The authors of [9] reported DC data for 802.11a/g networks under different internet services. Due to the significantly enhanced throughput of Wi-Fi 6, the DC values for most applications reported in this study are notably lower than those in [9], particularly for YouTube 1080p video streaming, where the maximum mean DC was 87.4% in [9], compared to 5.3% in this work. However, the reported mean DC for video calling and file transfer in [9] is lower than the corresponding values in this study. This discrepancy can be attributed to differences in application requirements and technological advancements:

for video calling, the lower DC in [9] likely reflects the lower QoS requirements at the time, such as reduced resolution and frame rates, resulting in lower traffic demands; for file transfer, the higher DC in this study is explained by the improvements in OFDMA and MIMO technologies introduced in Wi-Fi 6, which significantly enhance time-domain efficiency and channel capacity, allowing for more consistent and sustained transmissions.

Poor radio conditions significantly elevated DC values for most applications, e.g., AP-side 4K video streaming mean DC increased from 3.1% to 19%, FTP downloads increased from 43.1% to 88.6%, except for FTP upload, where AP-side mean DC decreased from 21.1% to 8% due to reduced uplink transmission efficiency. This highlights the impact of retransmissions and lower MCS under degraded SNR, which increases the duration of active signals and potentially elevates exposure levels. These findings underscore the need to consider radio-condition variations in real-world exposure assessments. Ref. [14] investigated the mean DC of uplink traffic for various network applications over 15 min under good, moderate, and bad radio conditions on 802.11a/g networks. They reported that DC increased with deteriorating signal quality, ranging from 0.21% to 73.7%. Although [14] focused on uplink signals, while the measurements in this study under the worst radio conditions primarily addressed downlink signals at the AP, a direct quantitative comparison is not feasible. However, the main conclusion aligns between the two works: radio channel quality significantly impacts DC. Furthermore, their observation that the average DC for FTP upload increased from 56.8% under good radio conditions to 73.7% under bad radio conditions corroborates the corresponding trends reported in this study.

Since the AP in this study supports MU-MIMO and beamforming, signal power distribution may vary depending on the device location. However, to minimize bias, measurements were taken under controlled conditions with the UD positioned at a fixed LOS distance for single-user scenarios. The exposure levels varied significantly across different UDs. UWiA exhibited the highest exposure levels of 4.7 V/m (E_{max}), nearing the levels measured at the AP, while mobile phones showed the lowest levels, which were 1.5 V/m (E_{max}) due to their optimized antenna designs and lower transmission power. Ref. [17] evaluated the maximum exposure levels and DC for Wi-Fi 6 devices, including AP and a mobile phone, under varying frequency bands, bandwidths, and output power conditions. Unlike this study, they used the iperf3 application to control traffic (up to 400 Mbps) and forced maximum channel utilization to assess exposure levels. Their findings indicated that DC proportional to data rate, with DC reaching up to 100% at the 5 GHz band. Regarding exposure levels, they reported that for an AP operating at 80 MHz bandwidth and 100% output power, the power density measured 35 cm from the AP was approximately 0.1 W/m^2 (6.1 V/m). For a mobile phone operating at 25% output power, the power density measured 30 cm from the device was approximately 0.02 W/m^2 (0.87 V/m). In comparison, the corresponding values reported in this study are 4.3 V/m for the AP and 1.5 V/m for the mobile phone. Although both results are of the same order of magnitude, the differences arise from measurement uncertainties, variations in device output power (devices in this study did not necessarily operate at their maximum or predefined power levels), and differences in experimental conditions. These results underscore the crucial role of device design, e.g., the number and layout of antennas, as well as the transmission power, in influencing exposure characteristics and the necessity of device-specific evaluations in exposure studies.

Multi-user scenarios led to increased DC values compared to single-user cases, resulting in proportionally higher average exposure levels. The rise in exposure levels was most pronounced for applications like video streaming and web browsing, which rely on intermittent high data-rate transmissions. However, the overall electric-field strength remained in compliance with ICNIRP guidelines, with the highest DC-weighted average exposure level (4.2 V/m) representing only 6.9% of the ICNIRP limit. These results demonstrate Wi-Fi 6's ability to manage multi-user environments efficiently without exceeding safety limits, even under increased traffic loads.

The experiments were conducted in a controlled laboratory environment, which, while minimizing interference, may not fully reflect real-world conditions. Future studies should expand to more complex environments with varied user densities and interference sources, e.g., residential, urban, suburban, office, and industrial, etc. Additionally, the investigation of long-term exposure patterns and their correlation with DC dynamics under dynamic network loads warrants further exploration.

5. Conclusions

This study provides a comprehensive evaluation of the DC and EMF exposure characteristics of Wi-Fi 6 networks across various bandwidths, application types, radio conditions, and multi-user scenarios. The results demonstrate that the DC ranged over 0.7% to 94.3% and that DC and EMF exposure levels are strongly impacted by Internet service traffic patterns, device-specific designs, and environmental factors such as signal quality and user density. Importantly, the study highlights the necessity of incorporating realistic DC values into EMF assessments to avoid significant overestimations when using max-hold measurements. Despite increased DC in multi-user scenarios, all measured exposure levels remained well within ICNIRP limit, with a maximum average exposure level of 4.2 V/m. These findings provide practical guidance for future Wi-Fi 6 exposure assessment, numerical dosimetry, etc., and deliver critical insights for regulatory policy development.

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