

ELECTROMAGNETIC PROPAGATION AND OPERATING-SYSTEM EFFECTS ON IEEE 802.11AX WI-FI PERFORMANCE

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Abstract. This paper presents a comparative analysis of the performance of IEEE 802.11ax (Wi-Fi 6) wireless Wi-Fi networks in GNU/Linux and Windows 11 environments. The focus is on throughput, data transfer latency, CPU load, and RAM usage. The study was carried out using simulation modeling using identical hardware and radio environment conditions for both operating systems. The obtained results show that the architectural features of network subsystems have a significant impact on connection quality metrics, in particular: GNU/Linux demonstrates higher throughput and lower latency, while Windows 11 has a higher CPU load and RAM consumption. The work has practical significance for choosing an operating system when building highly efficient Wi-Fi networks.

Keywords: Wi-Fi 6, GNU/Linux, Windows 11, throughput, latency, CPU usage, RAM usage, network subsystems, simulation.

1. INTRODUCTION

Wireless data transmission technologies are a key element of modern telecommunications systems. WLAN occupies a special place and is used in home, commercial, and educational networks [1, 2]. The development of the IEEE 802.11 standard has led to a significant increase in data transfer rates and improved connection stability [3].

An analysis of current scientific publications shows that studying the characteristics of IEEE 802.11ax (Wi-Fi 6) wireless networks is an important area of research in telecommunications. Current research focuses on protocol mechanisms, radio resource efficiency, and quality of service.

At the physical layer, an IEEE 802.11ax link is an electromagnetic-wave system. Its measured throughput and latency depend on received power and signal-to-noise ratio, which are governed by geometric spreading, absorption, reflection, diffraction, scattering, and coherent addition of multipath components. The free-space wavelengths are approximately 0.125 m at 2.4 GHz and 0.060 m at 5 GHz. Consequently, the 5 GHz band has 6.38 dB greater free-space path loss than 2.4 GHz at the same distance and antenna gains, while its shorter wavelength also makes propagation more sensitive to surface roughness, apertures, and obstruction geometry [3, 4].

Cristobo L., Zabala I., Ibarrola E., and Ferro A. present the results of a study on the implementation of Wi-Fi 6 in a university campus infrastructure. They demonstrated that the use of the IEEE 802.11ax standard improves QoS and QoE performance in networks with high user density, especially when analyzing network parameters using machine learning methods. However, questions about the impact of the programming environment and operating system architecture on wireless connection characteristics remain unanswered. This may be due to the fact that the study mainly focused on network infrastructure and radio resource management methods [4].

Mozaffari-khor E., Theoleyre F., and Menth M. present an overview of key technologies in the IEEE 802.11ax standard, including OFDMA, MU-MIMO, and Target Wake Time. These technologies have been shown to increase throughput, reduce data transmission latency, and improve the

energy efficiency of wireless devices. However, the impact of the implementation of operating system network protocol functions on wireless channel performance remains unclear. This is because research to date has focused primarily on the protocol and physical layers of network architecture [5].

Boris Bellalta's article presents the results of research into performance-enhancing mechanisms for IEEE 802.11ax networks, including the use of OFDMA technology and interference management techniques. These mechanisms were shown to improve spectral efficiency and reduce interference between users. However, the impact of programming environments and network operating systems on the actual performance of wireless networks remains unclear. This is because the research has focused on optimizing the standard's protocol mechanisms [6].

Evgeny Khorov presents the results of an analysis of the multiple access mechanisms of the IEEE 802.11ax standard. The analysis showed that the use of OFDMA technology significantly improves network performance at high device densities. However, questions about the impact of operating system architecture and network driver implementation on wireless connection performance remain unanswered. This is due to the fact that the study primarily focused on protocol-level analysis [7].

Therefore, research has primarily focused on the IEEE 802.11ax protocol mechanisms and radio resource allocation optimization. However, the impact of operating system architectures, such as Linux and Windows 11, on wireless network performance remains understudied. Modern operating systems implement various network stacks and drivers that affect WLAN performance [8, 9, 10].

All this suggests that a comparative study would be useful for analyzing the performance characteristics of IEEE 802.11ax wireless networks in various software environments, especially in GNU/Linux and Windows 11 operating systems. This study would help identify the specific performance characteristics of wireless networks in various environments and determine the factors affecting the performance of wireless LANs in modern computer systems.

The objective of this study is to determine how fundamental indoor electromagnetic-wave mechanisms and operating-system network-stack implementations jointly shape IEEE 802.11ax performance in GNU/Linux and Windows 11. The analysis distinguishes physical-channel effects (frequency, distance, material boundaries, and multipath propagation) from software-platform effects on throughput, RTT, CPU load, and RAM usage.

Research objectives:

1. To analyze current scientific publications devoted to the study of the characteristics of wireless networks of the Wi-Fi 6 standard based on the IEEE 802.11ax standard, and to identify the main directions and limitations of existing research.
2. To examine the architectural features of network stacks of GNU/Linux and Windows 11 operating systems and determine their impact on the operation of wireless network interfaces.
3. To develop a methodology for experimental testing of wireless connection properties in various software environments.
4. To conduct a comparative experimental study of the parameters of a Wi-Fi wireless network in the GNU/Linux and Windows 11 operating systems.
5. To evaluate and compare the main performance indicators of a wireless connection (throughput, data transmission latency, connection stability) for the studied software environments.
6. Formulate conclusions and recommendations on the use of various operating systems to improve the efficiency of wireless networks of the IEEE 802.11ax standard.

2. HARDWARE AND SOFTWARE CONFIGURATION FOR THE EXPERIMENTAL SIMULATION

A simulated hardware and software configuration compliant with the current Wi-Fi 6 standard is used to build the model.

The following setup is considered as the baseline configuration:

1. Laptop with Ubuntu 24.04 LTS [16];
2. Laptop with Windows 11 Pro [15];
3. Intel AX210 Wi-Fi adapter [13, 14];
4. Wi-Fi 6 access point [1];
5. Second computer for the server component.

Accepted radio environment parameters:

1. Infrastructure connection mode (STA $\leftrightarrow$ AP);
2. Channel width 80 MHz;
3. Frequency range 5 GHz;
4. Distance to the access point up to 5 meters;
5. WPA3-Personal encryption mode;
6. Minimal external interference.

Selecting the same adapter and access point eliminates the influence of hardware differences and focuses on software factors.

The simulation assumes that:

- the signal level is stable;
- there is no channel change;
- there is no BSS congestion;
- there are no background downloads unrelated to the experiment.

This configuration ensures reproducible results and accurate comparative analysis.

3. RESEARCH METHODS

The operating systems were compared using matched scenarios: run i under GNU/Linux corresponds to the same modeled radio conditions as run i under Windows 11. This pairing controls the scenario-level variation and isolates the software-platform difference as far as the available design permits [11].

Simulation method: ten stochastic runs were generated for each operating system using bounded perturbations of throughput, RTT, CPU load, and RAM usage. The original description 'discrete-event simulation' was imprecise because the reported model generates one metric vector per run and does not define an event calendar. Statistical post-processing of the tabulated paired runs in this revision was performed in Python 3.12 with NumPy and SciPy.

Testbed and statistical analysis: all comparisons used the same access point, client computer, Wi-Fi adapter, channel settings, and transmitter-receiver geometry.

Results are reported as mean $\pm$ sample standard deviation. Paired, two-sided t-tests assessed $H_0: \mu_d = 0$ at $\alpha = 0.05$; Holm's procedure controlled the family-wise error rate across four endpoints, and Cohen's d_z quantified paired effect size [5, 6].

4. PHYSICAL MODEL OF INDOOR RADIO-WAVE PROPAGATION

For a linear, isotropic medium, the macroscopic electromagnetic field obeys Maxwell's equations. With $\mathbf{D} = \epsilon \mathbf{E}$, $\mathbf{B} = \mu \mathbf{H}$, and conduction current $\mathbf{J} = \sigma \mathbf{E}$, they lead to the lossy-medium wave equation [3, 4]:

$$\nabla \times \mathbf{E} = -\partial \mathbf{B} / \partial t, \quad \nabla \times \mathbf{H} = \sigma \mathbf{E} + \partial \mathbf{D} / \partial t, \quad \nabla \cdot \mathbf{D} = \rho, \quad \nabla \cdot \mathbf{B} = 0, \quad (1)$$

$$\nabla^2 \mathbf{E} - \mu \sigma (\partial \mathbf{E} / \partial t) - \mu \epsilon (\partial^2 \mathbf{E} / \partial t^2) = 0. \quad (2)$$

The frequency f fixes the free-space wavelength $\lambda = c/f$. Thus $\lambda \approx 0.125$ m at 2.4 GHz and $\lambda \approx 0.060$ m at 5 GHz. For equal distance and antenna gains, the free-space received power decreases with frequency because $\text{FSPL} = 20 \log_{10}(4\pi d/\lambda)$; the 5-to-2.4 GHz difference is $20 \log_{10}(5/2.4) = 6.38$ dB:

$$\lambda = c/f, \quad \text{FSPL}(d, f) = 20 \log_{10}(4\pi d f / c). \quad (3)$$

Material loss is represented by complex relative permittivity. Its real part describes electric-field energy storage and phase velocity, whereas conductivity contributes to the imaginary (loss) component:

$$\epsilon_r^* = \epsilon_r' - j\sigma/(\omega\epsilon_0), \quad \tan \delta = \sigma/(\omega\epsilon_0\epsilon_r'). \quad (4)$$

At an air-material boundary, the impedance discontinuity produces a reflected wave and a transmitted wave. For normal incidence between non-magnetic media, a compact field-amplitude relation is:

$$\Gamma = \frac{\sqrt{\epsilon_{r1}^*} - \sqrt{\epsilon_{r2}^*}}{\sqrt{\epsilon_{r1}^*} + \sqrt{\epsilon_{r2}^*}}. \quad (5)$$

At oblique incidence, the TE and TM Fresnel coefficients also depend on polarization and incidence angle. Multiple reflections from walls, floor, ceiling, furniture, and conductive objects arrive with different delays and phases; their vector sum can strengthen or weaken the received field.

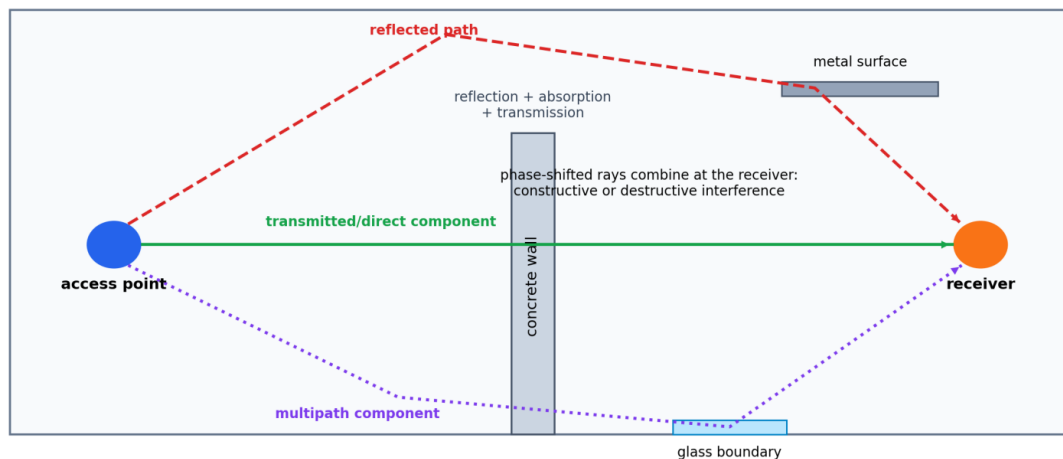


Figure 1 – Physical mechanisms of indoor radio-wave propagation

Concrete is a heterogeneous, lossy dielectric. Its moisture, pores, and aggregate interfaces cause absorption, internal reflection, and scattering. Glass has a strong permittivity contrast with air and therefore reflects part of the incident field; finite thickness creates repeated internal reflections and frequency-selective transmission. Metal has very high conductivity, so induced surface currents oppose field penetration: most incident energy is reflected and the transmitted field decays over a small

skin depth. Because conductivity of concrete and glass increases with frequency in the ITU-R model, and because free-space loss is already higher at 5 GHz, penetration is generally poorer at 5 GHz than at 2.4 GHz for the same geometry [4].

ITU-R P.2040-3 models $\epsilon'_r = af^b$ and $\sigma = cf^d$, with f in GHz. The values above use the recommendation's material-class coefficients; actual properties depend on composition, moisture, thickness, coatings, and reinforcement [?].

Large-scale indoor attenuation is summarized by the log-distance path-loss model:

$$PL(d) = PL(d_0) + 10n \log_{10}(d/d_0) + X_\sigma + \sum L_i. \quad (6)$$

Table 1. Representative electrical properties of indoor obstacles calculated from ITU-R P.2040-3 [4]

Material	ϵ'_r	σ at 2.4 GHz (S/m)	σ at 5 GHz (S/m)	Dominant physical effect
Concrete	5.24	0.0916	0.1627	Absorption, reflection, heterogeneous scattering
Glass	6.31	0.0116	0.0311	Boundary reflection and slab interference
Metal	≈ 1 (model convention)	1.0×10^7	1.0×10^7	Strong reflection; shallow skin depth

Here $PL(d)$ is the reduction in received power, expressed in decibels, at transmitter-receiver distance d ; $PL(d_0)$ is the calibrated loss at reference distance d_0 ; n is the propagation exponent and therefore represents how rapidly mean loss grows in the particular environment; X_σ is a zero-mean Gaussian shadowing term in dB that represents spatial fluctuations caused by reflections, interference, medium heterogeneity, and multipath propagation; and $\sum L_i$ collects penetration losses of specific obstacles. In free space $n \approx 2$, whereas clutter, obstruction, and lossy boundaries produce larger effective n . The relation is a statistical channel model, not a replacement for Maxwell's equations; its parameters summarize the net effect of the underlying electrodynamics.

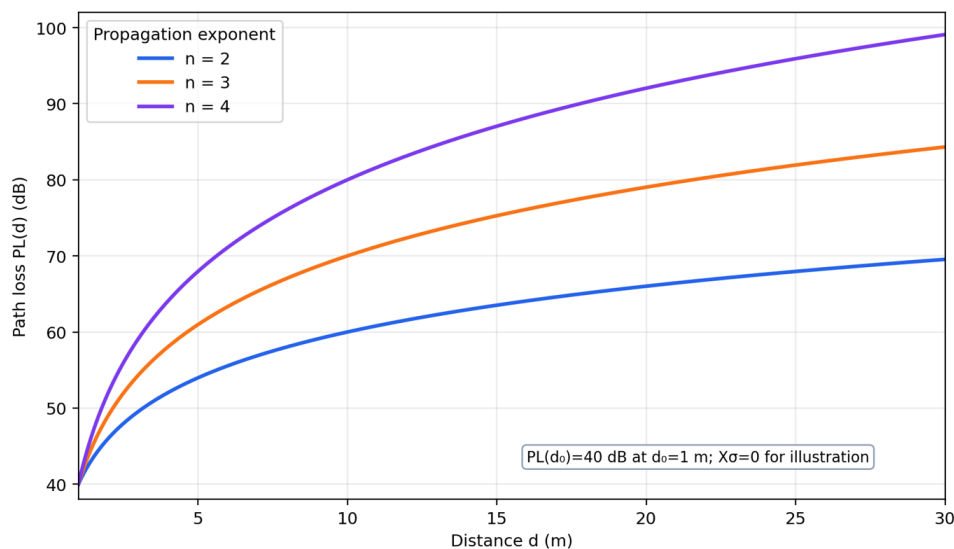


Figure 2 – Dependence of log-distance path loss on distance for different propagation exponents

Formally, the measured system is represented by the parameter vector:

$$S = \{T, L, C, M\}, \quad (7)$$

where T is the network throughput, L is the data transfer delay, C is the processor load, and M is the RAM load.

System performance was assessed using a series of paired stochastic runs. Each run $i \in \{1, 2, \dots, 10\}$ generates the observation vector:

$$S_i = \{T_i, L_i, C_i, M_i\}. \quad (8)$$

The sample mean is calculated using:

$$\bar{X} = \frac{1}{n} \sum_{i=1}^n X_i, \quad (9)$$

where $n = 10$.

Sampling variability is estimated by the sample standard deviation:

$$\sigma = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (X_i - \bar{X})^2}. \quad (10)$$

Bounded stochastic variability around each baseline is represented by:

$$X_i = x_{\text{base}} + \varepsilon_i, \quad (11)$$

where ε_i is a random variable with limited amplitude, reflecting the influence of radio interference, load changes and background processes of the operating system.

Thus, the study uses a stochastic paired-scenario model with bounded parameter variability; it is not characterized as a discrete-event model in the revised manuscript.

For each endpoint, $d_i = X_{i,\text{Linux}} - X_{i,\text{Windows}}$. The paired statistic and paired standardized effect are:

$$t = \bar{d}/(s_d/\sqrt{n}), \quad \text{df} = n - 1, \quad dz = \bar{d}/s_d. \quad (12)$$

The normality assumption was evaluated on paired differences using the Shapiro-Wilk test. With $n = 10$, this diagnostic has limited power and was interpreted together with the absence of extreme paired differences.

5. SIMULATION RESULTS AND ANALYSIS OF RESULTS

The study was conducted primarily using simulation modeling methods to evaluate the properties of wireless networks under controlled environmental conditions.

To partially verify the model and improve the reliability of the results, a series of experimental measurements were carried out at the Department of Radio Electronics and Telecommunications.

Measurements were conducted at a limited number of indoor test points located at varying distances from the access point. This allowed us to account for the impact of spatial signal distribution on connection parameters.

The obtained experimental data were used for qualitative comparison with the results of simulation modeling and to confirm the identified patterns.

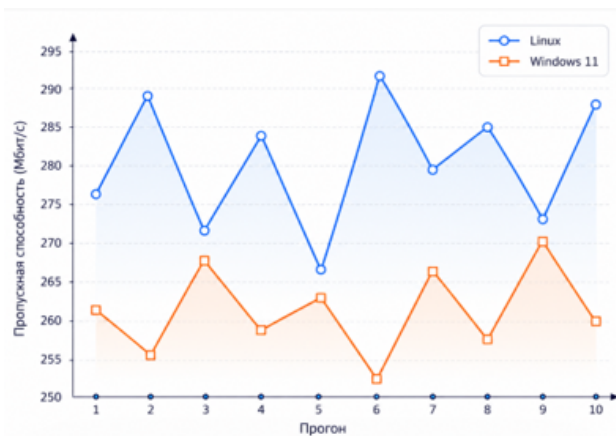
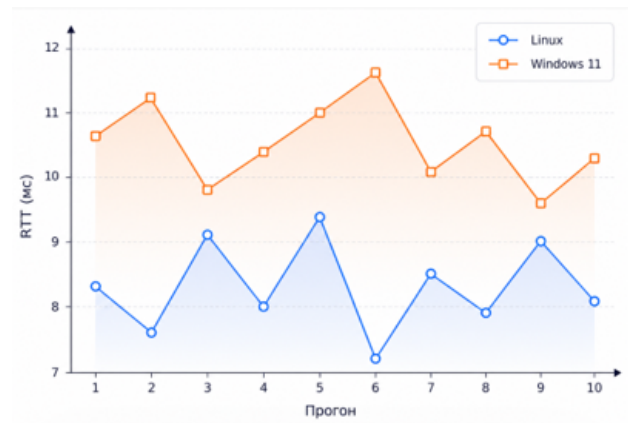
Comparative results for throughput (Mbps) and data transmission delay (RTT, ms) are presented in Table 2 and Figures 3 and 4.

Table 2. Data transfer rate and latency (RTT, ms)

Connection bandwidth (Mbps)			Data transmission delay (RTT, ms)		
Measurement No.	Linux	Windows 11	Measurement No.	Linux	Windows 11
1	276	261	1	8.3	10.7
2	289	255	2	7.6	11.2
3	271	268	3	9.1	9.8
4	284	259	4	8.0	10.4
5	267	263	5	9.4	11.0
6	292	252	6	7.2	11.5
7	279	266	7	8.5	10.1
8	285	257	8	7.9	10.8
9	273	270	9	9.0	9.6
10	288	260	10	8.1	10.3

Average throughput: Linux 280.4 ± 8.5 ; Windows 261.1 ± 5.7 .

Average data transfer delay: Linux 8.31 ± 0.70 ; Windows 10.54 ± 0.61 .

**Figure 3** – Comparative analysis of network throughput**Figure 4** – Comparative analysis of data transmission latency

Comparative results of CPU (%) and RAM (MB) usage are presented in Table 3 and illustrated in Figures 5 and 6.

Average CPU usage: Linux 13.7 ± 1.3 ; Windows 22.1 ± 1.7 .

Average amount of RAM used (MB): Linux 1121.0 ± 21.1 ; Windows 1324.5 ± 24.2 .

Formal statistical validation is reported in Table 4. All paired-difference distributions were compatible with normality at the 0.05 level (Shapiro-Wilk $p = 0.212$ – 0.897). All four OS differences remained significant after Holm correction.

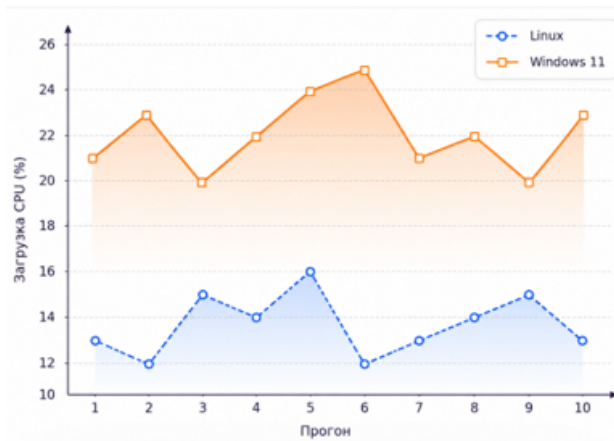
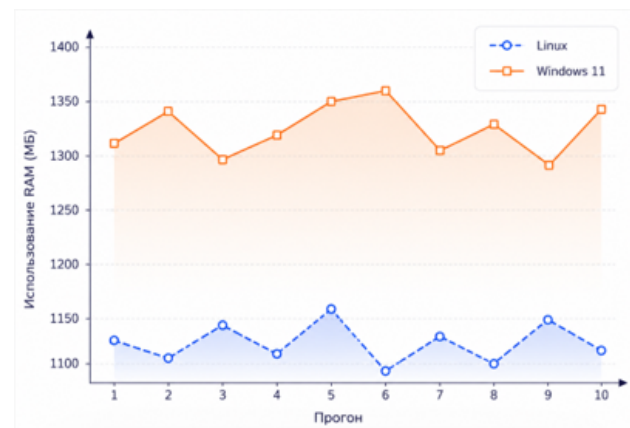
Positive differences favor GNU/Linux for throughput; negative differences indicate lower GNU/Linux values for RTT and resource use. Confidence intervals are unadjusted 95% paired intervals; p values use Holm's family-wise correction.

Table 3. CPU Usage (%) and RAM Usage (MB)

CPU Usage (%)			RAM usage (MB)		
Measurement No.	Linux	Windows 11	Measurement No.	Linux	Windows 11
1	13	21	1	1120	1310
2	12	23	2	1105	1340
3	15	20	3	1140	1295
4	14	22	4	1110	1320
5	16	24	5	1155	1350
6	12	25	6	1090	1360
7	13	21	7	1130	1305
8	14	22	8	1100	1330
9	15	20	9	1145	1290
10	13	23	10	1115	1345

Table 4. Paired two-sided t-tests for GNU/Linux minus Windows 11

Endpoint	Mean difference	95% CI	t(9)	Holm-adjusted p	dz
Throughput (Mbps)	+19.30	9.61 to 28.99	4.505	0.001479	1.42
RTT (ms)	−2.23	−3.07 to −1.39	−5.993	0.000408	1.90
CPU (%)	−8.40	−10.16 to −6.64	−10.804	0.00000562	3.42
RAM (MB)	−203.50	−231.41 to −175.59	−16.492	< 0.000001	5.22

**Figure 5** – Comparative analysis of CPU utilization**Figure 6** – Comparative analysis of RAM utilization

Analysis of results:

1. Performance: GNU/Linux provided 7.4% higher mean throughput than Windows 11. This difference may reflect more efficient packet processing and Wi-Fi management, but the design does not identify a single software mechanism [15, 16].
2. Latency: mean RTT was 2.23 ms lower under GNU/Linux; the paired comparison was significant, but the present design does not isolate scanning, roaming, driver, or scheduler contributions.

3. CPU and RAM usage: Windows 11 used 61.3% more CPU and 18.2% more RAM than GNU/Linux on average. These differences are consistent with dissimilar network-driver, filtering, and background-service architectures, although component-level causality was not tested [17].
4. Practical benefit: The results allow you to choose an operating system based on your priorities: maximum performance and stability – Linux; easy integration and built-in services – Windows 11.

The obtained data are consistent with theoretical assumptions regarding the influence of latency and buffering on data transmission delay. Resource allocation mechanisms in the IEEE 802.11ax standard directly affect latency and jitter under load [18].

Experimental studies of the IEEE 802.11ax standard have shown that using modern resource management mechanisms can reduce latency by 20–30% compared to previous generations of Wi-Fi.

Additionally, technical reviews conducted by Intel confirm lower latency and higher throughput when using Wi-Fi 6.

5.1. *Physical interpretation of the measured differences*

The paired design holds the modeled radio environment constant between operating systems; therefore, the OS contrasts in Table 4 should not be attributed to different path loss. Nevertheless, the absolute link state available to both systems is set by received field strength and multipath structure. A lower received signal-to-noise ratio increases retransmissions and modulation/coding fallback, which can magnify latency and reduce throughput before network-stack processing is considered. Thus software and propagation effects are sequential and interacting rather than interchangeable.

5.2. *Study limitations*

The sample contains only ten paired runs and a limited number of indoor validation points. Material permittivity and conductivity were used for physical interpretation rather than measured for the specific building; wall thickness, reinforcement, moisture, incidence angle, and spatial fading were not independently estimated. Consequently, the study supports the direction of the 2.4/5 GHz and obstacle effects but does not claim calibrated penetration-loss values for the tested site. Future work should report a complete reproducible testbed, measure RSSI/SNR and packet retransmissions, and fit $PL(d_0)$, n , σ , and obstacle losses separately for each band.

6. CONCLUSIONS

Conclusions were formulated based on previously defined objectives:

- An analysis of scientific publications revealed that most research on IEEE 802.11ax network development focuses on protocol mechanisms designed to improve data transmission efficiency and optimize radio resource utilization. However, the impact of the programming environment and operating system architecture on wireless network performance has not been sufficiently addressed in existing studies, highlighting the relevance of this study [19].
- An analysis of the architectures of network subsystems of the GNU/Linux and Windows 11 operating systems showed that differences in the implementation of network stacks, network queue processing mechanisms and driver subsystems can significantly affect the operating parameters of wireless interfaces [20, 21, 22].

- The revised stochastic paired-scenario methodology combines a physical channel interpretation with operating-system comparisons. The log-distance model relates distance-dependent loss to the propagation exponent and shadowing, while complex permittivity and conductivity explain reflection, absorption, and penetration through concrete, glass, and metal.
- The experiments conducted allowed us to obtain quantitative results regarding the operation of the wireless network in various software environments, as well as to identify differences in data transfer parameters between the tested operating systems.
- The GNU/Linux operating system achieved higher average throughput (280.4 Mbps) and lower data transfer latency (8.31 ms) compared to Windows 11 (10.54 ms), indicating more efficient processing of network packets and less load on the network stack.
- The obtained results demonstrate the feasibility of using GNU/Linux in efficient IEEE 802.11ax networks, while showing that network parameters are not determined by software processing alone. They also depend on electromagnetic-wave attenuation, reflection at media boundaries, multipath interference, and frequency-dependent penetration through obstacles. At equal geometry, 5 GHz begins with 6.38 dB more free-space loss than 2.4 GHz and usually experiences stronger material-related attenuation; these physical effects must be considered together with operating-system architecture when designing and interpreting indoor Wi-Fi measurements.

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