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Analyzing the Effectiveness of Wi-Fi 6E in Mitigating Interference in Industrial Environment

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Abstract

Wi-Fi is a widely used wireless technology that is constantly evolving to meet demands for high throughput, real-time communication, dense networks, and resource efficiency. It provides broadband wireless connectivity between end users via unlicensed 2.4GHz and 5GHz frequency bands. Despite many benefits offered by the technology such as mobility, flexibility, and low cost, the limitation in propagating radio frequency (RF) signals over the existing frequency becomes a challenge in some environments, especially in a densely packed manufacturing environment. Thus, this study aims to investigate the effectiveness of the newly introduced Wi-Fi 6E which uses a 6GHz unlicensed frequency band in mitigating the effect of RF interference and obstructions in a densely packed manufacturing environment. This study focuses on evaluating the Wi-Fi performance of a selected printing manufacturing building under line-of-sight (LOS) and non-line-of-sight (NLOS) environments. The effect of obstacles, the source of interferences, and the distance toward the Wi-Fi signal strength and latency are measured using Acrylic W-Fi Analyzer, NetSpot Heatmapper and Ping tools. The results indicate that at the same distance in both NLOS and LOS environments, the 6GHz frequency has the lowest latency compared to the 2.4GHz and 5GHz frequencies. Additionally, the signal strength received from the 6GHz access point (AP) is significantly high at shorter distances in high interference environments but decreases as the distance between the AP and the end devices increases. The findings of this research can significantly enhance existing knowledge by offering valuable insights into the potential application of Wi-Fi 6E for Wi-Fi deployment in manufacturing environments.

1. Introduction

Industry, alongside the Medical and Science sectors, is among the sectors encompassed in the trio of sectors, industrial, scientific and medical networks (ISM) permitted to utilize unlicensed frequency bands, namely 2.4GHz and 5GHz. Within these unlicensed frequency bands, individuals can utilize frequency-supported devices without the necessity of registering with the authorized entity. The author, Edward *et al.,* [1] reported the commencement of IEEE 802.11 evolution can be traced back to the inception of the Wi-Fi legacy standards: 802.11b, 802.11a, and 802.11g. In the preliminary stage of IEEE 802.11 implementation, the focus revolved around providing users with the capability of mobility while compromising on the aspect of speed. The provision of data rates at 11Mbps and 54Mbps allowed users to effectively participate in routine networking activities like email correspondence, web browsing, and online discussions. During that time, the quantity of network-connected devices was considerably lower than it is presently. Nevertheless, as mentioned by K. Pahlavan and P. Krishnamurthy, [2], as more complex applications emerged and an increasing number of users across various sectors, including the industry, adopted the technology, the current data rate became insufficient to accommodate the growing user base. Today, the Wi-Fi landscape emphasizes not only mobility but also performance. The previously available data rates are no longer satisfactory for conducting activities over Wi-Fi networks. Consequently, this prompted the IEEE to introduce advanced IEEE 802.11 standards, namely IEEE 802.11n, 802.11ac, and the most recent one is 802.11ax.

The evolution of wireless technology has had a big impact on today's interconnected world. It changed the way people, things, and the whole world connected and communicated. Earlier in the year 2018, Cisco, [3] in their report had expected 71% mobile connectivity by 2023 and in the year 2024, as mentioned by M. Natkaniec and N. Bieryt, [4] the wireless traffic has increased as expected. According to K. Pahlavan and P. Krishnamurthy, [2], the flexibility of wireless technology has increased the usage of Wi-Fi to be adapted to daily usage. In addition, previously, as reported in a study by Roziyani *et al.,* [5] the convergence of communication technologies and applications is driving the demand for new and innovative services that integrate communication, technology, and media. In the realm of the manufacturing sector, Wi-Fi has been effectively employed as a substitute for wired Ethernet networking in situations where the installation of cables poses challenges, incurs high costs, or is simply unfeasible.

Many studies have been conducted to explore the applications of Wi-Fi technologies in industry operations. For instance, Wi-Fi plays a prevalent role in establishing connections for Automated Guided Vehicles (AGV), sensors, and data gathering essential for the day-to-day operations within industries. This technology also facilitates adaptable device management, thereby enhancing the feasibility and serviceability of devices located in remote stations as deployed in the study by P. Srinivasarao *et al.,* [6]. Consequently, A. Konikov, [7] agreed that it enables the wireless regulation of appliances and operational procedures. On the other hand, Elene et al., [8] supported that within the domain of logistics and warehousing, Wi-Fi has proven instrumental for companies in streamlining data administration and monitoring assets within warehouse facilities.

Nevertheless, as more devices are connected to the network, the issue of performance due to obstacles and interference has now become an issue. The challenge of interference as highlighted by Gavasin et al., [9] particularly in densely populated areas, emerged as a significant factor contributing to diminished Wi-Fi performance. Several studies have been conducted to examine issues related to the performance of Wi-Fi in industrial environments. Concerns include slow adoption rates due to reliability and determinism issues, susceptibility to interference and multi-path fading effects, and difficulties in effectively supporting distributed real-time control applications. The utilization of unlicensed frequency bands in research conducted by Candell et al., [10] showed results in lower reliability and determinism compared to wired networks, which hinders their acceptance as primary communication method. Furthermore, the presence of disturbances and interference in Wi-Fi networks obstruct reliable communication, rendering them inefficient for supporting real-time control applications. Additionally, according to Cena et al., [11] stringent network planning requirements may lead to increased intra-network interference, even following the implementation of frequency planning algorithms, underscoring the challenges associated with ensuring optimal Wi-Fi performance in industrial environments. To address these issues, a study focusing on the efficacy of the newly introduced unlicensed frequency band, 6GHz, which aims to alleviate interference in high-density areas, is carried out in an industrial context.

2. Methodology

A scientific research methodology is used in conducting this study. It involves four phases which consist of theoretical study, experimental setup, data collection, and analysis and discussion. Fig. 1 shows the research flow used in this study.

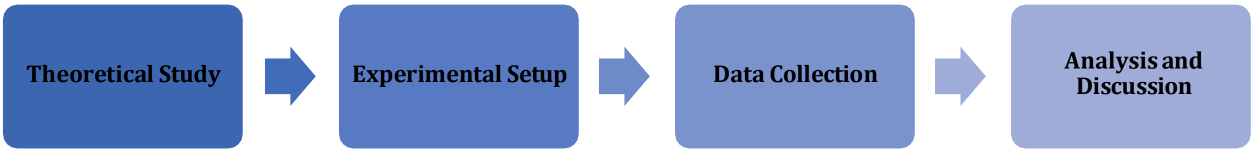


Fig. 1 *Research workflow*

2.1 Theoretical Study

In the theoretical study phase, in-depth examinations of Wi-Fi technologies have been conducted, including current trends, challenges, industrial applications, and existing research. This analysis aimed to identify gaps in the literature. Furthermore, the key parameters and tools for measuring performance have been identified. The results of this phase are discussed in the Introduction Section.

2.2 Experimental Setup

The research location was at the Aiman Printing building. A company that runs a printing business that utilizes many printing machines connected to the network by both wired and wireless. In addition, bundled papers and boxes in the building are expected as the source of obstructions that obstruct the AP from transmitting Wi-Fi signal to wireless printers and all connected wireless computers in the network. This has caused delays in performing business activities.

Before running the experimental setup, a network testing design has been prepared. The experiment has been designed to simulate the environments to suit the aims of the study which is to investigate the effectiveness of the 6GHz unlicensed frequency band in mitigating the obstacle and source of interferences in a densely packed manufacturing environment. The experimental setup was focused on measuring the performance based on frequency bands 2.4GHz, 5GHz and 6GHz.

Fig. 2 illustrates how the hardware setup has been done. During the experiment, the Wi-Fi performance was tested in two scenarios which were Line-of-Sight (LOS) and Non-Line-of-Slight (NLOS). The stations (STA) were positioned in the scenario of; i) behind the obstructed wall, ii) behind the metal-surrounded area, iii) surrounded by sources of wireless interference sources such as cordless phones, and iv) free of obstacle and interference sources. Different scenarios setup gives insight into the effects of obstacles and interference towards the performance of Wi-Fi using 2.4GHz, 5GHz, and 6GHz unlicensed frequency bands. Fig. 3 shows a setup to simulate a LOS environment where the AP was placed on a table and STA was located close to the AP, while Fig. 4 shows the NLOS setup in which the AP was installed at a higher location.

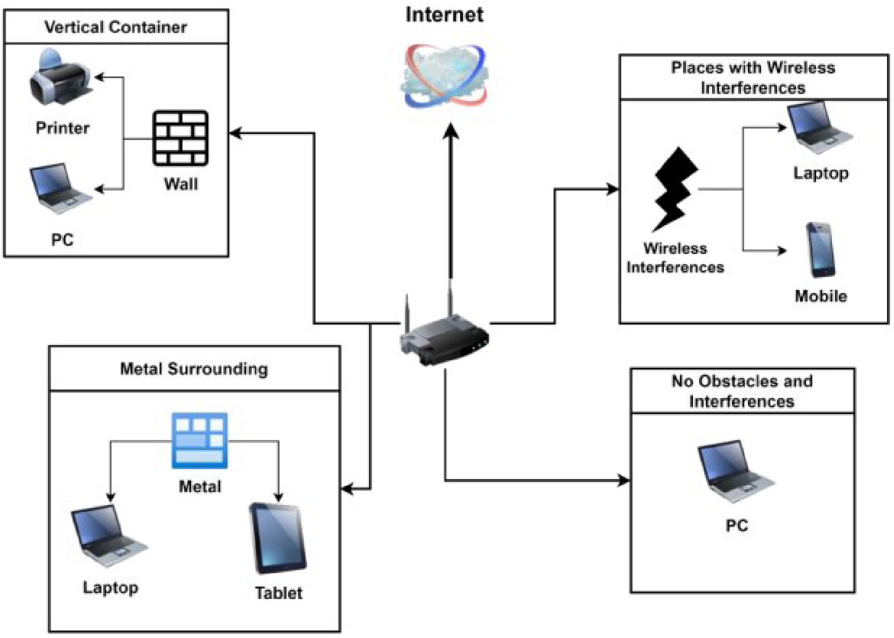
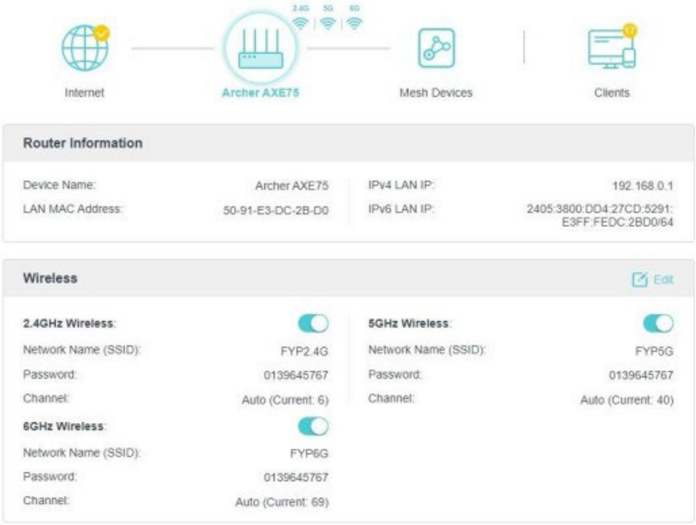


Fig. 2 *Experimental setup*

Fig. 3 *LOS testing scenario*

Fig. 4 *NLOS testing scenario*

Using the Basic Service Set (BSS) network topology, one Tri-Band AP which supports 2.4GHz, 5GHz and 6GHz unlicensed frequency bands has been configured to allow communication between seven end devices which later will be referred to as STA in four different network scenarios. Fig. 5 shows the three different SSIDs configured to represent each unlicensed frequency band, respectively; SSID FYP2.4G, FYP5G and FYP6G. Dynamic IP address has been configured on the AP which also acts as the DHCP server and all STAs are set to obtain IP address automatically from the AP. Suitable network analyser tools have been installed to examine the effect of obstacles and source interference toward the unlicensed frequency band. Table 1 depicts the five tools utilized to measure Wi-Fi performance which were signal strength and latency for all scenarios which are Acrylic Wi-Fi Analyzer, NetSpot and ping utility.



Router Information

Device Name: Archer AXE75
LAN MAC Address: 50-91-E3-DC-2B-D0
IPv4 LAN IP: 192.168.0.1
IPv6 LAN IP: 2405:3800:DD4:27CD:5291:E3FF:FEDC:2BD0/64

Wireless

2.4GHz Wireless:
Network Name (SSID): FYP2.4G
Password: 0139645767
Channel: Auto (Current: 6)

6GHz Wireless:
Network Name (SSID): FYP6G
Password: 0139645767
Channel: Auto (Current: 69)

5GHz Wireless:
Network Name (SSID): FYP5G
Password: 0139645767
Channel: Auto (Current: 40)

Fig. 5 *AP Software setup*

Table 1 *Tools used for testing*

Tools	Measuring
Acrylic Wi-Fi Analyzer	Signal Strength Inference, channel
NetSpot	Wi-Fi Heatmap
Ping	Latency

2.3 Data Collection

Testing has been conducted in both LOS and NLOS environments using 2.4GHz, 5GHz, and 6GHz frequencies. The network analyzer, as shown in Table 1, was used to measure and analyze two key Wi-Fi parameters: signal strength and bandwidth latency. Detailed parameter analysis is provided in the following sub-sections.

2.3.1 Signal Strength

Received signal strength was one of the key performance parameters measured in this study. It is crucial to measure signal strength to ensure optimal coverage and good network performance in the deployment area. As discussed by Aileen *et al.,* [12] in their research, the received signal strength can vary depending on the obstructing materials around the deployment area. Therefore, assessing signal strength before Wi-Fi implementation can help network implementers identify weak signal areas and manage any potential interference in the deployment area.

An investigation of Wi-Fi signal performance in an industrial environment was conducted using two Wi-Fi network analyzers: NetSpot Heatmapper and Acrylic Wi-Fi Analyzer. While both tools serve the same overarching purpose, they focus on different objectives. NetSpot Heatmapper was employed to generate visual heatmaps of Wi-Fi signals in the targeted area, allowing us to identify zones with weak or no signal from the nearest installed access points. Concurrently, Acrylic Wi-Fi Analyzer was used to measure and analyze specific network performance parameters, including signal strength, channel utilization, and security methods. The combined results from these tools facilitated an in-depth analysis of the impact of different frequencies on the industrial network environment. The Acrylic WiFi Analyzer captured Wi-Fi signals 20 times at 10-second intervals. The signal measurements were collected periodically and then averaged. This practice, as proposed by El Khaled et al., [13] aims to reduce the fast-fading effect that happens in Wi-Fi connections. To conduct the signal measurement, the experimental setup considered factors contributing to the received signal strength. Friis Transmission Equation as shown in Eq. 1 is referred to as a reference in determining the factors that affect received signal strength. As shown in Eq. 1, distance *(Dr)* is one factor affecting Wi-Fi received signal strength. Thus, the distance factor has been chosen to determine the performance of Wi-Fi in this study. Table 2 shows the notation of Eq. 1 used as a reference for experimental setup.

$$Prx(dbm) = Ptx + Gtx + Grx + 20\log_{10}\left(\frac{\lambda}{4\pi Dr}\right) \tag{1}$$

Table 2 *Friis transmission equation notation*

Equation Variable	Meaning
Prx	Received Power (dBm)
Ptx	Transmit Power (Watt)
Grx	Received Gain (dB)
Gtx	Transmit Gain (dB)
Dr	Distance between Transmitter and Receiver
λ	Speed of light /frequency

Fig. 6 shows three different distances tested to measure the effect of frequency on the signal strength in the tested environments. The testing was conducted at different distances which were 5 meters, 10 meters, and 15 meters. Based on the designed distances, the Acrylic Wi-Fi Analyzer which was installed in the receiver will detect the Wi-Fi signal. The signal result is shown in unit decibel milliwatt (dBm) where a closer value to zero will indicate a better signal.

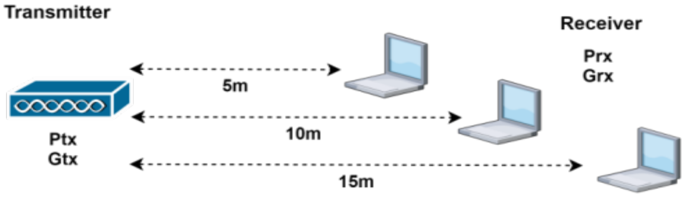


Fig. 6 *Receiving signal strength testing by distances*

As for the heatmap testing, the NetSpot Heatmapper was used. The AP was placed in a position and the NetSpot client walked around at 15 different walking points within the experimental area. The heatmap results were captured. Fig. 7 shows the heatmap result captured using the NetSpot Heatmapper in the targeted areas.

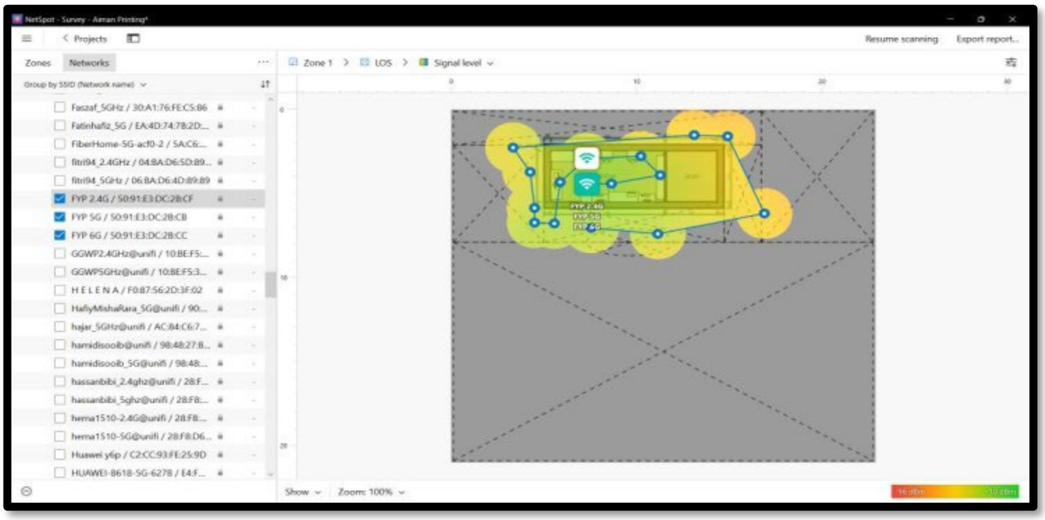


Fig. 7 *NetSpot heatmap testing*

2.3.2 Latency

Latency is the time taken for a data packet to travel from a sender to a receiver. According to Sultan et al. latency indicates responsiveness and performance for real-time applications in a network [15]. Lowering latency can reduce delays and it is important in providing a good user experience. Therefore, when performing Wi-Fi planning, maintaining low latency is crucial to ensure optimal network performance [16]. For this study, the ping command is used to test the latency between AP and STA in both LOS and NLOS environments using 2.4GHz, 5GHz and 6GHz frequency bands. The ping result has been analyzed to see the effect of environments on the frequencies in both NLOS and LOS environments.

2.4 Performance Evaluation and Discussion

Based on collected data in the previous phase, performance analysis based on 2.4GHz, 5GHz and 6GHz is evaluated and analysed. The effect of obstacles based on LOS and NLOS environments on the tested frequency was analysed and discussed. This evaluation will provide valuable insights into the capabilities of Wi-Fi 6E in mitigating interference and obstacles in the tested areas. The results from this study perhaps could be a guideline to network designers in performing Wi-Fi planning which involves Wi-Fi 6E deployments in the industrial environment.

3. Results and Discussion

This section presents Wi-Fi performance from tests conducted across various unlicensed frequency bands; 2.4GHz, 5GHz and 6GHz, highlighting the effectiveness of 6GHz band in mitigating interference and obstruction.

3.1 Signal Strength

Prior to conduct detail investigation on the effect of the frequencies toward the selected industry environment, Acrylic Wi-Fi Analyzer has been utilized to study the current wireless network health by examine the Wi-Fi signal strength in the tested area. Fig. 8 presents a part of Wi-Fi signal strength scanning results from an Acrylic Wi-Fi Analyser, indicating the testing area is congested due to interference from nearby wireless networks. Approximately 50 Wi-Fi connections were detected in the vicinity, categorizing the area as high-density with numerous SSIDs broadcasted on different frequency bands. Within the test environment, as highlighted in a dotted box, the SSID ***FYP_6G***, which uses 6GHz frequency, shows the best signal strength with a reading of -44dBm, while the other SSIDs show low received signal strength readings.

A study by Adam *et al.,* [17] characterized congested Wi-Fi networks as having excessive traffic and interference on their wireless channels, leading to reduced performance and potential connectivity issues for connected devices. This observation aligns with David Plets *et al.,* [18], who noted that high-user-density environments, such as offices or public spaces, exacerbate congestion as multiple devices compete for limited bandwidth. A significant contributor to this congestion is overlapping channels, especially in densely populated areas where many networks operate on the same or adjacent channels. This interference as mentioned by Edward Au *et al.* [1] is more prevalent in the 2.4 GHz band due to its limited non-overlapping channels, compromising signal integrity and reducing throughput.

SSID	#	MAC Address	RSSI	SNR	Channel	Band	Width	802.11	Max. Rate	Retries	WEP
FYP 6G	13	50:91:E3:DC:2B:CC	-44	N/A	97+101+105+...	6GHz	160	ax	2268	0	
Mahat1100_5G	2	C0:C9:E3:D3:47:A7	-80	N/A	36+40+44+48	5GHz	80	a, n, ac	866.7	0	
hamidisoolb_...	9	98:48:27:B8:15:D6	-89	N/A	36+40+44+48	5GHz	80	a, n, ac	866.7	0	
Norakmal 72 ...	12	72:68:CC:CD:A4:A4	-89	N/A	149+153+157...	5GHz	80	a, n, ac, ax	2268	0	
Wi-Fi free	14	5C:A6:E6:7A:CA:1F	-88	N/A	36+40+44+48	5GHz	80	a, n, ac	866.7	0	
HUAWEI-B618...	16	E4:FD:A1:E4:62:7F	-87	N/A	36	5GHz	20	a, n, ac	1300.05	0	
amerjitasha_...	17	64:EE:B7:81:2E:F7	-91	N/A	36+40+44+48	5GHz	80	a, n, ac	866.7	0	
Izzati Azeman...	21	9C:A2:F4:75:0E:8A	-88	N/A	149+153+157...	5GHz	80	a, n, ac, ax	1201	0	

Fig. 8 *Wi-Fi scanning result from acrylic Wi-Fi*

Fig. 9 and Table 3 depict the Wi-Fi signal strength by distances for frequencies 2.4GHz, 5GHz, and 6GHz in the LOS and NLoS environments. In a five-meter distance, for LoS environment, 2.4GHz shows the highest received signal with a reading of -23dBm, followed by 5GHz; -32dBm and the lowest was 6GHz which received -40dBm. For a 10-meter distance, the same trends are shown where 2.4GHz with a reading of -38dBm has the highest received signal strength as compared to 5GHz; -41dBm and 6GHz; -55dBm. The received signal strength for both 5 meters and 10 meters is categorized as excellent as both readings are between -30dBm to -60dBm. Previously, Roziyani et al., [14] categorized the received signal strength with a reading -65dBm as excellent which allows users to conduct many network activities in the industry environment. However, when the distance between AP and the STA was increased to 15 meters, the received signal for all frequencies started to drop where for 2.4GHz, the reading decreased to -52dBm,5Ghz; -59dBm and the most drastic decrease was on 6GHz with reading -81dBm and rated as fair signal strength. The author, Ayman et al., [19] mentioned that the fair rating indicates low signal reception, thus contributing to the unstable network connection which results in low network performance.

As for the NLoS environment, at 5 meters, 2.4GHz shows the highest received signal strength with a reading of -22dBm, followed by 5GHz; -29dBm and the lowest was 6GHz; which received -37dBm. For a 10-meter distance, the received signal strength for all frequencies shows a significant decrease where 2.4GHz received -48dBm, 5GHz received - 49dBm, and 6GHz received -64dBm. In NLoS environments, even though the received signal strength was still excellent, the decreasing value was more drastic as compared to the LoS environment. The reading even worsened when the distance was increased to 15 meters. For 2.4GHz, the received signal strength decreased to -58dBm, followed by 5GHz with a reading of -65dBm and the 6GHz dropped to -82dBm.

Generally, there was a drop in signal strength in the NLOS scenario compared to the LOS scenario. As illustrated in Fig. 2, for NLoS testing, the signal from AP was obstructed by obstacles such as machines made from metal, boxes, papers, and other sources of interference. According to Aileen et al., [12], the received signal strength differs according to the type of materials that the wireless penetrated. That will be the possible reason for the signal degradation that happened in the tested environment. In addition, the results show that as the distance increases, the received signal strength decreases. The measured results reflected the theory of radio rules by

Rappaport et al., [20] where, as the higher the frequency the shorter the transmitter 6GHz has the highest frequency compared to 2.4GHz and 5GHz and with the higher frequency, the susceptibility to interference is increased, therefore signal cannot travel far. Thus, during Wi-Fi planning phase, ifthe6GHzfrequency is proposed to be deployed in the network, the distance between the AP and the STAs should be highly considered.

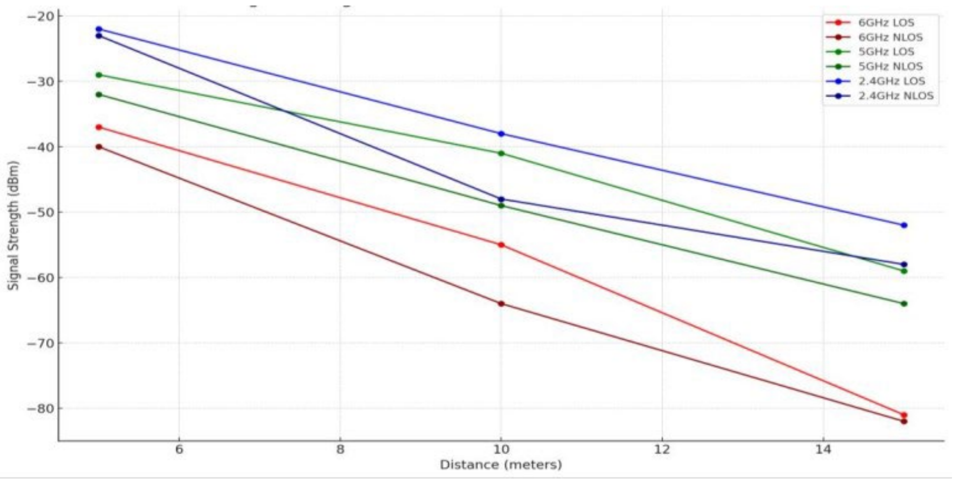


Fig. 9 *Signal strength vs distances by frequencies in LoS and NLoS environments*

Table 3 *Signal strength vs frequencies by LoS and NLoS environments*

Distance (meter)	2.4GHz		5GHz		6GHz	
	LOS	NLOS	LOS	NLOS	LOS	NLOS
5	-22	-23	-29	-32	-37	-40
10	-38	-48	-41	-49	-55	-64
15	-52	-58	-58	-64	-81	-82

The second method of measuring signal strength was using NetSpot Heatmapper. Figs 10, 11 and 12 illustrate the heatmaps of the signal strengths during the experimental phase. Fig. 13 depicts the signal detected when STA is walking around the 15 points. The lowest signal received by the 6GHz AP was during the NLOS test where it only received -76.4dBm at walking point 14 while at walking point 15, no signal was detected. For LOS, an excellent signal still be detected until walking point 15 with -41dBm. Specifically, the 6GHz frequency consistently exhibited stable connectivity despite having the shortest range. Conversely, the 5GHz frequency showcased a moderate range yet displayed instability. The 2.4GHz frequency provided the most expansive coverage area; however, its stability was compromised. Furthermore, the heatmap color-coding system indicates that areas highlighted in red signify poorer signal strength, while green ones denote satisfactory signal quality.

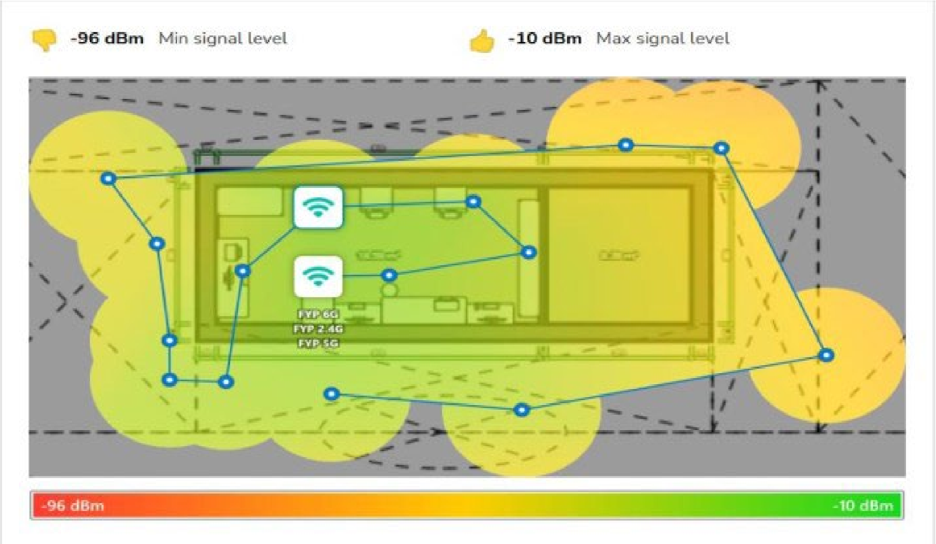


Fig. 10 *Heatmap data for 2.4GHz, 5GHz and 6GHz Wi-Fi signal at tested area*

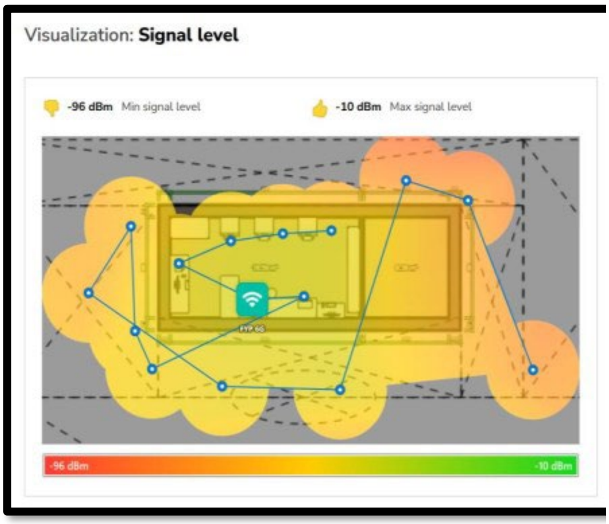


Fig. 11 *Wi-Fi heatmap 6Ghz LOS With 15 walking points*

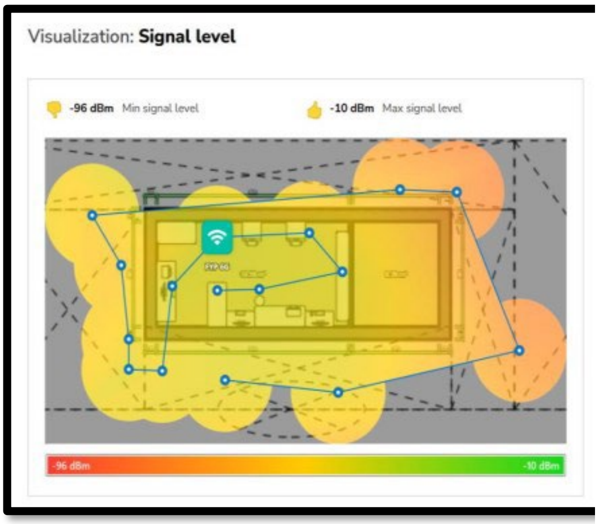


Fig. 12 *Heatmap 6GHz NLOS With 15 walking points*

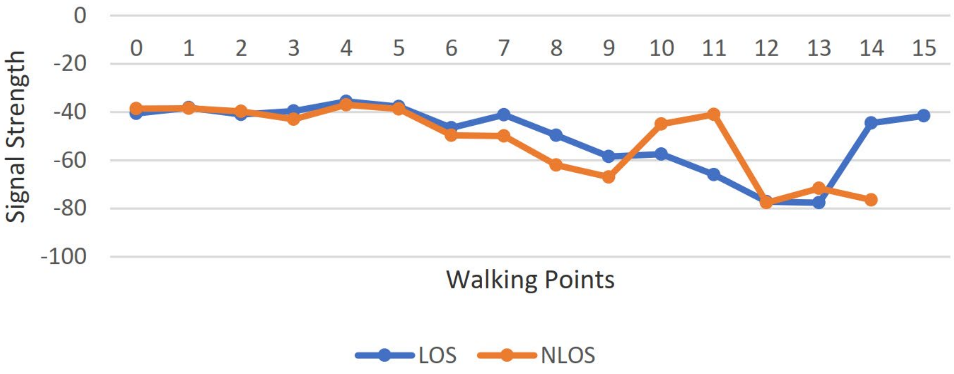


Fig. 13 *6GHz signal strength from heatmap result with 15 walking points*

3.2 Latency

Fig. 14 and Table 3 depict the latency by distances for frequencies 2.4GHz, 5GHz, and 6GHz in the LOS and NLoS environments for distances of 5 meters, 10 meters, and 15 meters. At 5 meters, the 6GHz frequency shows impressive performance with a latency of only 2ms. This low latency sets 6GHz as highly suitable for applications where minimal delay is critical. In contrast, both the 5GHz and 2.4GHz frequencies set are significantly behind, with latencies of 17ms and 19ms respectively. Higher latency means higher time taken for a data packet to travel from a sender to a receiver. At 10 meters, the latency for 6GHz increased to 11ms, while for 5GHz showed lower latency by 10ms. However, the latency tested on the 2.4GHz drastically dropped to 31ms. Lastly, at 15 meters, latency recorded for 6GHz has gradually increased to 23ms and spiked to 30ms for 5GHz. Surprisingly, for 2.4GHz, the latency reading was recorded to be dropped to 9ms. From the results, we can see latency recorded for 5GHz and 2.4GHz was fluctuated and not as stable as 6GHz.

For the NLoS environment, latency for all frequency bands was increased as compared to the LoS environment. In the NLoS environment, even though the distance is the same, due to the obstruction, the time it takes for the signal to reach the targeted STA is increased. At 5 meters, 6GHz shows a latency of 15ms, followed by 5GHz; 32ms, and 2.4GHz; 29ms. While at 10 meters, the latency improved for 6GHz and 5HGz but increased for 2.4GHz by 11ms, 21ms, and 33ms respectively. At 15 meters, the latency keeps increasing for all frequency bands where 6Ghz records 31ms and 35ms for both 5GHz and 2.4GHz.

Overall, in both environments, the latency captured on all frequency bands showed an increasing value as the distance between the AP and the client increases to 10 meters and it even worsens when the distance increases to15 meters. However, at higher distances, 2.4GHz and 5GHz show fluctuating latency as compared to 6GHz. These results highlight the superior latency stability advantage of the 6GHz band over other frequency bands, especially in the NLoS environment. According to *Sufyan et al.,* [21], in the highly dense environment, 6GHz which is employed in Wi-Fi6E shows better performance as the frequency is susceptible to interference which results more stable connection. For 5GHz frequency, at higher distances, it exhibits varying latency values which could be attributed to the interference. While 2.4GHzshows the most unstable latency compared to others. As illustrated in Fig. 2, this area is very highly dense where more than 50 APs are broadcasting their signal in the same vicinity area. This has contributed to the unstable latency recorded for 2.4GHz. Therefore, this observation suggests that although 6GHz offers compelling latency benefits at shorter distances, it exhibits greater vulnerability to signal attenuation as the distance increases.

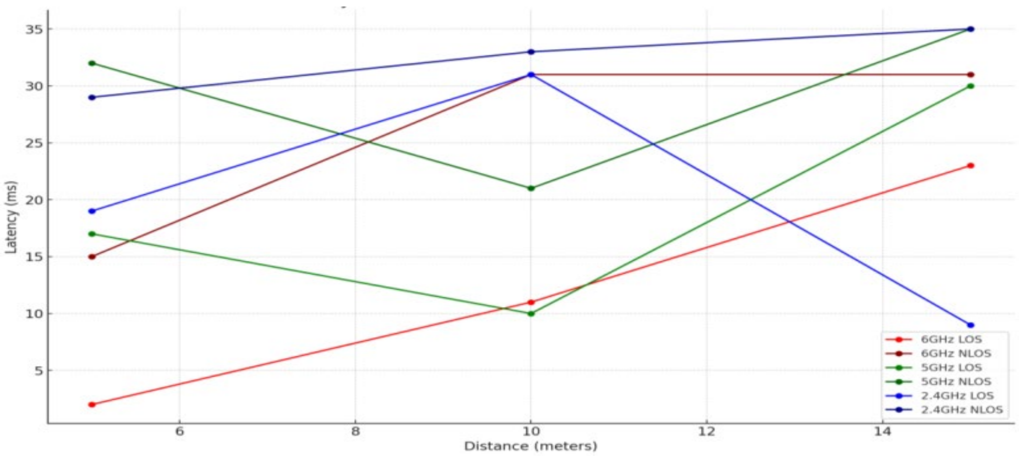


Fig. 14 *Latency vs distance by frequencies in LoS and NLoS environment*

Table 4 *Signal strength Vs frequencies by distance in LoS and NLoS environments*

Distance (meter)	Latency (ms)					
	6GHz		5GHz		2.4GHz	
	LOS	NLOS	LOS	NLOS	LOS	NLOS
5	-22	-23	-29	-32	-37	-40
10	-38	-48	-41	-49	-55	-64
15	-52	-58	-58	-64	-81	-82

Several key observations and conclusions emerge based on the analysis involving latency testing, heatmap data analysis, and performance metrics across 2.4GHz, 5GHz, and 6GHz frequencies. The 6GHz frequency exhibits low latency, particularly at shorter distances in NLOS conditions, but shows susceptibility to interference at longer distances, resulting in notable signal strength degradation. In contrast, the 5GHz and 2.4GHz frequencies demonstrate better resilience to interference and maintain more consistent signal strengths over extended distances.

The heatmap insights show that while the 2.4GHz frequency offers expansive coverage, it suffers stability issues, leading to areas with weaker signal strength. The 6GHz frequency, with limited range, provides stable connectivity yet is vulnerable to interference, while the 5GHz frequency balances coverage and stability but exhibits instability in certain regions. All three frequencies display varying susceptibility to interference, with the 6GHz band being particularly sensitive, despite its latency advantages. The 5GHz band, though more resilient, faces challenges in NLOS scenarios, and the 2.4GHz band contends with interference from household devices and neighboring networks.

While the 6GHz band offers compelling latency benefits, strategic network planning is essential due to interference concerns, while the 5GHz band shows subtle performance, and the 2.4GHz band remains relevant for broader coverage despite limitations. Optimal frequency selection requires understanding interference dynamics, environmental factors, and application requirements, especially considering 6GHz's proximity advantages against interference and 2.4GHz's relevance for broader coverage-centric applications.

4. Conclusions

In conclusion, this research has effectively investigated the effectiveness of the newly introduced Wi-Fi 6E, which operates on the 6GHz frequency band, in mitigating RF interference and obstructions within a densely packed manufacturing environment. The findings indicate that the 2.4GHz band provides the best signal strength across all tested distances. However, the 6GHz band delivers more stable latency in both LOS and NLOS conditions. This leads to a more reliable connection and improved network performance, particularly in high-density manufacturing areas. Therefore, when deploying Wi-Fi 6E in such environments, optimal placement of access points is essential to ensure enhanced performance throughout the deployment areas.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception, methodology, and design:*** *Roziyani Rawi, Muhamad Za'im Afham Zainal Abidin, Noormadinah Allias;* ***data collection:*** *Muhamad Za'im Afham Zainal Abidin, Roziyani Rawi;* ***analysis and interpretation of results:*** *Roziyani Rawi, Noormadinah Allias;* ***draft manuscript preparation:*** *Roziyani Rawi, Muhamad Za'im Afham Zainal Abidin , Nur Farahwahida Ab Aziz; Manuscript* ***review, intellectual content and supervision:*** *Mohd Rizal Mod Isa, Mohd Nazri Ismail;* ***supervision:*** *Mohd Rizal bin Mohd Isa, Mohd Nazri Ismail, Aznida Abu Bakar Sajak, Nur Diyana Kamarudin. All authors reviewed the results and approved the final version of the manuscript.*

References

[1] Au, E., Wilhelmsson, L., Baykas, T., & Kim, J. (2022) Guest editorial: recent and future evolution of Wi-Fi. *IEEE Communications Standards Magazine*, *6*(2), 8-11, https://doi.org/10.1109/MCOMSTD.2022.9855241

[2] Pahlavan, K., & Krishnamurthy, P. (2021). Evolution and impact of Wi-Fi technology and applications: A historical perspective. *International Journal of Wireless Information Networks*, *28*, 3-19, https://doi.org/10.1007/s10776-020-00501-8

[3] Cisco, U. (2020). Cisco annual internet report (2018–2023) white paper. *Cisco: San Jose, CA, USA*, *10*(1), 1-35.

[4] Natkaniec, M., & Bieryt, N. (2023). An Analysis of the Mixed IEEE 802.11 ax Wireless Networks in the 5 GHz Band. *Sensors*, *23*(10), 4964, https://doi.org/10.3390/s23104964

[5] Rawi, R., Isa, M. R. M., Ismail, M. N., Sajak, A. A. B., & Sulaiman, M. A. M. (2022, July). A survey: Readiness of Malaysian higher education institutes towards the adaptations of industry revolution 4.0. *2022 1st International Conference on Information System & Information Technology (ICISIT)* (pp. 267-271), https://doi.org/10.1109/ICISIT54091.2022.9872852

[6] Srinivasarao, P., Saiteja, K. V., Prudhviraj, K., Reddy, N. P., & Tejaswini, R. (2018). Industrial device control using Wi-Fi module. *Iconic Research and Engineering Journals (IRE)*, *1*.

[7] Konikov, A. (2020). Promising wireless applications in the construction industry. *E3S Web of Conferences* (164), 10043, https://doi.org/10.1051/e3sconf/202016410043

[8] Kokoreva, E., Shurygina, K., & Bragin, A. (2022). Impact of Wi-Fi network coverage planning on the logistics objects' location accuracy. *E3S Web of Conferences* (363), 01041, https://doi.org/10.1051/e3sconf/202236301041

[9] Gadasin, D. V., Shvedov, A. V., & Vakurin, I. S. (2020, March). Designing WI-FI wireless networks with high density of subscriber service. *2020 Systems of Signals Generating and Processing in the Field of on Board Communications,* 1-4, https://doi.org/10.1109/IEEECONF48371.2020.9078567

[10] Candell, R., Hany, M. K., Perez-Ramirez, J., & Conchas, J. (2023). An IEEE Standard for Industrial Wireless Performance Evaluation. *IEEE Internet of Things Magazine*, *6*(1), 82-88, https://doi.org/10.1109/IOTM.001.2200069

[11] Cena, G., Scanzio, S., & Valenzano, A. (2016). Seamless link-level redundancy to improve reliability of industrial Wi-Fi networks. *IEEE Transactions on Industrial Informatics*, *12*(2), 608-620, https://doi.org/10.1109/TII.2016.2522768

[12] Aileen, A., Suwardi, A. D., & Prawiranata, F. (2021). Wifi signal strength degradation over different building materials. *Engineering, MAthematics and Computer Science Journal (EMACS)*, *3*(3), 109-113, https://doi.org/10.21512/emacsjournal.v3i3.7455

[13] El Khaled, Z., Ajib, W., & Mcheick, H. (2022). Log distance path loss model: Application and improvement for sub 5 ghz rural fixed wireless networks. *IEEE Access*, *10*, 52020-52029, https://doi.org/10.1109/ACCESS.2022.3166895

[14] Rawi, R., Isa, M. R. M., Ismail, M. N., Sajak, A. A. B., & Yahaya, Y. H. (2024). Predictive Wireless Received Signal Strength Using Friis Transmission Technique. *JOIV: International Journal on Informatics Visualization*, *8*(2), 983-990, https://dx.doi.org/10.62527/joiv.8.2.2178

[15] Sultan, J. M., Osmadi, I. A., & Manap, Z. (2022). Real-time Wi-Fi network performance evaluation. *International Journal of Informatics and Communication Technology*, *11*(3), 193-205, https://doi.org/10.11591/ijict.v11i3.pp193-205

[16] Rawi, R., Isa, M., Ismail, M., Sajak, A. A. B., Zamrol, A., Osman, M., F. Maskat, K., Putra Ahmad Baidowi, Z. M., & Kamarudin, N. D. (2024) Predicting Latency and Signal Strength in Wifi Network Using Queuing Technique. *Journal of Engineering Science and Technology, 19(2),* 222-235.

[17] Adams, A., Obrecht, R. F., Wilt, M., Barcklow, D., Blitz, B., & Chew, D. (2022). Persistent Weak Interferer Detection in WiFi Networks: A Deep Learning Based Approach. *arXiv preprint arXiv:2205.11360*, https://doi.org/10.48550/arXiv.2205.11360

[18] Plets, D., Tanghe, E., Paepens, A., Martens, L., & Joseph, W. (2016). WiFi network planning and intra-network interference issues in large industrial warehouses. *2016 10th European Conference on Antennas and Propagation (EuCAP),* 1-5, https://doi.org/10.1109/EuCAP.2016.7481517

[19] El-Saleh, A. A., Alhammadi, A., Shayea, I., Hassan, W. H., Honnurvali, M. S., & Daradkeh, Y. I. (2023). Measurement analysis and performance evaluation of mobile broadband cellular networks in a populated city. *Alexandria Engineering Journal*, *66*, 927-946, https://doi.org/10.1016/j.aej.2022.10.052

[20] Rappaport, T. S., MacCartney, G. R., Samimi, M. K., & Sun, S. (2015). Wideband millimeter-wave propagation measurements and channel models for future wireless communication system design. *IEEE transactions on Communications*, *63*(9), 3029-3056, https://doi.org/10.1109/TCOMM.2015.2434384

[21] Sufyan, A., Khan, K. B., Khashan, O. A., Mir, T., & Mir, U. (2023). From 5G to beyond 5G: A comprehensive survey of wireless network evolution, challenges, and promising technologies. *Electronics*, *12*(10), 2200, https://doi.org/10.3390/electronics12102200