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Path Loss of Indoor Hotspot and Indoor Factory Environments for 5G Wireless Networks

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Abstract

The increased exploration of wireless communication networks in various fields has significant implications for automating daily human tasks and creating smart environments. However, to make such implementations successful, it is essential to investigate the characteristics of wireless channels. Path loss is a fundamental factor in wireless network communications and measures signal strength. The main objective of this proposal is to identify the criteria to be considered when designing and developing wireless sensor network WSN applications for indoor hotspot (InH) and indoor factory (InF) environments. This research investigates the 3GPP Indoor model in (InH) and (InF) environments. It considers the impact of Line-of-Sight (LOS), Non-Line-of-Sight (NLOS), and human blockage on path loss. Further, the InH scenario has been compared to the InF scenario. The results show that path loss in NLOS conditions is more variable than in LOS conditions, regardless of the human obstruction. In general, the results demonstrate the difference in path loss between InH and InF scenarios falls within a range of 9.1275–7.175 dB.

Keywords: Computer Networks; Indoor Factory (InF); Indoor Hotspot (InH); Path Loss; Wireless Network and communications

1. Introduction

Wireless sensor networks (WSNs) applications may be applied in military, agriculture, industry, healthcare, and environmental monitoring. Each WSN application has its own specific needs, difficulties, and limitations. For example, an agricultural WSN application needs to monitor soil moisture levels, and a healthcare WSN application needs to keep track of patient vital signs. Thus, optimizing the design and development of WSN applications to meet the demands of various applications is significant. These needs determine the requirements of the hardware, protocols, and network architectures of WSN to achieve the efficient performance of its applications [1]-[3]. Path loss is critical because it directly influences the network's performance and lifetime. The signal suffers attenuation as it passes through the environment because of obstacles, distance, interference, and the propagation medium itself. Weaker received signals due to path loss, which may lead to communication failures, decreased signal quality, and an increased risk of noise. Overcoming this requires using higher transmission power by the nodes to establish reliable communication links. Transmitting at higher power levels consumes more energy, significantly impacting the nodes' battery life and overall network lifetime. Hence, path loss directly impacts link quality, energy efficiency, and network lifetime. Accurate path loss modeling and effective mitigation strategies are essential for achieving reliable and efficient wireless communication in WSN applications [4]-[7].

In general, path loss in wireless communication results from the signal's attenuation as it propagates through the wireless medium. Some of the common factors contributing to path loss include LOS, NLOS, human blockage, and the surrounding environment.

The indoor factory environment (InF) encompasses settings where various industrial activities occur, such as manufacturing, mining, chemical processing, and more in these environments. The main objective of such an environment is production efficiency, which includes enhancing productivity, reducing downtime, and optimizing processes to improve overall operational efficiency [8]. The InF environment generally connects people, products, machines, industrial control, and information systems [9]. Applying automation in InF involves using technology to automate manufacturing facility processes. This includes robotics, sensors, IoT devices, data analytics, and more.

Implementing wireless technology in a manufacturing or industrial setting might be challenging because the nature of the manufacturing environment presents several radio propagation problems. Industrial wireless channels face many challenges associated with designing communication systems, for instance, obstructing the direct line of sight between communication nodes, reflective obstacles caused by surfaces made of metal and concrete, and electromagnetic interference (EMI) with radio frequency interference (RFI) that could be generated by machinery and equipment used in industrial environments [10],[11].

The 5G technology offers several advantages that suit these applications, such as low latency, high bandwidth, and reliability [12],[13]. 5G mobile telecommunications offers superfast broadband with no need for landlines, facilitating the creation of smart factories. By leveraging the capabilities of 5G, industrial environments can achieve higher levels of automation, monitor assets in real-time, optimize supply chains, and even enable technologies like augmented reality (AR) for remote assistance and maintenance tasks. This can lead to reduced downtime and increased productivity and ultimately contribute to the growth and evolution of various industries [14]-[16].

Previous research often conducted theoretical analyses to estimate the path loss exponent, which describes the rate at which signal power decreases with distance. Although these theoretical analyses are valuable for understanding the fundamental behavior of path loss, they may not account for practical measurements and real-world environmental conditions. This research investigates 5G technologies, including millimeter wave propagation, in an indoor environment characterized by various capacities attributed to using different models. It presents an analysis of the study of path loss in wireless communication in both environments (InH and InF). Further, it proposed six practical models to investigate the performance of 5G in an indoor environment. A comparison has been demonstrated between the InH and InF scenarios to examine the additional impact of environment and human blockage on path loss.

This proposal aims to examine the path loss in conditions of InH and InF based on 5G to clarify and determine the requirements and specifications of WSN applications in the InF environment. Thus, developers will become aware of these needs to be considered when developing InH and InF applications.

The rest of this research is organized as follows: Section 2 reviews related work. Section 3 presents the path loss model. Section 4 presents simulated models and results. Section 5 highlights the conclusion.

2. Related Work

Overall, research and analysis of path loss in wireless communication, including WSNs, play a crucial role in optimizing the design and performance of wireless systems and applications by considering real-world conditions and practical measurements. It helps develop reliable communication protocols, efficient network planning, and resource allocation for various wireless applications.

Abrishambaf et al. [17] introduced an experimental analysis of path loss exponents, shadowing effects, and their impact on Received Signal Strength Indicator (RSSI) measurements, which play a crucial role in wireless communication systems. These factors determine how the signal strength changes over distance and in different environments. Each of these aspects has been looked at in three different environments: free space, indoor (building), and industrial. The authors compare the obtained results to the available results in the theoretical analysis of the literature.

In [18], Elmezughi et al. measured propagation over three frequency bands in an inside corridor setting: above 6 GHz: 14 GHz, 18 GHz, and 22 GHz. These measurements were taken for both LOS and NLOS. The purpose of the study was to develop wireless channel models that take the effects of frequency and distance into account and to compare the effectiveness of two path loss prediction models: the single-frequency floating intercept (FI) model and the single-frequency close-in (CI) free space reference distance model. In all the implemented frequencies, the produced models of CI and FI have the same results as those of LOS. The CI model increased the path loss exponent (PLE) at the higher frequencies.

El Hajj et al. [19] examined the impact of different types of antennas and their positioning on the response of a wireless channel angular impulse in an indoor environment. It aims to determine the main requirements for installing wireless personal area networks and local networks (WPANs and WLANs) to achieve optimal performance and coverage.

Abdulwahid et al. [20] analyzed the performance of two different frequency bands: the C-band and the millimeter-wave band. The study focused on two different propagation scenarios: LOS and NLOS within an indoor environment. The results showed the fundamental relationship between signal intensity and distance. The correlation between path loss and separation distance controls it.

Al-Samman et al. [21] conducted a study involving ultra-wideband channel measurements within millimeter-wave frequency bands. They specifically investigated 19 GHz, 28 GHz, and 38 GHz frequencies. The study employed an ultra-wideband channel sounder with a 1 GHz bandwidth to perform measurements in an indoor-to-outdoor environment, focusing on the NLOS scenario. The study's results led the authors to conclude that specific time delays, represented in nanoseconds (ns), were reliable for 5G systems in short-range applications. These time delays were noted as 26.1 ns, 25.8 ns, and 27.3 ns for the frequencies 19 GHz, 28 GHz, and 38 GHz, respectively.

In [22], Sun et al. presented a study investigating indoor environments' multipath effects. The primary aim was understanding how multipath propagation impacts signal behavior in NLOS scenarios. The study explained the reflection effect on received power, which was more noticeable in indoor NLOS environments than the diffraction effect.

Bian et al. [23] presented a study that examines the propagation of 60 GHz waves in a corridor environment. It has employed the shooting and bouncing ray tracing/image (SBR/image) method to analyze the behavior of the investigated waves. The study focused on propagation features in LOS and NLOS scenarios.

Aldossari [24] has introduced a methodology that aims to predict path loss using artificial intelligence and data-driven techniques. It has been applied in an indoor environment, and the obtained results showed an accuracy of 97.4%.

In [25], Samad et al. studied radio propagation and path loss in a staircase environment. Four path loss models have been employed to evaluate and analyze the path-loss characteristics. The models utilized were the alpha-beta model, the close-in-free-space reference distance model with frequency weighting, the alpha-beta-gamma model, and the close-in-free-space reference distance model. The study aims to understand the performance of these different models in this specific environment and to compare their outcomes. The study revealed specific path loss results for the alpha-beta model in the 3.7 GHz and 28 GHz bands. The path loss exhibited a difference of 1.29 dB at 3.7 GHz and 6.48 dB at 28 GHz between the measured and predicted values using the model. Additionally, it was noted that the path loss standard deviations found in this study were lower than those found in other investigations.

All the aforementioned research presented various studies on path loss in indoor environments, considering many conditions such as millimeter wave band, path loss model, LOS, and NLOS. This research investigates using a wireless network in InF as it guarantees automation results in enhanced productivity and reduces downtime. It also identifies the challenges that face this process as the InF environment is complex enough to implement a wireless network smoothly. The INF environment includes various obstacles, including machines, people, and sharp edges, that influence signal propagation and cause path loss. This study evaluates how 5G technologies, with their advanced features such as beamforming and higher frequency bands, affect path loss in an indoor factory environment. Compare these effects between InF and InH environments. Further, it studies the characteristics of the indoor factory environment in terms of obstacles and reflections that impact the propagation of 5G signals. This involves studying LOS and NLOS scenarios with the existence and absence of human blockage.

3. Path Loss Model

Many factors influence the transmitted signal, such as NLOS and weather. Fig. 1 shows the influenced factors.

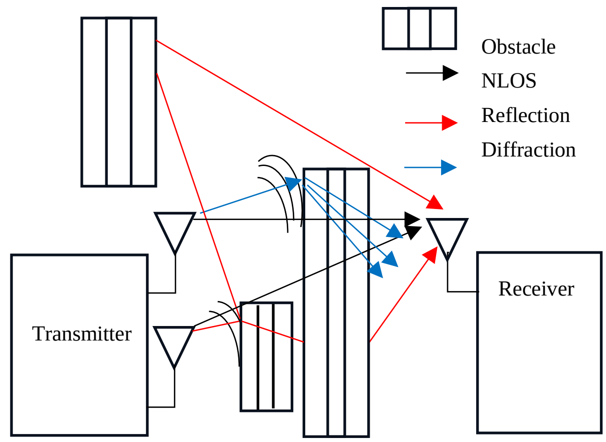

Figure 1. The Potential Losses Affecting the Transmitted Signal

The path loss model measures the signal strength as it travels wirelessly between nodes for a specific distance. It has a direct impact on designing and developing wireless communication. Besides, it studies the signal strength and its changes regarding distance and other impact factors. The close-in free space reference distance (CI) path loss model is commonly implemented for estimating path loss in wireless communication networks. This model considers the availability of (LOS) and (NLOS) in an indoor environment. The CI model has been defined using the distance between the sender and the receiver. It is typically used at 1 meter (the close-in reference distance), where the received power is measured. This distance has been chosen to simplify calculations and offer a simple formula for path loss estimation. One of the factors included in the CI model is free space attenuation. Equation 1 represents the free space path loss expressed using equation 2 and the close-in free space reference distance (CI) path loss model. [26]-[29].

$$\mathrm{PL}^{CI}(f,d)[dB] = FSPL(f,1\,m)[dB] + 10n\log_{10}\left(\frac{d}{d_0}\right) + AT[dB] + X_\sigma^{CI} \quad (1)$$

Where d ≥ d_0 m

$$FSPL(f,1\,m)[dB] = 10n\log_{10}\left(\frac{4d\pi}{\lambda}\right)^2$$

Where,

$$\lambda = \frac{c}{f}$$

So,

$$FSPL(f, 1\,m)[dB] = 10nlog_{10}\left(\frac{4\pi df}{c}\right)^2 \quad (2)$$

Where,

FSPL: Free Space Path Loss (in decibels, dB)

d: Distance between the transmitter and receiver (in meters)

λ: Wavelength of the signal (in meters, calculated as λ = c / f)

f: Frequency of the signal (in Hertz)

c: Speed of light in a vacuum (approximately 2.99792458 × 10^8 meters per second)

AT: the attenuation term induced by the atmosphere, accounting for factors like absorption, scattering, and molecular effects.

X_σ^{CI}: a zero-mean Gaussian random variable with a standard deviation σ in dB. It represents the large-scale shadow fading, where f denotes the carrier frequency in GHz, d is the 3D distance between T and R, n denotes the path loss exponent (PLE), and d_0 represents the free space reference distance in meters, which is set to 1 for the carrier frequency f, where c is the speed of light [27].

4. Simulated Model and Results

Path loss, the signal's attenuation or weakening as it travels through the environment, is a crucial component in wireless communication systems. Four simulated models have been proposed to implement path loss propagation models for each InF and InH scenario. The four models consider three important factors: LOS, NLOS, and human blockage. These factors can significantly affect the indoor environment's path loss and overall signal strength. The four proposed models aim to analyze the impact of LOS, NLOS, and human blockage on path loss regarding the distance that separates the transmitter and receiver. Additionally, it demonstrates a comparison between the InF and InH scenarios. Fig. 2 presents an example of an InF environment.

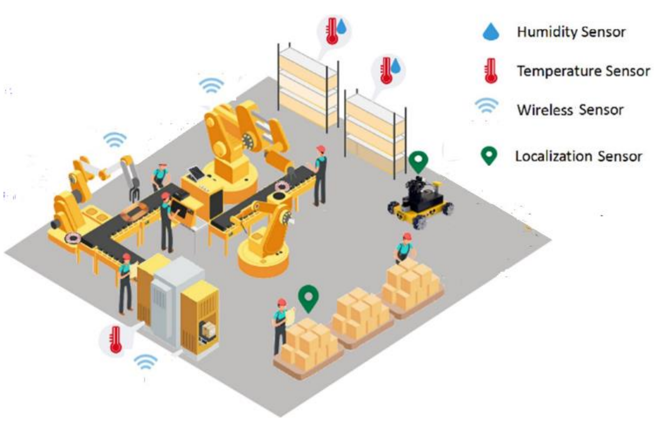

Figure 2. InF environment

Tables 1 and 2 present the simulation and human blockage parameters, respectively.

Table 1. Simulation Parameters

NO.	Parameter	Value
1.	Frequency	28 GHz
2.	RF Bandwidth	800 MHz
3.	Distance range between Transmitter and Receiver	(10 – 50) meter
4.	High difference between the Transmitter and Receiver	(1.5) meter
5.	Humidity	50%
6.	Temperature	20 °C
7.	Simulation number	40

Table 2. Human Blockage Parameters

NO.	Parameter	Value
1.	Mean Attenuation	14.4 dB
2.	Transmission Rate from Unshadow to Decay	0.2 second
3.	Transmission Rate from Unshadow to Shadow	8.1 second
4.	Transmission Rate from Shadow to Rise	7.8 second
5.	Transmission Rate from Rise to Unshadow	6.7 second

Each model has been applied when there is a human blockage and when there is not.

Fig. 3 and Fig. 4 demonstrate the InF and InH scenarios when there is LOS with human blockage and without human blockage, respectively.

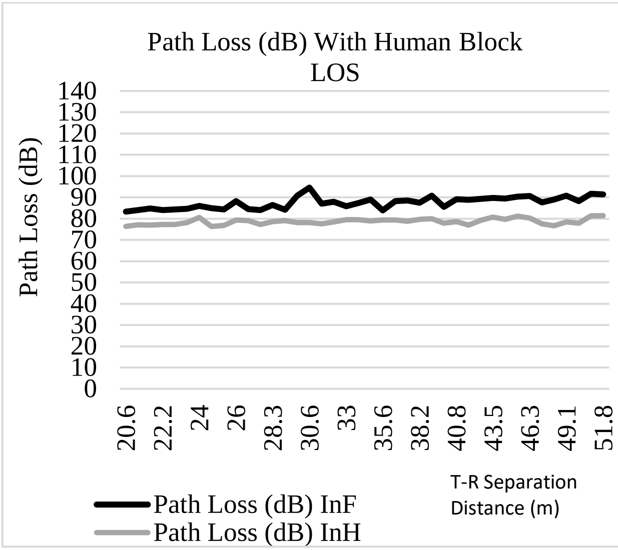

Figure 3. The Path Loss in InH and InF environments with LOS and Human Block

In both InF and InH scenarios, LOS between the transmitter and receiver can result in lower path loss than NLOS conditions. LOS propagation generally has fewer obstacles, allowing the signal to travel more directly between the devices, resulting in less attenuation.

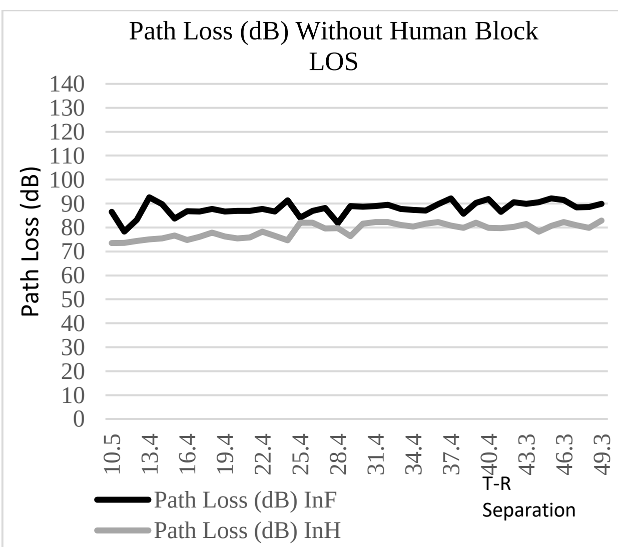

Figure 4. The Path Loss in InH and InF environments with LOS and without Human Block

The path loss in the InF scenario is more significant than the InH scenario in all the simulated T-R separation distances. In both scenarios, the path loss with human blockage is more important than without.

In the InH scenario, human blockage becomes a critical factor that can further attenuate the signal. This effect is significant at millimeter-wave frequencies, which are increasingly used in indoor environments for high data rates.

Fig. 5 and Fig. 6 elucidate the scenarios of InF and InH in the NLOS condition with and without human blockage, respectively. The path loss fluctuates in the InF and InH scenarios with and without human blockage. The path loss in the InF scenario is greater than that in the InH scenario. In a typical InF scenario, the signal propagation is affected mainly by the presence of machines, walls, furniture, and other indoor objects.

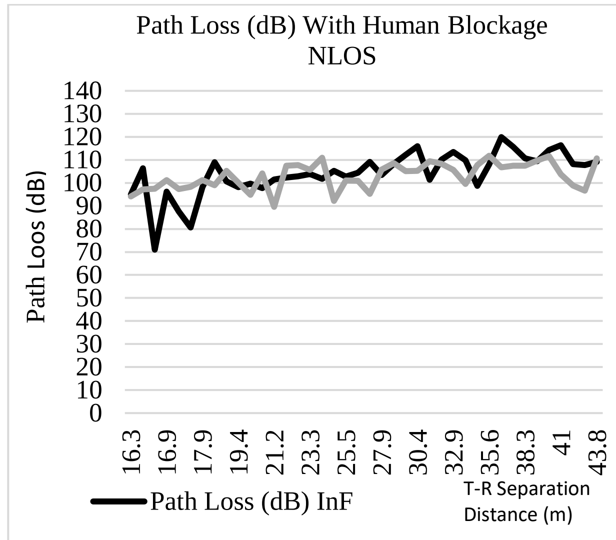

Figure 5. The Path Loss in InH and InF environments with NLOS and Human Block

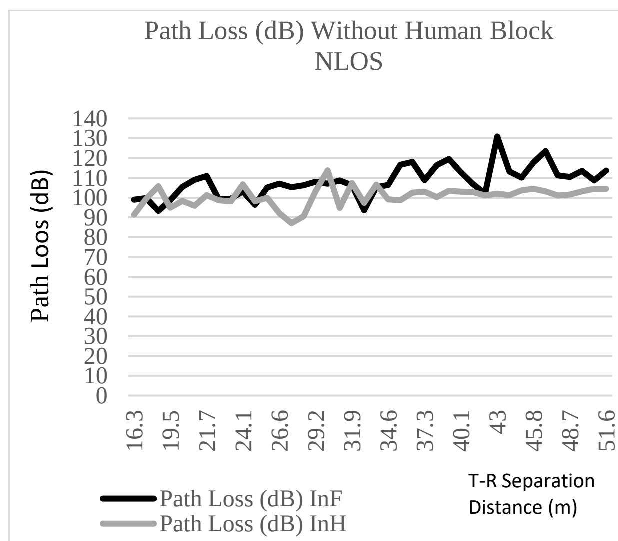

Figure 6. The Path Loss in InH and InF environments with NLOS and without Human Block

However, in the InH scenario, the presence of humans introduces dynamic blockages that can change rapidly over time.

Fig. 7 shows the average difference in path loss between InH and InF environments, which ranges from 9.1275 to 7.1975 dB.

This explains the behavior of sensors in the InH and InF environments and highlights the difference in path loss between them, which researchers and engineers must consider when designing and developing applications and protocols for these environments.

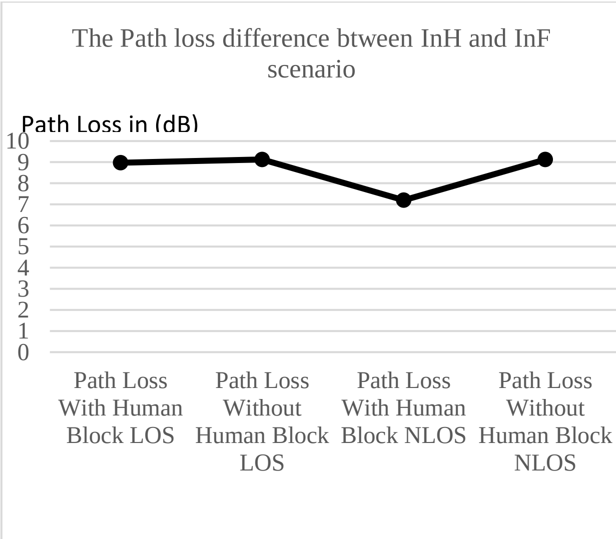

Figure 7. The Path Loss Average Difference between InH and InF Environments

Tables 3 and 4 compare the proposal results with the research in [20] in both LOS and NLOS conditions, respectively. The comparison considers delayed spread, path loss, and received power. Differences in implemented parameters, such as the distance between the transmitter and receiver, result in differences in the obtained values. In addition, the model in the study of [20] was applied to a building that includes more than one floor and was established using a variety of building materials.

Table 3. Comparison Between The Proposal and Study In [20] (Los)

Parameter	Ranges Of This Study	Ranges Of Study [20]
Delayed Spread (NS)	0 – 26	0 – 35
Path Loss (DB)	50 - 90	90 -130
Received Power (DBM)	(-40) – (-55)	(-40) – (-80)

Table 4. Comparison Between The Proposal Results And Study In [20] (Nlos)

Parameter	Ranges Of This Study	Ranges Of Study [20]
Delayed Spread (NS)	0 – 50	0 – 14
Path Loss (DB)	60 - 120	150 – 250
Received Power (DBM)	(-50) – (-90)	(-100) – (-250)

5. Conclusion

This research investigates and analyzes the path loss of 5G wireless networks in indoor environments. It considers various factors such as LOS, NLOS, and human blockage. It has been proposed that four different simulated models be used at a frequency of 28 GHz, with varying distances between the sender and receiver ranging between 10 and 50 meters. In addition, it examines the impact of weather conditions such as humidity and temperature. The simulator, Nyusim, was used to implement the four suggested models. The obtained results have revealed several indications. First, the path loss in the InF environment is higher compared to the InH environment. This may be explained by the presence of obstacles and machines in operation. Second, path loss increases along with the transmitter and receiver's distance from one another. This is common in wireless communications, where signal strength decreases with distance. Third, in the LOS situation, the path loss in InF is more significant than that in InH. This results from current obstructions and human body parts in the InF environment, causing blockage and signal absorption. However, in the NLOS case, the path loss fluctuated in both the InF and InH scenarios because the NLOS conditions are more complex and variable. Fourth, the average variance of path loss in all cases was between 9.1275 dB and 7.1975 dB. This indicates the variability in the signal strength, and it is significant to consider these variations in network development and design.

The results of this research were important for enhancing network design and deployment techniques. In addition to understanding the issues and benefits of deploying 5G networks in both InF and InH environments, considering weather conditions, such as humidity and temperature, can contribute to more accurate modeling of real-world scenarios. As a result, this study presents the main measurements that influence the WSN application performance in the InH and InF environments. The developers must consider these measurements.

Conflict of interest

The authors have no conflicts of interest in the publication of this manuscript.

Author Contribution Statement

Intisar SH. Al-Mejibli contributed to the design and implementation of the research.

Hussein A. Mohammed and Haider Kadhim Hoomod contributed to analyzing the results and the manuscript writing.

All authors contributed to the validation and final writing of the manuscript.

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