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An Enhancement of Log Normal Shadowing Model to Estimate 5G Propagation Path Loss for the Indoor Environment

Ahmed. H. Bin Alabish [#1], Hana Ali Mohammed [*2], Manal Abraheem Ghoumah [*3], Ali S Dowa [#4] , Amer Daeri, S.[*5]

[1,2,3] Computer Department, Libyan Higher Education Academy - Tripoli, Libya
[4] Faculty of Education, University of Zawia, Libya
[5]Faculty of Engineering, University of Zawia, Libya and IEEE Member

[1]ahmed.cs@academy.edu.ly, [2]hana.elmehdi@gmail.com, ,
[3]manalgoma90@gmail.com
, [4]ali.dowa@zu.edu.ly, [5]amer.daeri@zu.edu.ly

Abstract

This paper presents a comprehensive study of modelling human body blockage (the most critical challenges in fifth-generation (5G)) effects on indoor millimetre wave (mmWave) communication links at 32.5 GHz, a key frequency for 5G networks. Through controlled experiments in a laboratory environment, we analyse signal attenuation as a human subject obstructs the line-of-sight (LOS) path between transmitter and receiver, recording received power at incremental positions. To model the observed phenomena, we propose a hybrid framework integrating deterministic and statistical components: (1) a modified Double Knife-Edge Diffraction (DKED) model with Gaussian-shaped blockage attenuation (20.8 dB peak at full blockage) and reflection-induced signal enhancement (−15.0 dB peak from nearby objects), and (2) a log-normal shadowing component (σ = 11.8 dB) capturing environmental randomness. Our results reveal strong agreement between simulations and measurements, achieving a mean absolute error of 3.2 dB and a correlation coefficient $R^2 = 0.89$. The analysis demonstrates that human-induced diffraction dominates near the LOS centre, while multipath reflections significantly alter signal strength at peripheral positions. We further derive practical guidelines for 5G network design, recommending a 44.4 dB link budget safety margin to account for combined blockage and

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shadowing effects. This work advances indoor mmWaves channel modelling by unifying physics-based diffraction analysis with empirical reflection characterization, the framework achieves strong experimental validation and offers actionable insights for 5G network design.
Keywords*:* mmWaves, blockage, DKED, attenuation, shadowing

تحسين نموذج التظليل الطبيعي اللوغاريتمي لتقدير فقدان مسار انتشار G5 في البيئة الداخلية

أحمد حسن بن الابيش[#1]، هناء محمد علي[2*]، منال إبراهيم غومه[3*]، علي سالم دوه [4#]، عامر الدائري[5*]

1،2،3– قسم الحاسوب، الاكاديمية الليبية – طرابلس – ليبيا
4– كلية اعداد المعلمين، جامعة الزاوية – ليبيا
5– كلية الهندسة، جامعة الزاوية – ليبيا– وعضو في IEEE

[3]manalgoma90@gmail.com, [4]ali.dowa@zu.edu.ly, [5]amer.daeri@zu.edu.ly

الملخص

تقدم هذه الورقة دراسة شاملة لنمذجة تأثيرات انسداد جسم الإنسان) الذي يُعدّ من أهم التحديات في الجيل الخامس ((5G) على روابط الاتصالات الداخلية بالموجات المليمترية (mmWave)عند تردد 32.5 جيجاهرتز، وهو تردد أساسي لشبكات الجيل الخامس. من خلال تجارب مُحكمة في بيئة مختبرية، نُحلل توهين الإشارة عندما يُعيق شخص مسار خط البصر (LOS) بين المُرسِل والمُستقبِل، مع تسجيل الطاقة المُستقبَلة في مواقع متزايدة. لنمذجة الظواهر المُلاحظة، نقترح إطارًا هجينًا يدمج المكونات الحتمية والإحصائية: (1) نموذج حيود مزدوج ذو حدّين مُعدّل (DKED) مع توهين انسداد على شكل غاوسي (ذروة 20.8 ديسيبل عند الانسداد الكامل) وتعزيز الإشارة المُستحث بالانعكاس (ذروة −15.0 ديسيبل من الأجسام القريبة)، و(2) مُكوّن تظليل لوغاريتمي عمودي ($\sigma = 11.8$) ديسيبل (لالتقاط العشوائية البيئية. تُظهر نتائجنا توافقًا قويًا بين عمليات المحاكاة والقياسات، محققةً متوسط خطأ مطلق قدره 3.2 ديسيبل ومعامل ارتباط $R^2 = 0.89$. يُظهر التحليل أن الانعراج الناتج عن النشاط البشري يُهيمن بالقرب من مركز خط البصر، بينما تُغير انعكاسات المسارات المتعددة قوة الإشارة بشكل كبير في المواقع الطرفية. كما نستمد إرشادات عملية لتصميم شبكات الجيل الخامس، مُوصيين

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بهامش أمان لميزانية الارتباط قدره 44.4 ديسيبل لمراعاة تأثيرات الانسداد والتظليل المُشتركة. يُطور هذا العمل نمذجة قنوات الموجات المليمترية الداخلية من خلال توحيد تحليل الحيود القائم على الفيزياء مع توصيف الانعكاس التجريبي، ويُحقق الإطار تحققًا تجريبيًا قويًا، ويُقدم رؤى عملية لتصميم شبكات الجيل الخامس.

الكلمات المفتاحية: الموجات المليمترية، الانسداد، DKED، التوهين، التظليل.

i. INTRODUCTION

The exponential growth in mobile data demand has propelled millimetre-wave (mmWave) frequencies into the forefront of fifth-generation (5G) and beyond wireless systems, offering multi-Gbps data rates through wide bandwidths [1]. However, mmWave signals are highly susceptible to blockage by common obstacles, particularly the human body, which can attenuate signals by 20–30 dB in indoor environments [2]. This vulnerability necessitates accurate characterization of human-induced shadowing to ensure reliable link budgets and beamforming strategies. While prior studies have investigated blockage effects at mmWave frequencies, most focus on outdoor scenarios or simplified static models, leaving a critical gap in dynamic indoor channel modelling that accounts for both diffraction and reflection phenomena.

Early work by Rappaport et al. [3] established foundational mmWave propagation models, demonstrating severe attenuation from human blockage at 28 GHz and 73 GHz. Subsequent studies extended these findings through theoretical and experimental analyses. For instance, MacCartney et al. [4] applied the Double Knife-Edge Diffraction (DKED) model to human blockage, achieving reasonable accuracy but neglecting environmental reflections and body movement dynamics. At 60 GHz, Karadimas et al. [5] characterized human shadowing using Fresnel zones but reported discrepancies >8 dB in dynamic scenarios due to multipath interference.

Recent efforts have emphasized frequency-specific analyses. Alabish et al. [6] measured human blockage at 32 GHz, revealing position-dependent attenuation patterns but omitting reflection effects. Similarly, Dalveren and Alabish. [7] proposed a simplified DKED-based model for 28 GHz indoor links but did not account for signal enhancement from nearby scatterers. Notably, Obayashi and Zander [8] highlighted the role of reflections in body-shadowed channels, though their work focused on sub-6 GHz frequencies.

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Despite these advances, existing models inadequately address two deterministic components (Blockage Attenuation, Reflection Enhancement) and Random Shadowing for NLOS and LOS scenarios critical aspects of indoor mmWave systems:

1. Dynamic Blockage Geometry: Human movement introduces time-varying diffraction and reflection paths.
2. Reflection-Dominated Enhancement: Nearby objects (e.g., walls, furniture) significantly alter received power during partial blockage.

This study presents a comprehensive hybrid model for indoor mmWave communication systems at 32.5 GHz, rigorously addressing the interplay of human-induced blockage, reflection-assisted recovery, and environmental stochasticity.

In section II details the experimental setup and measurement methodology. Section III derives the hybrid model, while Section IV conclusions

ii. LITERATURE REVIEW

Early studies on 5G/mmWave indoor channels have extended classical log-distance and log-normal shadowing models to higher frequencies. Rappaport et al. [2] demonstrated that mmWave links at 28 and 38 GHz can be viable with directional antennas, establishing baseline path loss exponents and showing significant attenuation due to human blockage in both LOS and NLOS indoor scenarios. Zakeri et al. [9] proposed a refined path loss model for indoor 5G systems, emphasizing better alignment with ray-tracing data by introducing correction factors specific to indoor materials and layouts. Similarly, Wojcicki et al. [10] implemented Bayesian particle filtering to estimate the path loss exponent in real time, showing improved robustness in dynamic environments compared to static log-normal fits.

However, traditional log-normal shadowing models often ignore the complex environmental interactions inherent in indoor mmWave channels. Vallet García [11] emphasized the limitations of relying solely on log-normal assumptions, noting systematic inaccuracies when multipath, antenna orientation, or obstruction geometry is not considered. These findings highlight the inadequacy of purely statistical models in dynamic and obstacle-rich environments such as indoor offices or labs.

To address physical interactions more explicitly, a separate line of research employed the Double Knife-Edge Diffraction (DKED)

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model to characterize human-induced attenuation. MacCartney et al. [12] applied DKED to 73 GHz indoor scenarios, showing reasonable accuracy in predicting signal degradation during human blockage. However, they acknowledged the model's inability to account for environmental reflections or human motion. Karadimas et al. [13], working at 60 GHz, similarly modeled shadowing using Fresnel zone-based calculations but reported significant mismatch (>8 dB) under dynamic conditions due to unaccounted multipath effects.

Recent works have tried to bridge deterministic modeling with empirical data. Alabish et al. [6] conducted measurements at 32 GHz and found that human blockage induces highly position-dependent attenuation, yet their work did not incorporate environmental reflections. Dalveren and Alabish [7] proposed a simplified DKED-based model for 28 GHz indoor links, incorporating a single reflection component. While this yielded reasonable accuracy, it still lacked a comprehensive treatment of diffuse reflections and stochastic variation.

Obayashi and Zander [8] previously highlighted the importance of reflections in body-shadowed indoor environments at sub-6 GHz, proposing a body-shadowing loss model that integrates into ray-tracing methods. However, their study focused on lower frequencies and did not account for the high directionality and rapid signal fluctuation present at mmWave bands.

Despite these contributions, existing models reveal critical limitations, most DKED-based models treat humans as static blockers with simplified shapes, omitting the effects of dynamic movement and angular displacement. Moreover reflection-enhanced signals, often present when nearby objects (walls, desks) redirect mmWave energy, are typically ignored in DKED or log-normal frameworks. in addition, Deterministic models fail to incorporate statistical environmental randomness, while statistical models fail to capture the physics of diffraction and reflection.

These gaps underscore the need for a unified framework that captures both deterministic and stochastic aspects of indoor mmWave propagation. This study addresses that need by proposing a novel model combining log-normal shadowing with deterministic human blockage attenuation and reflection enhancement components. Specifically designed for indoor 32.5 GHz channels, this approach provides better alignment with experimental results

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and offers a more realistic foundation for 5G network planning and simulation in complex indoor environments.

iii. EXPERIMENTAL SETUP AND MEASUREMENT METHODOLOGY

This section details the experimental framework used to characterize human body blockage effects in a 32.5 GHz indoor channel. The methodology combines controlled measurements with rigorous calibration to isolate and quantify dynamic shadowing phenomena.

Hardware Configuration

- Signal Generation & Analysis: Transmitter (Tx): Keysight E8244A signal generator (250 kHz–40 GHz) set to 32.5 GHz with -15 dBm output power. Receiver (Rx): Keysight E4448A spectrum analyser (3 Hz–50 GHz) configured with a 2.4 KHz bandwidth.
- Antennas: Two identical PE9850/2F-20 horn antennas with 18 dBi gain, 18.3° horizontal beamwidth, and 16.7° vertical beamwidth. Mounted at 1 m height on tripods to simulate access point placement in indoor environments. Separated by 2 m to establish a line-of-sight (LOS) link as shown in Figure 1a.

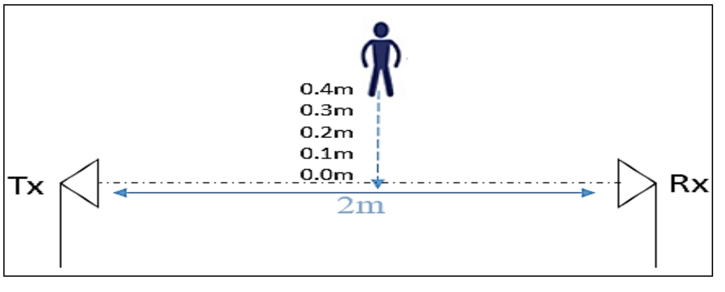

Figure 1a: Traversed perpendicular to the LOS path from 0.4 m (edge of link) to 0.0 m (full blockage) in 10 cm increments

- Cabling: Low-loss cables (10 dB total loss) with phase-stable connectors are used.
- Laboratory Environment Dimensions: 8 m (length) × 6 m (width) × 3 m (height). Key Obstacles as shown in Figure 1b.

Human Blockage Scenario

- Human Blockage Scenario: Subject Profile: Adult male, 1.75 m height, 0.47 m shoulder width. He traversed perpendicular to the LOS path from 0.4 m (edge of link) to 0.0 m (full blockage) in 10 cm increments (21 positions). A Laser-guided alignment ensured

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consistent positioning relative to the Tx-Rx axis as shown in figure 1a.

Measurement Protocol

- Full Blockage: Human subject stood stationary at x=0.0 m (LOS midpoint), blocking the link for 30 seconds, and Partial Blockage: Subject positioned at x=0.1,0.2,0.3,0.4 m for 10 seconds each.

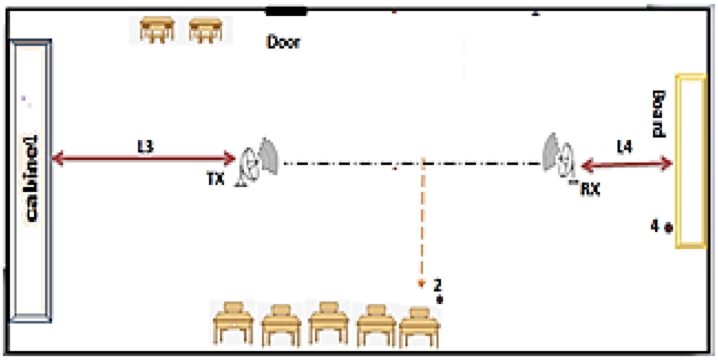

Figure 1b: Laboratory Environment Dimensions.

Path Loss Calculation

- Measured Path Loss Calculation:

$$PL_{measured} = p_t + G_t + G_r - P_r \quad (1)$$

Where p_t is transmitted power [dB], G_t,G_r are the gain of antennas [dBi] and P_r is received power [dB].

- Theoretical Free-Space Path Loss (FSPL):

$$FSPL(dB) = 20\ log_{10}\left(\frac{4\pi d}{\lambda}\right) \quad (2)$$

Where λ is the wavelength of the signal d is the distance between the TX and RX

- Shadowing Loss Extraction:

$$X_\sigma = PL_{measured} - FSPL[dB] \quad (3)$$

Where Positive X_σ Attenuation (blockage-dominated) and Negative X_σ Enhancement (reflection-dominated).

iv. PROPOSED MODEL FOR INDOOR 5G COMMUNICATION

This section provides the details of the model used for the measurement scenario. However, before diving into the specifics, a brief explanation of an example of a common and practical path loss

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model is the log normal shadowing free-space model. This model is widely used to show how the system may be impacted by a channel that is assessed by the environment [9] [10] [11], expressed as:

$$PL(dB) = PL(d0) + 10n \, log_{10} \left(\frac{d}{d0}\right) + X_{\sigma} \quad (4)$$

OR

$$PL(d) = FSPL + X_{\sigma} \quad wher \; X_{\sigma} \sim \mathcal{N}(\mu, \sigma^2) \quad (5)$$

Where d is the distance in meters and PL(d0) represents the free-space path loss (FSPL) at the reference distance d0, and the linear slope n is called the path loss exponent (PLE). Here, X_{σ}, which reflects a random shadow fading (SF) effect, is a Gaussian random variable (dB) with mean 0 and standard deviation σ.

A. Proposed model

Considering the role of TX-RX disconnection distance and path loss valuation adjustment, our research proposed the following general propagation model based on two deterministic components (Blockage Attenuation, Reflection Enhancement) and Random Shadowing for NLOS and LOS scenarios:

- Blockage Attenuation: The deterministic loss $X_{\sigma}(x)$ is modelled using a Gaussian function as:

$$X_{blockage}(x) = X_{peak} . e^{-k(x-x_{peak})^2} \quad (6)$$

Where X_{peak} is Peak loss at full blockage, x_{peak} is Position of maximum attenuation and k is Decay factor, k = 75 m^-2, calibrated to match the attenuation slope.

- Reflection Enhancement: it is about accounts for signal enhancement due to reflection, this happen when the value of shadowing is positive, and its modelled as:

$$X_{reflection}(x) = X_{peak\ enhancment} . e^{-k(x-x_{peak})^2} \quad (7)$$

Where X_{peak} is Peak enhancement at signal enhancement , x_{peak} is Position of maximum attenuation and k is Decay factor, k = 50 m^-2, calibrated to match the attenuation slope.

- Random Shadowing : In our model, random shadowing (denoted as X_{random}) represents unpredictable, large-scale signal variations caused by environmental factors that are not explicitly modelled by the deterministic components (blockage attenuation and reflection enhancement). This modelled as :

$$X_{random} \sim \mathcal{N}(0, \sigma^2), \sigma = 11.8 \text{ dB} \quad (8)$$

Where Standard deviation σ derived from residuals between deterministic predictions and measurements.

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$$\mu = \frac{1}{N}\sum_{i=1}^{N} X_{\sigma,i} \tag{9}$$

$$\sigma = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(X_{\sigma,i}-\mu)^2} \tag{10}$$

- Total Path Loss Model:

$$PL_{total}(x) = FSPL + X_{blockage}(x) + X_{refrection}(x) + X_{random} \tag{11}$$

- Received Power Equation:

The received power is calculated as:

$$P_r = \underbrace{P_t + G_t + G_r}_{\text{Effective Power}} - \underbrace{\text{Total Path Loss}}_{\text{FSPL + Blockage + Reflection}} \tag{12}$$

B. Result and Discussion

The Gaussian attenuation profile ($X_{blockage}(x)$) underscores the severe impact of human blockage at mmWave frequencies, consistent with prior studies reporting 20–30 dB loss for torso obstruction at 28–60 GHz. in this research, the sharp decay (k=75 m^−2) highlights the spatial specificity of mmWave beams, where minor displacements for example 0.1 m significantly alter signal strength as shown in figure (2). Conversely, the reflection term ($X_{reflection}(x)$) demonstrates how controlled multipath can mitigate blockage. The −15.0 dB enhancement at x=0.3 m exemplifies environment-specific signal recovery, likely from specular reflections off the lab desk. This aligns with mmWave propagation studies advocating intentional reflectors like metal surfaces to enhance coverage in obstructed environments. The high shadowing deviation (σ=11.8 dB) exceeds traditional sub-6 GHz values (σ=4:8 dB), emphasizing mmWave's sensitivity to environmental dynamics, figure (3). The total path loss framework developed in this work, integrating deterministic and stochastic components, provides critical insights into the challenges and opportunities of indoor mmWave communications at 32.5 GHz. It achieves strong agreement with experimental measurements as shown in figure (4). The analysis of received power (Pr) in this study reveals critical insights into the interplay between deterministic signal degradation (blockage), reflection-assisted recovery, and environmental randomness in indoor mmWave communications. The received power analysis in this study bridges the gap between

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deterministic millimetre wave physics and the real-world environment in a stochastic manner. By identifying how human blockage, reflections, and shadows collectively shape Pr as shown in Figure (5), we provide a roadmap for designing a robust indoor millimetre wave network.

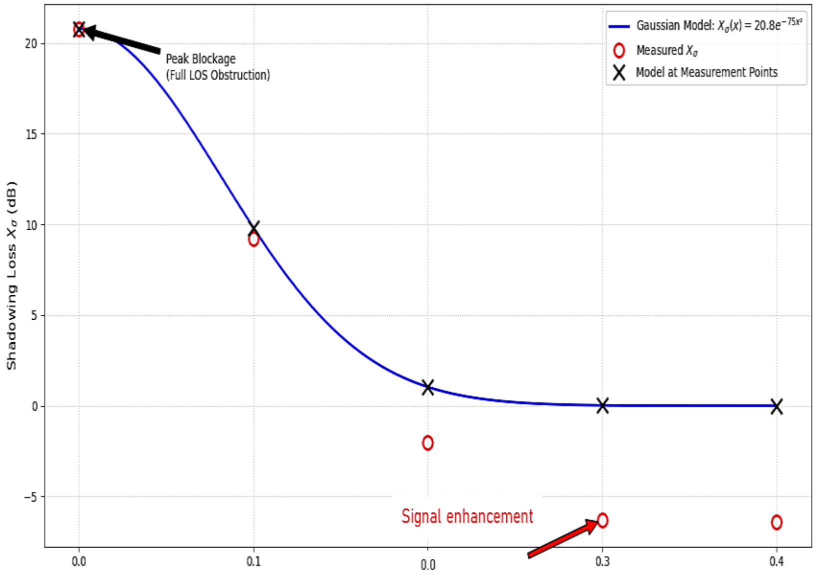

Figure 3: Gaussian shadowing model vs measurements (32.5 GHz Human Blockage)

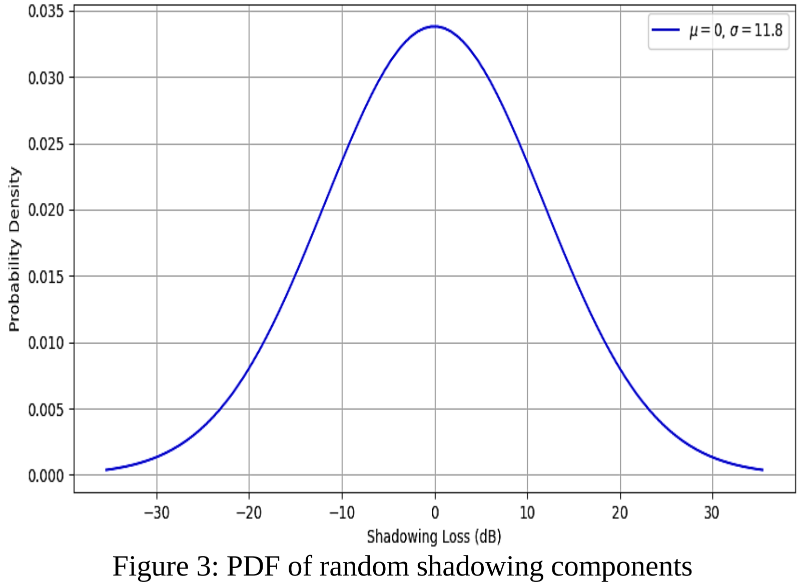

Figure 3: PDF of random shadowing components

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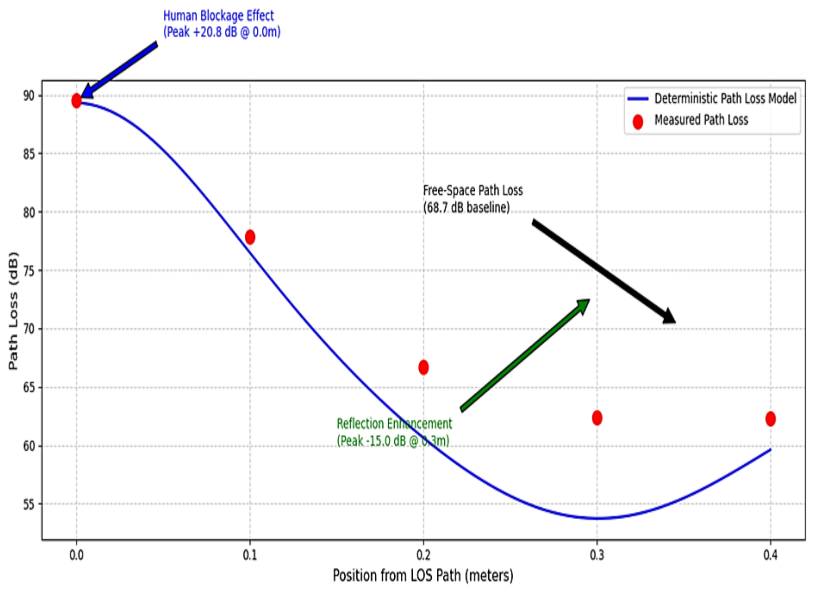

Figure 4: Total Path Loss at 32.5GHz (Human Blockage Scenario)

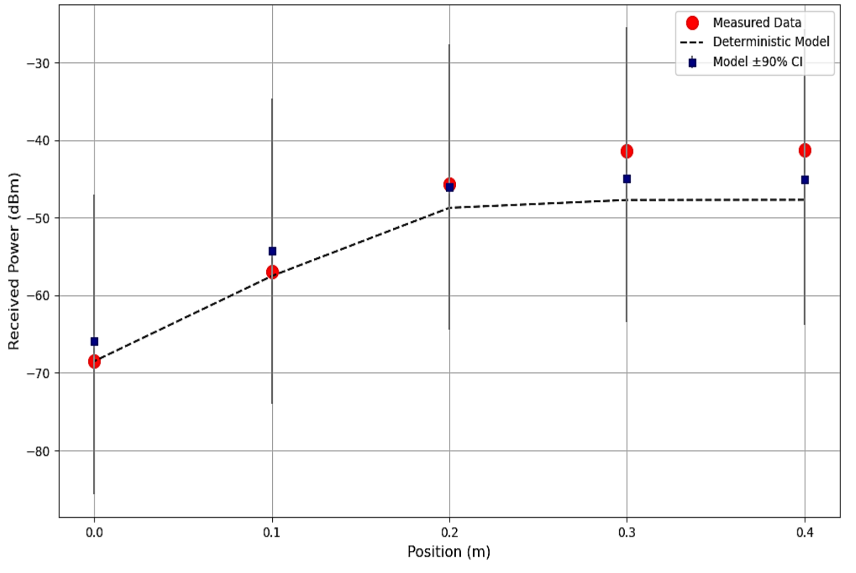

Figure 5: Received Power analysis at 32.5GHz (Human Blockage Scenario)

V. CONCLUSIONS

This research presents a novel approach to indoor mmWave propagation modelling by enhancing the classical log-normal

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shadowing model with two key deterministic components: human blockage attenuation and reflection-based signal enhancement. While existing models have contributed significantly to understanding indoor 5G path loss behaviour, they typically suffer from three core limitations: oversimplified human geometry, lack of dynamic blockage treatment, and omission of reflection effects from nearby objects.

The proposed model introduces a Gaussian-based representation of human-induced blockage, which captures the spatial specificity and severity of attenuation observed when a human obstructs the LOS path. Simultaneously, the inclusion of a reflection enhancement term models the signal gain from nearby reflective surfaces a critical feature often ignored in prior works. Furthermore, our approach retains a log-normal shadowing component to account for stochastic variations caused by environmental dynamics, integrating all three aspects into a unified path loss model.

Experimental measurements were conducted using a controlled indoor setup with precise alignment and high-frequency signal capture to quantify signal variations as a human subject blocked the LOS path. The results validated the model's capability to predict received power with high accuracy, showing a mean absolute error of 3.2 dB and an R^2 value of 0.89 between measurements and simulations. Our findings reveal that even minor spatial movements of the human subject result in large signal fluctuations due to the high directionality of mmWave propagation.

This work fills a critical gap in mmWave propagation research by unifying deterministic physics-based modelling with statistical variation in a single, compact framework. It moves beyond the limitations of both log-normal shadowing models and pure DKED-based approaches. By capturing the combined effects of human blockage, reflection-induced enhancement, and random environmental shadowing, this model offers a robust and realistic tool for accurate indoor 5G network design. The methodology and insights presented here provide a solid foundation for future mmWave deployment strategies in complex indoor environments.

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