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Comparative study of distance metrics for indoor radio propagation modeling in complex environments

Jonathanh Ta
CPE Lyon
José-María Molina-García-Pardo
josemaria.molina@upct.es
University of Cartagena
Juan Pascual-García
University of Cartagena
Fabián Correa-Quinchía
University of Cartagena

Research Article

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Posted Date: April 1st, 2026

DOI: https://doi.org/10.21203/rs.3.rs-9039504/v1

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Additional Declarations: No competing interests reported.

Comparative study of distance metrics for indoor radio propagation modeling in complex environments

Jonathanh Ta [1], José-María Molina-García-Pardo [2], Juan Pascual-García [2], Fabián Correa-Quinchía [2]
jonathanh.ta@cpe.fr, josemaria.molina@upct.es, juan.pascual@upct.es, fabian.correa@edu.upct.es
[1]Dept. of Computer and Network Engineering, CPE Lyon, Villeurbanne, France
[2]Dept. of Information and Communication Technologies, University of Cartagena, Cartagena, Spain
Corresponding author: José-María Molina-García-Pardo - josemaria.molina@upct.es

Abstract

This paper investigates experimentally and theoretically the impact of distance metric selection on path-loss modeling in indoor corridor environments under non-line-of-sight (NLoS) conditions. Measurements were conducted at five central frequencies between 2 and 7.4 GHz and complemented with deterministic ray-tracing simulations in a geometry-accurate environment. Five propagation models (FI, CI, CIF, ABG, Molisch) were evaluated using both Euclidean and Manhattan distance definitions, and their performance was assessed through the standard deviation error σ. Results show that the Manhattan metric consistently improves the accuracy of geometry-sensitive models, particularly the Molisch formulation, by better approximating the effective propagation path in structured indoor layouts. The findings highlight the importance of incorporating environmental topology into distance definitions for reliable NLoS path-loss prediction in sub-7 GHz and lower mid-band frequencies.

Keywords: Indoor NLoS propagation, Path-loss modeling, Distance metrics, Manhattan and Euclidean distance, Corridor environments

1. Introduction

The increasing demand for higher data rates, lower latency, and improved reliability continues to push wireless systems toward higher frequency bands. Beyond the traditional FR1 (sub-7 GHz) and FR2 (mmWave) ranges, recent studies identify the emerging "upper mid-band" or FR3 (7-15 GHz) as a promising candidate for 5G-Advanced and 6G, offering wider bandwidths than FR1 while maintaining more favorable propagation characteristics than FR2 [1]. Although only one of the frequencies used here lies near the lower edge of FR3, the objective is not to characterize FR3 directly but to analyze propagation trends relevant to the transition between FR1 and the emerging mid-band.

Propagation modeling in these intermediate frequencies remains an active research topic. Classical models such as CI, FI, ABG, and CIF are widely used in FR1 and FR2 scenarios [2], while spatially consistent extensions have been proposed for mmWave channels [3]. Their applicability to intermediate bands, however, requires further investigation, especially in environments where propagation paths are strongly constrained by geometry. In such cases, the definition of distance between transmitter and receiver becomes critical. Several studies have shown that Manhattan distance can better represent real propagation trajectories in structured indoor or urban environments, particularly in rectilinear corridors and street-canyon layouts [4-7].

This work contributes to this context by analyzing propagation at 2, 3, 3.9, 5.3, and 7.4 GHz in a controlled indoor corridor, consistent with recent measurement efforts in intermediate bands [8]. Five path-loss models (FI, CI, CIF, ABG, Molisch) are evaluated under both Euclidean and Manhattan distance definitions. The study combines experimental measurements with deterministic ray-tracing simulations in a geometry-accurate environment [4], followed by statistical analysis to quantify prediction errors and assess model robustness. The goal is to determine how the choice of distance metric affects model accuracy in NLoS indoor corridors and to identify which models benefit most from a geometry-aware distance definition.

2. Scenario and channel sounder

4.1. Indoor scenario and measurement setup

The measurement campaign was conducted in the basement of the Universidad Politécnica de Cartagena, a geometry-constrained indoor layout representative of corridors and intersections. The transmitter (Tx) was placed at a fixed reference point, while the receiver (Rx) was moved along five predefined routes, starting 1 m from the transmitter, to capture both line-of-sight (LoS) and non-line-of-sight (NLoS) propagation. The LoS routes consisted of a short 12m left-segment and a longer 54m right-corridor, whereas the NLoS routes included three segments of 28m (NLoS 1), 24m (NLoS 2), and 28m (NLoS 3), respectively, navigating around walls and doorways. For all measurements, the height of both antennas was 1.7 m. The overall layout and the measurement trajectories are shown in Fig. 1.



Fig. 1. Indoor measurement layout of the basement corridor.

To perform the measurements, a complete transmission and reception chain was assembled. The signal source was a Rohde & Schwarz SMB100A microwave generator, selected for its wide operating range (100 kHz to 40 GHz) and support for analog and digital modulation formats. In this study, it was configured to generate continuous-wave signals at 2 GHz, 3 GHz, 3.9 GHz, 5.3 GHz, and 7.4 GHz, with an output power of 0 dBm, respecting the input limits of the amplifier. These frequencies were selected because they correspond to the minima of the antennas' reflection coefficient (S11), ensuring optimal matching and maximizing the radiated power at each operating point. Signal amplification was provided by a ZVE-8G module with a gain of 25 dB, ensuring sufficient signal strength for detection across the full measurement range. The receiver chain consisted of an Anritsu Field Master Pro MS2090A spectrum analyzer, capable of real-time RF and microwave signal acquisition from 9 kHz to 32 GHz. It was paired with an EM-6116 antenna, offering 1 dBi gain and sensitivity across 2-10 GHz.

Data acquisition and storage were automated using a MATLAB application developed in previous research at the university. The complete hardware configuration is shown in Fig. 2.

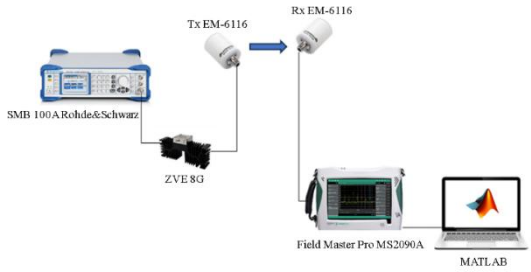

Fig. 2. Hardware setup used for the propagation measurements.

The Manhattan distance was computed as the sum of the orthogonal corridor segments between Tx and Rx, based on the floor plan geometry. Each turn in the corridor was treated as a breakpoint, and the total distance was obtained by summing the lengths of the horizontal and vertical segments connecting Tx and Rx.

4.2. Wireless inSite simulation environment

In addition to the measurement campaign, deterministic ray-tracing simulations were performed in Wireless InSite using the X3D propagation model. The indoor geometry was reproduced in the simulator, including walls, doors, and corridor topology, to ensure consistency with the real environment. To accurately capture multipath propagation, the maximum number of reflections was set to 20, allowing the simulator to account for the rich scattering and multiple-bounce interactions characteristic of indoor corridors. Crucially, the electrical properties of each wall were modified for each frequency, following the frequency-dependent permittivity and conductivity models provided in ITU-R P.2040-3 [9]. This ensured that reflection, transmission, and absorption effects were accurately represented across the 2-7.4 GHz range. The transmitter and receiver positions were configured to match the measurement routes of Fig. 1, enabling direct comparison between simulated and measured received power. Nevertheless, the simulated environment does not include furniture or human presence; these factors can increase variance and affect real-world path-loss measurements.

The simulations provided complementary insights into multipath behavior and wall penetration losses and served as a reference for validating the path loss models considered in this study. As with any deterministic ray-tracing approach, the simulated results do not capture small-scale irregularities such as furniture or human presence. The resulting simulation environment is shown in Fig. 3.

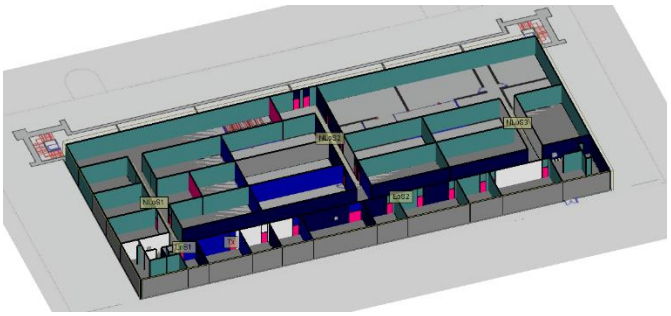

Fig. 3. Wireless InSite environment

3. Propagation models

The characterization of large-scale attenuation in indoor environments relies on analytical path-loss models that relate the received signal to the transmitter-receiver separation, the operating frequency, and the propagation conditions encountered along the route. These models express the path loss $PL(d,f)$ using parameters such as the intercept α, the distance-dependence coefficient or path-loss exponent β, the frequency-dependence coefficient γ, and, when relevant, a reference frequency f_0 [10]. The first model considered is the Floating-Intercept (FI) model, a purely empirical formulation in which both the intercept and slope are fitted directly from the data according to

$$PL_{FI}(d,f)[\text{dB}] = \alpha + 10\cdot\beta\cdot\log_{10}(d) + \chi_\sigma^{FI} \tag{1}$$

making it flexible but not physically anchored.

To introduce physical meaning, the Close-In (CI) model anchors the path loss to the free-space loss at 1 m (dB), which gives

$$PL_{CI}(d,f)[\text{dB}] = FSPL(f,1m) + 10\cdot\beta\cdot\log_{10}\left(\frac{d}{1m}\right) + \chi_\sigma^{CI} \tag{2}$$

where β becomes directly interpretable as the path-loss exponent.

Since indoor attenuation often varies with frequency, the CI model can be extended to the Close-In Frequency-Dependent (CIF) model by adding a frequency-dependent correction term, leading to

$$PL_{CIF}(d,f)[\text{dB}] = FSPL(f,1m) + 20\cdot\log_{10}(f) + 10\cdot\beta\cdot\left(1+\gamma\cdot\left(\frac{f-f_0}{f_0}\right)\right)\cdot\log_{10}(d) + \chi_\sigma^{CIF} \tag{3}$$

where γ captures how strongly the environment reacts to frequency changes.

A more flexible empirical alternative is the Alpha Beta Gamma (ABG) model, which independently fits distance, frequency, and an offset term through

$$PL_{ABG}(d,f)[\text{dB}] = 10\cdot\beta\cdot\log_{10}(d) + \alpha + 10\cdot\gamma\cdot\log_{10}(f) + \chi_{\sigma}^{ABG} \quad (4)$$

allowing it to adapt to a wide range of environments at the cost of physical interpretability. Finally, the Molisch model adopts a piecewise formulation particularly suited to indoor corridors with turn or transitions between LoS and NLoS [3].

The LoS segment is modeled as

$$\begin{aligned} PL_{MOLISCH}(d_{LoS})[\text{dB}] = {} & FSPL(f,1m) \\ & +10\cdot\beta_{LoS}\cdot\log_{10}(d_{LoS}) + \Delta_{LoS} + \chi_{\sigma}^{MOLISCH} \end{aligned} \quad (5)$$

and each subsequent segment $n+1$ updates the path loss recursively through

$$\begin{aligned} PL_{n+1}(d_{n+1})[\text{dB}] = {} & PL_n(d_n) + \Delta_{n+1} + \chi_{\sigma}^{MOLISCH} \\ & +10\cdot\beta_{n+1}\cdot(\log_{10}(d_{n+1}) - \log_{10}(d_n)) \end{aligned} \quad (6)$$

$$\text{where, } \Delta_{n+1}[\text{dB}] = PL_{n+1}(d_n) - PL_n(d_n) \quad (7)$$

allowing the model to capture abrupt changes in propagation conditions. Together, these models span a range of modeling philosophies, from single-slope empirical fits to segment-aware formulations specifically suited to environments with geometric transitions.

4. Results

This section evaluates the performance of the five propagation models (FI, CI, CIF, ABG, Molisch) under non-line-of-sight (NLoS) conditions. Only NLoS routes are considered, since in line-of-sight (LoS) scenarios the Euclidean and Manhattan distances coincide and the choice of metric has no impact. In NLoS, however, reflections and diffractions dominate, making the distance definition a key modeling parameter. These considerations highlight the need to examine how each model responds to distance definitions.

Model accuracy is assessed through the standard-deviation error σ between measured or simulated path loss and model predictions. Each model is evaluated under both distance metrics, and results are presented separately for measurements and simulations. The objective is to determine how a geometry-aware distance definition affects model performance and whether the Manhattan metric better represents the effective propagation length imposed by the corridor topology.

4.1. Measurement

The measurement campaign was conducted along three NLoS receiver trajectories, as shown in Fig. 1. These routes include multiple turns and obstructions, creating a waveguiding environment that strongly constrains the dominant propagation paths. In this configuration, the corridor layout produces a stable propagation pattern along the entire measurement path. The corresponding σ values obtained using Euclidean and Manhattan distances are reported in Table 1.

TABLE 1. Standard deviation obtained with both metrics (dB)

EUCLIDEAN					
σ	FI	CI	CIF	ABG	Molisch
NLoS1	1.90	2.35	4.83	4.69	2.53
NLoS2	2.56	3.26	4.82	6.03	1.86
NLoS3	2.30	3.09	5.07	4.30	2.26
σ total	2.25	2.90	4.91	5.01	2.21
MANHATTAN					
σ	FI	CI	CIF	ABG	Molisch
NLoS1	2.20	3.12	5.05	4.70	2.54
NLoS2	2.57	3.39	4.56	5.82	1.80
NLoS3	2.59	2.87	5.14	4.30	2.22
σ total	2.45	3.12	4.92	4.94	2.19

Using the Euclidean distance, the Molisch model achieves the lowest σ values across all NLoS routes, with a total error of 2.21 dB. This confirms the effectiveness of its piecewise formulation in capturing abrupt changes in propagation conditions, such as those caused by corridor turns and obstructions. The relatively low standard-deviation values observed in the measurements are consistent with the highly waveguiding nature of the corridor and the use of continuous-wave signals, which reduces small-scale fading. The FI model follows, while CI, CIF, and ABG exhibit higher deviations, indicating that single-slope or frequency-dependent models do not fully capture the geometric constraints of indoor corridors, consistent with observations in [2, 6].

When the Manhattan distance is applied, the σ values change from 2.25 dB to 2.45 dB for FI, from 2.90 dB to 3.12 dB for CI, and from 2.21 dB to 2.19 dB for Molisch. CIF and ABG remain largely insensitive to the choice of distance metric, with total σ values of 4.92 dB and 4.94 dB, respectively. These numerical variations reflect how the Manhattan metric approximates the effective propagation length imposed by the corridor topology. Similar behavior has been reported in street-canyon and indoor-corridor studies, where Manhattan-type metrics better represent the physical propagation geometry [3, 5, 7].

4.2. Simulation

The Wireless InSite simulations were performed using the same transmitter and receiver positions as in the measurement campaign, ensuring a consistent basis for comparison between real and deterministic environments. The simulated NLoS trajectories reproduce the corridor geometry, including walls, intersections, and turns, which allows the ray-tracing engine to capture the dominant reflection and diffraction mechanisms. The standard-deviation errors σ obtained for all propagation models, using both Euclidean and Manhattan distance definitions, are summarized in Table 2.

TABLE 2. Standard deviation obtained with both metrics (dB)

EUCLIDEAN					
σ	FI	CI	CIF	ABG	Molisch
NLoS1	5.01	9.26	6.52	6.01	4.81
NLoS2	5.70	5.94	6.17	6.39	5.67
NLoS3	4.92	5.38	5.15	5.30	4.79
σ total	5.21	6.86	5.95	5.90	5.09
MANHATTAN					
σ	FI	CI	CIF	ABG	Molisch
NLoS1	5.19	8.71	6.53	6.01	4.95
NLoS2	5.51	5.72	5.99	6.22	5.48
NLoS3	4.90	5.17	5.12	5.30	4.84
σ total	5.20	6.53	5.88	5.84	5.09

Using the Euclidean distance, the Molisch model gives the lowest total σ with 5.09 dB, followed by FI with 5.21 dB. CI, CIF, and ABG reach 6.86 dB, 5.94 dB, and 5.90 dB. Although the absolute errors are higher than in the measurements, which is expected in an idealized ray-tracing environment without small-scale irregularities, the relative ranking of the models remains the same. This confirms that segment-aware formulations remain effective in geometrically constrained scenarios.

With the Manhattan distance, the Molisch model again yields 5.09 dB. FI changes slightly from 5.21 dB to 5.20 dB, and CI decreases from 6.86 dB to 6.53 dB. CIF and ABG remain almost unchanged, with total σ values of 5.88 dB and 5.84 dB. These results mirror the measurement trends and show that only geometry-sensitive models benefit from a rectilinear distance definition.

Overall, the simulations confirm the measurement-based observations. The Molisch model consistently provides the lowest σ values, and the Manhattan metric offers a more realistic approximation of the effective propagation path in corridor-dominated environments.

4.3. Overall analysis

Across both measurement and simulation datasets, and across both Euclidean and Manhattan distance definitions, the results converge toward the same conclusion: the combination of the Molisch model and the Manhattan distance metric provides the most accurate and physically consistent representation of NLoS indoor corridor propagation. The Molisch model consistently yields the lowest σ values in Tables I through IV, which is expected in environments where propagation is strongly influenced by geometric transitions, waveguiding effects, and NLoS segmentation [3-6]. The Manhattan distance improves accuracy for geometry-sensitive models because it approximates the rectilinear propagation constraints imposed by the corridor topology, a behavior widely documented in propagation-aware modeling of street canyons and indoor corridors [3, 5, 7]. CIF and ABG show limited benefit from the Manhattan metric and do not outperform simpler models, confirming that their flexibility does not translate into improved accuracy when geometry dominates the propagation mechanisms [2, 6].

Overall, the results demonstrate that accurate NLoS indoor path-loss modeling requires both a geometry-aware distance metric and a model capable of adapting to segment-dependent propagation behavior. The Molisch model, combined with Manhattan distance, satisfies both requirements and therefore emerges as the most reliable choice for this type of indoor environment.

5. Conclusion

This work examined the influence of the distance metric on indoor path-loss modeling in a corridor environment under non-line-of-sight conditions. Since Euclidean and Manhattan distances behave identically in line-of-sight scenarios, the analysis focused exclusively on NLoS measurements and simulations, where the choice of metric has a meaningful impact. The results clearly indicate that the distance definition is a central element in accurately representing the effective propagation path in indoor corridors, where the dominant energy flow is constrained by the corridor geometry rather than by the direct Euclidean separation.

Across all measurement locations and in both datasets, the Manhattan distance changed the standard deviation error from 2.25 dB to 2.45 dB for FI, from 2.90 dB to 3.12 dB for CI, and from 2.21 dB to 2.19 dB for Molisch in the measurements, and from 5.21 dB to 5.20 dB for FI, from 6.86 dB to 6.53 dB for CI, and from 5.09 dB to 5.09 dB for Molisch in the simulations. This reflects the ability of a geometry-aware metric to better approximate the true propagation path in NLoS conditions dominated by reflections and diffractions. In contrast, the Euclidean metric systematically underestimated the effective path length, leading to higher residual errors.

Among the evaluated models, the Molisch formulation remained the most accurate under both metrics, and its performance was further strengthened when combined with the Manhattan distance, confirming the relevance of segment-aware modeling in complex indoor geometries

Considering these results, the findings demonstrate that the choice of distance metric is a key factor in NLoS indoor path-loss prediction. The Manhattan distance provides a more physically meaningful representation of the propagation path in corridor environments and is particularly suitable for rectilinear indoor NLoS environments similar to the one studied here, while its benefit in open or irregular layouts may be reduced. When paired with the Molisch model, it offers a reliable and accurate framework for modeling path loss in indoor environments where geometry strongly shapes the propagation mechanisms.

Author Contributions. All authors contributed to the conception and design of the study. Material preparation, measurement activities, and data collection were performed by Jonathanh Ta and Fabián Correa-Quinchía under the supervision of José-María Molina-García-Pardo and Juan Pascual-García. Data processing, statistical analysis, figure preparation, and the development of the simulation environment were carried out by Jonathanh Ta, who also conducted the Wireless InSite ray-tracing experiments with assistance from Fabián Correa-Quinchía. The first draft of the

manuscript was written by Jonathanh Ta, and all authors provided comments on earlier versions, contributed to the interpretation of the results, and approved the final manuscript.

Funding. This work was supported by project PID2022-136869NB-C32 funded by MICIU/AEI/10.13039/501100011033 and co-funded by the European Union through the "FEDER A way of making Europe" program.

Data Availability. The datasets and simulation files used in this study are available from the corresponding author, upon request.

Ethics, Consent to Participate, and Consent to Publish. Not applicable (this study involves no human participants, animals, or personal data).

Competing Interests. The authors declare no competing interests.

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