



Semi empirical path-loss modeling and cross-validation of industrial links at 5 GHz

Modelado semiempírico de la pérdida por trayectoria y validación cruzada de enlaces industriales en 5 GHz

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ABSTRACT

Introduction: Wireless links in industrial plants are exposed to metallic structures, absorbing materials, machinery, and multipath conditions that can reduce the accuracy of general propagation models. **Objective:** To develop and validate a semi-empirical path-loss model for 5 GHz point-to-point links in a paper and sugar industrial environment. **Methods:** Two line-of-sight links, Panasa-ISC and Panasa-Bomba 2, installed at approximately 15 m height, were analyzed. Eight spatial points were defined on each link, and eight received-power measurement series were collected using an RF analyzer, a Wi-Fi monitoring application, and a drone. Mean values were compared with the Friis free-space model and two industrial reference parameterizations. The α , β , and A path-loss parameters were fitted in MATLAB and evaluated using root mean square error and cross-validation between links. **Results:** The model fitted with Panasa-Bomba 2 yielded $\alpha=1.73$, $\beta=2.09$, and $A=0.8417$. Its RMSE against the mean series was 1.20 dB on the source link and 2.87 dB when applied to the Panasa-ISC link. In both scenarios, it outperformed the Friis model and the absorbing-industrial reference, whose errors ranged from 4.11 to 5.93 dB. **Conclusions:** Local measurement-based semi-empirical fitting improved received-power estimation and showed transferability between two nearby industrial paths. The model can support preliminary link planning under line-of-sight conditions, distances below 500 m, and operation near 5 GHz.

Keywords: radio propagation; industrial environment; path loss; 5 GHz; semi-empirical modeling.

RESUMEN

Introducción: Los enlaces inalámbricos en plantas industriales están expuestos a estructuras metálicas, materiales absorbentes, maquinaria y condiciones de multitrayectoria que pueden reducir la precisión de los modelos generales de propagación. **Objetivo:** Desarrollar y validar un modelo semiempírico de pérdida por trayectoria para enlaces punto a punto en la banda de 5 GHz en un entorno industrial papelerero y azucarero. **Métodos:** Se analizaron dos enlaces con línea de vista, Panasa-ISC y Panasa-Bomba 2, instalados aproximadamente a 15 m de altura. En cada enlace se definieron ocho puntos espaciales y se realizaron ocho series de medición de potencia recibida mediante un analizador RF, una aplicación de monitoreo Wi-Fi y un dron. Los valores promedio se compararon con el modelo de espacio libre de Friis y con dos parametrizaciones industriales de referencia. Los parámetros α , β y A del modelo de pérdida por trayectoria se ajustaron en MATLAB y se evaluaron mediante la raíz del error cuadrático medio y validación cruzada entre enlaces. **Resultados:** El modelo ajustado con Panasa-Bomba 2 obtuvo $\alpha=1.73$, $\beta=2.09$ y $A=0.8417$. Su RMSE frente a la serie promedio fue 1,20 dB en el enlace de origen y 2,87 dB al aplicarse al enlace Panasa-ISC. En ambos escenarios superó al modelo de Friis y a la referencia industrial absorbente, cuyos errores alcanzaron entre 4,11 y 5,93 dB. **Conclusiones:** El ajuste semiempírico basado en mediciones locales mejoró la estimación de potencia recibida y mostró capacidad de transferencia entre dos trayectos industriales cercanos. El modelo es aplicable como herramienta de planificación preliminar bajo condiciones de línea de vista, distancias inferiores a 500 m y operación cercana a 5 GHz.

Palabras clave: propagación radioeléctrica; entorno industrial; pérdida por trayectoria; 5 GHz; modelado semiempírico.

INTRODUCTION

Wireless connectivity has become an important component of automation, monitoring, and information exchange in industrial plants. The recent evolution of the Industrial Internet of Things and private networks has increased the need for links with greater availability and predictable behavior, especially when communications support mobile terminals, monitoring equipment, or distributed control systems^{1,2}. Contemporary characterization campaigns show that factory environments exhibit properties that differ from those of offices and residential spaces because of the concentration of conductive surfaces, machinery, aisles, stored materials, and mobile elements; therefore, specific channel modeling remains necessary^{3,4}.

Industrial propagation involves reflection, absorption, diffraction, and scattering mechanisms that can produce high multipath richness, a phenomenon documented in different factory environments^{5,6}. Research conducted in workshops, warehouses, and factories has described specular and diffuse components, temporal variations, delay spread, and loss exponents that depend on the geometry and materials present^{7,8}. This variability explains why a general model, although useful as a reference, can yield appreciable errors when used to size power, link margin, or coverage without considering the physical conditions of the scenario.

Among the reference models, free-space propagation serves as a starting point for estimating the minimum attenuation associated with distance and frequency. However, industrial environments frequently require empirical or semi-empirical factors to adjust this relationship. Ai et al. proposed loss prediction methods based on room electromagnetics and industrial measurements (9), whereas Ferrer-Coll et al. distinguished between strongly absorbing and highly reflective environments and demonstrated that channel parameters vary according to the nature of the material and the infrastructure (10). Previous and subsequent studies have confirmed that measurement-based models allow local conditions to be represented with greater fidelity (11,12).

The 5 GHz band is particularly relevant because it is used in WLAN technologies and other short- and medium-range industrial applications. Campaigns at 5.1, 5.4 and 5.85 GHz, among other nearby frequencies, have been reported both in indoor scenarios and in operational industrial facilities, showing that the presence of metal, warehouses, robots and production structures modifies the loss slope and dispersion of the channel^{13,14,15}. Scenario-dependent variations have also been described in point-to-point links close to this band, so that the parameters obtained in one installation should not be automatically assumed to be valid for another without an independent transfer evaluation or validation¹⁶.

A key methodological aspect is to distinguish between model fit and generalization capability. A model may exhibit low error on the same data used for its estimation while losing precision when applied to another route. Cross-validation between physically distinct links within the same industrial zone is a simple strategy for assessing parameter stability and avoiding model selection based solely on fitting performance.

This study restructures and updates a set of field measurements developed in an industrial environment in the Marcelino Maridueña canton, Ecuador, and analyzes it using a scientific article approach. The objective was to develop and validate a semi-empirical path loss model for point-to-point links near 5 GHz, comparing its performance with reference models using RMSE and cross-evaluation between two industrial links.

Methods

A channel characterization study was carried out based on field measurements and semi-empirical modeling. The experimental set comes from the degree work developed by Delgado Neira at the Escuela Superior Politécnica del Litoral¹⁷. For this article, the data were reorganized, the analysis was concentrated on the variables necessary for the estimation of loss by trajectory and the discussion was updated with specialized literature.

The scenario was located in the Marcelino Maridueña canton, province of Guayas, Ecuador, and included the infrastructure of Papelera Nacional S.A. and Ingenio San Carlos. A total of 2 point-to-point links in operation and with line-of-sight conditions were analyzed. The Panasa-ISC link connected the Papelera Nacional power plant with a point at Ingenio San Carlos and had an approximate total separation of 224 m. The Panasa-Bomba 2 link connected the power plant with a pumping station and reached approximately 396 m. The antennas were installed at a height close to 15 m above ground. The experimental documentation records operation within the range of 5.18 to 5.19 GHz, a transmission power of 15 dBm, and gains of 3 dBi in transmission and reception.

The Panasa–ISC link used Ubiquiti LiteBeam M5 antennas, and the Panasa–Bomba link used 2 Ubiquiti NanoStation M5 antennas. Power measurements were performed with an RF Explorer spectrum analyzer and a WiFi Analyzer application installed on a mobile terminal. The measurement system was raised by a drone to a height equivalent to that of the link path. The application enabled the identification of the transmitter's MAC address and the discrimination of the signal of interest from other nearby emissions in the same band.

8 measurement points distributed along the path were defined for each link. For Panasa–ISC, the distances from the transmitter were 18.29, 36.88, 62.21, 89.48, 119.35, 144.90, 170.48, and 195.75 m. For Panasa–Bomba 2, the distances were 23, 72, 92, 154, 203, 248, 301, and 359 m. For each spatial set, 8 series of received power were recorded, yielding 64 values per link for analysis. For fitting and comparison, the average of the 8 observations at each point was used.

The path loss formulation was derived from the free-space propagation reference in ITU-R Recommendation P.525-4 [18] and from the parameterization used in the experimental work. Received power was expressed by the following equations:

$$PL(d,f) = 10\beta \log_{10}(f) + A + 10 \log_{10}[(4\pi/c)^2] + 10\alpha \log_{10}(d) \quad (1)$$

$$P_{rx} = P_{tx} + G_{tx} + G_{rx} - PL(d,f) \quad (2)$$

where PL is path loss in dB; d is the distance between the transmitter and the measurement point; f is frequency in Hz; c is the speed of light; α is the exponent associated with variation with distance; β is the frequency exponent; A is a correction constant; P_{tx} is the transmitted power; and G_{tx} and G_{rx} are the antenna gains. The reference distance was 1 m, so terms associated with d_0 are simplified in the form presented.

3 parameterizations were used as references: Friis, with $\alpha=2$, $\beta=2$, and $A=0$; an absorbent industrial model, denoted model A, with $\alpha=1.99$, $\beta=2$, and $A=0.01$; and a reflective industrial model, denoted model R, with $\alpha=1.86$, $\beta=1.82$, and $A=-5.03$. The last 2 parameters come from the characterization framework for absorbent and reflective industrial environments described by Ferrer-Coll et al. [10].

The parameters specific to each link were estimated in MATLAB using the Curve Fitting Toolbox. Although the original report describes the procedure generally as regression, the fitting code uses nonlinear least squares to estimate α , β , and A. An independent model was generated for Panasa–ISC and another for Panasa–Bomba 2. Model quality was quantified using the root mean square error:

$$RMSE = \sqrt{[(1/n) \sum (P_{med,i} - P_{est,i})^2]} \quad (3)$$

Validation was performed at 2 levels. First, each parameterization was compared with the average of the measurements for the corresponding link. Second, a cross-evaluation was applied: the model obtained from Panasa–ISC was used to estimate Panasa–Bomba 2, and the model obtained from Panasa–Bomba 2 was used to estimate Panasa–ISC. The model with the lowest error and best stability between both paths was considered the most suitable candidate to represent the studied scenario.

Table 1. Main characteristics of the links and measurement procedure

Characteristic	Panasa–ISC	Panasa–Bomba 2
Approximate total separation	224 m	396 m
Operating band	5.18–5.19 GHz	5.18–5.19 GHz
Propagation condition	Line of sight	Line of sight
Approximate antenna height	15 m	13–15 m
Transmission power	15 dBm	15 dBm
Tx / Rx gain	3 / 3 dBi	3 / 3 dBi
Antenna	Ubiquiti LiteBeam M5	Ubiquiti NanoStation M5
Spatial points	8	8
Measurement series per point	8	8

Note. The experimental documentation shows minor discrepancies when assigning 5.18 or 5.19 GHz to each link; therefore, the observed interval is reported without modifying the power or RMSE results from the source.

RESULTS

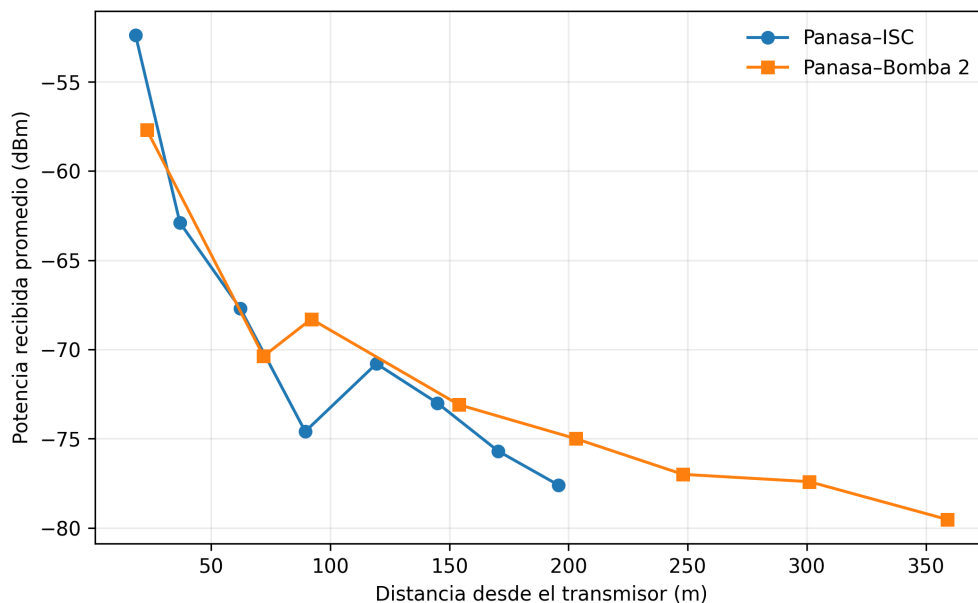
The average measurements showed an overall reduction in received power as distance increased, but with local variations consistent with multipath effects. In Panasa–ISC, mean power decreased from -52.4 dBm at 18.29 m to -77.6 dBm at 195.75 m. In Panasa–Bomba 2, it decreased from -57.7 dBm at 23 m to -79.53 dBm at 359 m. In both paths, points deviating from a strictly monotonic decrease were observed.

At Panasa–ISC, a pronounced reduction around 89.48 m was notable, followed by a power increase at 119.35 m, whereas at Panasa–Pump 2 a local increase at 92 m was recorded relative to the preceding point. The scenario inspection described in the original campaign attributed these variations to terrain features, metal structures, storage areas, and possible additive reflections. These patterns justify using environment-specific parameters instead of exclusively assuming ideal propagation.

Table 2. Average received power at the 8 points for each link

Point	ISC distance (m)	Mean ISC (dBm)	Distance to Pump 2 (m)	Pump 2 average (dBm)
1	18,29	-52,40	23,00	-57,70
2	36,88	-62,90	72,00	-70,38
3	62,21	-67,70	92,00	-68,30
4	89,48	-74,60	154,00	-73,10
5	119,35	-70,80	203,00	-75,00
6	144,90	-73,00	248,00	-77,00
7	170,48	-75,70	301,00	-77,41
8	195,75	-77,60	359,00	-79,53

Figure 1. Behavior of average received power in the 2 industrial links



Note. The decreasing trend with distance exhibits local deviations associated with the physical conditions of the path and multipath.

The initial comparison with the reference models showed that Friis and model A were substantially closer to the measurements than model R was. In Panasa–ISC, the RMSE values were 5.76 dB for Friis, 5.93 dB for model A, and 30.58 dB for model R. In Panasa–Bomba 2, values of 4.11, 4.29, and 29.34 dB were obtained, respectively. Due to its high deviation, parameterization R was not competitive in either of the 2 links, even though reflective phenomena occurred at specific points.

Fitting the Panasa–ISC link yielded $\alpha=2.235$, $\beta=2.103$, and $A=-9.243$. The output of the Curve Fitting Toolbox reported an RMSE of 2.739 dB for the fitting procedure.

For Panasa–Pump 2, $\alpha=1.73$, $\beta=2.09$, and $A=0.8417$ were estimated, with a fitting RMSE of 1.526 dB. When the error was recalculated against the average series used in the validation tables of the original work, the values were 2.16 dB for the Panasa–ISC model on its own link and 1.20 dB for Panasa–Pump 2 on its original link.

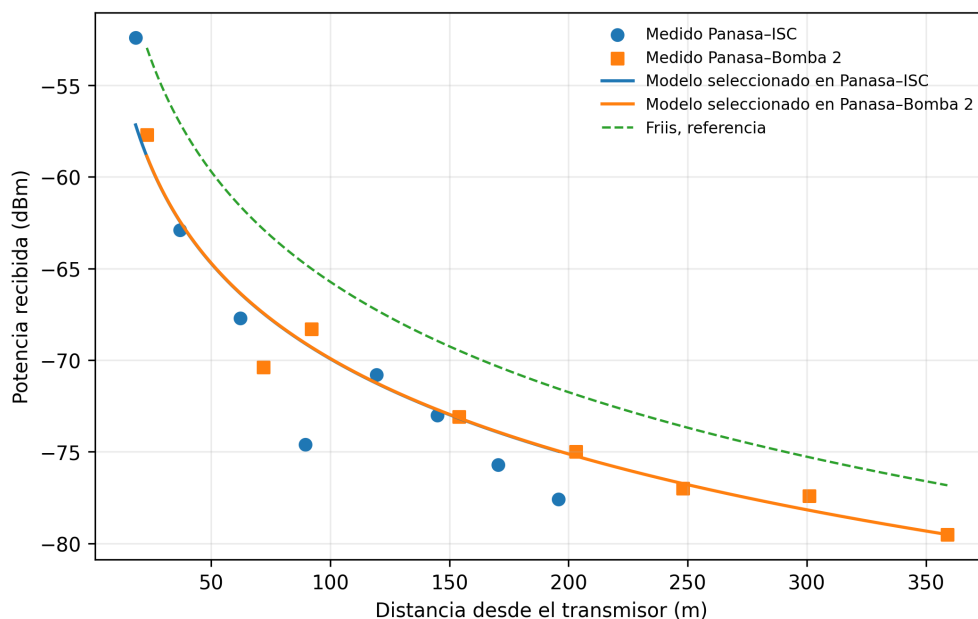
Cross-validation allowed identification of the model with the best transferability. When the Panasa–ISC model was applied to Panasa–Bomba 2, the RMSE was 2.98 dB; the Panasa–Bomba 2 model applied to Panasa–ISC yielded 2.87 dB. The latter maintained a clearly lower deviation than Friis and model A in the cross-link, while preserving the lowest error on its own data set.

Table 3. Parameters and performance of the evaluated models

Model	α	β	A	RMSE of fit (dB)	RMSE in Pump 2 (dB)	RMSE in ISC (dB)
Friis	2,00	2,00	0	—	4,11	5,76
Industrial A	1,99	2,00	0,01	—	4,29	5,93
Industrial R	1,86	1,82	-5.03	—	29,34	30,58
Panasa–ISC	2,235	2,103	-9.243	2,739	2,98	2,16
Panasa–Pump 2	1,73	2,09	0,8417	1,526	1,20	2,87

Note. The fitting RMSEs correspond to the output of the Curve Fitting Toolbox. The RMSEs for each link correspond to the evaluation against the average series used in the validation. The Panasa–ISC model evaluated at Bomba 2 and the Panasa–Bomba 2 model evaluated at ISC represent the cross-validation.

Figure 2. Validation of the selected model against measurements from both links



Note. The selected model uses $\alpha=1.73$, $\beta=2.09$, and $A=0.8417$. The curves were plotted using the frequencies reported in the individual analyses of each link; the reported RMSE values were retained from the original evaluation.

Considering both the fitting error and the behavior on the unused link for parameter estimation, the Panasa–Bomba 2 model showed the best overall performance. The observed RMSE range in validation was 1.20–2.87 dB, versus 4.11–5.76 dB for Friis and 4.29–5.93 dB for model A. This difference indicates that the local fit significantly reduced the estimation error within the measured domain.

DISCUSSION

The main finding was that a semi-empirical parameterization obtained in one of the links maintained a reduced error when moved to the second path. This observation is relevant because different industrial studies have shown that propagation is strongly dependent on local geometry, metal density, and plant activity^(2,4,19).

Cross-validation does not eliminate site dependence, but it offers stronger evidence than an adjustment evaluated only with the same data used to estimate the parameters(5).

The value $\alpha=1.73$ for the selected model is lower than the free-space exponent of 2. Low exponents have been reported in certain industrial environments and can occur when the physical structure produces multiple paths that contribute energy at the receiver. Ai et al. observed reduced exponents and a strong influence of multipath in factory environments²⁰, whereas Tanghe et al. described large-scale characteristics and temporal fading at 5200 MHz that differ from those observed in conventional offices²¹. The result does not imply a physical gain over free space at every point, but rather that the average power fit over the studied interval exhibits a smaller slope.

The local deviations recorded in both links are consistent with the non-uniform nature of industrial scenarios. The literature has documented dense and specular components in workshops and warehouses, as well as energy clustering in the delay domain^{22,23,24}. Other studies of manufacturing infrastructure have shown that the electromagnetic response can vary substantially depending on the materials and the configuration of the environment⁷. In the analyzed data, signals from both mechanisms coexisted: metallic structures capable of generating reflections and paper or cardboard storage areas with greater absorption. For this reason, it is more appropriate to describe the scenario as heterogeneous than to assign it a single electromagnetic label.

The proximity of the frequencies used at 5.2 GHz to those of previous campaigns enables a particularly relevant comparison. Holfeld et al. studied 5.85 GHz in an automation cell with moving robots¹⁵; Jaeckel et al. measured at 5.4 GHz in operational industrial facilities¹⁴; Lyczkowski et al. analyzed 5.1 GHz along with other sub-6 GHz bands¹³; and Zhang et al. conducted SISO and MIMO measurements at 5.5 GHz for IIoT¹. Overall, these works indicate that the 5 GHz range requires parameterizations suited to the specific industrial configuration and that multipath can remain intense even under line-of-sight.

The performance of the Friis model requires a nuanced interpretation. Although its RMSE values of 4.11 and 5.76 dB were higher than those of the selected model, it followed the general trend of the measurements and outperformed the R model used as a reference. This confirms its usefulness as an initial approximation for link budgets, as established by Recommendation ITU-R P.525-4¹⁸, but it also shows the benefit of an empirical correction when greater precision is needed. Similar results have motivated specific industrial models, from measurement-based formulations to methods based on room electromagnetics^{9,11,25}.

The difference between the RMSE reported by the fitting tool and the RMSE calculated over the average series must remain explicit. The code for the experimental work used nonlinear least squares fitting, whereas the subsequent tables evaluated the curves against spatial averages. Both indicators correspond to different stages and should not be presented as if they were interchangeable. This methodological precision improves the reproducibility of the study and avoids attributing to the model a single error value outside the context in which it was calculated.

The Panasa-Bomba 2 model reduced the error compared with Friis in both its origin link and its cross link. From a practical perspective, this suggests that calibration with a reduced set of points can be useful for adjusting preliminary estimates in installations with similar topology. The measurement, fitting, and validation methodology is consistent with the approach historically used in channel characterization^{12,26,27}. Furthermore, the statistical models developed for 2 and 5 GHz scenarios highlight the importance of comparing propagation behavior in different configurations¹⁶.

The results must be interpreted within the conditions of the study. Only two links located in the same industrial area were analyzed, and both maintained line of sight. The maximum separation was less than 400 m, the antennas were located at approximately 13 to 15 m in height, and the operating band was limited to values close to 5.2 GHz. There was also no third independent site for external validation, nor measurements intended to explicitly separate the effect of rain, humidity, machinery activity, or temporal variation in noise. The use of eight spatial points and eight series per link made it possible to identify the average trend, but it does not characterize all possible configurations of an industrial plant.

Another limitation is related to the acquisition of received power using portable instrumentation and an aerial platform. Although the procedure made it possible to measure at link height without modifying the facilities in operation, the accuracy depends on the stability of the drone's position, the behavior of the measurement device, and the radio-frequency activity present during each campaign. Subsequent studies should incorporate synchronized spectrum logging, traceable calibration of receivers, meteorological information, and campaigns on different days and at different production levels.

As a future line, the same strategy can be extended to non-line-of-sight links, variable heights,

different types of industry, and the 2.4 and 5 GHz bands. It would also be convenient to compare the model with contemporary sub-6 GHz industrial channel methodologies and with models oriented toward 5G private networks, where path loss, temporal dispersion, polarization, and dense multipath components are studied simultaneously^{3,19,28}. Recent multiband campaigns also offer a useful reference for extending this type of validation¹³. A multicenter database would allow estimating confidence intervals of the parameters and determining under what conditions the model ceases to be transferable.

CONCLUSIONS

The analysis of 2 industrial links in the 5 GHz band made it possible to obtain a semi-empirical path loss model with better accuracy than the general references evaluated. The model derived from the Panasa–Bomba 2 link, with $\alpha=1.73$, $\beta=2.09$, and $A=0.8417$, exhibited the most stable overall behavior when considering both the local fit and the application to the second link.

Cross-validation was decisive for the selection. The RMSE of the selected model was 1.20 dB in Panasa–Bomba 2 and 2.87 dB in Panasa–ISC, whereas Friis reached 4.11 and 5.76 dB and industrial model A 4.29 and 5.93 dB. Consequently, calibration based on local measurements reduced the error without losing estimation capability when transferring between 2 nearby paths with similar industrial characteristics.

Point variations in power confirmed that the industrial channel cannot be interpreted solely as a uniform drop with distance. The received power was locally modified by reflections originating from the metallic infrastructure, the presence of absorbing materials, and the geometry of each path. The resulting model summarizes the average behavior, but it does not replace the specific evaluation of multipath or interference when the application requires high reliability.

The model is appropriate as a preliminary planning tool for point-to-point line-of-sight links, antennas installed at approximately 15 m, distances less than 500 m, and frequencies close to 5 GHz. Its application outside this domain requires new measurements and validation before using the parameters as a design reference.

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CONFLICT OF INTEREST

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AUTHORSHIP CONTRIBUTIONS

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Methodology: Washington Antonio Delgado Neira.

Investigation: Washington Antonio Delgado Neira.

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