On Indoor Coverage Models for Industrial Facilities

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***Abstract*— It is shown analytical and measurement results in order to compare five different indoor path loss propagation models in industrial environments: one-slope; dual-slope; partitioned; Cost-231 multi-wall model and average walls. It is concluded that the dual slope propagation model allows a better estimation among the selected models because the propagation loss rate increases abruptly beyond a certain distance from the transmitter in large industrial environments.**

***Keywords* – industrial WLANs; 802.11; coverage.**

I. INTRODUCTION

The economy in the globalized world is highly dynamic and competitive. Therefore, it is necessary that the production lines in industrial facilities can be easily changed, moved and added. This market pressure has driven an increasing demand to implement robust wireless networks to control and manage industrial processes. However, the lack of human and capital resources can hinder implementation of wireless networks in small industries. To turn over this situation, the Federal University of Rio Grande do Sul in Brazil (www.ufrgs.br) has been developing multidisciplinary research activities to develop a simple, fast and inexpensive methodology to set up wireless networks that attend capacity and coverage issues. Design, implement and optimize industrial wireless network require a deep understanding of radio wave propagation in indoor production facilities, which proves to be a harsher environment than offices due to steel constructions that create reflections and the obstructing machinery (that also can be a source of electromagnetic interference).

This contribution focus on a comparative analyzes of path loss propagation models in indoor industrial environments at 2.4 GHz Industrial, Scientific and Medical (ISM) band. Five propagation models have been selected a priori: one-slope; dual-slope; partitioned; Cost-231 multi-wall model and average walls. This paper is organized as follows. Section II discusses related works on this arena. Section III summarizes the path loss indoor propagation models investigated in this contribution. Section IV describes the experimental set up and the procedures used to determine the parameters of the investigated propagation models. Section V shows a comparison between numerical and field results in small and medium industrial plants, focusing on the tradeoffs between accuracy and complexity. Section VI compares site survey and numerical results. Finally, Section VII presents our final remarks.

II. RELATED WORK AND MOTIVATION

There have been intensive research activities to characterize the wireless propagation channel in industrial environments. One of the first concerns deals with the impact of the electromagnetic noise radiated from industrial machinery on wireless communications. Fortunately, field measurements have shown that this electromagnetic interference is negligible above 1.5 GHz [4]. Hence, the 2.4 GHz ISM band was chosen to carry out the field measurements presented in this paper.

It was verified in [2] that the presence of large metal obstacles encountered in typical industrial environments (as machines and production stocks) can cause an increasing of the signal strength in its vicinities due to the constructive effects of stationary waves. Field measurements were performed in [3] to investigate the impairments in the wireless range due to multipath propagation in industrial environments. Fortunately, the simulation and tests results showed a good coverage, since the reflected signals can cover areas behind the obstacles. The one-slope path-loss model [5, p. 75] was used in [4] to predict the coverage in industrial environments. Interestingly, it was noticed that even with the changing of the receiving antenna height between 0.5 to 2 m, the network range does not change significantly. However, it was not investigated if the one-slope model would be the most suitable one for indoor industrial environments among other indoor propagation models proposed in the open literature.

The main objective of this paper is to choose an empirical propagation model to provide first order coverage prediction results in indoor industrial environments using simple and inexpensive tools. The cited previous works [1-2] used software tools based on ray-tracing technique to predict the signal levels. Although this method is more accurate than the statistical propagation models, it demands a costly design effort, which may not be easily available for medium and small industries. On the other hand, many excellent contributions have focused only on the one-slope propagation model [4]. This paper analyzes comparatively, besides the one-slope model, four more propagation models. One selected model is the dual-slope model [5, p.80], which offers a better accuracy than the one-slope model in office environments. The partitioned model, that has been used for micro-cells planning [5, p.79], is also analyzed in this paper. Propagation models that consider the walls attenuation in an explicit way are also taken into account, as the widely used COST231 multi-wall model [6]. Another investigated model is the average walls model, which was proposed in [7] to minimize the design effort of wireless local area networks (WLANs).

II. PATH LOSS PROPAGATION MODELS

A. One-Slope Model

The path loss in dB is given by

$$L_{dB} = L_{0,dB} + 10nlog_{10} \tag{1}$$

where $L_{0,dB}$ is the path loss obtained at distance of *1.0 m* from the transmitter and the path loss exponent n is determined experimentally using a linear interpolation procedure [5, p. 75].

B. Dual-Slope Model

The path loss in dB is given by [5, p.80]

$$L_{dB} = L_{0,dB} + \begin{cases} 10n_1 log_{10} d, & 1m < d \le d_{bp} \\ 10n_1 log_{10} d_{bp} + 10n_2 log_{10}\left(\frac{d}{d_{bp}}\right), & d > d_{bp} \end{cases}, \quad (2)$$

where the path loss exponents n_1 and n_2 are determined experimentally. Basically, this model divides the distances into line-of-sight (LOS) and obstructed LOS regions. The breakpoint distance d_{bp} takes into account that in indoor environments the ellipsoidal Fresnel zone can be obstructed by the ceiling or the walls, anticipating the LOS region. It can be estimated analytically using (3), where h_b and h_m denote the shortest distance from the ceiling or wall of the access point (AP) and station (STA), respectively.

$$d_{bp} = \frac{4h_b h_m}{\lambda}, \quad (3)$$

where λ denotes the wavelength.

C. Partitioned Model

The path loss in dB is given by

$$L_{dB} = L_{0,dB} + \begin{cases} 20log_{10} d\,, & 1m < d \le 10m \\ 20dB + 30log_{10}\left(\frac{d}{10m}\right), & 10m < d \le 20m \\ 29dB + 60log_{10}\left(\frac{d}{20m}\right), & 20m < d \le 40m \\ 47dB + 120log_{10}\left(\frac{d}{40m}\right), & d > 40m \end{cases}. \quad (4)$$

This model uses pre-determined values for the path loss exponents and breakpoint distances, according to previous field measurement campaigns [5, p.79].

D. COST 231 - Multi-Wall Model

The path loss in dB for environments with just one floor is given by (5), where the integer k_w is the number of wall types; k_{wi} and L_{wi} denote the number and loss of the *ith* wall type, respectively [6].

$$L_{dB} = L_{0,dB} + 20log_{10} d + \sum_{i=1}^{k_w} k_{wi} L_{wi}. \quad (5)$$

The free-space path loss (FPL) in linear scale is given by

$$L_0 = \left(\frac{4\pi d_0}{\lambda}\right)^2, \quad (6)$$

For 2.4 GHz ISM band (λ=0.125 m) and d_0=*1m*, then the FPL in dB, $L_{0,dB}$, is equals to 40.2 dB. For practical reasons, the wall types are divided in only 2 categories, as shown in Tab. I.

TABLE I.
WALL TYPES FOR COST231 MULTI-WALL MODEL.

Wall type	Description	Value [dB]
L_{w1}	Light wall: plasterboard, particle board or thin (<10 cm), light concrete wall.	3.4
L_{w2}	Heavy wall: thick (>10 cm), concrete or brick	6.9

E. Average Walls Model

This model is based on the Cost-231 multi-wall, excepted that the loss due to obstructing walls is aggregated in just one parameter L_w [7]. Therefore, for a single floor environment the path loss estimated by (5) is modified to

$$L_{dB} = L_{0,dB} + 20log_{10} d + k_w L_w, \quad (7)$$

where k_w denotes the number of penetrated walls. In order to determine the parameter L_w, each wall obstructing the direct path between the receiver and the transmitter antennas must have its loss measured as follows. The loss of the first wall in dB is given by (8), where $L_{0,dB}$ is the path loss in dB obtained at *1.0 m* distant from the transmitter; L denotes the measured total loss in dB at *1.0 m* distant from the first obstructing wall.

$$L_1 = L - L_{0,dB} - 20log_{10} d_1. \quad (8)$$

The loss in dB of the second obstructing wall is estimated by

$$L_2 = L - L_{0,dB} - 20log_{10} d_2 - L_1, \quad (9)$$

where L now denotes the measured total loss in dB at *1.0 m* distant from the second obstructing wall. Notice that the loss of the first wall was also taken into account to determine L_2.

Inducing this process, the *ith* wall loss is given by

$$L_i = L - L_{0,dB} - 20log_{10} d - \sum_{j=1}^{i-1} L_j, \quad (10)$$

where the sum spans the losses of all walls obtained previously. After all wall losses of the environment had been obtained, then parameter L_w is estimated as the arithmetic average of all wall losses.

III. MEASUREMENT PROCEDURES

A. Facilities Description

The site survey measurements were conducted in two industrial plants, both metalworking processing factories. Fig. 1a shows the smallest facility: it is a single building with an area of *650* m^2. A black dashed line symbolizes a path that has one obstructing wall. Fig. 1b shows a larger plant, whose total area is approximately *6630* m^2. The black dashed line shows that there are paths with at least four obstructing walls. Both buildings exhibit similar constructive properties: concrete floor and metal ceilings supported by steel truss work. The walls are made of thick concrete masonry with *15-20 cm* wide. The height of each building is approximately *7-8 m*. Most of the industrial inventories are made of metal: milling machines, lathes, grinding machines and stocks made mainly of iron and steel material.

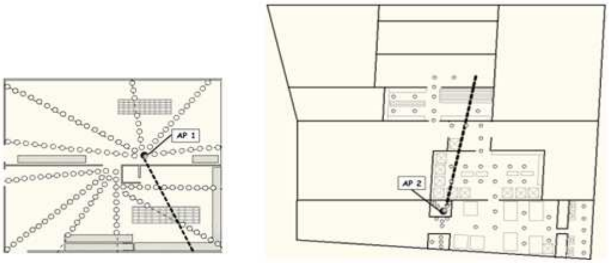


Figure 1. Measure points used to determine the parameters for one-slope and dual-slope path loss models: (a) small and (b) large facilities.

B. Measurement Set Up

The transmitter is an access point (AP) router, *D-Link DI-524*, with one transmitting antenna configured to a fixed transmitted power. This transmitter, as shown in Fig. 1, was mounted in a fixed location at different heights for each one of the two buildings: *2.0 m* (AP1) and *4.85m* (AP2), respectively. The receiver consists of a laptop equipped with an 802.11a/b/g card adapter. The receiver was at *1.0 m* height and the measurements were collected at different distances from the transmitter. The measurements were performed using the following conventional laptop use: the AP's antenna is located at *90*^{o} from the ground and the notebook is parallel to the ground, facing the AP's direction. The free software *Netstumbler* installed in the laptop was used to measure automatically at each second the Received Signal Strength Indicator (RSSI) in dBm of the beacon frames transmitted by the AP. It was performed *20* sample measurements with small displacements in order of the wavelength (λ = *0.125m*) to estimate the mean received power in dBm (P_{rx}) at each selected point. The path loss for each distance is given by

$$L_{dB} = EIRP - P_{rx}, \tag{11}$$

where EIRP denotes the AP effective isotropic radiated power in *dBm*. By measuring the received power level (P_{rx}) at *1 m* from the receiver antenna, then the term L_{dB} is equal to *40.2 dB* (free-space path loss in dB $L_{o,dB}$ as defined in item D of *Section III*). Therefore, the EIRP for each AP can be computed by (11).

C. *Estimation of the Path Loss Models Parameters*

To determine the parameters for the *one-slope* and *dual-slope* propagation models, the measured points (depicted as white circles at Fig. 1) were separated among them from *1* to *5* meters. In the presence of large obstacles, like machines, stored materials and walls, the respective measure was made right behind it.

To estimate the parameters for the *average walls model*, it is necessary to measure the path loss at *1 m* after each wall that obstructs the LOS path, as described in Section III. For the *COST 231 model*, the concrete walls were considered as heavy walls, as described in Tab. I. The parameters of the *partitioned model* are pre-determined, according to (4).

IV. NUMERICAL AND MEASUREMENT RESULTS

The average measurements of the selected points shown in Fig. 1 and the numerical results of one-slope, dual slope and partitioned models are depicted in Figs. 2a and 2b for the small and the large facility, respectively. The path loss in *dB* is plotted as a function of the transmitter-receiver (T-R) distance.

The one-slope model is given by (12) and (13) for small and large facilities, respectively. A linear interpolation procedure was used to determine the parameters: the inclination denotes the path loss exponent *n* and the intersection at the distance of *1 m* corresponds for $L_{0,dB}$.

$$L_{dB} = 38.66 + 13.55 log_{10} d. \tag{12}$$

$$L_{dB} = 28.23 + 34 log_{10} d. \tag{13}$$

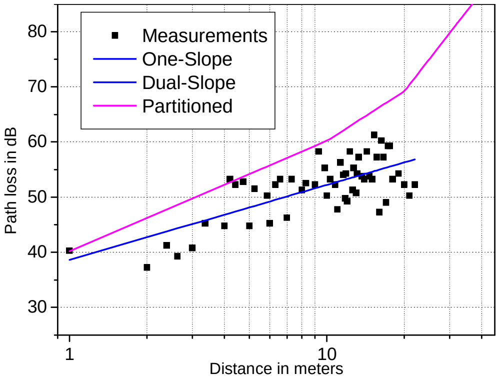


Figure 2a. Small facility.

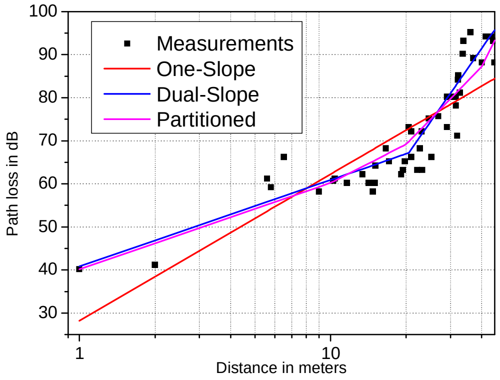


Figure 2b. Large facility.

Figure 2. Measurement and numerical results for one-slope, dual-slope and partitioned propagation models.

It is necessary to determine the breakpoint distance to set up the dual-slope model. However, estimating the breakpoint distance using (3) is not adequate for indoor environment because the network users (laptops and industrial machines) usually are located in low heights (i.e., up to *2 m* at most of the cases). Changing the receiving antenna height from *0.5* to *2.0 m*, then the breakpoint distance would increase four times, according with (3). This result contradicts the practical results obtained in [4], where it is shown a very limited effect on the received power for this amount of receiving antenna height variation. Therefore, it is used the the following procedure to estimate the breakpoint distance [8]: it consists on finding the minimum residual sum of squares between the dual slope model prediction resulted by the estimated breakpoint and the data measured. For the small facility the estimate breakpoint distance is *17 m*. This breakpoint was not taken into account since this point is near the farthest distance from the AP, as shown in Fig. 1a. Hence, the resultant model consists of a unique slope, as given by (12). For the large facility the estimate breakpoint distance is 20 m, in agreement with measurement results shown in Fig. 2b. Therefore, the dual slope model is given by

$$L_{dB} = 42.52 + \begin{cases} 18.14 log_{10} d, & 1m < d \le 20m \\ 11.57 + 84.42 log_{10}\left(\frac{d}{20}\right), & d > 20m \end{cases}. \tag{14}$$

Comparing (13) with (14), it can be seen that the parameter $L_{0,dB}$ obtained in the one-slope model results resulted in a lower value than the one obtained using the dual-slope model. Notice that, as the first segment inclination in dual-slope model considers only measurements for the closest distances, the interpolation procedure gives a lesser path loss exponent value for the first segment in (14) than the one obtained for the one-slope model in (13), whose computation takes into account the measurement results for all distances. This difference in the path loss exponent explains the discrepancy on the achieved values for the parameter $L_{0.}$ The path loss exponent *n* in (14) is less than *2* for the first segment, resulting in a better propagation path loss than the ideal free space channel (*n=2*), as obtained in [2].

Tab. II shows the mean errors and standard deviation between measured and numerical results for the one-slope, dual-slope and partitioned propagation models.

Analyzing the results show in Fig. 2 and Tab II, it can be inferred that the dual-slope model responds for the best estimation in relation to the first three analyzed models. It is interesting to observe that for AP2, where the breakpoint distance is inside the building, the partitioned model (whose parameters are pre-determined) allows to obtain lesser error values than the commonly used one-slope model (whose parameters were obtained from the best linear fit against the measured values at the site). These results reinforce that a better accuracy is achieved using multi-slope models.

TABLE II.

STATISTICAL DATA PATH FOR THREE LOSS MODELS: ONE-SLOPE; DUAL SLOPE AND PARTITIONED.

Model	Mean Error (dB)		Standard Deviation (dB)	
	AP 1	AP 2	AP 1	AP 2
One-Slope	3.14	5.22	1.9	3.84
Dual-Slope	3.14	2.81	1.9	2.92
Partitioned	8.30	3.45	4.77	3.15

Figures 3a and 3b show measurement and numerical (dual slope, COST 231, average walls) results for the path loss in *dB* as a function of T-R distance for small and large facilities, respectively. Instead of using all the measured points to plot the measurement data, it is used only the points related to one particular radial direction of each AP (depicted as a black dashed line in Fig 1a and 1b).

The parameters for the COST 231 in (5) are: *(i)* both facilities have concrete masonry walls with width at least *15 cm*, which are considered as L_{W2} wall type with *6.9 dB* attenuation for each obstructing wall; *(ii)* the number of walls in the paths analyzed (depicted by the dashed line in Fig. 1) is one and four for the small and the large facility, respectively.

For the average walls model, the aggregated wall loss L_w is experimentally determined in according with the item E of Section III. This procedure results in the data shown in Tab. III. Different attenuations among the walls due to the distinct surroundings are verified. Even negative values are possible to be obtained (as in walls 1 and 4 for AP2 in Tab III). They do not represent a signal gain. They infer that the exponent *n=2* assumed by this model overestimate the path loss at that particular distance. Nevertheless, the mean wall loss always results in a positive value [7].

TABLE III.

WALL LOSS FOR THE AVERAGE WALLS MODEL.

Wall	AP 1	AP 2
1	0.83 dB	-1.71 dB
2		12.11 dB
3		9.06 dB
4		-4.52dB
Mean	0.83 dB	3.67 dB

Using the values shown in Tab. III, the average walls model for small and large facilities is given by (15) and (16), respectively.

$$L_{dB} = 40.2 + 20log_{10}d + k_w \cdot 0.83. \tag{15}$$

$$L_{dB} = 40.2 + 20log_{10}d + k_w \cdot 3.67. \tag{16}$$

Tab. IV shows the mean and standard deviation error between measured and numerical results for dual-slope, COST 231 and average walls models. Analyzing Fig. 3 and Tab. IV, it can be concluded that the COST 231 and average walls models do not allow a good agreement with the measured data. Both models consider *n=2* (characterizing a free-space channel) whose value is greater than the exponent obtained by the dual-slope for the first segment in (12) and (14). This greater exponent *n* value contributed for an overestimated path loss prediction in most measured locations. In synthesis, for both environments the dual-slope model allows a better estimation of the path loss statistics. Notice that the standard deviation of the prediction error, as shown in Tab. IV, complies with the shadowing margin, usually around of *10 dB* for indoor environments [5, p.78].

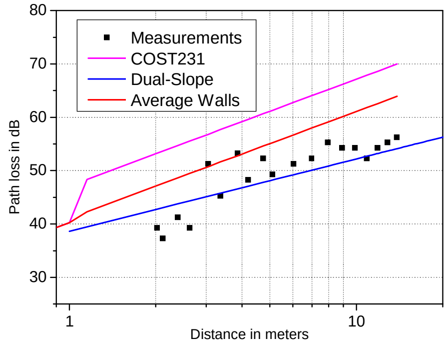


Figure 3a. Small facility.

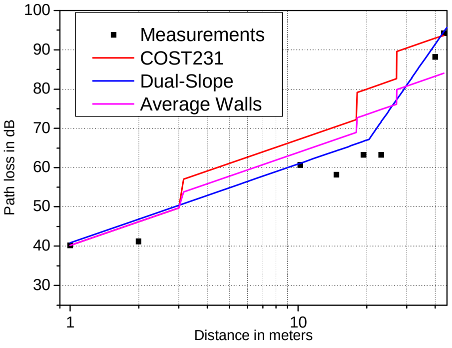


Figure 3b. Large facility.

Figure 3. Measurement and numerical results for dual-slope, COST 231 and average walls propagation models.

TABLE IV.

STATISTICAL DATA PATH FOR THREE LOSS MODELS: DUAL-SLOPE, COST 231 AND AVERAGE WALLS.

Model	Mean Error (dB)		Standard Deviation (dB)	
	AP 1	AP 2	AP 1	AP 2
Dual-Slope	3.14	2.81	1.9	2.92
COST 231	12.73	8.56	3.85	5.08
Average Walls	6.67	4.95	3.80	3.45

V. SITE SURVEY

Fig. 4a shows the coverage map for the small and large facilities based on RSSI. The circles (dashed lines) stand for the dual slope estimation for the following received power boundaries: *-50 dBm*, *-70 dBm* and *-80 dBm*. Fig. 4a shows that the measured and numerical results match well for the small facility. The dual slope circle estimates adequately the attenuation from the nearby obstacles that reduced the signal strength. However, it does no predict the accentuated attenuation in the Water Closet (WC) walls, approximately of *6 dB*. The walls next to WC present a greater attenuation than other building walls because inside them there are pipes embedded [7]. Also, it can be seen that for paths where there is absence of obstructing objects (the dotted line labeled as unobstructed path in Fig 4a), then the signal coverage reaches farther distances, emphasizing the effect of attenuation from industrial inventories (*4-5 dB* of loss has been observed on the measured data).For large facilities, Fig. 4b also depicts that a reasonable agreement between the dual slope estimation and the site survey, except for the office room where the RSSI was greater than predicted. However, this result is expected because office environments do not provide large metal obstacles that could reduce the RSSI, allowing the signal coverage reach farther distances.

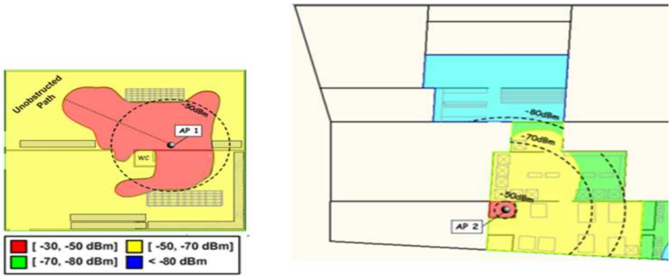


Figure 4. Coverage maps obtained by the site survey: (a) small and (b) large facilities.

Fig. 5 shows the prediction error for a significant set of measured locations. It can be seen that the prediction errors respect the minimum shadowing margin of *10 dB* as proposed in [4] over several industrial topographies (even the dark brown bars do not surpass this value in Fig 5). This margin is included in the link budget to account for the effects of shadowing fading and temporal fading.

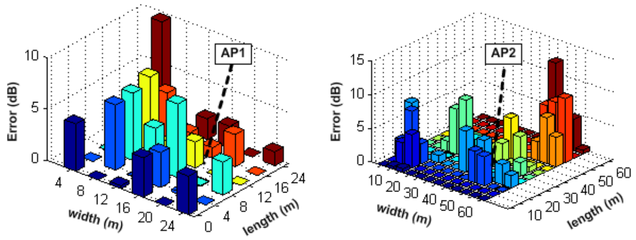


Figure 5a –AP1: small facility. Figure 5b –AP2: large facility.

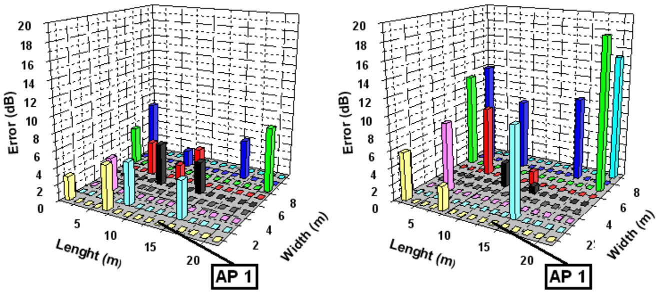
Figure 5. Errors between received power between dual slope model estimation and site survey measurement.

We investigate in [9], using analytical and measurement results, the same five different indoor path loss propagation models in office environments: one-slope; dual-slope; partitioned; COST-231 multi-wall model and average walls. Fig. 9 shows the prediction error when it is used the average walls and dual-slope models. Although, the dual-slope model presents a good accuracy, the average walls model has the best results when testing its scalability in office environments, as shown in Tab V. The present contribution shows that dual-slope model has the best results for industrial sites. However, it not necessarily might allow an accurately prediction at different types of indoor environments where the walls can be the predominant obstacles [9].

TABLE V

MEAN ERROR AND STANDARD DEVIATION FOR DUAL-SLOPE AND AVERAGE WALLS PROPAGATION MODELS AT 25 SELECTED POINTS [9].

Model	Mean Error (dB)		Standard Deviation (dB)	
	AP 1	AP 2	AP 1	AP 2
Average Walls	2.67	7.52	2.56	6.84
Dual-Slope	6.41	9.25	4.73	7.89



(a) Average walls model for AP1. (b) Dual Slope model for AP1.

Fig. 9 – Errors between received power between estimation and site survey measurement [9].

VII. CONCLUSIONS

This paper analyzed comparatively the accuracy of five propagation models (one-slope; dual-slope; partitioned; Cost-231 multi-wall model and average walls) for indoor industrial environments in order to determine a simple procedure for industrial WLAN planning using inexpensive resources. It has been concluded that the one-slope model responds for the best agreement for the small facilities, where the farthest distance between the transmitter and receiver is around *20 m*. For larger industrial environments, the path loss rate increases at distances greater than *20 m* and the dual-slope model proves to be more appropriate to estimate the path loss. In relation to the models that consider the wall attenuation, like COST 231 and average walls model, the path loss prediction is overestimated because industrial environments are usually large rooms where walls are not the predominant obstacles, as the industrial machines and stored materials are. In synthesis, the dual slope model allows first order results to optimize the APs placement, reducing the WLAN installation cost.

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