A New Propagation Model for 2.4 GHz Wireless LAN

Rafael S. de Souza and Rafael D. Lins
Universidade Federal de Pernambuco
Recife, PE - Brazil

Abstract — **This paper presents a detailed study of large-scale path loss on wireless networks operating in accordance with the standard IEEE 802.11g at 2.4 GHz in indoor and outdoor environments. A new propagation model is proposed. A comparative analysis of the existing and proposed models and the effects of the temperature and relative humidity on signal attenuation is made.**

Keywords **—humidity, modeling, propagation, wireless LAN.**

I. Introduction

WIRELESS networks based on the standard IEEE 802.11 are of widespread use today to provide Internet access in homes, offices, hotels or public sites. Suitably allocating wireless access points (AP), minimizing implementation costs and improving network performance is a challenge for those that deploy this kind of solution. Thus, understanding the behavior of electromagnetic propagation through typical environments for wireless networks is fundamental. This paper presents a brief review of some path-loss models found in the literature for wireless propagation in the 2.4 GHz band, followed by a proposal for a new model based on field measurements and a comparative analysis between the introduced and existing models. Measurements were made using 802.11g based wireless router at outdoor and indoor environments under the observation of climatic factors, specifically temperature and air relative humidity, to identify some practical effects of these aspects over wireless propagation and taking them into account into the new model.

II. Path-Loss Models for Wireless Propagation in the 2.4 GHz Band

Path-loss (PL) or large-scale propagation models represents a way to predict the behavior of signal propagation over large distances variations [1]. Typically they estimate the attenuation imposed to the transmitted signal (*PL*), in decibels (dB), as a function of distance (*d*) and considering some parameters with values fixed or established from measured data.

The literature describes several path loss models, but most of them were developed for mobile communications and consider some typical features of that service (Okumura and Hata model, for example) [2]. In this paper only models for wireless networks, or those developed for frequency bands that encompasses the 2.4 GHz band, were considered.

A. The Model of Young

The model proposed by Young is based on data collected in outdoor environments at New York City in 1952 over a frequency range from 150 MHz to 3.7 GHz [2]. The use of this model for signal propagation in wireless networks is unusual, but it seems to be applicable because its band range includes the 2.4 GHz band. The formula of the model of Young is:

$$PL(d) = \frac{d^4}{G_t G_r (h_t h_r)^2 \beta} \tag{1}$$

where d is the distance between transmitter and receiver, G stands for the antenna gains, and h their height (indices t and r indicate a transmitter or receiver). The parameter β is called the *clutter factor* [2] and is experimentally obtained. Supposing that the antennas of the transmitter and receiver are similar and have gain $G_t = G_r = 1$ and that both are placed at the same height $h_t = h_r = 1$, then formula (1) can be simplified into:

$$PL(d) = \frac{d^4}{\beta'} \tag{2}$$

or, expressing in dB units

$$PL(d)[dB] = 40\log(d) - 10\log(\beta'). \tag{3}$$

B. Log-distance Model

This is probably the most referenced model in the technical literature for signal propagation modeling in wireless networks [3-9]. It assumes an exponential relationship between incremental path loss and distance [10],

$$PL(d) \propto \left(\frac{d}{d_0}\right)^n \tag{4}$$

where d is the distance between transmitter and receiver, d_0 is a reference distance (typically assumed to be 1 m) and n is the attenuation factor [10]. From this relationship the path loss function, in dB units, is defined by:

$$PL(d)[dB] = PL(d_0)[dB] + 10 \cdot n \cdot \log\left(\frac{d}{d_0}\right). \tag{5}$$

Formula (5) indicates that the path loss at a given distance d

Rafael Santos de Souza is with Universidade Federal de Pernambuco (DES/UFPE), Recife – Pernambuco - Brazil. E-mail: rafael.souza@globo.com
Rafael Dueire Lins is with Universidade Federal de Pernambuco (DES/UFPE), Recife – Pernambuco - Brazil. E-mail: rdl@ufpe.br

is the sum of the path loss observed at a reference distance d_0 and the additional loss imposed by (4). The attenuation factor n is found experimentally.

C. The Multi-slope Model

The plotting of formula (5) on a logarithmic scale yields a straight line with slope determined by the attenuation factor n. The multi-slope model proposes a more flexible approximation with many segments and different slopes for each segment [11]. A special case of multi-slope model is the one that considers only two segments, known as *dual-slope* model. A formula for the model is:

$$PL(d)[db] = \begin{cases} PL(d_0) + 10 n_1 \log\left(\frac{d}{d_0}\right) & \text{if } d_0 < d < d_{bp} \\ PL(d_0) + 10 n_1 \log\left(\frac{d_{bp}}{d_0}\right) + 10 n_2 \log\left(\frac{d}{d_{bp}}\right) & \text{if } d > d_{bp} \end{cases} \quad (6)$$

where n_1 and n_2 stand for the slope of the first and second segments, d_0 represents a reference distance and d_{bp} indicates the breakpoint between segments. A way to find the parameter d_{bp} is presented at [7] and values for outdoor propagation of n_1=2 and n_2=4 are suggested.

D. The Model of De Oliveira et al.

Published in reference [12], this model was initially proposed for mobile phone propagation. Although, the approach defined at this model, considering that signal attenuation has logarithmic and linear relation with distance (not only logarithmic):

$$PL(d)[dB] = P_0 - 10 \cdot \log\left(\frac{d}{d_0}\right) + 10 \cdot m \cdot \left(\frac{d}{d_0}\right) \quad (7)$$

where P_0 and m are measured experimentally in such a way to minimize the root mean square error of the values predicted by the model.

E. The ITU Model

The model of ITU (International Telecommunication Union) was developed for indoor WLAN operating from 900 MHz to 100 GHz [13]. The proposed attenuation formula is:

$$PL(d)[dB] = 20 \cdot \log(f) + N \cdot \log(d) + \mathrm{Lf}(m) - 28 \quad (8)$$

where f indicates the operational frequency in MHz, N is the distance power loss coefficient, Lf is the floor penetration loss factor and m is the number of floors between AP and terminals. Some specific formulas for Lf are defined in [13] as a function of the frequency and different kinds of environments.

F. The Log-distance Model with floor and partition attenuation factor

This model is based on the log-distance model adapted to indoor propagation considering the effects of floors, soft partitions and walls between AP and wireless terminals [10]. Using this model the attenuation at a point at a distance d from the source can be computed using the formula:

$$PL(d)[dB] = PL(d_0) + 10 \cdot n \cdot \log\left(\frac{d}{d_0}\right) + FAF[dB] + p \cdot SPAF[dB] + q \cdot WAF[dB] \quad (9)$$

where FAF (floor attenuation factor), $SPAF$ (soft partition attenuation factor), and WAF (wall attenuation factor) represent the loss increment caused by each kind of obstacle. Parameters p and q indicate the number of soft partitions and walls between the transmitter and receiver. Reference [10] suggests a value of n=2 for free space propagation in this model (additional path loss is attributed to physical obstructions).

G. The Cheung, Sau and Murch Model

The model proposed by Cheung, Sau and Murch incorporates ideas from the dual-slope and the log-distance models with floor and partition attenuation factor [4]. The improvement proposed in this model is to consider the effects of floors and walls as a function of the incidence angle between propagation direction and the obstacle.

$$PL(d)[dB] = PL(d_0)[dB] + 10 \cdot \log\left(\frac{d}{d_0}\right)^{n_1} \cdot U(d_{bp} - d) + 10 \cdot \left[\log\left(\frac{d_{bp}}{d_0}\right)^{n_1} + \log\left(\frac{d}{d_{bp}}\right)^{n_2}\right] \cdot U(d - d_{bp}) + \sum_{p=1}^{P} \frac{WAF(p)}{\cos\theta_p} + \sum_{q=1}^{Q} \frac{FAF(q)}{\cos\theta_q} \quad (10)$$

where:

- $U(d)$ = 0 for $d < 0$;
- θ_p and θ_q indicates the incidence angle between the propagation direction and the wall p or floor q, respectively;
- P and Q are the total number of walls and floors between the transmitter and receiver, respectively.

III. FIELD MEASUREMENTS

A. Methodology

Field measurements were made using the following equipments and software:

- Toshiba Laptop, Satellite A105, with Windows XP Professional and Intel PRO 3945ABG wireless adapter;
- Linksys WRT54G wireless router (mode OFDM 802.11g, channel 3 ≈ 2,422MHz);
- WirelessMon Professional 2.0 from Passmark;
- Minipa MT-241 thermo-hygrometer.

Measurements were made in 4 different environments, 2 outdoors and 2 indoors. Laptop and wireless router were always positioned 1 meter from the floor and attenuation data was collected from WirelessMon Professional. Every measurement point was visited at least twenty times. At each visit a 60 second measurement was made and the software registered 30 attenuation values.

Outdoor measurements were conducted at 2 places: Centro de Tecnologia e Geociências from UFPE (called environment outdoor 1) and at a small street located at the metropolitan area of Recife, PE, Brazil (called environment outdoor 2). Indoor measurement were conducted in two apartments located in the metropolitan area of Recife, Brazil, (for now on called indoor 1 and 2), both single floor. In the first one, measurements were made in two distinct paths (ray 1 and ray 2). Table 1 shows the number of measurement points at each one and the total number of measurements made at each point.

TABLE I
POINTS AND NUMBER OF MEASUMENTS IN EACH ENVIRONMENT.

Environment	Measurement points	Nr. of measurements
Outdoor 1	9	35
Outdoor 2	5	20
Indoor 1, ray 1	6	30
Indoor 1, ray 2	6	30
Indoor 2	6	20

The distance from AP of each measurement point, in each environment, is shown on Tables II and III.

TABLE II
MEASUREMENT POINTS DISTANCE FROM AP (OUTDOOR)

Points	Outdoor 1	Outdoor 2
1	1m	1m
2	15m	10m
3	30m	20m
4	45m	30m
5	60m	40m
6	75m	-
7	90m	-
8	105m	-
9	120m	-

TABLE III
MEASUREMENT POINTS DISTANCE FROM AP (INDOOR)

Points	Indoor 1, ray 1	Indoor 1, ray 2	Indoor 2
1	1m	1m	1m
2	2.6m	2.6m	3m
3	4.3m	5.3m	6m
4	6.3m	7.9m	9m
5	8.3m	10.3m	12m
6	10.3m	12.3m	15m

B. *Results*

Tables IV and V show the mean attenuation value of each point at outdoors and indoors environments, respectively. The maximum and minimum values of temperature (T) and relative humidity (RH) observed during measurements are indicated on Table VI.

TABLE IV
OUTDOOR MEASUREMENT

	Mean attenuation (dB)		Standard deviation (dB)	
Points	Out 1	Out 2	Out 1	Out 2
1	37.33	36.89	2.01	1.07
2	52.54	60.58	2.04	1.24
3	60.44	73.74	2.25	2.50
4	71.41	80.03	1.88	1.35
5	78.75	79.60	2.57	1.58
6	76.07	-	2.05	-
7	79.23	-	2.36	-
8	83.30	-	2.05	-
9	84.51	-	1.92	-

TABLE V
INDOOR MEASUREMENT

	Mean attenuation value (dB)			Standard deviation (dB)		
Points	In 1, ray 1	In 1, ray 2	In 2	In 1, ray 1	In 1, ray 2	In 2
1	37.76	37.76	33.48	2.88	2.88	1.80
2	42.51	57.83	47.01	3.00	2.05	2.80
3	50.50	61.82	58.49	1.71	1.53	2.80
4	56.66	70.24	72.31	2.09	2.50	3.09
5	59.78	74.58	84.21	2.27	2.31	1.61
6	63.86	82.46	87.91	2.84	2.37	2.65

TABLE VI
MAXIMUM AND MINIMUM VALUES OF TEMPERATURE AND RELATIVE HUMIDITY OBSERVED AT EACH ENVIRONMENT

	RH		T (°C)	
Environment	Min.	Max.	Min.	Max.
Outdoor 1	40%	77%	28	35
Outdoor 2	48%	72%	29	33
Indoor 1	55%	81%	26	31
Indoor 2	66%	78%	27	30

IV. ANALYSIS

Measurement results were divided into two groups. The first one, with the results of outdoor 1 and indoor 1, was used to identify the effects of climatic factors over signal attenuation and develop a new propagation model. The second group, with the results of outdoor 2 and indoor 2, was used to validate the proposed model.

The effects of the relative humidity were identified splitting the results of outdoor 1 measurement into 3 subgroups respecting relative humidity order. The same was done to the results of indoor 1 measurement. For each subgroup the corresponding attenuation factor (from log-distance model) was identified using Matlab 7.0 Curve Fitting Tool. Tables VII and VIII present the results of such analysis.

TABLE VII
RELATIVE HUMIDITY EFFECTS ON OUTDOOR 1 DATA

	Subg. 1	Subg. 2	Subg. 3
Number of measurements	12	11	12
RH – Min.	40%	57%	71%
RH – Max.	56%	69%	77%
N	2.049	2.078	2.154

TABLE VIII
RELATIVE HUMIDITY EFFECTS ON INDOOR 1 DATA

	Subg. 1	Subg. 2	Subg. 3
Number of measurements	10	10	10
RH – Min.	55%	65%	72%
RH – Max.	61%	71%	81%
n (for ray 1)	2.234	2.265	2.491
n (for ray 2)	3.705	3.702	3.925

From tables VII and VIII it is possible to identify a direct influence of relative humidity on signal attenuation. On both cases, outdoor 1 and indoor 1, the higher attenuation factor was observed with subgroup 3 where measurement data was collected with higher relative humidity levels.

V. THE NEW MODEL

Using multiple linear regressions, an adequate combination of variables for attenuation data (from outdoor 1 and indoor 1 data) was sought off. The idea was to find a model such that

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + ... + \beta_k X_k + \varepsilon \qquad (11)$$

where Y should indicate signal attenuation and X_i the explanatory variables. Possible variables considered at this search were: d, log(d), log(RH) and log(T). Table IX indicates R^2 coefficient (parameter that indicates how well the proposed combination explains dependent variable variations [14]) of each considered possibility when applied to outdoor 1 and indoor 1 data. The following facts were observed:

1. Including variable d to the model only considering log(d) increases the R^2 coefficient;
2. In all cases, add log(RH) increases the R^2 coefficient too;
3. Although presenting a better R^2 coefficient, the combination at the fourth line of table IX yields a problem: the parameter β_4, in all cases, had a confidence interval including zero. Thus, to provide the stability of the parameters, variable log(T) should be removed [14].

Other combinations of variables, different from the ones on Table IX and using absolute values of temperature and relative humidity were tested too. The best result still was that achieved on the fourth line of Table IX, however. Thus, the proposed model taking into account the influence of air humidity in 802.11g propagation is:

$$PL(d, RH)[dB] = \beta_0 + \beta_1 \log(d) + \beta_2 d + \beta_3 \log(RH). \qquad (12)$$

TABLE IX
MULTIPLE LINEAR REGRESSION APPLIED TO
OUTDOOR 1 AND INDOOR 1 MEASUREMENT DATA

Model	R^2 coeff. (Outdoor 1)	R^2 coeff. (In.1, ray 1)	R^2 coeff. (In.1, ray 2)
$Y = \beta_0 + \beta_1 \log(d)$	89.98%	88.76%	94.16%
$Y = \beta_0 + \beta_1 \log(d) + \beta_2 d$	94.41%	92.08%	94.47%
$Y = \beta_0 + \beta_1 \log(d) + \beta_2 d + \beta_3 \log(UR)$	94.61%	93.11%	94.85%
$Y = \beta_0 + \beta_1 \log(d) + \beta_2 d + \beta_3 \log(UR) + \beta_4 \log(T)$	94.61%	93.19%	94.87%
$Y = \beta_0 + \beta_1 d + \beta_2 \log(UR)$	83.10%	90.50%	87.70%
$Y = \beta_0 + \beta_1 d + \beta_2 \log(UR) + \beta_3 \log(T)$	83.32%	91.53%	88.08%

VI. MODEL VALIDATION

Considering a second set of indoor and outdoor data a comparative analysis of performance was made to validate the new model proposed. The parameters used for each model were determined with Matlab 7.0 Curve Fitting Tool and the *regress* function. The root mean square error was used for comparison. The results are shown on Tables X to XIV. Only measurement points with $d > 1$m were considered.

TABLE X
COMPARATIVE ANALYSIS FOR
OUTDOOR 1 DATA MEASUREMENTS

Model	Parameters	RMSE
Young	$B' = 0.1995$	4.791 Db
Log.(d)	$n = 2.093$	5.287 dB
Dual-slope	$n_1 = 2$; $n_2 = 4$; $d_c = 50$m	4.553 dB
De Oliveira *et al.*	$P_0 = 55.05$dB; $m = 0.0497$	7.433 dB
Proposed	$\beta_0 = 37.67$; $\beta_1 = 15.402$; $\beta_2 = 0.155$; $\beta_3 = 7.508$; UR = 0.61	3.277 dB

TABLE XI
COMPARATIVE ANALYSIS FOR INDOOR 1,
RAY 1, DATA MEASUREMENTS

Model	Parameters	RMSE
ITU	$N = 20.94$	3.535 dB
Log(d)	$n = 2.33$	2.958 dB
Log(d) with *WAF*	$n = 2$; $WAF = 6.29$ dB	4.181 dB
Cheung, Sau and Murch.	$n_1 = 2$; $n_2 = 2.5$; $d_c = 10$m; $WAF = 6.29$dB; $\theta = 0^o$	4.183 dB
Proposed	$\beta_0 = 38.63$; $\beta_1 = 11.157$; $\beta_2 = 1.724$; $\beta_3 = 18.417$; UR = 0.67	1.323 dB

TABLE XII
COMPARATIVE ANALYSIS FOR INDOOR 1, RAY 2, DATA MEASUREMENTS

Model	Parameters	RMSE
ITU	$N = 35.65$	3.168 dB
Log(*d*)	$n = 3.777$	3.293 dB
Log(*d*) with *WAF*	$n = 2$; $WAF = 6.29$ dB	4.267 dB
Cheung, Sau e Murch.	$n_1 = 2$; $n_2 = 2.5$; $d_c = 10$m; $WAF = 6.29$dB; $\theta_1 = 54^o$; $\theta_2 = 36^o$	3.993 dB
Proposed	$\beta_0 = 41.87$; $\beta_1 = 30.598$; $\beta_2 = 0.607$; $\beta_3 = 16.844$; UR = 0.67	2.967 dB

TABLE XIII
COMPARATIVE ANALYSIS FOR OUTDOOR 2 DATA MEASUREMENTS

Model	Parameters	RMSE
Young	$\beta' = 0.01075$	2.815dB
Log(*d*)	$n = 2.739$	2.810 dB
Dual-slope	$n_1 = 2$; $n_2 = 4$; $d_c = 50$m	11.431 dB
De Oliveira *et al.*	$P_0 = 47.98$dB; $m = 0.1433$	9.642 dB
Proposed	$\beta_0 = 38.88$; $\beta_1 = 25.849$; $\beta_2 = 0.099$; $\beta_3 = 11.56$; UR = 0.61	2.638 dB

TABLE XIV
COMPARATIVE ANALYSIS FOR INDOOR 2 DATA MEASUREMENTS

Model	Parameters	RMSE
ITU	$N = 35.9$	7.932 dB
Log(*d*)	$n = 4.235$	6.263 dB
Log(*d*) with *WAF*	$n = 2$; $WAF = 6.29$ dB	13.113 dB
Cheung, Sau e Murch.	$n_1 = 2$; $n_2 = 2.5$; $d_c = 10$m; $WAF = 6.29$dB; $\theta_1 = 30^o$; $\theta_2 = 60^o$	7.138 dB
Proposed	$\beta_0 = 41.17$; $\beta_1 = 19.407$; $\beta_2 = 2.4527$; $\beta_3 = 72.813$; UR = 0.72	2.291 dB

Figure 1 presents the attenuation curves for models and parameters shown on Table XIV and the real data collected from measurements made in the Indoor 2 environment. In Figure 1 it is possible to see that the curve produced by the proposed model is the one that best fits the real data.

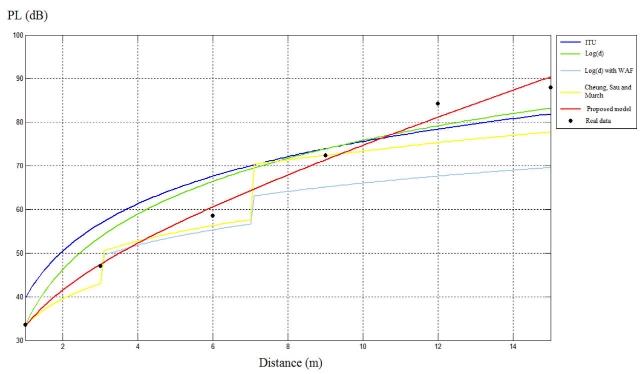

Figure 1. Attenuation curves for models and parameters at Table XIV.

VII. Conclusions and Lines for Further Work

The experiments performed show that the relative humidity affects 802.11g propagation range. To the best of the knowledge of the authors of this paper, no previous reference in the literature reports on such factor. A new propagation model is proposed and validated. This new model presents better propagation prediction results than any other of the existing models.

Some lines for future work are drawn:

- To analyze the effects of signal attenuation over some qualitative aspects of computer networks;
- To study the effect of relative humidity in the 5GHz band;
- To investigate possible effects of temperature over signal attenuation at places with wider temperature range;
- To develop an algorithm to determine signal attenuation maps based on the proposed model.

References

[1] T. S. Rappaport, *Wireless Communications Principles and Practice*. New Jersey: Prentice Hall, 2002.

[2] J. S. Seybold, *Introduction to RF Propagation*. New Jersey: John Wiley & Sons, 2005.

[3] J. Lloret *et al.*, “A fast design model for indoor radio coverage in the 2.4 GHz wireless LAN”, in *Proc. 1st International Symposium on Wireless Communications Systems*, Mauritius, 2004, pp. 408-412.

[4] K.-W. Cheung, J.H.-M. Sau and R. D. Murch, A new empirical model for indoor propagation prediction, *IEEE Transactions on Vehicular Technology*, vol. 47, no. 3, pp. 996-1001, Aug. 1998.

[5] L. C. Liechty, E. Reifsnider and G. Durgin, Developing the Best 2.4 GHz Propagation Model from Active Network Measurements, *IEEE 66th Vehicular Conference*, Baltimore, 2007, pp. 894-896.

[6] B. Sujak *et al.*, Indoor propagation channel models for WLAN 802.11b at 2.4 GHz ISM band, in *Proc. Asia-Pacific Conference on Applied Electromagnetics*, Kuala Lampur, 2005, pp. 373-377.

[7] J. B. Andersen, T. S. Rappaport and S. Yoshida, Propagation Measurements and Models for Wireless Communications Channels, *IEEE Communications Magazine*, vol. 33, ed. 1, pp. 42-49, Jan. 1995.

[8] G. J. M. Janssen and R. Prasad, Propagation measurements in an indoor radio environment at 2.4 GHz, 4.75 GHz and 11.5 GHz, *IEEE 42nd Vehicular Technology Conference*, Denver, 1992, vol. 2, pp. 617-620.

[9] R. Akl, D. Tummala and X. Li, Indoor Propagation Modeling at 2.4 GHz for IEEE 802.11 Networks, in *Proc. 6th IASTED International Multi-Conference on Wireless and Optical Communications*, Banff, 2006. Available: http://www.cse.unt.edu/~rakl/ATL06.pdf.

[10] S. Y. Seidel and T. S. Rappaport, 914 MHz Path Loss Prediction Models for Indoor Wireless Communications in Multifloored Buildings, IEEE Transactions on Antennas and Propagation, vol. 40, no. 2, pp. 207-217, Feb. 1992.

[11] A. Goldsmith, *Wireless Communications*. New Jersey: Prentice Hall, 2005.

[12] J. N. C. de Oliveira *et al.*, A New Propagation Model for Cellular Planning, in *Proc. VI International Telecommunications Symposium*, pp. 35-37. IEEE Press, 2006

[13] ITU-R Recommendations. *Propagation data and prediction methods for the planning of indoor radiocommunication systems and radio local area networks in the frequency range 900MHz to 100GHz*, ITU-R P.1238-5, Feb. 2007.

[14] D. G. Kleinbaum *et al.*, *Applied Regression Analysis and Other Multivariable Methods*. California: Duxbury Press, 1998.