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Modified Empirical Mobile Radio Path Loss model for Indoor Propagation

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***Abstract*— Site specific path loss modeling is a major requirement in the indoor environment, to achieve a good quality of the received signal and improve the performance of wireless systems. The need is to optimize the existing propagation models and suggest accurate, reliable and flexible models. In this paper, a modified empirical indoor propagation model is suggested to model the path loss of the mobile radio signals at 2.4 GHz in a better manner. The experimental scenario is an indoor corridor with three glass partitions in the building of Deccan College of Engineering and Technology at Hyderabad. The received mobile signal strengths are collected at specific distances of 1m up to 10 m in the corridor. The available indoor empirical models are implemented and based on comparison with measurements, Motley – Kennan model is selected for optimization. The modification is done by including break points at the locations of the partitions and additionally including glass reflection coefficient and polarization mismatch in the analysis. The path loss exponents used in the computations are determined statistically by Minimum Mean Square Error method. The modified model improves the path loss by 0.68 db compared to the original model. It has the lesser values of Mean Error (4.398), Mean Square Error (26.79) and RMSE (5.17) compared to the original model. The results validate the performance of the modified model to estimate the path loss of the mobile radio signals in an improved manner.**

Keywords—Path Loss, Path Loss Exponent, Motley Kennan model, Modified model, Reflection coefficient, Root Mean Square Error.

I. INTRODUCTION

The rapid advancement in the wireless communication systems, has initiated the need for accurately characterizing the propagation medium. In the indoor environment, the radio channel varies to a large extent depending on the position of access points, the layout of the building, construction materials and the nature of obstacles encountered in the propagation path [1]. The complex indoor structure degrades the quality of the received signal. Hence there is a requirement for accurate estimation of radio path loss, which could be used to predict coverage areas of WLAN signals and provide better quality of service to subscribers. Propagation models are mathematical tools that characterize the medium. The empirical models are simple and faster to implement. They can be adjusted by adding suitable correction factors and extrapolated to other frequencies. The deterministic models have the drawback of complex computations and the requirement of detailed physical and electromagnetic parameter database of the obstacles [1]. In the recent years many researchers have developed different models to estimate the path loss in the indoor scenario. Solahuddin et al, have implemented various indoor empirical models in class room scenario and optimized the partitioned based model for Non Line Of Sight (NLOS) propagation [2]. Andrade et al, had done extensive collection of field strengths inside two different buildings and path loss equations are determined using log-distance and log-normal shadowing model [3]. Lima and Menezes proposed an adjustment in the Motley-Keenan Model by, considering the thickness of the wall and loss due to the type of wall by which better prediction results were obtained [4]. Lun Li et al had proposed modification in multi wall model, by considering reflection through different obstacles such as wall, elevator and glass [5]. In most of these simulations, the path loss exponent used in the computations is obtained in a coarse way as the slope of the model curve. In this paper, the path loss exponent is obtained using Minimum mean Square Error method to obtain better predictions and improve the accuracy. Additionally, the reflection coefficients of the obstacles and the polarization mismatch loss are included in the analysis there by ensuring improved path loss estimation.

II. INDOOR MEASUREMENT DETAILS

The mobile signal strengths are collected using Network Signal Info Pro software tool commonly used to optimize mobile networks. The transmitter is a Cisco Linksys E900 Wireless Router. The receiver, a Samsung Tablet 3 is loaded with the Info Pro Tool that continuously records the mobile signal strengths. The dimensions of the corridor are 11.1m length, 4.5m width and 2.65m height. The adjacent walls of the corridor are made of concrete with permittivity ($\varepsilon_r = 7$) and glass partitions have permittivity ($\varepsilon_r=4$). Concrete ceiling is covered with gypsum board ($\varepsilon_r = 3$) and floor is covered with Porcelain tiles ($\varepsilon_r = 6$). The permanent glass partitions at 1m, 6m and 9 m respectively provide the Non Line Of Sight (NLOS) propagation. A detailed description of the indoor scenario and the measurement details are provided in paper [6].The received signal strengths are collected at fixed locations separated by 1m up to 10 m. At each location, a large number of samples are collected. As a preprocessing step, the signal strengths beyond the valid range termed as outliers are eliminated. Secondly, a low pass filtering is done to extract path loss and remove small scale fading [7]. The local mean of the path loss power has to satisfy the criteria of lying between 20 λ to 40 λ [7]. The preprocessing is an important step to separate large scale variations of the received signal strengths. Knowing the details of transmitted power (P_t), received power (P_r), cable losses(L_s), antenna gains (G_t, G_r) , the path loss is estimated from the collected received signal strengths as [6]

$$PL(d) = P_t - P_r + G_t + G_r - L_s \qquad (1)$$

The loss obtained from Equation 1, is used as a reference to validate the empirical models and the modified model.

III. PATH LOSS EXPONENTS BY MINIMUM MEAN SQUARE ERROR METHOD

The rate of propagation path loss as a function of distance gives the Path Loss Exponent (PLE). The value of the path loss exponent in the indoor varies from 1 to 2 [8]. It is extracted as the gradient of the path loss curve, or can be obtained from the regression line of the measured data. In order to increase the accuracy of prediction, PLE is estimated using the approach of Minimum Mean Square Error method [9]. The received power P_r (d) in terms of reference distance (d_0), PLE (n) at a distance ‘d’ from the transmitter is given as

$$P_r(d) = P_r(d_0) - 10n\log(d/d_0) \qquad (2)$$

The summation of the squared errors between the measured and estimated values must be minimized according to MMSE method given as [9].

$$E(n) = \sum_{i=1}^{k} (P_r - P_{r\,i})^2 \qquad (3)$$

The mean square error in Equation3, is minimized by setting the derivative of $E(n)$to zero given as

$$\frac{\partial E_{(n)}}{\partial n} = 0 \qquad (4)$$

Solving the above equation the path loss exponent ‘n’ is given

$$n = \frac{\sum_{i=1}^{k}\left(P_{r(d_o)} - P_{ri}\right)10\log\left(\frac{d}{d_o}\right)}{\sum_{i=1}^{k}\left(10\log\frac{d}{d_o}\right)^2} \qquad (5)$$

The Path Loss Exponents are modeled in a more precise manner compared to the traditional gradient approach. This improves the accuracy of path loss estimation.

IV. INDOOR EMPIRICAL PATH LOSS MODELS

The Empirical models are based on measurement data and factors such as type of scenario, distance and the frequency of the transmitter. It uses the equations obtained from various measurements under different constraints. Additional correction factors can be suitably added depending on the requirement. The different empirical models used for path loss estimation in the Indoor environment are briefly summarized.

A. Dual-Slope Model

Dual-slope model is a simple power law model that has two slopes and the propagation is explained by two Path Loss Exponents. The first PLE is computed for the Line Of Sight (LOS) and the second is for the Non-Line of Sight (NLOS) region. The point of change is defined by the breakpoint. The path loss in dB, given by [3] is

$$L = L_0 + 10n_1\log_{10}d \qquad d < d_{bp} \qquad (6)$$

$$10n_1\log_{10}d_{bp} + 10n_2\log_{10}(d/d_{bp}) \qquad d > d_{bp} \qquad (7)$$

The PLE’s, n_1 and n_2 are determined experimentally, d is the Transmitter-Receiver (T-R) separation distance and L_0 is the path loss in dB obtained at a reference distance of 1 meter from the transmitter. The method of selecting the breakpoints affects the performance of the model. This model is very simple and is most suitable for line of sight scenarios. The model does not consider the effect of obstacles and is not accurate.

B. Partitioned Model

The model consists of four different signal loss prediction formulas which are added to the path loss obtained with respect to reference distance ‘d_o’. The path loss in dB, given as [3, 10].

$$PL = PL_0 + \begin{cases} 20\log_{10}d & d < 10 \\ 20 + 30\log_{10}\left(\frac{d}{10}\right) & 10 < d < 20m \\ 29 + 60\log_{10}\left(\frac{d}{20}\right) & 20 < d < 40m \\ 47 + 120\log_{10}\left(\frac{d}{40}\right) & d > 40m \end{cases} \qquad (8)$$

Where PL_o is the path loss in ‘db’ at close in reference distance of 1 meter, d is the distance separating the transmitter and receiver. The drawback of this model is the value of path loss exponent, distance range and additional signal loss values are fixed and predetermined based on the research conducted previously[10].

C. Log-Normal Shadowing Model

The One-Slope model is extended to Log-Normal Shadowing model. It considers the effects of random shadowing arising due to various clutters. The term Xσ represents, zero-mean Gaussian distributed random variable with standard deviation (σ). This describes the shadowing effects and is included in the path loss calculation. The mean path loss in decibels is given as [11]

$$PL\,[dB] = PL(d_o) + 10n\log(d/d_o) + X\sigma \qquad (9)$$

Where $PL(d_0)$ is the path loss at reference distance d_0, n is the path loss exponent and 'd' is the distance between transmitter and receiver [12].

D. COST-231 Multi-Wall Model

The COST-231 Multi-Wall model considers the loss due to floors and walls in addition to free space loss. The path loss in db, due to COST-231 Multi Wall Model is given as [3]

$$\mathrm{PL_{CMW}(dB)} = \mathrm{L_0} + 20\log(\mathrm{d}) + \mathrm{K_f}^{\left[\frac{k_f+2}{k_f+1}-b\right]}\mathrm{L_f} + \sum_{i=1}^{w}\mathrm{K_{wi}}\,\mathrm{L_{wi}} \tag{10}$$

where, L_0 for 2.4 GHz is 40.2 db, K_{wi} is the number of penetrated walls of type i, K_f is the number of floors, L_{wi} is the loss of wall type i, L_f is the loss between adjacent floors, b is the empirical parameter specifying the nonlinear effects on path loss, i is the number of wall types. The attenuation of the signals while passing through the floors and walls are considered in this model. Hence it ensures better accuracy than the other empirical models.

The COST-231 Multi-Wall model was modified by considering the type of walls and the signal reflection parameter of the glass walls. The modified COST-231 Multi-Wall model is given as [5]

$$\mathrm{L} = \mathrm{Lo} + 10\gamma\log10(\mathrm{d}) + \sum_{i=1}^{K_f}\eta_{ci} + \eta_d + \eta_g + \eta_e \tag{11}$$

Where L_o is path loss at 1 meter, d is distance between transmitter and receiver in meters, γ is the path loss exponent, η_{ci} is the loss due to ith concrete wall, η_d and η_e are the loss factors for dry walls and elevators, K_f is the total number of concrete walls through which the signal propagates, η_d has different values depending on the thickness of the wall, η_g is the reflection factor from glass walls.

E. Motley-Keenan Model

The Motley-Keenan model considers the loss due to the walls. The attenuation due to reflection from different types of walls is considered in the path loss estimation. If PL_r is the reference loss in db measured at a distance of 1 meter from the transmitter, n is the path loss exponent, N is the number of walls between the transmitter and the receiver, the path loss in db is given as [13]

$$\mathrm{PL_{(d)}[dB]} = \mathrm{PL_r} + 10\mathrm{n}\log_{10}(\mathrm{d}) + \mathrm{k_f l_f} + \sum_{i=1}^{N}\mathrm{k_i l_{wi}} \tag{12}$$

k_i is the number of type i walls, k_f is the number of floors, l_f is loss associated with the floor and L_{wi} is the penetration loss in the type i walls. Lima et al has proposed an improved Motley-Keenan model and verified it to be more accurate, which added the thickness factor of wall. The modified Motley-Keenan model obtained by adding an adjusted term is given as [4][2]

$$\mathrm{PL(d)[dB]} = \mathrm{PLr} + 10\mathrm{n}\log(\mathrm{d}) + \sum_{i=1}^{N}\mathrm{k_i L_{0i}}\,2^{\log_3\left(\frac{e_i}{e_{0i}}\right)} \tag{13}$$

L_{0i} is the penetration loss in the type i reference wall e_{0i} is the thickness of the reference wall and e_i is the thickness of the type i wall which blocks the signal.

V. MODIFIED EMPIRICAL MODEL

The empirical Motley-Kennan model is modified for the scenario under consideration. The steps involved in modifying the Motley-Kennan model are briefly summarized.

Step 1: The model is selected for optimisation, since it has a better agreement with the measured path loss compared to the other models for the specified environment. The original Motley-Kennan model is given as

$$\mathrm{PL} = \mathrm{PL(r)} + \sum \mathrm{k_i l_i} + \mathrm{k_f l_f} + 10\mathrm{n}\log_{10}\mathrm{d} \tag{14}$$

The model prediction can be improved by including the path loss incurred due to obstacles which is achieved by adding break points at different location where LOS is changing to NLOS communication [14].

Step 2: In the modification process, the glass partitions at distances 1m and 6m are considered as breakpoints which are included in the path loss analysis. By considering the first break point (dbp1) at 1m and second break point (dbp2) at 6 m, the path loss Equation 14 is written as

$$\mathrm{PL} = \mathrm{PL(r)} + \sum \mathrm{k_i l_i} + \mathrm{k_f l_f} + 10\mathrm{n_1}\log_{10}\mathrm{d} \quad \text{for} \quad \mathrm{d} < \mathrm{d_{bp1}}$$

$$\sum \mathrm{k_i l_i} + \mathrm{k_f l_f} + 10\mathrm{n_1}\log_{10}\mathrm{d_{bp1}} + 10\mathrm{n_2}\log_{10}\mathrm{d}/\mathrm{d_{bp1}}$$

$$\text{for dbp1<d<dbp2}$$

$$\sum \mathrm{k_i l_i} + \mathrm{k_f l_f} + 10\mathrm{n_1}\log_{10}\mathrm{d}/\mathrm{d_{bp2}} + 10\mathrm{n_2}\log_{10}\mathrm{d}/\mathrm{d_{bp2}} + 10\mathrm{n_3}\log_{10}\mathrm{d}/\mathrm{d_{bp2}} \quad \text{for} \quad \mathrm{d} > \mathrm{dbp2} \tag{15}$$

The path loss exponents are computed at discrete distances of 1m using MMSE method and the average values before and after the break points are considered as in Equation 15.

Step 3: The glass reflection coefficient (η_g) and polarization loss factor are included in the above equation and the modified path loss model is given as

$$\mathrm{PL} = \mathrm{PL(r)} + \sum \mathrm{k_i l_i} + \mathrm{k_f l_f} + 10\mathrm{n_1}\log_{10}\mathrm{d} + \eta_g + \cos^2\phi \quad \text{for} \quad \mathrm{d} < \mathrm{d_{bp1}}$$

$$\sum \mathrm{k_i l_i} + \mathrm{k_f l_f} + 10\mathrm{n_1}\log_{10}\mathrm{d_{bp1}} 10\mathrm{n_2}\log_{1o}\mathrm{d}/\mathrm{d_{bp1}} + \eta_g + \cos^2\phi \quad \text{for} \quad \mathrm{dbp1} < d < dbp2$$

$$\sum \mathrm{k_i l_i} + \mathrm{k_f l_f} + 10\mathrm{n_1}\log_{10}\mathrm{d_{bp2}} + 10\mathrm{n_2}\log_{10}\mathrm{d}/\mathrm{d_{bp2}} + 10\mathrm{n_3}\log_{10}\mathrm{d}/\mathrm{d_{bp2}} + \eta_g \cos^2\phi \quad \text{for } \mathrm{d} > \mathrm{dbp2} \tag{16}$$

Polarization is an important factor for radio frequency antennas in radio communication. If the RF antenna polarization does not match that of the signal there is a corresponding decrease in the level of the signal. It is reduced by a factor of cosine of the angle between the polarization of the RF antenna and the signal [15]. Hence to compensate the mismatch, the polarization loss factor is included in the modified model. Additionally, the glass reflection coefficients used in the Equation 16, improves the path loss predicted by the modified model. The performance of the modified model presented in Equation 16 is evaluated by comparison with other models and measured path loss.

VI. RESULTS AND DISCUSSION

The mobile radio signals are collected at 2.4 GHz in the indoor environment. The collected field strengths are initially subjected to preprocessing to remove the field strengths beyond the specified limits. The large scale fading is filtered out and samples are averaged at each measurement instant. The mean and standard deviation of the received signal strengths are summarized in Table I

TABLE I
Statistics of Received Power

Statistics	Min	Max	Mean	Std
Measured Power (dbm)	-82.76	-85.91	-75.64	6.924

The received signals have a mean of -75.64dbm and a standard deviation of 6.924. The received signal strengths are averaged at each location, and are converted into path loss, using transmitted power, antenna gains and cable losses. The average signal strengths and the extracted path loss are summarized in Table II.

TABLE II
Received signal strengths and Pathloss

Distance (mts)	Measured Signal Strengths (dbm)	Path loss (db)
1	-77.96	94.96
2	-59.80	79.81
3	-68.76	85.76
4	-75.28	92.28
5	-75.61	92.60
6	-80.51	97.52
7	-74.28	91.28
8	-80.76	97.76
9	-80.68	97.68
10	-82.76	99.76

The measured path loss is used as a reference for path loss comparison. Knowing the received power and estimated path loss, the path loss exponents are computed using statistical MMSE method. The path loss exponents are summarized in Table III. The path loss exponents in Table III indicate the variation of path loss. Since the first partition is located at a distance of 1m, the corresponding PLE is higher at a distance of 6 m and around (9-10m) the path loss exponents have an increased value. The reason for this increase is due to the presence of second and third partitions. The obtained path loss exponents are used in simulating the path loss from the standard empirical models as in Table IV.

TABLE III
Path Loss Exponents by MMSE method

Distance (mts)	Path Loss Exponents
1	1.949
2	0.998
3	0.621
4	1.571
5	1.408
6	1.881
7	1.003
8	1.656
9	1.559
10	1.689

TABLE IV
Path Loss comparison of Empirical models

Empirical Indoor Models	Path Loss (db)			
	Min	Max	Mean	Std
Dual slope	76.79	86.79	83.35	3.19
Log Normal	82.18	92.18	88.74	3.18
Partitioned	69.8	99.8	89.48	9.55
Multiwall	55.3	85.3	74.98	9.55
Motley kennan	84.6	94.6	91.16	3.18
Measured Path Loss	79.8	99.76	92.94	6.18

From Table IV, comparing the model estimated mean path loss values with the measured path loss; it is found that the path loss estimated from Motley Kennan model and its standard deviation have a best agreement with measurements. The dual slope and lognormal model also have a better performance in terms of both mean path loss and standard deviation but not as good as Motley Kennan model. The partitioned model and Multiwall model has a larger standard deviation. From Table IV it can be concluded that Motley Kennan model has a better match with the measured path loss. Hence this model is selected for modification to further improve the path loss estimation. The path loss comparison of empirical models with respect to distance is shown in Figure1.

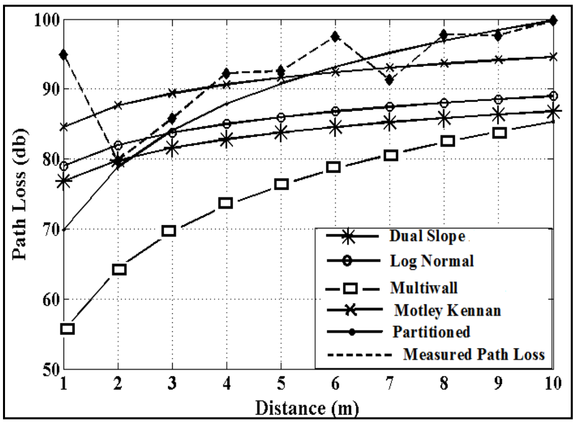

Fig1. Path Loss Comparison

A. Performance Evaluation of Modified Empirical model

The modified Motley Kennan model estimates the path loss by including breakpoints, reflection coefficients and polarization mismatch loss. The performance of the modified model is compared and the original Motley Kennan model and measurements. The path loss estimated by the modified model compared to the original Motley Kennan model is summarized in Table V and the comparison is shown in Figure 2.

TABLE V
Path Loss Comparison of the Modified Model

Empirical Models	**Path Loss (db)**			
	Min	**Max**	**Mean**	**Std**
Measured data	79.8	99.76	92.94	6.18
Motley kennan	84.6	94.6	91.16	3.18
Modified Model	87.54	94.04	91.81	3.069

From Table V, it is observed that the modified model has a better match with the measured path loss compared to the original model. Although the standard deviation of the modified model is almost comparable to the original model, the average path loss is improved by of 0.65 db compared to the original Motley Kennan model. The improvement in path loss suggests the efficiency of the modified model.

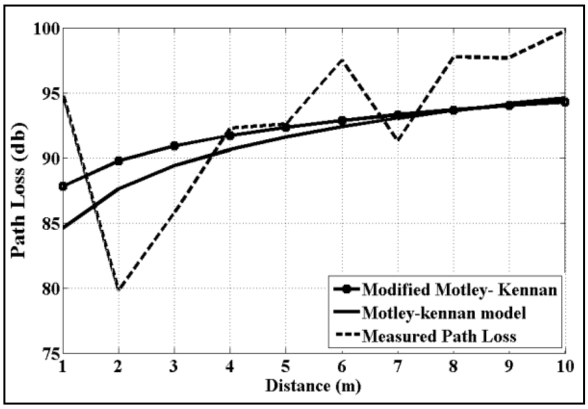

Fig2. Modified Path Loss Comparison

The performance evaluation in terms of error metrics is summarized in Table VI.

TABLE VI
Error metrics Comparison of Modified Path Loss Model

Error Metrics	**Modified Model (db**	**Motley Kennan model (db)**
Mean Error	4.398	4.416
MSE	26.798	27.067
RMSE	5.170	5.202

The lesser values of the error metrics justify the performance of the modified model. The path loss could further be improved with deterministic modeling, by considering the detailed physical and electromagnetic parameter database of the obstacles encountered in the propagation path. A combination of deterministic and empirical approaches can also be used to devise better path loss prediction models with greater prediction accuracy.

The contribution in this work is the precise statistical modeling of path loss exponents instead of obtaining it from the slope of model curve. Secondly the best empirical model is selected for modification, based on the comparison with measurements. The modified model considers the number of walls, its type, penetration loss, reflection coefficients of the obstacles and polarization mismatch effects. The results validate the efficient performance of the modified model.

VII. CONCLUSIONS

The paper analyses the performance of the existing empirical propagation models in the indoor environment in the context of estimating the path loss of mobile radio signals. The received signal strengths are collected in the indoor environment at 2.4 GHz frequency which is used to validate the empirical models. The indoor path loss models are implemented and a modified model is suggested. The performance of the modified model is validated by comparison with original model and measured path loss. The modified model has a path loss improvement of 0.65db. This justifies the efficiency of the proposed indoor empirical model. There is a scope for further improvement in path loss prediction, by modeling using deterministic and statistical approaches.

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TABLE VII
Parameters used in simulations

Parameters	Values
Transmitting frequency	2.4 G Hz
Transmitting Power	20 dbm
Height of the transmitting antenna	45 cms
Height of the receiving antenna	150 cms
Cable losses	3 db
Permittivity value of floor with porcelain tiles (epsilon)	6
Permittivity value of concrete wall	7
Reflection co efficient of ground	20
Permittivity value of glass window	4
Permittivity value of ceiling with gypsum board	3
Optimum Incident angle (α)	30

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