Tuning of Lee Path Loss Model for Arid Land based on Recent TETRA Measurements conducted in Riyadh City-Saudi Arabia

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Abstract — **In mobile radio system path loss models are necessary for a proper planning, interference estimations, frequency assignments, and cell parameters which are basic for network planning process as well as Location Based Services (LBS) techniques that are not based on GPS system. Empirical models are the most adjustable model that can be suited to different type of environments. In this paper, Lee path loss model has been tuned using Least Square (LS) algorithm to fit to TETRA measured data for suburban and urban arid areas. Consequently, Lee model's parameters (L_0, γ) are obtained for the targeted areas. The performance of the tuned Lee model is then compared to the three most widely used empirical path loss models; these are Hata, CCIR (ITU-R), and Cost 231 Walfisch-Ikegami non line-of-sight (CWI-NLOS) path loss models. The performance criterion selected for the comparison of various empirical path loss models are the Root Mean Square Error (*RMSE*) and goodness of fit (R^2). The *RMSE* and R^2 between the actual and the predicted data are calculated for various path loss models. It turns out that the tuned Lee model outperforms the others empirical models.**

Index Terms **— Lee path loss model, least square algorithm, TETRA.**

I. INTRODUCTION

In spite of development of numerous empirical path loss prediction models so far, generalization of these models to any environment is still questionable. They are suitable for particular areas (urban, suburban rural, etc), specific cell radius (macrocell, microcell, picocell), as well as specific terrain and climate. To overcome this drawback, empirical model’s parameters can be adjusted or tuned according to the targeted environment. The propagation model tuning should optimize the model parameters in order to achieve minimal error between predicted and measured signal strength. This will make the model more accurate for received wireless signal predictions.

Lee model is a modified power law model and has the ability to be customized to the local environment easier than Hata, CCIR (ITU-R) or COST 231 Walfisch-Ikegami non line-of-sight form (CWI-NLOS) models [1, 2]. Lee model superiority over the other empirical models motivates us to select and tune this model to our targeted environment which is described as arid environment [3]. The model reports the relation between the path losses measured in various areas and parameters such as frequency, distance, base station (BS) and mobile station (MS) heights. It has two modes: *area-to-area* and *point-to-point*. Even though Lee model was originally developed for use at 900MHz, the model includes a frequency adjustment factor that can be used to increase the frequency range analytically. A typical application involves taking measurements of the path loss in the target environment and then tuning the Lee model parameters to fit it to the measured data.

Unfortunately, Lee model was developed based on measurements conducted in climatic environments which differ widely from the arid environment of Saudi Arabia [2, 3]. In order to efficiently apply Lee model to arid climatic conditions of most parts in Middle East regions, model tuning process is required.

Due to the flat terrain nature of the targeted area (standard deviation of the terrain undulation of the targeted area is 17 m [4]), *area-to-area* Lee model mode has been selected in this study. We then use LS algorithm in matrix form to tune model's parameters to fit the data (received signal strength) obtained for the urban and suburban areas of Riyadh City-Saudi Arabia based on recently conducted TETRA measurements. A detailed description of the measurement set-up and procedure can be found in [5].

LS algorithm has been used to fit a linear model to data [6]. This process can be achieved by minimizing the summed square of residuals between measured data and prediction model data. The coefficients are determined by differentiating summed square of residuals with respect to each parameter and setting the result equal to zero.

II. AUTOMATIC LS TUNING ALGORITHM

The objective of propagation model tuning is to obtain values for model parameters that they are in agreement with measured data. When using these tuned parameters, the predicted signal level should have a minimum difference and variance when compared to measured signal level. The tuning or calibration process can be achieved either manually or automatically. The manual tuning process contains adjustment of the model parameters in order to set the *RMSE* between measured and predicted signals to zero. We then increment one parameter. These processes are repeated manually until any change in parameters will increase *RMSE* value. Manual tuning task requires a large number of repetitions before a near global minimum is obtained. In contrast, an automatic model-tuning algorithm is a straightforward process to achieve optimal solution. In this paper, LS algorithm is used to tune Lee model parameters automatically. This is presented as follows:

A. Lee Model:

Lee *area-to-area* mode model is given by [1]:

$$Loss = L_0 + \gamma \log(d) - 10\log(F_0) \tag{1}$$

where L_0 is a median path loss at reference point (near zone), here we use 1km as the reference point. γ is the slope of the path loss curve in dB⁄decade. F_0 is adjustment factor composed of several factors. These factors are BS antenna height correction factor (F_1), BS antenna gain correction factor (F_2), MS antenna height correction factor (F_3), MS antenna gain correction factor (F_4), and frequency adjustment factor (F_5). They are expressed as follows:

$$F_0 = F_1 F_2 F_3 F_4 F_5 \tag{2}$$

Where

$$F_1 = (h_b / 30.48)^2 \tag{3}$$

$$F_2 = (G_b / 4) \tag{4}$$

$$F_3 = (h_m / 3)^2 \tag{5}$$

when MS antenna height in meter > 3

$$F_3 = (h_m / 3) \tag{6}$$

when MS antenna height in meter < 3

$$F_4 = G_m / 1 \tag{7}$$

$$F_5 = (f / 900)^{-n} \tag{8}$$

where h_b is BS antenna height in meter, G_b is BS antenna gain in dBd, h_m is MS antenna height in meter, G_m is MS antenna gain in dBd ($0\ dBd = 2.14\ dBi$), and f is the operation frequency in MHz. All the values of the adjustment factors are independent of the environment types except the value of *n* (frequency adjustment coefficient) that depends upon it and it takes their values between 2and 3.

B. Path Loss Calculation:

The measured path loss (*PL*) for each location point (*d*) is given by [5]

$$PL(d) = EIRP_T + G_m - PM(d) \tag{9}$$

And

$$EIRP_T = P_T - L_C + G_b \tag{10}$$

Where, $EIRP_T$ is the effective isotropic radiated power of the TETRA base station, P_T is the BS transfer output power, L_C is antenna cable loss, and G_b, and G_m are BS and MS antenna gains. *PM*(*d*) is the measured TETRA MS signal strength at distance *d*. These values are known from the measurement process [5].

C. Tuning of Lee model parameters:

The residual between measured data and prediction model data for each location point is calculated by

$$e(d) = PL(d) - \left[L_0 + \gamma \log(d) - 10\log(F_0)\right] \tag{11}$$

The *RMSE* function of this residual will be as follows [6]:

$$E(L_0, \gamma) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left[e(d_i)\right]^2} \tag{12}$$

Where, *N* is number of measured points. To minimize *RMSE* function, it should be differentiated partially to their coefficients that achieve this minimization. To obtain Lee model's parameters (L_0, γ) that optimize equation (12), *N* equations based on equation (11) corresponding to *N* measured points should be solved. The *N* equations are given by:

$$\begin{aligned}
i=1:&\quad L_0 + \gamma \log(d_1) + A_1 = PL(d_1)\\
i=2:&\quad L_0 + \gamma \log(d_2) + A_2 = PL(d_2)\\
&::\\
i=N:&\quad L_0 + \gamma \log(d_N) + A_N = PL(d_N)
\end{aligned} \tag{13}$$

Equation (13) can be written in matrix form as follows:

$$\begin{bmatrix} 1 & \log(d_1) \\ 1 & \log(d_2) \\ :: & ::::: \\ 1 & \log(d_N) \end{bmatrix} \times \begin{bmatrix} L_0 \\ \gamma \end{bmatrix} = \begin{bmatrix} PL(d_1) - A_1 \\ PL(d_2) - A_2 \\ ::: \quad ::: \\ PL(d_N) - A_N \end{bmatrix}$$

Or $$W \times \overline{F} = Y \tag{14}$$

As evident from equation (14), the number of equations is greater than the number of unknown parameters (over determined system), so we used LMS algorithm to determine the values of L_0, γ that minimizes the residual $E(L_0, \gamma)$.

Also $A_1 = A_2 .. = A_N = A = -10\log(F_0)$.The minimal mean vector $\overline{F} = [L_0 \quad \gamma]^T$ can be obtained using LS algorithm as follows [6]:

$$\overline{F}_{LS} = \left[W^T W\right]^{-1} W^T Y \tag{15}$$

D. *Frequency adjustment factor optimization:*

Now the only parameter left that needs to be determined is *n*. To optimize the value of *n*, we vary its value from 2 to 3 in steps of 0.1 and use equation (15) to obtain L_0, and γ for each value of *n*. Also, for each value of *n*, *RMSE* and the goodness-of-fit which is so called coefficient of determination (R^2) are calculated. Then select the values of *n* and its corresponding L_0, and γ that achieve minimum *RMSE*. When we find the *RMSE* is same for each value of *n*, thus reducing the selection of *n* to be based on the maximum value of R^2 and if R^2 is similar then *n* near to the default value (2.5) has been selected. *RMSE* is calculated using equation (12) whereas; the coefficient of determination measures how successful the fit is in explaining the variation of the data. So, it is defined as the square of the correlation between the measured data values and data predicted values. R^2 always takes values between 0 and 1. As R^2 reaches 1, the regression points tend to align more accurately along the model curve. Mathematically it is given by [5].

$$R^2 = 1 - \frac{\sum_{i=1}^{N} [e(d_i)]^2}{\sum_{i=1}^{N} [PL(d_i) - \overline{PL}]^2} \tag{16}$$

where, $\overline{PL}$ is the mean of the measured signal.

III. RESULTS AND DISCUSSIONS

To verify the tuned Lee path loss model, comparison between path loss predicted and measured data have been performed for some of TETRA BSs that cover the suburban and urban areas of the Riyadh city. Base Stations, namely BS1 and BS7 cover part of the city suburban, whereas BS2, BS5, and BS9 cover urban area. These base stations are part of TETRA network system that cover whole Riyadh city. The network operates at 400 MHz band. Details of this network and conducted measurement can be found in [5]. The values of Lee path loss model parameters n, L_0, and γ for the five base stations are calculated and presented in Table 1. The performance of the tuned Lee model is then compared to the three most widely used empirical path loss models e.g., Hata, CCIR (ITU-R), and CWI-NLOS and the values of the two performance measures, *RMSE* and R^2, are tabulated in Tables 4 and 5 respectively.

For fair comparison, these models' parameters and correction factors are optimized to minimize their *RMSE* over the measured data. For Hata model, the large city with $f_{MHZ} > 300$ and $K = 0$ has been used for urban area whereas in the suburban case, the default is used. While for CCIR model, the optimal percentages of area covered by building for the urban and suburban base stations are obtained and given with those provided by Riyadh Municipality in Table 2. We referred this difference between the values provided by municipality and optimal ones to the building height which is lower in Riyadh city compared to European cites that CCIR had been developed in them. This deviation is considered as a limitation of CCIR model. CWI-NLOS combination factors are also optimized and illustrated in Table3. The optimization here is performed using trial and error until the minimal *RMSE* is achieved.

It seems from Table 1 that L_0 is very low in suburban area compared to urban area cases and hence the suburban's base stations ranges coverage (25km is the radius) are more than double of urban base stations ranges. While its values have inverse relation in urban areas to values of γ. Also, it is clear that their values obtained here are somewhat lower compared to its values reported in [2]. Moreover, they are in agreement with the previous obtained results in [5]. This is due to wider streets and lower building heights in most parts of the Riyadh city as well as the difference in the climate of area. This result enhances that path loss empirical models calibration to our environments is highly recommended.

From Tables 4 & 5, few points can be drawn. It is found that performance of the proposed tuned Lee model is the best as *RMSE* is the lowest and R^2 is the highest compared to other models. Hata, CCIR and CWI-NLOS empirical models, on the other hand, seem to overestimate the path loss for both suburban and urban environments. On the average, the tuned model performs well. The *RMSE* average for the tuned model is 3.961 dBm. While they are 5.3814 , 4.3192, 4.45 dBm for compared models, Hata CCIR and CWI-NLOS, respectively. In terms of goodness of fit, R^2 is found to be the highest for tuned lee model. The R^2 averages are 0.71, 0.474, 0.65, and 0.63 for tuned lee model, Hata , CCIR, and CWI-NLOS models respectively.

Although CCIR and CWI-NLOS models seem to be similar in terms of averages of *RMSE* and R^2, CCIR performs better than CWI-NLOS model in urban areas. In contrast, CWI-NLOS model performs better than CCIR model in suburban areas. However, both of them perform better than Hata model in suburban and urban areas.

IV. CONCLUSION

In this paper, we have introduced tuning of Lee path loss empirical model using automatic LS algorithm. This calibration is based on TETRA received signal measurements taken in Riyadh, Saudi Arabia. For verifying the LS algorithm technique and fair performance evaluation, the measured signals were compared against predicted ones using the tuned model in addition to the three most widely used empirical path loss models. These are Hata, CCIR and CWI-NLOS. We found that performance of the tuned Lee model is the best as *RMSE* is the lowest and R^2 is the highest compared to other models. Also, it is found that in general Hata, CCIR and CWI-NLOS empirical models overestimates the path loss for both urban and suburban environments. It is clearly evident that tuned Lee model shows the closest agreement with the measurement result. CCIR and CWI-NLOS models perform better than Hata empirical model.

Furthermore, it should be noted that the since the measurement were conducted in arid climatic conditions of Riyadh, the results obtained here is applicable to most parts of the Middle East regions having similar climatic conditions.

ACKNOWLEDGMENTS

The authors wish to thank the following agencies, companies and individuals who either participated or supported the propagation survey and data acquisition: SANG, GDoMS entities, Motorola, and Nasco companies, Cap. M. Al-sultan from SANG, Mr. S. Al-Shehree and Mr. K. Al-otaibi from GDoMS, and Mr. Abdel Nasser Abu Zaid from Motorola. Special thanks go to Dr. Saud Al-Semari for his support throughout.

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Table 1: Tuned Lee model parameters

Area Type **BSs** Para.	**Suburban**		**Urban**		
	BS1	**BS7**	**BS2**	**BS5**	**BS9**
n	2.6	2.2	2.5	2.1	2.5
L_0	2	2.2	29.82	14.57	48.44
γ	33.5	33.8	28.57	33.76	23.47

Table 2: CCIR model percentages of area covered by buildings (correction factor *B*); from Riyadh municipality and these obtained using optimization.

Area Type Building (%)	**Suburban**		**Urban**		
	BS1	**BS7**	**BS2**	**BS5**	**BS9**
From Municipality	5	7	20	25	20
From Optimization	5	5	12	15	10

Table 3: CWI-NLOS model parameters (parameters combination is obtained using optimization technique)

Parameters Area Type		Nominal building height(m)	Buildings center separation (m)	Street width between buildings(m)	Angle of incidence in degrees	Area type (0 for sub , 1 for urban)
Suburban	**BS1**	10	50	25	90	0
	BS7		40	20		
Urban	**BS2**	15	30	15	60	1
	BS5	25				
	BS9	15				

Table 4: *RMSE* comparison between Tuned Lee model with known models

	BSs	Tuned Lee	Hata	CCIR	CWI
Suburban	BS1	3.566	7.034	4.11	3.72
	BS7	4.866	5.833	5.126	4.89
Urban	BS2	3.889	4.20	4.20	4.88
	BS5	3.384	5.0	3.65	3.56
	BS9	4.10	4.84	4.51	5.20
Average *RMSE*		**3.961**	**5.3814**	**4.3192**	**4.45**

Table 5: R^2 comparison between Tuned Lee model with known models

Area type	BSs	Tuned Lee	Hata	CCIR	CWI
Suburban	BS1	0.8	0.21	0.73	0.78
	BS7	0.554	0.359	0.50	0.55
Urban	BS2	0.78	0.74	0.74	0.69
	BS5	0.87	0.71	0.845	0.85
	BS9	0.54	0.35	0.44	0.26
Average R^2		**0.71**	**0.474**	**0.65**	**0.63**