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A Novel LMMSE Based Optimized Perez-Vega Zamanillo Propagation Path Loss Model in UHF/VHF Bands for India

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Abstract—Cognitive radio is the enabling technology for license-exempt access to the TV White Spaces (TVWS). There is ever increasing demand of users in the broadcasting and communication services. Large portions of unused spectrum in the UHF/VHF bands exist in India which can be used on geographical basis. This paper describes a study on path loss variation in UHF/VHF bands in India. The aim of this study is to develop and optimize a path loss model based on Linear minimum mean square error estimation (LMMSE) for India. We propose the LMMSE based Optimized Perez-Vega Zamanillo propagation path loss model. The measured path loss values, collected across India, are compared with proposed Optimized Perez-Vega Zamanillo path loss model and other existing path loss models. It is found that Optimized Perez-Vega Zamanillo propagation path loss model has the least root mean square Error (RMSE) of 13.98 dB. Other existing path loss models have root mean square Error(RMSE) value greater than 24 dB. Therefore, Optimized Perez-Vega Zamanillo propagation path loss model is best suited for predicting coverage area, interference analysis in India for TVWS.

1. INTRODUCTION

Cognitive radio identifies other radios in the environments that might use the same spectral resources and then designs a transmission methodology that minimises interference to and from other radios. It is necessary to understand the propagation channel for the identification, design, implementation and analysis of transmission methodologies. Propagation channel determines how much power emitted by transmitter is received at the receiver and also the amount of interference created at the receiver. All communication services seek frequency bands below 3.5 GHz because these frequency bands have lower propagation loss. Therefore UHF/VHF bands are ideal candidates for setting up cognitive radios. Today most of the UHF/VHF bands are used by broadcast television. The U.S. regulatory body, the Federal Communications Commission, has recently adopted rules to allow unlicensed radio transmitters to operate in the broadcast television spectrum at locations where the spectrum is not being used by the licensed services [1]. The unused TV spectrum is often termed "white spaces". In order to utilise these "white spaces", we need accurate channel models.

Path loss measurements and model comparison have been done in different parts of India [2–8]. In [2] field strength measurements were conducted for VHF and UHF bands at different base station antenna heights in the Coastal South India. These measured values were compared with different prediction methods of Hata, ITU-R, Blomquist and Ladell, Egli, Ibrahim and Parsons. It was found that in sub-urban and urban regions Hata's method gave moderate agreement with the observed values. Mobile train radio measurements for UHF band in Northern India were presented in [3]. Comparison of three path loss models with measured data was presented in [3]. It was found that uniform theory of diffraction (UTD) gives good agreement in the urban zone, and over all Hata's model shows reasonable agreement in all the environmental zones. However, the study was restricted only to Northern India.

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In [4] mobile train measurements were conducted in the UHF band in Western India. Measured path loss values were compared with seven path loss models using standard deviation to show that Walfish and Bertoni's method gave good agreement followed by Hata. Investigation of attenuation of VHF signals in band I and band II for Chennai TV and FM stations has been done in [5]. The experimental data collected in a RF survey from Chennai TV and FM stations have been utilized to deduce path loss exponents and these have been compared with the exponents deduced from the Perez-Vega Zamanillo model. Path loss analysis using Pervez-Vega Zamanillo model in Indian subcontinent for UHF/VHF bands was presented in [6]. Experimental data were collected on signal measurements at 19 places in India, and all these experimental carrier levels of the signal originating from various transmitters were monitored at different distances, the signals levels were averaged and then converted into path loss values. These observed path loss values were converted into path loss exponents. These were compared with the model predicted values following the approach of Perez-Vega and Zamanillo. In [7] comparison of different path loss propagation models with measured field data was done in plane area in northern region of India, i.e., border district of Punjab and Jammu. It was found that Cost-231 model is best suited for plane area in northern region of the border district of Punjab (India). Path loss models for broadcasting applications namely free space, Okumara, Okumara Hata, Extension of Hata, Hata-Davidson Model and Extended COST-231 Hata models were compared with path loss measured in bordering area of Punjab (State: India) and bordering area of Jammu (State: India) at different powers and antenna heights of broadcasting station [8]. A common fixed numerical value was then calculated separately for each model after taking average MSE of the respective model. The fixed numerical value, found for each model was then added to the respective model formula to get a new modified formula. Modified models were found to be best fitted for 100 W and 10 KW FM stations.

In other countries like USA, Longley-Rice Irregular Terrain model (ITM) has shown good performance in predicting TVWS in Seattle, WA [9]. Therefore, we have used Longley-Rice Irregular Terrain model(ITM) to compare with the measured path loss data collected at different places in India. In [10] Field strength measurements were conducted along six routes that spanned urban, suburban and rural areas of Kwara State, Nigeria. Measurement results were then compared with pathloss prediction of eight widely used empirical models. Least squares and linear iterative methods are employed to optimise HataDavidson's model, as it showed best fit compared with other models. Propagation models for forest environments of Nigeria at the VHF and UHF bands are examined in [11]. The results of the paper [11] show that the ITU-R foliage attenuation model is not suitable to predict the propagation loss between the radio transmitter with height of 130 m and the receiver located near the forest ground. In [11] it was found that free space model (which considers only the direct ray) augmented by the appropriate vegetation loss is more accurate than the other models.

There are many path loss models in VHF/UHF bands as discussed in Section 2 of our paper. So, we wanted to find the best path loss model among all of these path loss models. India has many cities, with different terrain and sizes. Also, some cities are well developed and some cities are in developing stages. So, we have selected many cities for our study on path loss variation in various parts of India. In this paper, we have measured and collected the carrier signal level, from Doordarshan (DD) TV transmitters located in New Delhi, Mumbai, Hyderabad and Chennai. Table 1 shows details of DD TV transmitters situated in Hyderabad, Chennai, New Delhi and Mumbai. In addition, the measurement data given in [6], was also used. We select the Perez-Vega Zamanillo path loss model, for optimization using Linear minimum mean square error estimation (LMMSE) because Perez-Vega Zamanillo model showed good performance when compared to other known path loss models [12]. The performance of this Optimized model was compared with other propagation path loss models. Measured path loss values

Table 1. List of transmitters in India from where data was collected.

Location of Tx	Tx Height (m)	Tx Frequency (MHz)
Hyderabad	150	62.25, 224.25
Chennai	175	175.23, 189.26
New Delhi	235	175.25, 189.25
Mumbai	300	182.25, 224.25

were compared with predicted values from Optimized Perez-Vega Zamanillo, Perez-Vega Zamanillo, Longley-Rice, Hata, Egli, COST 231, Walfisch and Ikegami, Walfisch and Bertoni, ITU-R P.529-3, Green-Obaidat and FSPL models. It is found that Optimized Perez-Vega Zamanillo model is the best since it has the least Root Mean Square Error (RMSE) among the existing path loss models.

This paper is organised as follows: Section 1 provides introduction. Section 2 describes propagation models used for comparison. Section 3 provides the method of data collection. Section 4 describes the LMMSE Based optimization process. Section 5 gives plots comparing measured path loss and path loss predicted by various models. Section 6 gives the conclusion.

2. RADIO PROPAGATION PATH LOSS MODEL

A radio propagation model is an empirical mathematical formulation for characterization of radio wave propagation as a function of frequency, distance and other conditions. In this paper following 10 models have been considered.

2.1. Hata Model

This model was developed by Y. Okumura and M. Hata and is based on measurements in urban and suburban areas in Japan in 1968 [13]. The Okumura-Hata model also assumes that there are no dominant obstacles between the BS and the MS, and that the terrain profile changes only slowly [14].

2.2. Egli Model

Egli model is a terrain model for radio frequency propagation. This model is applicable at frequency from 40 MHz to 900 MHz. This model was developed from real-world data on UHF and VHF television transmissions in several large cities. It predicts the total path loss for a point-to-point link. This model does not take into account travel through some vegetative obstruction, such as trees or shrubbery [17].

2.3. Perez-Vega Zamanillo Model

Based on the FCC curves, Perez-Vega and Zamanillo developed a computational path loss model. It is a simple propagation model for the VHF and UHF bands. It allows the estimation of median path loss, received power, or electrical field strength which usually is sufficient in many practical applications. The model is independent of frequency and is applicable to outdoor environments in a range of distances from about 0.5 mi (800 m) up to 40 mi (64.36 km) and transmitting antenna heights from 100 ft (30.48 m) up to 2000 ft (609.6 m), and is based on a receiving antenna height of 30 ft (9 m) [15].

2.4. Cost-231 Model

It is extensively used model for predicting path loss in mobile wireless system. The frequency range of operation of this model is 500 MHz to 2000 MHz. This model requires that the base station antenna is higher than all adjacent rooftops [24, 25].

2.5. Walfisch-Ikegami Model

This model distinguishes between LOS and non-line-of-sight (NLOS) propagation situations. The model considers only the buildings in the vertical plane between the transmitter and the receiver. Since, there are a lot of objects in realistic areas such as buildings, houses, roads, trees and river. Also, it is very difficult to classify these objects in the propagation path. This make the WI model prone to errors [19].

2.6. Green-Obaidat Model

Green and Obaidat developed a path loss model for wireless LANs operating at 2.4 GHz that takes antenna height into account. This model considers the path loss due to Fresnel zone with near earth antenna height (i.e., typically between 1 and 2 meters) more accurately. This model does not take into account the impact of fading caused by several objects, e.g., building, foliage, etc. [21].

2.7. ITU-R P.529-3 Model

This model provides curves for predicting field strength under average conditions for three frequency ranges. It also provides analytical expressions which are valid for certain frequency ranges and conditions, and various correction factors which can be used to refine the average predictions. The material in the Recommendation is statistical in nature and oriented towards application to planning and system design [20].

2.8. Walfisch-Bertoni Model

This model is suited for dense urban areas in which the buildings have uniform height and separation distances. Any building height variations causes a significant error in the prediction of this model [18].

2.9. Free Space Path loss Model (FSPL)

Free-space propagation model is used to predict received signal strength when the path between the transmitter and the receiver is a clear and unobstructed line-of-sight [22].

2.10. Longley-Rice Model

The Longley-Rice model is a radio propagation model for predicting the attenuation of radio signals for a telecommunication link in the frequency range of 20 MHz to 20 GHz. The Longley-Rice model is also known as the Irregular Terrain Model (ITM) because it takes into account the terrain elevation and irregularities,(hills, mountains, etc.). The limitation of this model is that it does not take any account of buildings and foliage [23].

3. MEASUREMENT CAMPAIGN

This section describes the steps followed during data collection and it gives the description of the equipment used. The data collection tool is composed of Anritsu spectrum analyzer MS2713E global positioning system receiver set (GPS system). The height of Doordarshan (DD) TV transmitters located in Mumbai, New Delhi, Chennai and Hyderabad are 300 m, 235 m, 175 m and 150 m respectively. We wanted to obtain path loss measurement data for TV transmitters which differ significantly in their antenna heights. Therefore, we have selected these cities for data collection. Power levels of Doordarshan (DD) TV Transmitter in New Delhi, Mumbai, Hyderabad and Chennai cities were measured at different distances from the transmitter, using Anritsu spectrum analyzer MS2713E.

While transmission is taking place, Anritsu spectrum analyzer was placed inside a car and driven along the routes in Hyderabad, Chennai, Mumbai, New Delhi cities shown in Figures 1–4. Received power was measured continuously and stored in an external pen drive for subsequent analysis.

From these received power levels, path loss was calculated.

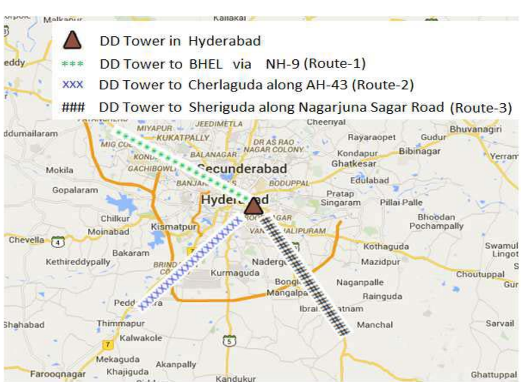

Figure 1. Measurement routes in Hyderabad.

Figure 2. Measurement routes in Mumbai.

Figure 3. Measurement routes in New Delhi.

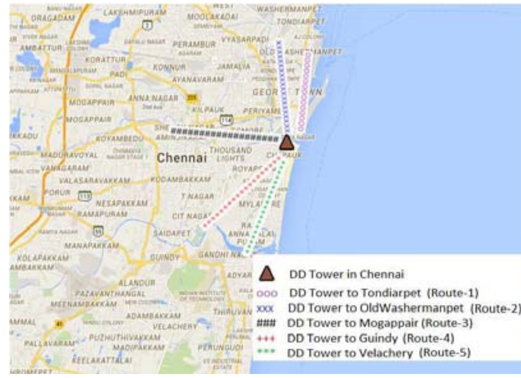

Figure 4. Measurement routes in Chennai.

We have used [6] to obtain path loss values of UHF/VHF transmitters located in other parts of India. From [6], measured pathloss exponent values (n) for received power of transmitters located in various parts of India were obtained. From these measured pathloss exponent values, path loss L in dB was calculated using formula given below:

$$L = 10n \log_{10}(d) + L_0 \,\text{dB}, \tag{1}$$

where d is distance between TX and RX in meters and L_0 is attenuation at 1 m in free space:

$$L_0 = 20 \log_{10}\left(\frac{4\pi}{\lambda}\right), \tag{2}$$

where λ is wavelength of transmitted wave in meters.

We have compared the measured path loss values with Perez-Vega Zamanillo, Hata, Egli, COST 231, Walfisch and Ikegami, Walfisch and Bertoni, ITU-R P.529-3, Green-Obaidat and FSPL models in [12]. It is found that measured path loss values are more close to Perez-Vega Zamanillo model.

4. OPTIMIZATION PROCESS

A general flow chart of optimization process used in this paper is shown in Figure 5. Note that this procedure was used to optimize Hata model in [16]. Measured path loss values were compared using RMSE, with predicted values from Perez-Vega Zamanillo, Hata, Egli, COST 231, Walfisch and Ikegami, Walfisch and Bertoni, ITU-R P.529-3, Green-Obaidat and FSPL models across 20 different places in India [12]. Perez-Vega Zamanillo model was found to be the better suited model for India. Therefore, Perez-Vega Zamanillo model is selected for optimization in block 2 of Figure 5. We have selected Linear minimum mean square error estimation (LMMSE) as the Optimization process. The optimised model is then validated in Mumbai, New Delhi, Hyderabad, Coastal Andhra, Chennai, Muzaffarnagar, Saharanpur, Pune, Neral, Ghaziabad, Meerut, Kalyan, Vangani, Talegaon, and Tirupati. Statistical analysis such as Root mean square error (RMSE) was used to compare between the Optimized model and other known models.

4.1. Optimization into the Model

In this paper, optimizing of Perez-Vega Zamanillo model is done using Linear minimum mean square error estimation(LMMSE). In the present study, observed path loss values at different receiving antenna heights have been corrected to 9 m height using the procedure given in [15].

Let n be the total number of set of measurements consisting of Path loss (Y) in dB at distance d meters from the transmitting antenna of height h in meters and whose frequency of transmission is f (Hz). From Perez-Vega Zamanillo model, Path loss Y_i in dB is expressed as below:

$$Y_i = Y_0 + 10n \log_{10}(d_i) \,\text{dB}, \tag{3}$$

where Y_i is the ith Measured Path loss in dB at distance d_i between TX and RX in meters for transmitter of height h_i and whose frquency of transmission is f_i. Y_0 is attenuation at 1 m in free space:

$$Y_0 = 20\log_{10}\left(\frac{4\pi}{\lambda_i}\right), \tag{4}$$

where λ_i is wavelength of ith transmitted wave in m. The path loss exponent is characterized as a function of distance and transmitting antenna height. According to Perez-Vega model n is given by:

$$n = \sum_{u=0}^{4}\sum_{v=0}^{4} a_{uv} {h_i}^u {d_i}^v. \tag{5}$$

The values of coefficients a_{uv} are given in [15].

Combining (3), (4), (5) we get:

$$Y_i = 20\log_{10}\left(\frac{4\pi}{\lambda_i}\right) + 10\sum_{u=0}^{4}\sum_{v=0}^{4} a_{uv} {h_i}^u {d_i}^v \log_{10}(d_i). \tag{6}$$

Equation (6) can be further simplified as:

$$Y_i = 20\log_{10}\left(\frac{4\pi}{c}\right) + 20\log f_i + 10\sum_{u=0}^{4}\sum_{v=0}^{4} a_{uv} {h_i}^u {d_i}^v \log_{10}(d_i). \tag{7}$$

Using Table 2, above equation can be written as:

$$Y_i = a_0 + \sum_{k=1}^{26} a_k X_k. \tag{8}$$

Terms a_0, a_1, a_2, a_3, ..., a_{26} are all constants. Omitting subscript i for simplification, we have:

$$Y = a_0 + \sum_{k=1}^{26} a_k X_k, \tag{9}$$

Now we have a LMMSE estimator $(\hat{Y}_l)$, where estimation of random variable Y is based on observations of multiple random variables, X_1, X_2, X_3, ..., X_{26}.

Table 2. Expression of random variables in Perez-Vega Zamanillo model.

Random Variable	Expression
X_1	$\log f_i$
X_2	$h_i^0 d^0 \log d_i$
X_3	$h_i^0 d_i^1 \log d_i$
X_4	$h_i^0 d_i^2 \log d_i$
X_5	$h_i^0 d_i^3 \log d_i$
X_6	$h_i^0 d_i^4 \log d_i$
X_7	$h_i^1 d_i^0 \log d_i$
X_8	$h_i^1 d_i^1 \log d_i$
X_9	$h_i^1 d_i^2 \log d_i$
X_{10}	$h_i^1 d_i^3 \log d_i$
X_{11}	$h_i^1 d_i^4 \log d_i$
X_{12}	$h_i^2 d_i^0 \log d_i$
X_{13}	$h_i^2 d_i^1 \log d_i$

Random Variable	Expression
X_{14}	$h_i^2 d_i^2 \log d_i$
X_{15}	$h_i^2 d_i^3 \log d_i$
X_{16}	$h_i^2 d_i^4 \log d_i$
X_{17}	$h_i^3 d_i^0 \log d_i$
X_{18}	$h_i^3 d_i^1 \log d_i$
X_{19}	$h_i^3 d_i^2 \log d_i$
X_{20}	$h_i^3 d_i^3 \log d_i$
X_{21}	$h_i^3 d_i^4 \log d_i$
X_{22}	$h_i^4 d_i^0 \log d_i$
X_{23}	$h_i^4 d_i^1 \log d_i$
X_{24}	$h_i^4 d_i^2 \log d_i$
X_{25}	$h_i^4 d_i^3 \log d_i$
X_{26}	$h_i^4 d_i^4 \log d_i$

The LMMSE estimator may be written in the form

$$\hat{Y}_l = \hat{y}(X) = a_0 + \sum_{j=1}^{26} a_j X_j. \tag{10}$$

Now we have to find coefficients a_i such that mean square error is minimized, i.e.,

$$\min_{a_i} E\left[\left(Y - \left(a_0 + \sum_{j=1}^{26} a_j X_j\right)\right)^2\right]. \tag{11}$$

To minimize the expression in (11), we differentiate it with respect to a_i for $i = 0, 1, 2, \ldots, 26$, and set each of the derivatives to 0. First differentiating with respect to a_0 and setting the result to 0, we have

$$E[Y] = E[a_0 + \sum_{j=1}^{26} a_j X_j] = E[\hat{Y}_l], \tag{12}$$

$$\Longrightarrow a_0 = \mu_Y - \sum_{j=1}^{L} a_j \mu_{X_j}, \quad \text{where} \quad \mu_Y = E[Y] \quad \text{and} \quad \mu_{X_j} = E[X_j]. \tag{13}$$

Using (13) to substitute for a_0 in (10), it follows that

$$\hat{Y}_l = \mu_Y + \sum_{j=1}^{26} a_j \left(X_j - \mu_{X_j}\right). \tag{14}$$

Using (14), mean square error criterion (11) can be rewritten as :

$$E\left[\{(Y - \mu_Y) - \left(\hat{Y}_l - \mu_Y\right)\}^2\right] = E\left[\left(\tilde{Y} - \sum_{j=1}^{26}\left(a_j \tilde{X}_j\right)\right)^2\right], \tag{15}$$

where

$$\tilde{Y} = Y - \mu_Y, \quad \tilde{X}_j = X_j - \mu_{X_j}. \tag{16}$$

Differentiating (15) with respect to each of the remaining coefficients a_i, $i = 1, 2, \ldots, 26$, and setting the result to zero produces the equations

$$E\left[\left(\tilde{Y} - \sum_{j=1}^{26} a_j \tilde{X}_j\right)\tilde{X}_i\right] = 0, \quad i = 1, 2, \ldots, 26. \tag{17}$$

From (14) and (17), we have

$$E[(Y - \hat{Y}_l)\tilde{X}_i] = 0, \quad i = 1, 2, \ldots, 26. \tag{18}$$

From (17) we have

$$\sum_{j=1}^{L} \sigma_{X_i X_j} a_j = \sigma_{X_i Y}, \tag{19}$$

where $\sigma_{X_i X_j}$ is the covariance of X_i and X_j and $\sigma_{X_i Y}$ is the covariance of X_i and Y_i. Collecting these equations in matrix form, we obtain

$$\begin{bmatrix} \sigma_{X_1X_1} & \sigma_{X_1X_2} & \cdots & \sigma_{X_1X_{26}} \\ \sigma_{X_2X_1} & \sigma_{X_2X_2} & \cdots & \sigma_{X_2X_{26}} \\ \vdots & \vdots & \ddots & \vdots \\ \sigma_{X_{26}X_1} & \sigma_{X_{26}X_2} & \cdots & \sigma_{X_{26}X_{26}} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_{26} \end{bmatrix} = \begin{bmatrix} \sigma_{X_1Y} \\ \sigma_{X_2Y} \\ \vdots \\ \sigma_{X_{26}Y} \end{bmatrix}. \tag{20}$$

This set of equations are referred to as the normal equations. These normal equations can be written in more compact matrix notation:

$$(C_{XX})A = C_{XY}, \tag{21}$$

where the definitions are evident on comparing last two equations.

The solution of this set of 26 equations in 26 unknowns yields the a_j for $j = 1, \ldots, 26$, and these values may be substituted in (14) to completely specify the estimator. In matrix notation the solution is

$$A = (C_{XX})^{-1} C_{XY}. \tag{22}$$

Measurement data collected for transmitters located in Mumbai, New Delhi, Hyderabad, Coastal Andhra, Ghaziabad, Meerut, Kalyan, Vangani, Talegoan, Pangoli, Karjat and Chennai, was used to calculate $\sigma_{X_iX_j}$ and σ_{X_iY} values. These calculated $\sigma_{X_iX_j}$ and σ_{X_iY} values are substituted in (22), to get the coefficients of Optimized Perez-Vega Zamanillo Model as given below in Table 3.

Table 3. Coefficients of optimized Perez-Vega Zamanillo model.

Coefficients	Value
a_0	$-1.316059571257524e$+002
a_1	10.749305655172163
a_2	55.244971979911995
a_3	$-5.259259194608717e$-004
a_4	7.511798058893486e-009
a_5	$-1.728227920979650e$-014
a_6	$-2.094620171015809e$-019
a_7	-0.838372052342023
a_8	3.279221332838490e-005
a_9	$-5.477200369749959e$-010
a_{10}	2.792227844898064e-015
a_{11}	3.132291099616113e-021
a_{12}	0.010636668971601
a_{13}	$-4.145240978477376e$-007

Coefficients	Value
a_{14}	7.243743776746409e-012
a_{15}	$-4.024001323345321e$-017
a_{16}	$-2.279606949659275e$-023
a_{17}	$-4.412139591311738e$-005
a_{18}	1.685472705671079e-009
a_{19}	$-2.919411953590148e$-014
a_{20}	1.486966165594136e-019
a_{21}	2.349453443660299e-025
a_{22}	5.958804483573685e-008
a_{23}	$-2.242115276950905e$-012
a_{24}	3.826254001773790e-017
a_{25}	$-1.738412909795608e$-022
a_{26}	$-5.206773596529897e$-028

5. COMPARISON RESULTS

In this section we present performance comparison in terms of RMSE. For uniformity the observed path loss values at different receiving antenna heights have been corrected to 9 m height using the procedure given in [15]. We have compared measured path loss values with predicted values from Optimized Perez-Vega Zamanillo, Perez-Vega Zamanillo, Longley-Rice, Hata, Egli, COST 231, Walfisch and Ikegami, Walfisch and Bertoni, ITU-R P.529-3, Green-Obaidat and FSPL models. In Hyderabad, Chennai, Mumbai and New-Delhi cities, path loss for Longley-Rice model was calculated using Point-to-Point method. For other places, path loss for Longley-Rice model was calculated using Area Prediction method.

Root Mean Square Error (RMSE) was calculated between measured path loss value and those predicted by path loss model using

$$\text{RMSE} = \sqrt{\left(\sum (P_m - P_r)^2 / N\right)}, \tag{23}$$

where
P_m: Measured Path Loss (dB)
P_r: Predicted Path Loss (dB)
N: Number of Measured Data Points.

Tables 4 & 5 show the RMSE obtained between measured path loss and those predicted by the path loss models across 48 routes in India. Optimized Perez-Vega Zamanillo model is validated at different

Table 4. Comparison of RMSE for various path loss models with measured data.

Location of Transmitter	Transmitter Frequency (MHz)	Transmitter Height (m)	RMSE for Optimized Perez-Vega Zamanillo (dB)	RMSE for Perez-Vega Zamanillo (dB)	RMSE for Hata (dB)	RMSE for Green Obaidat (dB)	RMSE for Walfisch Ikegami (dB)	RMSE for Walfisch Bertoni (dB)
Coastal Andhra (Urban)	150	16	3.534071	1.928734	8.617627	24.92429	24.779159	35.659767
Coastal Andhra (Urban)	150	30	5.00466	1.846684	8.731298	24.54734	18.929366	20.370636
Coastal Andhra (Urban)	150	40	8.491702	2.310596	8.617888	24.570284	16.362293	18.920772
Coastal Andhra (Urban)	440	30	9.715568	2.417757	4.863326	26.608021	19.222075	18.418948
Coastal Andhra (Urban)	440	40	11.772175	2.762024	5.229462	25.984307	16.032524	17.59117
Chennai (route-1)	175.23	175	16.1604	43.266549	32.214485	69.149439	36.088907	27.962848
Chennai (route-2)	175.23	175	12.271322	45.522951	33.956242	71.023336	38.36332	29.047682
Chennai (route-3)	175.23	175	11.754603	47.410859	36.03672	72.385147	41.201276	30.552929
Chennai (route-4)	175.23	175	13.353393	40.127996	30.053401	63.650893	37.931666	22.515824
Chennai (route-5)	175.23	175	12.025285	42.958959	33.202365	67.914384	40.184195	26.584949
Chennai (route-1)	189.26	175	14.747048	46.161976	35.675225	73.707279	38.324451	31.942417
Chennai (route-2)	189.26	175	12.911291	42.470917	30.751453	67.054919	35.600167	25.088119
Chennai (route-3)	189.26	175	10.996772	51.62265	40.356003	77.014495	44.847835	34.950577
Chennai (route-4)	189.26	175	8.965308	42.92699	32.673092	66.668522	40.137027	24.940018
Chennai (route-5)	189.26	175	10.103468	46.196329	36.266491	70.998208	42.817729	29.495679
Ghaziabad	320	30	10.550893	16.459898	22.211366	14.328105	13.845147	34.474538
Hyderabad (route-1)	62.25	150	28.785712	72.572123	59.578224	97.326394	70.944087	55.350714
Hyderabad (route-2)	62.25	150	29.251249	68.371554	58.715296	93.478383	73.920539	52.158673

Location of Transmitter	Transmitter Frequency (MHz)	Transmitter Height (m)	RMSE for Optimized Perez-Vega Zamanillo (dB)	RMSE for Perez-Vega Zamanillo (dB)	RMSE for Hata (dB)	RMSE for Green Obaidat (dB)	RMSE for Walfisch Ikegami (dB)	RMSE for Walfisch Bertoni (dB)
Hyderabad (route-1)	224.25	150	17.271673	47.446138	39.007547	73.353159	46.346816	31.884137
Hyderabad (route-2)	224.25	150	7.446961	44.902007	33.085971	69.753323	37.708881	27.213414
Hyderabad (route-3)	224.25	150	12.518862	42.333018	34.078104	67.395188	42.453747	26.231866
Kalyan	320	49	15.622345	6.156842	8.364521	27.519219	14.544003	17.162961
Kurla	320	32	26.4429	15.079199	8.02059	39.886769	21.164916	8.997678
Meerut	320	40	10.550893	16.459898	22.211366	14.328105	13.845147	34.474538
Mumbai (route-1)	182.25	300	17.682736	61.563193	46.015483	84.318475	45.88266	42.07352
Mumbai (route-2)	182.25	300	6.88652	42.913344	34.024177	65.499205	39.085761	24.888407
Mumbai (route-1)	224.25	300	12.182778	43.058666	32.064011	65.166273	33.746457	25.893359
Mumbai (route-2)	224.25	300	19.218936	56.808463	42.462367	80.324414	41.331471	38.525012
Mumbai (route-3)	224.25	300	7.894556	34.562467	27.487063	57.639087	32.337596	17.399604
Muzaffarnagar	320	40	11.023052	19.153957	23.361808	9.229004	6.821531	35.317779
Neral	320	25	9.380195	6.575476	8.031796	28.148601	18.703303	20.092804
New Delhi (route-1)	175.25	235	9.663962	53.732046	45.711076	78.549451	52.077073	37.531463
New Delhi (route-2)	175.25	235	10.490144	43.29448	37.663299	70.55457	44.088478	30.237051
New Delhi (route-3)	175.25	235	8.278358	45.916731	39.148277	71.350224	46.100547	30.61131
New Delhi (route-1)	189.25	235	9.963577	41.117641	35.342401	68.044836	41.458921	27.734652
New Delhi (route-2)	189.25	235	8.972927	40.040521	33.87377	65.499275	40.923211	24.841618
New Delhi	320	40	17.287122	9.81371	13.264309	26.422852	10.529273	22.413681
Pune	320	45	11.632418	12.088047	17.391776	19.234135	8.712402	27.717504
Saharanpur	320	40	8.996877	15.797657	19.849099	12.279645	5.595488	31.847499
Talegaon	320	115	13.706138	8.437785	8.358142	29.58864	13.723777	15.226172
Tirupati	189.25	30	16.40488	5.284888	7.284491	32.337074	11.679938	16.043294
Vangani	320	26	8.249331	10.908134	18.201671	18.72141	13.123294	30.829985
Chennai (route-1)	62.25	130	24.652164	7.871311	4.871851	27.200754	24.22061	13.621755
Chennai (route-2)	62.25	130	22.361317	6.778475	5.640416	29.094933	27.427642	11.857094

Location of Transmitter	Transmitter Frequency (MHz)	Transmitter Height (m)	RMSE for Optimized Perez-Vega Zamanillo (dB)	RMSE for Perez-Vega Zamanillo (dB)	RMSE for Hata (dB)	RMSE for Green Obaidat (dB)	RMSE for Walfisch Ikegami (dB)	RMSE for Walfisch Bertoni (dB)
Chennai (route-3)	62.25	130	24.310852	6.631586	9.535392	29.925722	29.225285	13.598483
Chennai (route-4)	62.25	130	27.565855	11.975789	10.992581	26.82781	27.533619	17.71194
Chennai (route-5)	62.25	130	23.079392	7.933264	7.243036	27.946695	28.445512	13.660561
Chennai (route-6)	62.25	130	21.285998	6.69998	7.64971	30.482901	30.045861	11.49775
Average RMSE (dB)	-	-	13.98788831	28.9306304	24.95804302	49.54073948	31.21697881	26.31589898

Table 5. Comparison of RMSE for various path loss models with measured data.

Location of Transmitter	Transmitter Frequency (MHz)	Transmitter Height (m)	RMSE for Free Space (dB)	RMSE for Egli (dB)	RMSE for Cost-231 (dB)	RMSE for ITU-R P.529-3 (dB)	RMSE for Longley Rice (dB)
Coastal Andhra (Urban)	150	16	32.481693	120.932299	5.16105	8.812686	15.443014
Coastal Andhra (Urban)	150	30	26.584644	121.342566	5.276135	8.934519	12.464804
Coastal Andhra (Urban)	150	40	24.001216	121.362515	5.162812	8.833159	11.569846
Coastal Andhra (Urban)	440	30	31.620139	119.251826	10.46289	5.464588	18.845938
Coastal Andhra (Urban)	440	40	28.43764	119.904403	10.834781	5.89166	17.436528
Chennai (route-1)	175.23	175	44.454981	78.91671	34.480981	32.214485	42.593168
Chennai (route-2)	175.23	175	46.79447	76.03508	36.278288	33.956242	46.346478
Chennai (route-3)	175.23	175	49.601941	74.75169	38.354676	36.03672	48.43179
Chennai (route-4)	175.23	175	46.265179	83.156138	32.347478	30.053401	45.106953
Chennai (route-5)	175.23	175	48.618527	79.254706	35.523938	33.202365	46.361891

Location of Transmitter	Transmitter Frequency (MHz)	Transmitter Height (m)	RMSE for Free Space (dB)	RMSE for Egli (dB)	RMSE for Cost-231 (dB)	RMSE for ITU-R P.529-3 (dB)	RMSE for Longley Rice (dB)
Chennai (route-1)	189.26	175	47.073855	74.352359	37.453657	35.675225	45.123219
Chennai (route-2)	189.26	175	44.417506	79.660436	32.560302	30.751453	43.926262
Chennai (route-3)	189.26	175	53.610895	70.174203	42.16046	40.356003	52.565339
Chennai (route-4)	189.26	175	48.932702	79.7398	34.489771	32.673092	47.874808
Chennai (route-5)	189.26	175	51.628408	76.186965	38.074002	36.266491	48.635438
Ghaziabad	320	30	20.82504	134.585928	25.331469	22.758307	7.606284
Hyderabad (route-1)	62.25	150	74.951388	49.759445	69.07302	59.578224	63.931063
Hyderabad (route-2)	62.25	150	77.966714	53.681808	68.280178	58.635772	70.363707
Hyderabad (route-1)	224.25	150	55.843944	74.147292	38.120372	38.973798	52.643145
Hyderabad (route-2)	224.25	150	47.215411	76.504965	32.19213	33.085971	40.180846
Hyderabad (route-3)	224.25	150	51.939931	79.804414	33.194311	33.978343	49.234658
Kalyan	320	49	24.402232	118.99	10.977469	8.424396	17.590746
Kurla	320	32	31.710758	106.620855	6.738227	8.02059	27.248884
Meerut	320	40	20.82504	134.585928	25.331469	22.758307	7.606284
Mumbai (route-1)	182.25	300	54.533615	63.877614	48.089677	46.015483	54.055552
Mumbai (route-2)	182.25	300	47.768622	81.961598	36.097144	32.896392	44.209666
Mumbai (route-1)	224.25	300	43.112149	84.337111	31.21802	31.728206	40.09859
Mumbai (route-2)	224.25	300	50.695381	68.673055	41.587554	42.462367	50.184329
Mumbai (route-3)	224.25	300	41.839201	89.420866	26.602297	25.950156	37.69197
Muzaffarnagar	320	40	13.297329	137.709464	26.707089	24.492622	5.554998
Neral	320	25	28.805545	118.192959	10.693912	8.031796	20.077267
New Delhi (route-1)	175.25	235	60.583736	69.506165	48.052233	45.193729	57.786141
New Delhi (route-2)	175.25	235	52.607232	78.112397	39.991326	36.198582	45.829496
New Delhi (route-3)	175.25	235	54.622868	76.409975	41.489406	38.375249	51.361278
New Delhi (route-1)	189.25	235	50.28768	80.324094	37.141605	33.974308	44.080905

Location of Transmitter	Transmitter Frequency (MHz)	Transmitter Height (m)	RMSE for Free Space (dB)	RMSE for Egli (dB)	RMSE for Cost-231 (dB)	RMSE for ITU-R P.529-3 (dB)	RMSE for Longley Rice (dB)
New Delhi (route-2)	189.25	235	49.7607	81.815966	35.685509	32.958375	46.74191
New Delhi	320	40	20.469321	122.158881	15.824168	13.264309	15.838948
Pune	320	45	16.396865	129.156962	20.480173	17.649377	8.201219
Saharanpur	320	40	15.148229	134.244973	23.212977	20.947544	4.361736
Talegaon	320	115	23.246175	117.488583	9.75684	8.31993	20.103109
Tirupati	189.25	30	20.32507	114.481924	6.297165	7.284491	16.60808
Vangani	320	26	21.277754	129.260862	21.25272	18.211985	11.940045
Chennai (route-1)	62.25	130	28.06711	118.893701	9.399013	7.663228	5.843671
Chennai (route-2)	62.25	130	31.271608	117.029331	11.929025	6.217767	5.867691
Chennai (route-3)	62.25	130	32.918977	117.12852	14.369721	7.729493	5.512854
Chennai (route-4)	62.25	130	31.141728	121.139491	13.277847	12.631406	8.35588
Chennai (route-5)	62.25	130	32.248312	118.528393	12.376877	8.486163	4.688437
Chennai (route-6)	62.25	130	33.882946	115.984028	14.203048	6.278878	6.122784
Average RMSE (dB)	-	-	39.26067515	97.69873425	27.15823358	24.96453402	31.04682602

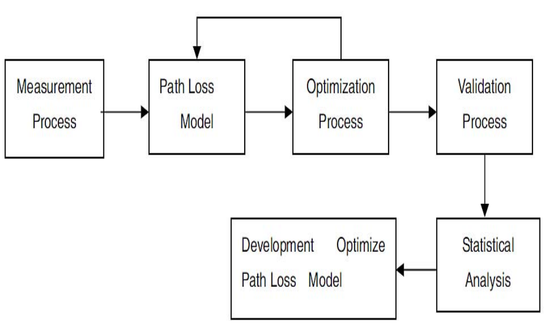

Figure 5. Flow chart of optimization process.

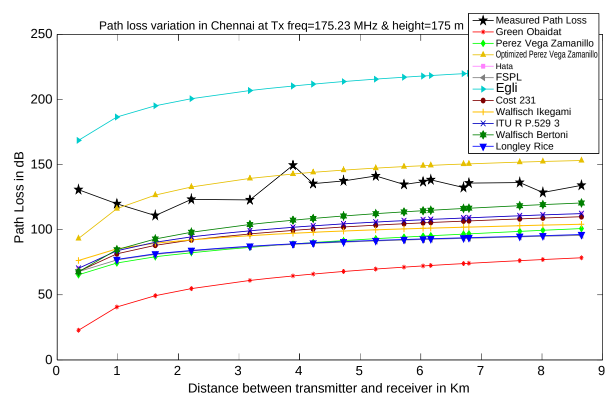

Figure 6. Comparison of path loss models in Chennai.

locations in Mumbai, New Delhi, Hyderabad, Coastal Andhra, Chennai, Muzaffarnagar, Saharanpur, Pune, Neral, Ghaziabad, Meerut, Kalyan, Kurla, Vangani, Talegaon, and Tirupati. Note that these paths were not used in estimating the Optimized model parameters.

Figures 6 to 16 show the plots of measured path loss in dB with the path loss predicted by 11 path loss models. Figure 6 shows the variation of measured path loss along with 11 different path loss models, in Chennai city. For Chennai city, Optimized Perez-Vega Zamanillo model is closer to the

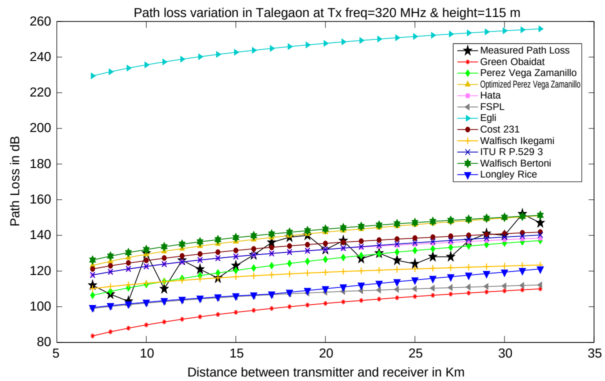

Figure 7. Comparison of path loss models in Talegaon.

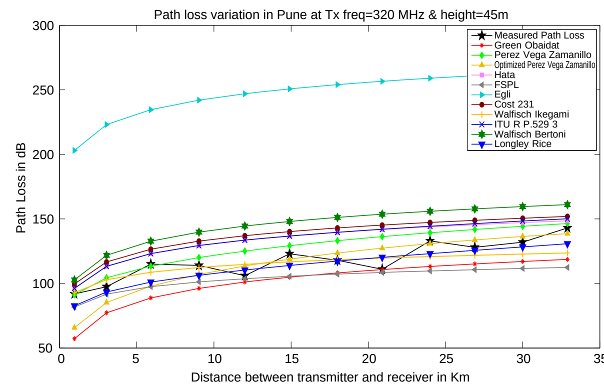

Figure 8. Comparison of path loss models in Pune.

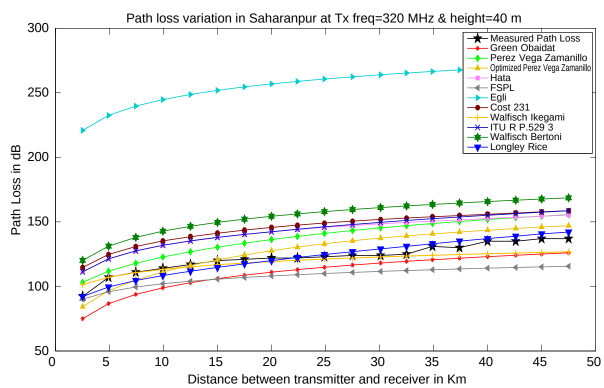

Figure 9. Comparison of path loss models in Saharanpur

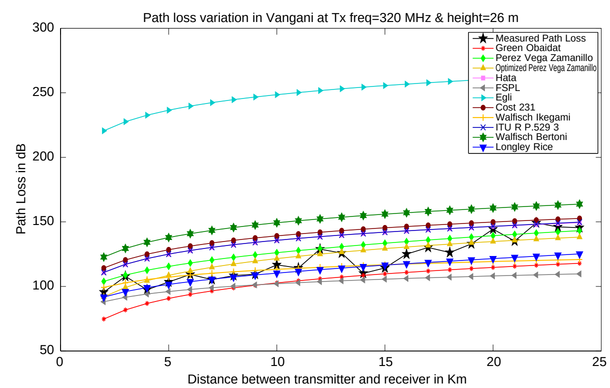

Figure 10. Comparison of path loss models in Vangani.

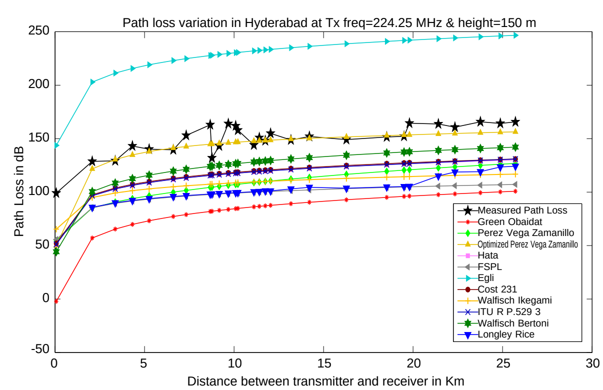

Figure 11. Comparison of path loss models in Hyderabad.

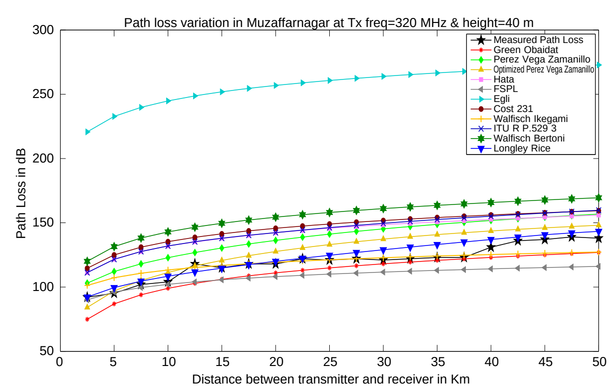

Figure 12. Comparison of path loss models in Muzaffarnagar.

measured path loss values. Figure 11 shows the variation of path loss as a function of distance for Doordarshan (DD) TV tower located in Hyderabad along one radial. In this figure observed values are plotted from 0.5 km to 27 km. Optimized Perez-Vega Zamanillo model is found to give excellent agreement with observed values. All other models have large deviation with the observed path loss values. From Table 4 it is clear that Optimized Perez-Vega Zamanillo model has the best performance in Hyderabad city as it has the least RMSE of 7.44 dB, followed by Walfisch Bertoni model. Among the

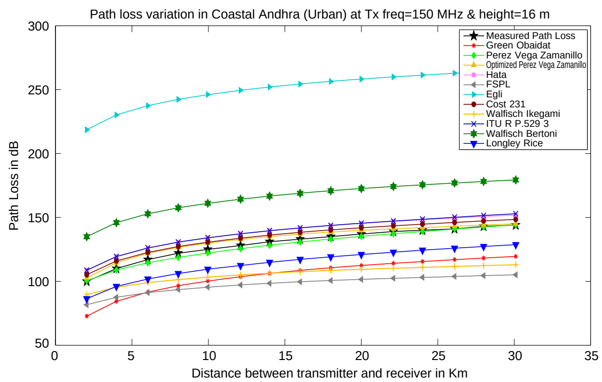

Figure 13. Comparison of path loss models in Coastal Andhra.

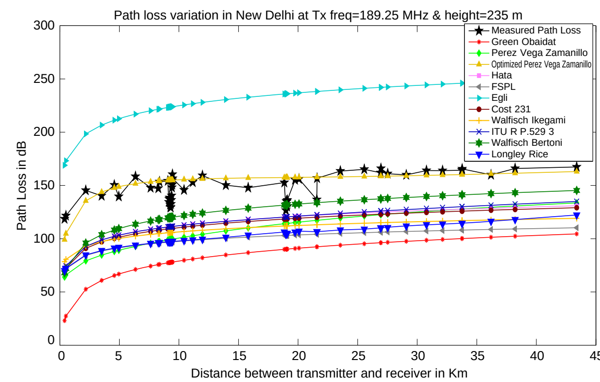

Figure 14. Comparison of path loss models in New Delhi.

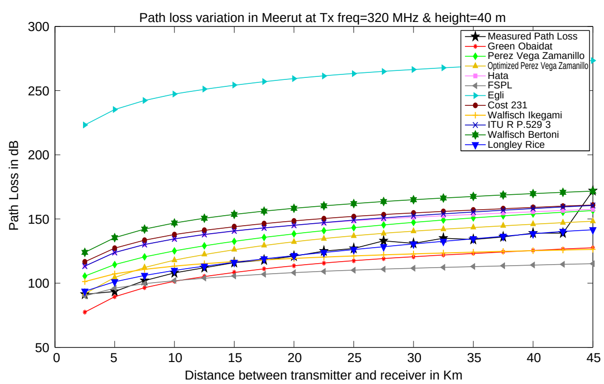

Figure 15. Comparison of path loss models in Meerut.

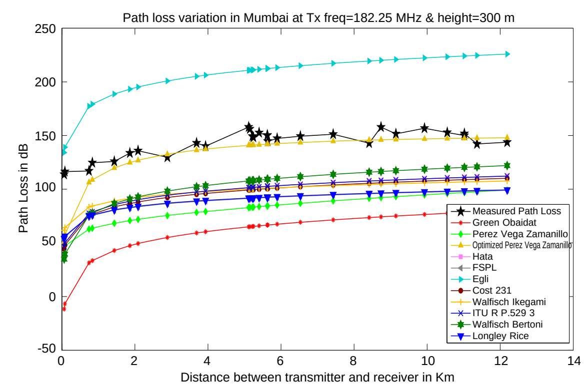

Figure 16. Comparison of path loss models in Mumbai.

11 path loss models discussed, Egli model has the worst performance in Hyderabad city as it has the maximum RMSE of 79.8 dB. Similarly, Figure 14 shows the variation of measured path loss and various path loss models w.r.t distance in New Delhi. For New Delhi city, Optimized Perez-Vega Zamanillo model is in reasonable agreement with the measured path loss values. Figure 16 shows the variation of measured path loss w.r.t distance and also of 11 different path loss models in Mumbai city. It is observed that Optimized Perez-Vega Zamanillo model is closer to the measured path loss values. For Mumbai city, Optimized Perez-Vega Zamanillo model has the least root mean square error. In [12], we found that Perez-Vega Zamanillo model is better model for India because it had the least RMSE of 16.93 dB. Therefore, Perez-Vega Zamanillo model was selected for Optimization in this paper. In our paper [12], we have considered 15 paths in India for comparison of different path loss models. In this paper, we have the compared different path loss models with the measured path loss data, collected across 48 different paths in India. We find that RMSE of Perez-Vega Zamanillo model increases from 16.93 dB in [12] to 28.9 dB. We can see that the performance of Optimized Perez-Vega Zamanillo model is best in Hyderabad, Chennai, New Delhi, Ghaziabad, Mumbai, Meerut, and Vangani. Overall we can see that performance of Optimized Perez-Vega Zamanillo model is best since it has the least average RMSE of 13.98 dB which is the least among the 11 path loss models discussed. Other path loss models over estimate the path loss because average root mean square error (RMSE) for other path loss models is more than 24 dB. Therefore, Optimized Perez-Vega Zamanillo model is the best suited path loss model for India.

6. CONCLUSION

In this paper, we have used the measurement data of path loss in (dB) at different distances for transmitters in UHF/VHF bands, located at 21 different places in India. Optimized Perez-Vega Zamanillo model is validated at different locations in Mumbai, New Delhi, Hyderabad, Coastal Andhra, Chennai, Muzaffarnagar, Saharanpur, Pune, Neral, Ghaziabad, Meerut, Kalyan, Kurla, Vangani, Talegaon, and Tirupati. We have compared the performance of 11 different known models with measured data in terms of root mean square error (RMSE). RMSE obtained between Measured Path loss and those predicted by the path loss models were compared across 48 routes in India. We can see that the performance of Optimized Perez-Vega Zamanillo model is best in Hyderabad, Chennai, New Delhi, Ghaziabad, Mumbai, Meerut, and Vangani. We found that performance of Optimized Perez-Vega Zamanillo model is best as average root mean square error is 13.98 dB which is lowest when compared to other models. Other path loss models over estimate the path loss because average root mean square error (RMSE) for other path loss models is more than 24 dB. India is a country with wide terrain and climatic conditions. There is lot of variation in height of buildings in different cities of India. Also, there is a wide variation in sizes of cities in India. All these factors may have caused the RMSE of the optimized model to become higher than the original model in some parts of India. We conclude that Optimized Perez-vega zamanillo path loss model can be used in India for predicting coverage area for TVWS.

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REFERENCES

1. First Report and Notice of Rulemaking in the Matter of Unlicensed Operation in TV Broadcast Bands, ET Docket No. 04-186, Adopted Oct. 18, 2006.
2. Prasad, M. V. S. N. and I. Ahmad, “Comparison of some path loss prediction methods with VHF/UHF measurements,” *IEEE Transactions on Broadcasting*, Vol. 43, No. 4, 459–486, Dec. 1997.
3. Prasad, M. V. S. N. and R. Singh, “UHF train radio measurements in northern India,” *IEEE Transactions on Vehicular Technology*, Vol. 49, No. 1, 239–245, USA, Jan. 2000.
4. Prasad, M. V. S. N. and R. Singh, “Terrestrial mobile communication train measurements in western India,” *IEEE Transactions on Vehicular Technology*, Vol. 52, No. 3, 671–682, May 2003.
5. Prasad, M. V. S. N., T. Rama Rao, I. Ahmad, and K. M. Paul, “Investigation of VHF signals in bands I and II in southern India and model comparisons,” *Indian Journal of Radio and Space Physics*, Vol. 35, 198–205, Jun. 2006.
6. Prasad, M. V. S. N., “Path loss exponents deduced from VHF amp; UHF measurements over Indian subcontinent and model comparison,” *IEEE Transactions on Broadcasting*, Vol. 52, No. 3, 290–298, 2006.
7. Pathania, P., P. Kumar, and B. Shashi Rana, “Performance evaluation of different path loss models for broadcasting applications,” *American Journal of Engineering Research (AJER)*, Vol. 3, No. 4, 335–342, 2014.
8. Pathania, P., P. Kumar, and B. Shashi Rana, “A modified formulation of path loss models for broadcasting applications,” *International Journal of Recent Technology and Engineering (IJRTE)*, Vol. 3, No. 3, 44–54, Jul. 2014.
9. Ying, X., C. W. Kim, and S. Roy, “Revisiting TV coverage estimation with measurement-based statistical interpolation,” http://www.dynamicspectrumalliance.org/assets/Revisiting_TV_Coverage_Estimation_with_Measurement-based_Statistical_Interpolation_08202014.pdf.

10. Faruk, N., A. A. Ayeni, Y. Adediran, and N. Surajudeen-Bakinde, "Improved pathloss model for predicting TV coverage for secondary access," *International Journal of Wireless and Mobile Computing*, Vol. 7, No. 6, 565–576, 2014.
11. Mohammed Al Salameh, S. H., "Lateral ITU-R foliage and maximum attenuation models combined with relevant propagation models for forest at the VHF and UHF bands,"*NNGT Int. J. on Networking and Communication*, Vol. 1, Jul. 2014.
12. Sridhar, B. and M. Z. A. Khan, "RMSE comparison of path loss models for UHF/VHF bands in India," *2014 IEEE Region 10 Symposium*, 330–335, Kuala Lumpur, Malaysia, Apr. 14–16, 2014.
13. Hata, M., "Empirical formula for propagation loss in land mobile radio services," *IEEE Trans. Vehicular Technology*, Vol. 29, 317–325, 1980.
14. Farhoud, M., A. El-Keyi, and A. Sultan, "Empirical correction of the Okumura-Hata model for the 900 MHz band in Egypt," *International Conference on Communications and Information Technology (ICCIT-2013): IEEE Wireless Communications and Signal Processing*, 386–390, Beirut, Lebanon, Jun. 19–21, 2013.
15. Perez-Vega, C. and J. M. Zamanillo, "Path-loss model for broadcasting applications and outdoor communication systems in the VHF and UHF bands," *IEEE Transactions on Broadcasting*, Vol. 48, No. 2, 91–96, Jun. 2002.
16. Roslee, M. B. and K. F. Kwan, "Optimization of Hata propagation prediction model in suburban area in Malaysia," *Progress In Electromagnetics Research C*, Vol. 13, 91–106, 2010.
17. Egli, J. J., "Radio propagation above 40 MC over irregular terrain," *Proceedings of the IRE*, Vol. 45, No. 10, 1383–1391, 1957.
18. Sharma, P. K. and R. K. Singh, "Comparative study of path loss model depends on various parameter," *International Journal of Engineering Science and Technology*, Vol. 3, 4683–4690, Jun. 2011.
19. Dayanand, A., K. Deepak, and P. Tejas, "Statistical tuning of Walfisch-Ikegami model in urban and suburban environments," *Fourth Asia International Conference on AMS*, 538–543, Kota Kinabalu, Malaysia, 2010.
20. ITU-R P.529-3, "VHF/UHF propagation data and prediction methods required for the terrestrial land mobile services," 1994.
21. Green, D. B. and M. S. Obaidat, "An accurate line of sight propagation performance model for Ad-Hoc 802.11 wireless LAN (WLAN) devices," *Proceedings of IEEE ICC 2002*, New York, Apr. 2002.
22. http://en.wikipedia.org/wiki/Free-space_path_loss.
23. Rice, P. L., A. G. Longley, K. A. Norton, and A. P. Barsis, "Transmission loss predictions for tropospheric communications circuits," Technical Note 101, US Department of Commerce NTIA-ITS, 1967.
24. Rappaport, T. S., *Wireless Communications Principles and Practice*, Prentice Hall, 2002.
25. Erceg, V., K. V. S. Hari, et al., "Channel models for fixed wireless applications," Tech. Rep., IEEE 802.16 Broadband Wireless Access Working Group, Jan. 1986.