COMPARATIVE ANALYSIS OF PATH LOSS PREDICTION MODELS FOR URBAN MACROCELLULAR ENVIRONMENTS

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Abstract

A comparative analysis of path loss prediction models for urban macrocellular environments is presented in this paper. Specifically, three path loss prediction models namely free space, Hata and Egli were used to predict path losses. The calculated path loss values were compared with practical measured data obtained from a Visafone base station located in Uyo, Nigeria. The comparative analysis reveals that the mean square error (MSE) for free space, Hata and Egli were 16.24dB, 2.37dB and 8.40dB respectively. The results showed that Hata's model is the most accurate and reliable path loss prediction model for macrocellular urban propagation environments, since its MSE value of 2.37dB is smaller than the acceptable minimum MSE value of 6dB for good signal propagation.

Keywords: macrocellular areas, path loss prediction models, Hata model, mean square error

1. Introduction

Nowadays, wireless communication technology is influencing every area of modern life, and has encouraged useful researches in nearly all fields of human endeavour. Cellular services are today being used by millions of people worldwide. The third generation (3G) wireless network such as code division multiple access (CDMA2000) is designed to facilitate high-speed data communications in addition to voice calls.

Importantly, the knowledge of the propagation characteristics of a mobile radio channel is essential for designing any wireless (mobile) communication system in a given region [1]. In terrestrial cellular radio systems, radio signals generally propagate by means of any or a combination of these three basic propagation mechanisms; reflection, diffraction, and scattering [2, 3]. One of the most important features of the propagation environment is path (propagation) loss. Path loss is defined as the difference (in dB) between the effective transmitted power and the received power, and may or may not include the effect of the antenna gains [4]. Path loss may be due to many effects, such as free-space loss, refraction, diffraction, reflection, aperture-medium coupling loss, and absorption (penetration) losses. Path loss is also influenced by terrain contours, environment (urban or rural, vegetation and foliage), propagation medium (dry or moist air), the distance between a base station (BS) and mobile station (MS), and the height and location of transmitting and receiving antennas.

Usually, the calculation of path loss is called path loss prediction. On the basis of the mobile radio environment, path loss prediction models are classified into two main categories: outdoor and indoor prediction models [4]. Furthermore, with respect to the size of the coverage areas the outdoor path loss prediction models are subdivided into megacellular, macrocellular, and microcellular, whereas the indoor prediction models are subdivided into two classes: Picocellular and femtocellular [3]. Megacell areas are extremely large cells spanning hundreds of kilometers. “Megacells are served mostly by low-earth orbiting mobile satellites”.

Macrocellular areas span a few kilometres to tens of kilometers, depending on the location [5]. These are the traditional “cells” corresponding to the coverage area of a base station associated with traditional cellular telephony base stations. The frequency of operation is mostly around 900MHz. Macrocells can be classified into different channel types: urban, suburban, and rural propagation environments [6]. Microcells are cells that span hundreds of metres to a kilometre. The span of picocells is between 30m and 100m, while femtocells span from a few metres to few tens of metres.

The path loss prediction (propagation) models are broadly divided into three types, namely: theoretical, empirical, and site-specific models [7]. This paper addresses the comparisons between the theoretical path loss models, empirical path loss models and the practical measured path losses from a Visafone CDMA2000 base station. At the end of the comparative analysis using different propagation models, the most accurate and reliable path loss prediction model that could be adopted for urban path loss calculations in Nigeria is recommended.

1.1. Contribution and relevance of the study

The need for efficient planning in mobile radio systems is extremely important because imprecise path loss prediction models always lead to networks with high co-channel interference and waste of power. An accurate estimation of path loss is useful for predicting coverage areas of base stations, frequency assignments, proper determination of electric field strength, interference analysis, handover optimization, and power level adjustments. Most of the existing path loss prediction models have limitations. By comparing them with the practical measured data, the most accurate path loss prediction model for urban propagation environment is highlighted. The telecommunication companies in Nigeria whether based on GSM or CDMA technologies operating at radio frequency band of 800 to 900MHz, should apply the knowledge presented in this article in radio link budget design and analysis so as to further improve their services, thereby serving high quality signals to their teeming subscribers in urban areas.

1.2. Arrangement of the paper

The rest of the paper is arranged as follows: a review of existing path loss prediction models such as Free space, Plane earth propagation, Okumura, Hata and Egli are presented in section 2. In section 3, predicted path loss values were obtained from a numerical problem using the path loss prediction models, while section 4 describes the data collection method for measured path loss values. Section 5 dwells on results, while discussion, conclusion and recommendation are presented in section 6 followed by references.

2. Review of Related Works

In this section, some existing theoretical, empirical and terrain-specific path loss models are reviewed. Sample models reviewed includes, the Free space path loss model [4], Plane earth propagation model [4, 11], Okumura model [8], Hata model [4], and Egli model [10]. These models reveal that path loss increases as the transmitter-receiver separation distance increases.

2.1. Theoretical path loss models

Theoretical models were derived based on the physical laws of wave propagation. The theoretical path loss prediction models are divided into two basic types; namely: Free space path loss model, and Plane earth propagation model.

2.1.1. Free space path loss model

In free space, the wave is not reflected or absorbed [7]. The free space path loss model is used to predict received signal strength when the transmitter and receiver have a clear, unobstructed line of sight path between them. Satellite communication systems and microwave line of sight radio links typically undergo free space propagation. The free space power received by a receiver antenna from a radiating transmitter antenna is given by [3],

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L} \qquad (1)$$

where: $P_r(d)$ is the received power which is a function of the transmitter-receiver separation distance, P_t is the base station transmit power, G_t is the transmitter antenna gain, G_r is the receiver antenna gain, λ is the signal wavelength, d is the distance between transmitting and receiving antennas, L is the system loss factor not related to propagation ($L \geq 1$).

Quantitatively, path loss in decibel is

$$PL(dB) = P_t(dB) - P_r(dB) \qquad (2)$$

The path loss in decibel for the free space model when antenna gains are included is given by [4],

$$PL(dB) = 100\log_{10}\frac{P_t}{P_r} = -10\log_{10}\left(\frac{G_t G_r \lambda}{(4\pi)^2 d^2 L}\right) \qquad (3)$$

When antenna gains are unity (isotropic antennas), Equation (3) can be re-written as

$$PL(dB) = -10\log_{10}\left(\frac{\lambda^2}{(4\pi)^2 d^2}\right) \qquad (4)$$

or

$$PL(dB) = 10\log_{10}\left(\frac{(4\pi)^2 d^2}{\lambda^2}\right) \qquad (5)$$

According to Nadir et al [7], substituting (λ (in km) = 0.3/f (in MHz)), and rationalizing Equation (5), produces the generic free space path loss formula, which is stated in Equation (6):

$$PL(dB) = 32.5 + 20\log_{10}(\text{f in MHz}) + 20\log_{10}(\text{d in km}) \quad (6)$$

where f is the carrier frequency.

The path losses predicted by the free space path loss model of either Equation (5) or Equation (6) are not accurate, because most often mobiles antennas in urban areas generally do not have line of sight path to base stations.

2.1.2. Plane earth propagation model

The Free space propagation model does not consider the effects of propagation over ground. When a radio wave propagates over ground, some of the power will be reflected due to the presence of ground and then received by the receiver. The Plane earth model computes the received signal to be the sum of a direct signal and that reflected from a flat, smooth earth. The path loss equation for the Plane earth model is [4].

$$PL(dB) = 40\log_{10} d - 20\log_{10} h_b - 20\log_{10} h_m - 10\log_{10} G_b - 10\log_{10} G_m \qquad (7)$$

where d represents the path length in metres, h_b and h_m in metres are the antenna heights at the base station and the mobile respectively, while G_b and G_m are the gains of the base and mobile stations respectively.

When the transmitting and receiving antennas are omnidirectiional, Equation (7) reduces to Equation (8), as illustrated by [7, 11].

$$PL(dB) = 40\log_{10} d - 20\log_{10} h_b - 20\log_{10} h_m \qquad (8)$$

The Plane earth model is not appropriate for mobile CDMA/GSM path loss predictions because it does not consider the reflections from buildings, multiple propagations and diffraction effects. Furthermore, if the mobile height changes (as it does in practice) then the predicted path loss also changes.

2.2. Empirical path loss models

Empirical models are usually a set of equations derived from extensive field measurements [8, 9]. There are various empirical path loss prediction models for macrocellular areas such as Okumura model, Hata model, and Egli model. These models depend on location, frequency, range and clutter type such as urban, sub-urban and countryside [7].

2.2.1. Okumura model

The Okumura's model [8] is an empirical model based on extensive drive test measurements made in Japan at several frequencies within the range of 150 to 1920MHz, but is extrapolated up to 3000MHz. Okumura's models is developed for macrocells with cells diameters of 1 to 100km. The height of the base station antenna is between 30-100m [4]. The Okumura's model takes into account some propagation parameters such as the type of environment and the terrain irregularity.

Okumura developed a set of curves giving the median attenuation relative to free space (A_{mu}), in an urban area over a quasi-smooth terrain with a base station effective antenna height (h_b) of 200m and a mobile antenna height (h_m) of 3m. These curves were developed from extensive measurements using vertical omni-directional antenna at both the base and mobile, and are plotted as a function of frequency in the range of 100MHz to 1920 MHz, and as a function of distance from the base station in the range 1km to 100km [4]. The plots of $A_{mu}(f, d)$ and correction factor (G_{AREA}) for a wide range of frequencies is shown in Figure 1 [12].

The path loss prediction formula according to Okumura's model is expressed as [4, 8, 12, 13]:

$$L_{50}(dB) = L_F + A_{mu}(fd) - G(h_b) - G(h_m) - G_{AREA} \quad (9)$$

where L_{50}(dB) is the median value (i.e. 50^{th} percentile) of path (propagation) loss, L_F is the free space loss, and can be calculated using either Equation (5) or Equation (6), A_{mu} is the median attenuation relative to free space, $G(h_b)$ is the base station antenna height gain factor, $G(h_m)$ is the mobile antenna height gain factor, and G_{AREA} is the gain or correction factor due to the type of environment.

$A_{mu}(f, d)$ and G_{AREA} are determined by looking up Okumura curves shown in Figure 1.

$G(h_b)$ and $G(h_m)$ are calculated using these simple formulae:

$$G(h_b) = 20\log_{10} \quad 1000m > h_b > 30m \quad (10)$$

$$G(h_m) = 10\log_{10}\left(\frac{h_m}{3}\right) \quad h_m \leq 3m \quad (11)$$

$$G(h_m) = 20\log_{10}\left(\frac{h_m}{3}\right) \quad 10m \leq h_m \leq 3m \quad (12)$$

Okumura's model is considered to be among the simplest and best in terms of accuracy in path loss prediction for mature cellular and land mobile systems in cluttered environment. The major disadvantage with Okumura model is its slow response to rapid changes in terrain, therefore the model is fairly good in urban and suburban areas, but not as good in rural areas [4].

2.2.2. Hata model

Hata model is an empirical formulation of the graphical path loss data provided by Okumura's model, and is valid from 150MHz to 1500MHz [13]. The standard formula for median path loss prediction model for urban macrocellular environment is given by [2, 4, 7, 9, 12].

$$\begin{aligned} L_{50}(\text{urban})(dB) &= 69.55 + 26.16\log_{10} f_c - \\ &\quad 13.82\log_{10}(h_b) - a(h_m) + \\ &\quad (44.0 - 6.55\log_{10} h_b)\log_{10} d \end{aligned} \quad (13)$$

where f_c is the carrier frequency (in MHz) from 150MHz to 1500MHz, h_b is the base station antenna height (in metres) ranging from

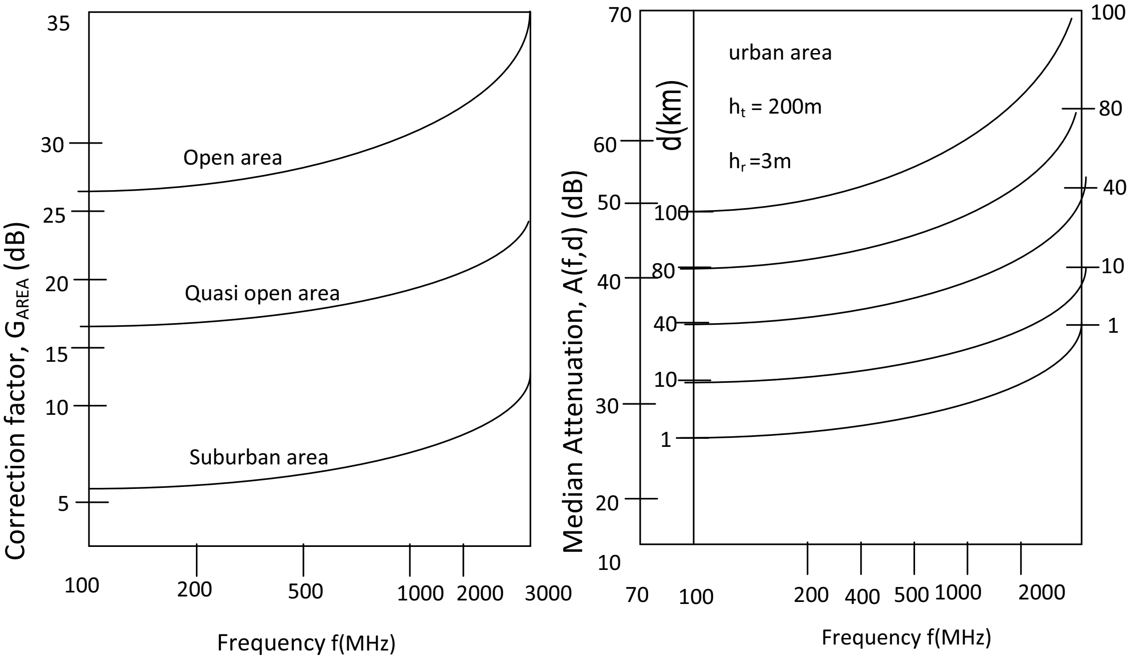

Figure 1: The correction factor G_{AREA} for different types of terrain and the median attenuation relative to free space over a quasi-smooth terrain.

30m to 200m, h_m is the mobile antenna height (in metres) ranging from 1m to 10m, d is the base station to mobile separation distance (in km), and $a(h_m)$ is the correction factor for effective mobile antenna height which is a function of the size of the coverage area.

For a large city (dense urban), the mobile antenna correction factor is given by:

$$a(h_m) = 3.2(\log_{10} 11.75h_m)^2 - 4.97dB \quad \text{for} f_c \geq 300MHz \qquad (14)$$

$$a(h_m) = 8.29(\log_{10} 1.54h_m)^2 - 1.1dB \quad \text{for} f_c \leq 300MHz \qquad (15)$$

For a small to medium sized city (urban), the mobile antenna correction factor is:

$$a(h_m) = (1.1\log_{10} f_c - 0.7)h_m - (1.56\log_{10} f_c - 0.8)dB \quad (16)$$

To obtain the path loss in suburban area, the standard Hata model in Equation (13) is modified as

$$L_{50}(dB) = L_{50}(\text{urban}) - 2[\log_{10}(f_c/28)]2 - 5.4 \qquad (17)$$

and for path loss in open rural environment, the formula is modified as

$$L_{50}(dB) = L_{50}(\text{urban}) - 4.78 \times 4 \times (\log_{10} f_c)^2 + 18.33 \times \log_{10} f_c - 40.94 \qquad (18)$$

Hata model is well suited for path loss predictions in macrocellular urban environment. It is the most widely used radio frequency propagation model for predicting the behavior of cellular transmission [12]. It includes the effects of diffraction, reflection and scattering caused by the city structures. The model is not suitable for microcell planning, and it is not valid for 1800MHz to 2000MHz personal communication systems (PCS) applications [7].

2.2.3. *Egli model*

The Egli's model [10] is a terrain model for radio frequency propagation. It predicts the total path loss for point-to-point link (line of sight transmission). Typically, it is suitable for cellular communication scenarios where one antenna is fixed and another is mobile. Egli model is applicable to scenarios where the transmission has to go over an irregular terrain. Egli model is not applicable to scenarios where some vegetative obstruction is in the middle of the link. The Eglis model is formally expressed as [12]:

$$PL(dB) = G_b G_m \left(\frac{h_b h_m}{d^2}\right)^2 \left(\frac{40}{f}\right)^2 \quad (19)$$

where: G_b is the gain of the base station antenna, whose unit is dimensionless, G_m is the gain of the mobile station antenna, whose unit is dimensionless, h_b is the height of the base station antenna in metres, h_m is the height of the mobile station antenna in metres, d is the distance from base station antenna to mobile station antenna in metres, and f is the frequency of transmission in megahertz (MHz).

3. Numerical Problem

A 900MHz cellular system operates in a medium urban city from a base station with height of 100m, and the mobile station installed in a vehicle has an antenna height of 2m. The distance between the mobile and the base station is 4km. The base station and mobile antennae are isotropic. Determine the path loss using the following path loss prediction models [3]:

(i) Free space path loss model,
(ii) Hata model and,
(iii) Egli model.

Repeat the numerical problem for cases in which the distance between the mobile and the base station are 1km, 2km, 3km, and 5km.

The numerical analysis of path loss using the path loss prediction methods are as presented. Given: f = transmission frequency = 900MHz,

h_b = base station antenna height = 100m,
h_m = mobile station antenna height = 2m,
d = base station to mobile separation distance = 4km,
G_b = base station antenna gain = 1,
G_m = mobile antenna gain = 1.

(i) The Free space path loss model is obtained from Equation (6):

$$\begin{aligned} PL(dB) &= 32.5 + 20\log_{10}(\text{f in MHz}) + 20\log_{10}(\text{d in km}) \\ &= 32.5 + 20\log_{10}900 + 20\log_{10}4 \\ &= 32.5 + 59.08 + 12.04 \\ &= 103.62dB \end{aligned}$$

The calculated Free space loss value is 103.62dB

(ii) The Hata model for a medium urban city based on Equation (13) is

$$\begin{aligned} L_{50}(urban)(dB) = 69.55 + 26.16\log_{10} f_c - 13.82\log_{10}(h_b) \\ -a(h_m) + (44.9 - 6.55\log_{10} h_b)\log_{10} d \end{aligned}$$

For a medium urban city, $a(h_m)$ is given by Equation (16)

$$a(h_m) = (1.1\log_{10} f_c - 0.7)h_m - (1.56\log_{10} f_c - 0.8)dB$$

$$a(h_m) = (1.1\log_{10}900 - 0.72)(2) - (1.56\log_{10}900 - 0.8)$$

$$a(h_m) = 1.29dB$$

$$\begin{aligned} L_{50}(urban)(dB) &= 69.55 + 26.16\log_{10}900 - \\ &\quad 13.82\log_{10}100 - 1.29 + (44.9 - \\ &\quad 6.55\log_{10}100)\log_{10}4 \end{aligned}$$

$$\begin{aligned} L_{50}(urban)(\text{dB}) &= 69.55 + 77.28 - 27.63 - 1.29 + 19.15 \\ &= 137.05\text{dB} \end{aligned}$$

The predicted path loss value according to Hata model is 137.05dB.

(iii) The Egli model is obtained from Equation (19)

$$\begin{aligned} PL(dB) &= G_b G_m \left(\frac{h_b h_m}{d^2}\right)^2 \left(\frac{40}{f}\right)^2 \\ &= (1)(1)\left(\frac{100\times 2}{4000^2}\right)^2 \left(\frac{40}{900}\right)^2 \\ &= 125.11dB \end{aligned}$$

The calculated path loss for Egli model is 125.11dB.

Applying the path loss prediction formulae stated in the above numerical solutions, the path loss results when the distance between the mobile and base station are 1km, 2km, 3km, 4km, and 5km are as shown in table 1.

Table 1: Numerical Path Loss for different Path Loss Prediction Models.

Distance (km)	**Free Space Model** (dB)	**Hata Model** (dB)	**Egli Model** (dB)
1.00	91.58	117.90	101.02
2.00	97.60	127.48	113.06
3.00	101.12	133.07	120.11
4.00	103.57	137.05	125.11
5.00	105.56	140.13	128.98

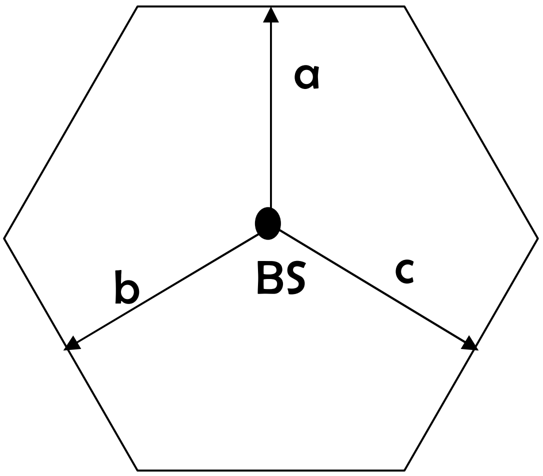

Figure 2: Diagram showing the base station (BS) transmitter and the three different radio routes.

4. Data Collection Method

This research requires practical measured data from the field for purpose of comparison with the results obtained from different path loss prediction models. This is done in order to obtain a reliable prediction of radio signal propagation for urban environments [14]. A drive test measurements for path loss data collection were conducted radically from a visafone CDMA2000 base station located at 29 Ikono street in Uyo City. The base station antenna height is 50m while the base station transmits frequency is 870.52MHZ. The field measurements from the base station transmitter were carried out along three different routes, designated as radio path a, b and c as depicted in Figure 2.

The data collection tools consist of a test phone connected through a cable to a laptop during the drive test, and a global positioning system (GPS). The laptop is equipped with ZXPOS CNT1 and CNA7 softwares. ZXPOS CNTI is a professional foreground test software for communication networks, whereas CNA7 is an analysis software [12,15]. The ZXPOS CNT1 and CNA7 were used in analyzing the CDMA2000 network measurement data for path loss calculations. The test phone was used to capture and collect the received power levels at the specified distances, and the collected signal strength were relayed to the laptop for displayed. The GPS was used to measure the transmitter to receiver (T-R) separation distances between the base station and the test phone. The experimental data were taken at distances ranging from 1km to 5km for the three radio paths. The measurement data such as the T-R separation distance in km, base station transmit power, mobile receiver (test phone) signal strength; antenna gains and the measured path loss in dBm are recorded in Table 2.

5. Results and Discussion

After determining the measured path losses for routes a, b, and c as shown in Table 2, radio path a is selected for comparative analysis with the path loss prediction model of Table 1. The numerical path loss for different path loss prediction models versus the practical measured path loss is shown in Table 3.

A more accurate comparative analysis for determining the best path loss prediction model for macrocellular environments is the use of the mean square error (MSE) approach. The MSE is the ratio of dispersion of measured path loss values and describes how good

Table 2: The collected measurements for CDMA2000 base station.

Radio path	T-R (km)	BS TX power (dBm)	MS Rx power (dBm)	BS Antenna gain (dBi)	MS Antenna gain (dBi)	Measured path loss (PL) (dBm)
a	1.00	40.00	-68.02	17.00	0.00	125.71
	2.00	40.00	-73.64	17.00	0.00	132.50
	3.00	40.00	-80.36	17.00	0.00	136.63
	4.00	40.00	-87.75	17.00	0.00	140.02
	5.00	40.00	-95.13	17.00	0.00	145.81
b	1.00	40.00	-66.58	17.00	0.00	124.30
	2.00	40.00	-74.13	17.00	0.00	130.25
	3.00	40.00	-80.92	17.00	0.00	136.24
	4.00	40.00	-86.00	17.00	0.00	141.00
	5.00	40.00	-94.25	17.00	0.00	147.02
c	1.00	40.00	-69.50	17.00	0.00	126.55
	2.00	40.00	-72.32	17.00	0.00	131.70
	3.00	40.00	-81.60	17.00	0.00	137.25
	4.00	40.00	-85.75	17.00	0.00	141.00
	5.00	40.00	-96.42	17.00	0.00	145.60

Table 3: Comparison of predicted path losses with the measured path losses.

Distance (km)	Free space model (dB)	Hata model (dB)	Egli model (dB)	Measured path loss (dB)
1.00	91.58	117.90	101.02	125.71
2.00	97.60	127.48	113.06	132.50
3.00	101.12	133.07	120.11	136.63
4.00	103.57	137.05	125.11	140.02
5.00	105.56	140.13	128.98	145.81

Table 4: MSE evaluations for Free space, Hata and Egli models.

d (km)	Free space model $(P_m - P_r)^2$	Hata model $(P_m - p_r)^2$	Egli model $(p_m - p_r)$
1.00	1164.86	61.00	609.60
2.00	1218.01	25.20	377.91
3.00	1260.96	12.67	272.91
4.00	1328.60	8.82	222.31
5.00	1620.06	32.26	283.25
	$\sum_{i=1}^{N}(p_m - p_r)^2 = 6592.49$	$\sum_{i=1}^{N}(p_m - p_r)^2 = 139.95$	$\sum_{i=1}^{N}(p_m - p_r)^2 = 1765.98$

the propagation model matches experimental data. It is commonly used to verify the accuracy of path loss models. The MSE according to [7, 16] is given by:

$$\mathrm{MSE} = \sqrt{\frac{1}{N}\sum_{I=1}^{N}(P_m - P_r)^2} \qquad (20)$$

where: P_m is the measured path loss (dB), P_r is the predicted path loss (dB), N is the number of measured data points.

Hence, the computed MSE for Free space path loss prediction model, Hata path loss prediction model, and Egli path loss prediction model are presented in Table 4.

$$\begin{aligned}\text{MSE (Free space model)} &= \sqrt{\textstyle\sum_{i=1}^{N}(P_m - P_r)^2/(N)} \\ &= \sqrt{6592.49/5} = 16.24\text{dB}\end{aligned}$$

$$\text{MSE (Hata model)} = \sqrt{139.95/5} = 2.37\text{dB}$$

$$\text{MSE (Egli model)} = \sqrt{1765.98/5} = 8.40\text{dB}$$

The mean square error analysis shows that Hata's path loss prediction model has the smallest MSE of 2.37dB. The Free space path loss prediction model and Egli's path loss prediction model have an MSE of 16.24dB and 8.40dB respectively.

6. Recommendation and Conclusion

6.1. Recommendation

The accuracy of the numerical path loss values for different path loss prediction models that were determined using hand calculation can be verified by using the online path loss calculators.

6.2. Conclusion

A comparative analysis of path loss prediction models for macrocellular urban environments is presented in this paper. The outdoor measurements were taken in Uyo urban, Nigeria in order to compare the practical path loss values with the measured path loss values. At the end of the comparative analysis using different path loss prediction models, Hata's model has the lowest MSE value of 2.37dB, which is an acceptable value since it is less than the minimum MSE value of 6dB for good signal propagation. Hence, the recommended path loss prediction model for urban path loss calculations in Nigeria is the Hata model. Telecommunication companies can improve their services by using the requisite Hata model in their link budget design and analysis.

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