On Propagation Path Loss Models For 3-G Based Wireless Networks: A Comparative Analysis

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Abstract

This paper studies comparatively, the most commonly used path loss models among others, for UMTS based cellular systems, with the goal of reporting through computer simulation, the most reliable one, suitable for efficient coverage planning. We experiment these path loss models using empirical data for macro-cellular (urban) environments. We observe that the Lee path loss model has an improved coverage performance compared to the COST-231 and ECC-33 path loss models respectively. The simulator could generically be adapted for other propagation environments.

Keywords: *UMTS, propagation path loss, macrocells, SIR*

1. INTRODUCTION

Third Generation (3G) wireless networks are based on the Universal Mobile Telecommunication System (UMTS) technology and are currently being installed in many countries with the aim of improving upon past technologies and fulfilling users' requirements. The current deployment of UMTS networks is not in many cases ubiquitous and is only concentrated in the congested urban business areas. They are used to provide either the special higher rate data services or increased capacity for handling the voice traffic in specific locations and are therefore complementary and supplemental to the GSM networks. The GSM networks are anticipated to stay around and even continue to grow and expand for at least the next half decade given the huge investments already made by the operators in the GSM infrastructure networks and their fine capability to handle voice, though not with the same spectral efficiency as the Wireless Code Division Multiple Access (WCDMA). This means that the island deployment of UMTS networks will be the trend for some time to come, and hence the requirement for the seamless roaming, handover, and inter-operation with the existing GSM networks to provide service coverage continuity and load sharing. Therefore, the elaborate interoperability and coordination mechanisms and features provided by the equipment need to be exploited by network planners to effectively result in the pooling of the resources, and hence produce the most efficient utilization of the limited expensive radio spectrums. The high throughput and capacity demand of the services anticipated for the 3G networks and the interference-limiting environment of the UMTS based systems require highly skilled radio planning practices and the use of spectral efficiency measures.

Signal propagation models are used extensively in network planning, particularly for conducting feasibility studies and performing initial system development [1]. The planning of cellular networks requires an understanding of basic concepts concerning the use of Radio signals. The path traveled by the signal from one point to another through or along a medium is called propagation [2]. In cellular networks, a signal is propagated to and from a base station. When a signal is transmitted through space, it gets weaker with the distance traveled, resulting in the received power being significantly less than the original transmitted power. This phenomenon is referred to as propagation loss. The propagation path between the transmitter and the receiver may vary from simple line-of-sight (LOS) to very complex one due to diffraction, reflecting and scattering, [3]. To estimate the performance of wireless channels, propagation models [4] are often used. The radio wave propagation or path loss models, the properties of the base station and the properties of the mobile station are required to calculate the radio coverage for a chosen base station. Path loss models represent a set of mathematical equations and algorithms which are applied for radio signal propagation prediction in certain environments. Path loss models describe the signal attenuation between a transmitting and a receiving antenna as a function of the propagation distance and other parameters which provide details of the terrain profile required to estimate the attenuating signal. This paper appraises a collection of path loss models through a comparative survey and simulates for each classification a generic case.

Due to the availability of several path loss models, it is therefore necessary to ascertain which of the most commonly used ones could be programmed for UMTS networks. The problem statement for this paper can therefore be expressed as follows:

(i) Which of the path loss models is best for UMTS Networks?
(ii) What limitations exist in these models?
(iii) How can these models be generically adapted?

2. PATH LOSS MODELS

Path loss is the difference (in dB) between the transmitted power and the received power. It represents the signal attenuation caused by free space propagation, reflection, diffraction and scattering [5]. Figure 1 illustrates the path loss between the transmitter and a receiver.

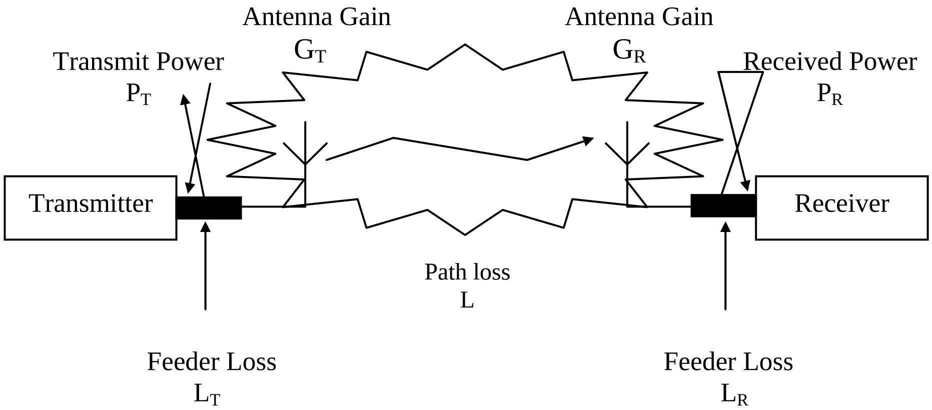

Figure 1. Path loss diagram

Though there exist various path loss models, the most commonly used ones include Free space model, COST-231 Hata model, Lee model and ECC-33 model

Free Space Model

The benchmark by which a loss in transmission is measured is the loss that would be expected in free space. In other words, the loss that would occur might absorb or reflect radiant energy [6]. This represents the ideal case which we hope to approach in our real world radio link. Calculating free space transmission loss requires a faithful representation of the transmitter and receiver characteristics [3].

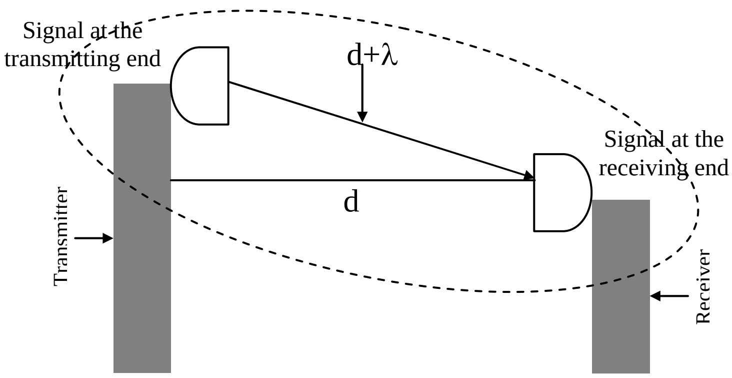

Figure 2. A Radio System Model

Consider a transmitter with power P_t coupled to an antenna which radiates equally in all directions as shown in figure 2. At a distance *d* from the transmitter, the radiated power is distributed over an area of $4\pi d^2$, so that the power flux density is

$$S = \frac{P_t}{4\pi d^2} \quad (1)$$

The transmission loss then depends on how much of this power is captured by the receiving antenna. If the captured area or effective aperture of the antenna is A_r, then the power which can be delivered to the receiver (assuming no mismatch or feeding losses) is simply

$$P_r = SA_r \quad (2)$$

For the hypothetical isotopic receiving antenna we have

$$A_r = \frac{\lambda^2}{4\pi} \quad (3)$$

where λ is the wavelength of the radio wave propagation. Combining equations (1) and (3) into (2), we have

$$P_r = P_t\left(\frac{\lambda}{4\pi}\right)^2 \quad (4)$$

The free space path loss between isotropic antennas is P_t/P_r. Since we are dealing with frequency rather than wavelength, we substitute C/f for λ (where *C* is the speed of light) to get

$$L_p = \left(\frac{4\pi}{C}\right)^2 f^2 d^2 \quad (5)$$

As a mobile user moves far away from the transmitter, the received local average signal strength (RLASS) gradually decreases. The signal strength can be predicted using the free space propagation model. The main advantage of this mode is that it takes implicitly into account, some important or main propagation factors such as frequency, distance and wavelength. It is computationally easy to implement for radio network planning purposes [7].

Free space model assumes that there is only one unobstructed LOS path between the transmitter and the receiver. However it rarely occurs in practice that the LOS is unobstructed, so that the estimation given by the model fails in most cases, [4].

The free space path loss equation is more usefully expressed logarithmically [3] as

$$P_L = (32.4 + 20\log F + 20\log d)dB \quad (6)$$

where

f = frequency in MHz
d = distance in km

This equation shows the relationship between the path loss, the frequency and distance of the transmission medium.

COST- 231 Hata model

Given the limitation of the Hata model to 1.5GHz and below, as well as the interest in personal communications systems operating near 1.9GHz, the "European cooperation in the field of scientist and technical research'' (COST) organization performed propagation measurements to extend the Hata model to 2GHz. This extended Hata model is applicable for frequencies from 1.5 to 2GHz, with other limitations identical to those of Hata model [8]. The COST-231 Hata model apart from being designed for frequency band covering 1.5 to 2GHz also contains corrections for urban, suburban and rural (flat) environments. Although its frequency range is outside that of the measurements, its simplicity and the availability of correction factors has seen it widely used for path loss prediction at this frequency band.

The basic equation for the path loss in dB [9] is

$$P_L = 46.3+33.9 \log_{10}(f)-13.82 \log_{10}(h_b) - ah_m + (44.9-6.55 \log_{10}(hb) \log_{10} d+C_m \quad (7)$$

where f is the frequency in MHz
d is the distance between AP and CPE antennas in km
h_b is the AP antenna height above ground level in meters (m)
The perimeter C_m is defined as $0\ dB$ for suburban or open environments and $3\ dB$ for urban environment. The perimeter ah_m is defined for urban environments as

$$ah_m = 3.20\ (\log_{10}(11.75hr))^2 - 4.97,\ for\ f > 400\ MHz \qquad (8)$$

and for suburban or rural (flat) environments:

$$ah_m = (1.1 \log_{10} f - 0.7)h_r - (1.56 \log_{10} f - 0.8). \qquad (9)$$

where h_r is the CPE antenna height above ground level.
Observation of (7) and (9) reveals that the path loss exponent of the prediction made by COST-231 is given by

$$^{n}COST = (44.9 - 6.55 \log_{10}(h_b))/10 \qquad (10)$$

To evaluate the applicability of the COST-231 model for the 3.5GHz band, the model predictions are compared against measurement for three different environment namely, rural (flat), suburban and urban. To show the COST-231 Hata model in a simpler form, the model (Ray, sxpt, 2007) is expressed as

$$P_L = L_0 + n\ \log f - 13.82 \log h_b - C_H + [\sigma - 6.55 \log h_b] \log d + c \qquad (11)$$

where

L = Median path loss in Decibel (dB)
f = Frequency of transmission, in megahertz (MHz)
h_b = Base station antenna height, in meters(m)
d = Link distance, in kilometer (km)
C_H = Mobile station antenna height correction factor

and

L_0 = 46.3
θ = 44.9
n = 33.9

$$C = \begin{cases} 0dB & for\ rural\ and\ suburban\ areas \\ 3dB & for\ urban\ areas \end{cases}$$

The Lee Model

The lee model has been widely used in the prediction of path loss in macrocell applications, particularly for systems operating near 900MHz and for ranges greater than 1.6km [10]. The Lee model specifies distinct parameters for varying region types. Lee model should not be expected to be accurate outside a relatively narrow range of frequencies near 900MHz.

The Lee model [10] is formally expressed mathematically as

$$P_L = L_0 + \delta \log d - 10 \log F_A \qquad (12)$$

where

P_L = the median path loss with units in decimal (db)
L_0 = the reference path loss along 1km; unit in db
δ = the slope of the path loss curve; unit in db
d = the distance on which the path loss is to be calculated; unit in meter (m)
F_A = The adjustment factor.

In a given location, the L_0 and δ parameters should be determined empirically through a set of measurements.

ECC – 33 Path Loss Model

The original Okumura experimental data were gathered in the suburbs of Tokyo [11]. The author refers to urban areas as subdivided into large city and medium city categories. Correction factors for suburban and open areas were also given. Since the characteristics of a highly built-up area such as Tokyo are quite different to those found in typical European suburban areas, use of the medium city model is recommended for European cities [12], [7]. Although the Hata Okumura model is widely used for UHF bands, its accuracy is questionable for higher frequencies [13]. The COST-231 model extended its use up to 2GHz but it was proposed for mobile systems having Omni-directional CPE antennas sited less than *3m* above ground level. A different approach was taken by the Electronic communication Committee (ECC) which extrapolated the original measurements by Okumura and modified its assumptions. The path loss equation for ECC-33 model [14] is defined as

$$P_L = A_{fs} + A_{bm} - G_b - G_r \tag{13}$$

where A_{fs}, A_{bm}, G_b *and* G_r are the free space attenuation, the basic median path loss, the *BS* height gain factor and the terminal (CPE) height gain factor. They are individually defined as

$$A_{fs} = 92.4 + 20log_{10}(d) + 20log_{10}(f)$$

$$A_{bm} = 20.41 + 9.83log_{10}(d) + 7.894log_{10}(f) + 9.56[log_{10}(f)]^2$$

$$G_b = log_{10}(h_b/200)\{13.958 + 5.8\,[log_{10}(d)]^2\}$$

and for medium city environments

$$G_r = [42.57 + 13.7log_{10}(f)]\,[log_{10}(h_r) - 0.585]$$

where *f* is the frequency in GHz
d is the distance between AP and CPE in km
h_b is the BS antenna height in meters
h_r is the CPE antenna height in meters

The medium city model is more appropriate for European cities whereas the large city environment should only be used for cities with tall buildings. It is interesting to note that the predictions produced by the ECC-33 model do not lie on straight lines when plotted against distance having a *log* scale. For the sake of completeness, the path loss gradient at *2km* will be compared with the path loss predicted by other models. The predictions using the ECC-33 model with the medium city option are compared with the measurements taken in suburban and urban environments.

3. SIMULATION MODEL

It is well known that the coverage of the cell has an inverse relationship with the user capacity of the cell [15]. An increase in the number of active users in the cell causes the total interference seen at the receiver to increase. This causes an increase in the power required to be received from the user which is due to the fact that each user has to maintain a certain signal-to-interference ratio (SIR) at the receiver for satisfactory performance. For a given maximum allowable transmission power, an increase in the required power reception will result in a decrease in the maximum distance a mobile can be from the base station thereby reducing the coverage. We consider an E_b/N_0 simulation-based model in a macro cellular environment [16] given by the equation:

$$S = \frac{\eta}{\dfrac{W/R}{E_b/I_0} - (N_s - 1)\alpha} \tag{14}$$

where *S* is received power

From equation (14), we can build the received power at the base station from user 1. This is given as

$$S = S_1 - P_L \tag{15}$$

where S_1 is the transmitted power and P_L is the path loss.

From equation (15), we obtain S_1, thus

$$S_1 = S + P_L \tag{16}$$

Since the characteristics of a mobile radio channel are directly influenced by the fluctuation of the received signals, each transmitted signal between the BS and MS through a radio channel experiences path loss, multi-path fading and shadowing. We can therefore express the received signal at the BS as

$$P_t = P_s + (P_L + z) \tag{17}$$

where P_t is the transmission power, P_L, the propagation loss and *z*, the loss due to shadow fading.

4. SIMULATION MODELS PROGRAMMING

The different path loss models are simulated in this paper. Having obtained, S_1, the transmitted power for a user (see equation 16), for CDMA systems, we now obtain through simulation, the path loss, P_L, for the different models. These path losses are substituted into equation (16) and the S_1 values for each model obtained through simulation. The simulation results are written to text files to enable easy access to the results. Results from the relationship in equation (16) are then plotted against distance, for each model, to help in the comparative analysis of the different path loss models.

The simulator has a Graphic User Interface (GUI) which acquires the simulation parameters for the different path loss models. Figure 3 shows the simulation data entries form. The form is made up of five sections. The first section accepts the *received power (S)*, a parameter required for all the simulations (see equation 16). The other sections acquire parameters for the different path loss models.

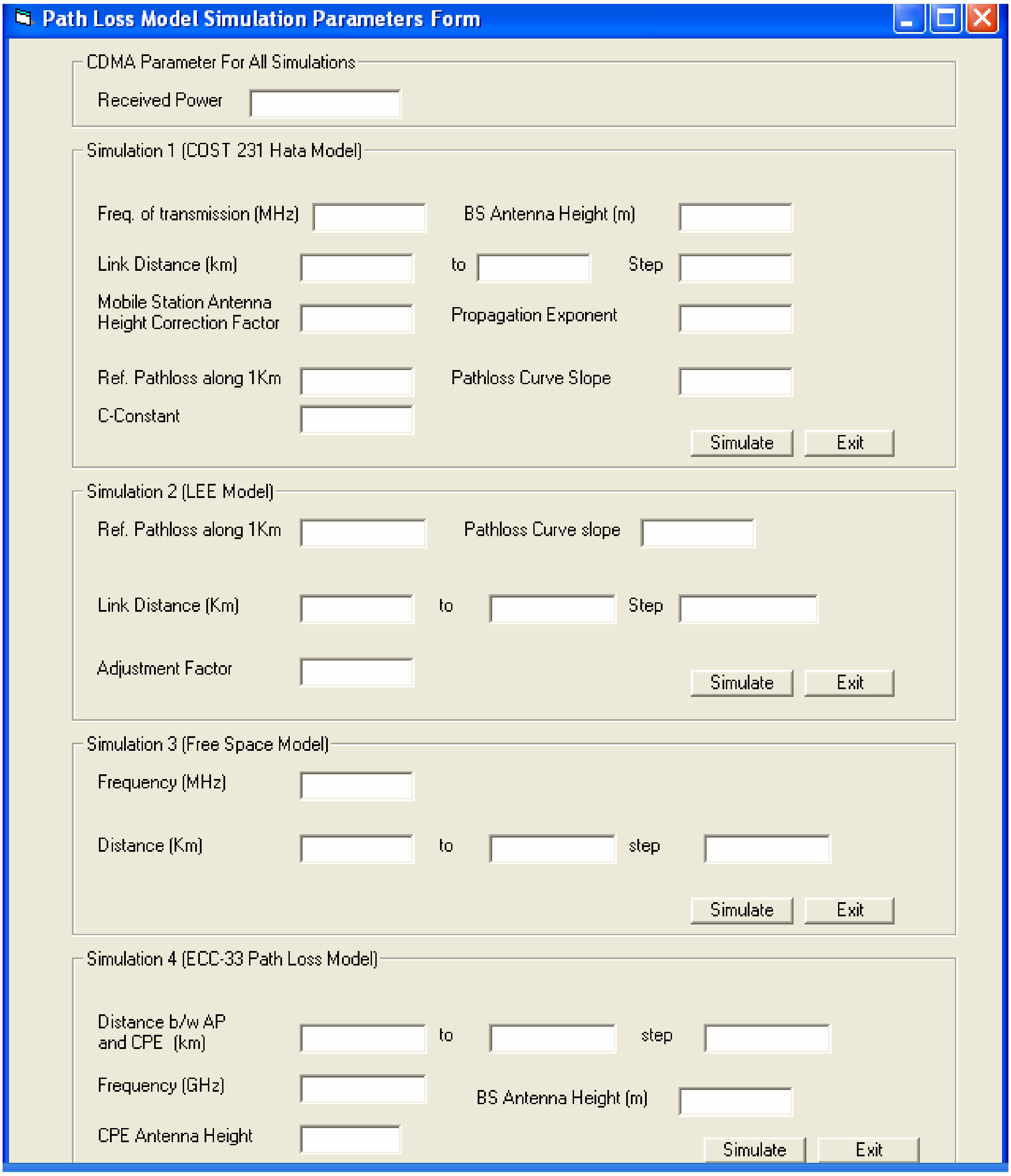

Figure 3. GUI form for Path Loss Models Simulation

5. SIMULATION RESULTS

There are three modeling paradigms [5], namely;

(i) Empirical models: based on measurement data, simple (uses few parameters), use statistical properties but are not very accurate

(ii) Semi-deterministic models: based on empirical models + deterministic aspects and

(iii) Deterministic models: site-specific, require enormous number of geometry information about the site the needs important computational effort and are accurate.

Empirical parameters for TIA/ELA Interim Standard-95 for spread spectrum cellular systems measured in [17], Islam, Abedin and Song (2006) were used in the study. These parameters were used to evaluate the path loss for the signal. The calculation is performed based on a Base Station System - ANDREW BTS antenna (Model no CTSD08-06156-0D). Below are the empirical values used for the simulation:

BTS transmitter power = 57dBm
BTS antenna height = 30m
Mobile antenna height = 1.5m
Link transmit frequency = 824 – 894MHz
BTS Receiver sensitivity = -121dBm
Path loss exponent (urban) = 3.5

Figures 4-7 shows the variation in path loss as the distance is varied. Prediction made by COST-231 Hata model is shown in figure 4, prediction made by Lee model in figure 5, prediction made by the Free space model in figure 6 and that of ECC-33 model in figure 7, respectively. As can be seen from these figures, the predictions of the various path loss models show a smooth and steady increasing predicted loss versus transmitting and receiving range (distance)/ kilometer (km). It is observed as expected by these models, except the free space path loss, that variations in the obstacles encountered on a specific path as distance is increased also gives rise to a variation in the path loss versus range. The reason for this performance is that in environments where many paths exist by which transmitted power can reach the receiver, interference among the multi-path receptions (which depend primarily on the phase relationship among these paths) will vary rapidly over distances.

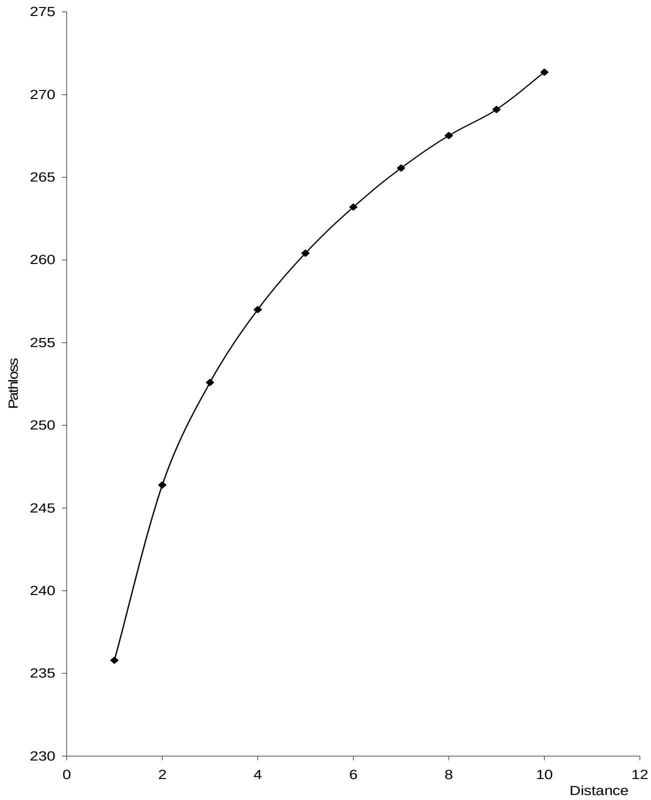

Figure 4. Plot of Path loss vs Distance for COST-231 Hata Model

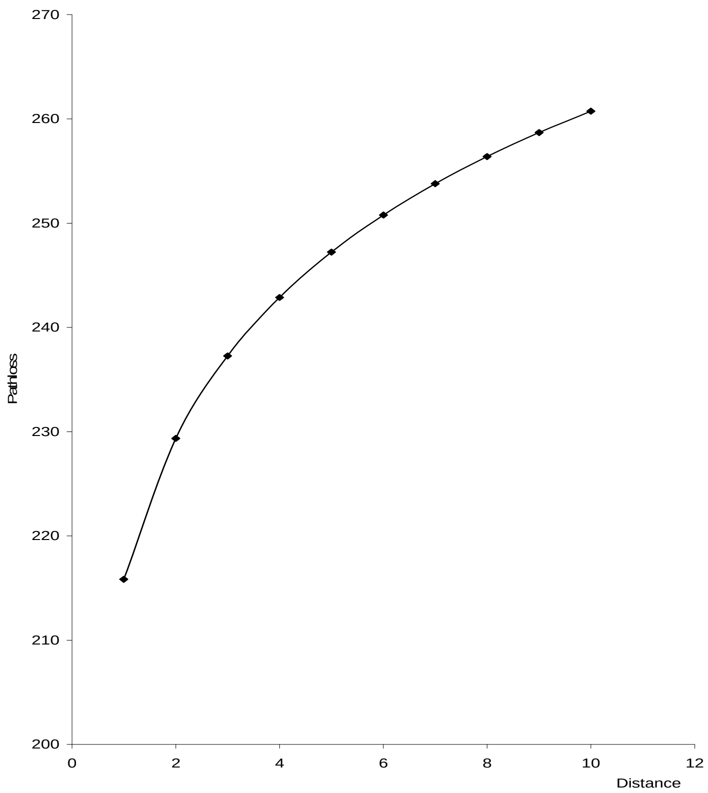

Figure 5. Plot of Path loss vs Distance for LEE Model

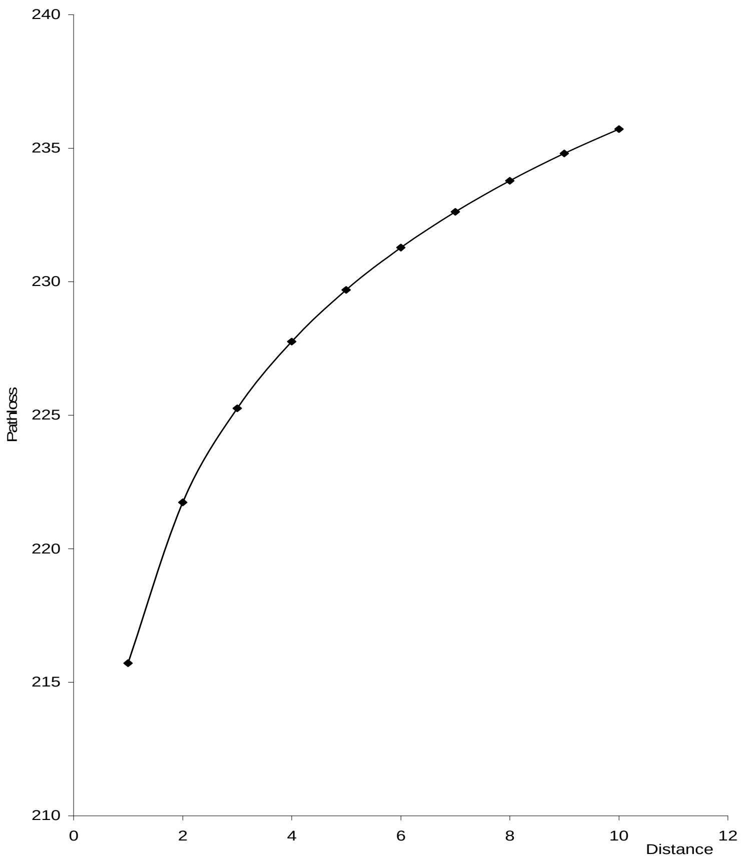

Figure 6. Plot of Path loss vs Distance for Free Space Model

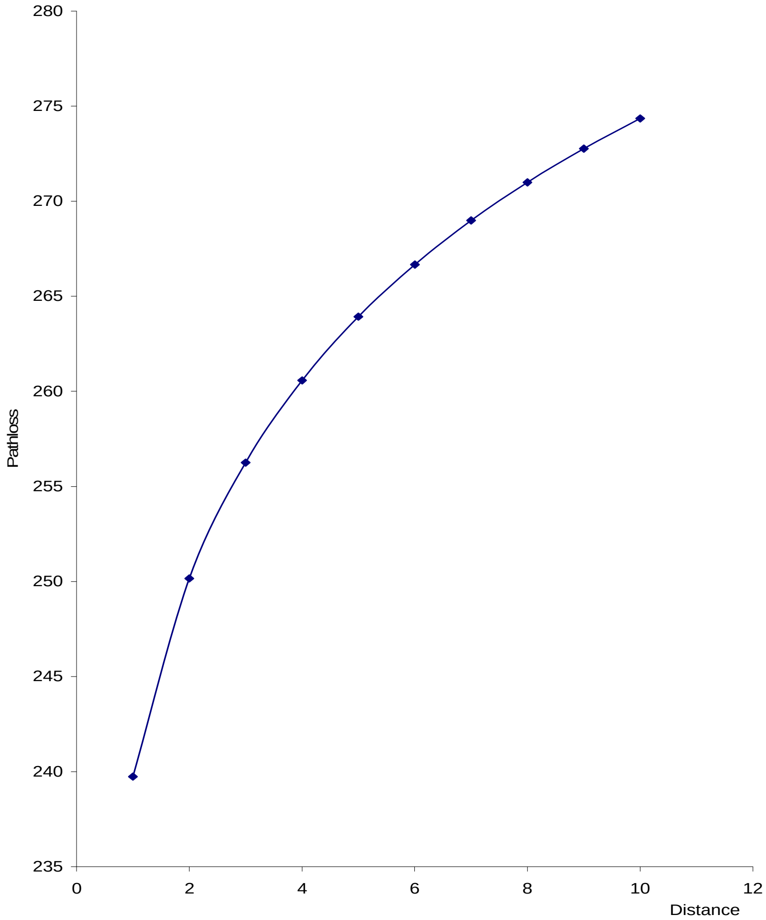

Figure 7. Plot of Path loss vs Distance for ECC-33 Model

A comparison of the path losses of COST-231 model, Lee model, and ECC-33 model with the Free space path loss model is shown in figure 8. The comparison is done to reflect a practical study of comparative performances. As observed in figure 8, the Lee model is closer to the free space model as compared to others. The ECC-33 model grossly over-predicts the path loss at higher distances. We concluded here that the best performance is given by the Lee model, particularly at farther distances. Therefore, in order to maximize the spectral efficiency of a cellular system, it is advisable to use the Lee model with appropriate factor as computed in the present study. We observe that all the models can be predicted using a logarithmic trend and therefore fit in the graph logarithmic trend equations to help predict new empirical results.

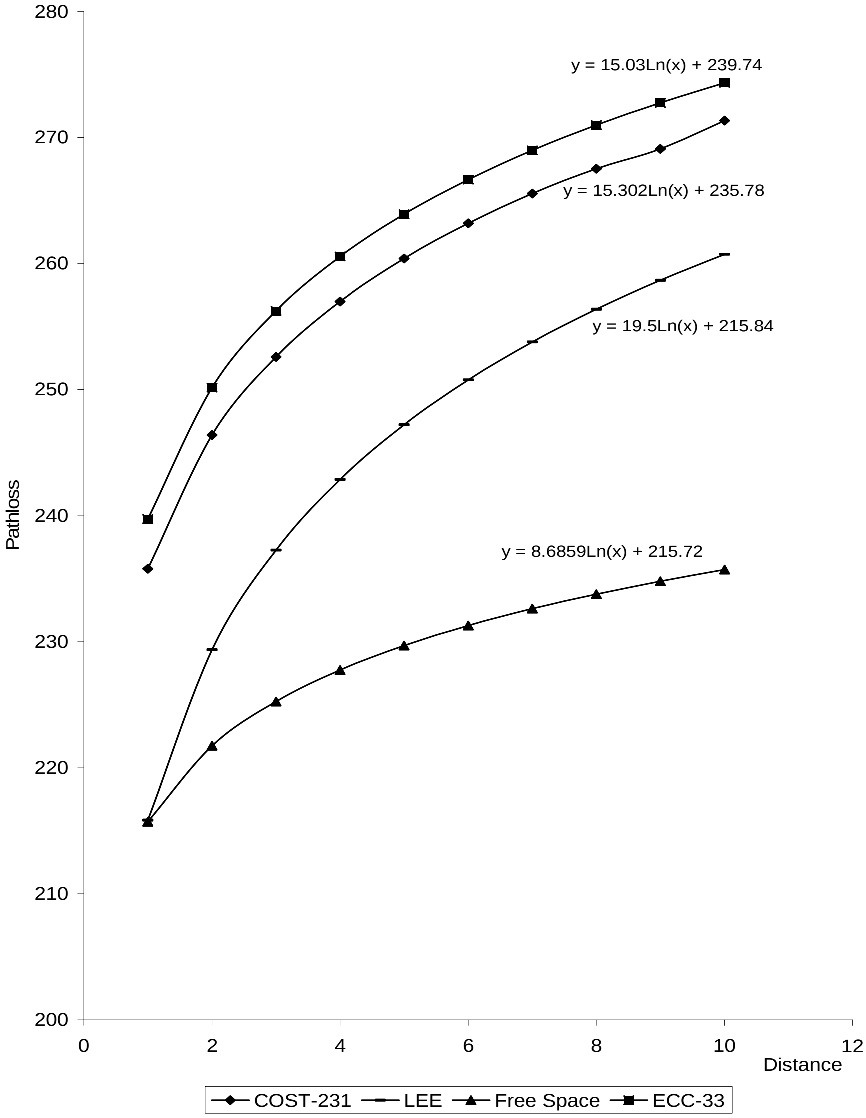

Figure 8. A Comparison Plot of all Models in the Study

6. CONCLUSION

Signal propagation models are used extensively in network planning, particularly for conducting feasibility studies and doing initial dimensioning. In this paper, an appraisal of commonly used path loss models was done. These models were adapted for UMTS network systems and simulated. The models selected for the simulation were the COST-231, Free space, Lee and ECC-33 path loss models. The simulation results were represented in the form of graphs and interpretations made. These interpretations clearly revealed the effect of path loss on UMTS wireless networks.

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