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*Original Article*

# Simple and Effective Electromagnetic Wave Propagation Loss Model in GSM Band for Smart Campus Applications

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***Abstract -*** *A simple and cost-effective empirical path loss model is crucial for mobile communication systems' link planning, optimization, and budgeting. Although numerous path loss models have been developed in the literature, many are complex and difficult to apply, highlighting the need for a more straightforward and economical solution. This paper presents the mathematical characterization of a Global System for Mobile communications (GSM) path loss dataset obtained from Covenant University in Ota, Nigeria. The developed empirical propagation model employs a step-wise curve fitting to the path loss data. The results show that the mathematical model agrees quite well with the measured data. The mathematical expression is also straightforward, easy to use, and suitable for GSM signal loss calculations, requiring minimal input parameters. In conclusion, the analysis results are promising and suggest that the proposed model is well suited for practical deployment in smart campus interconnectivity designs, optimization, and similar applications.*

***Keywords -*** *Electromagnetic wave propagation, Empirical model, GSM, Curve fitting, Propagation loss model.*

## 1. Introduction

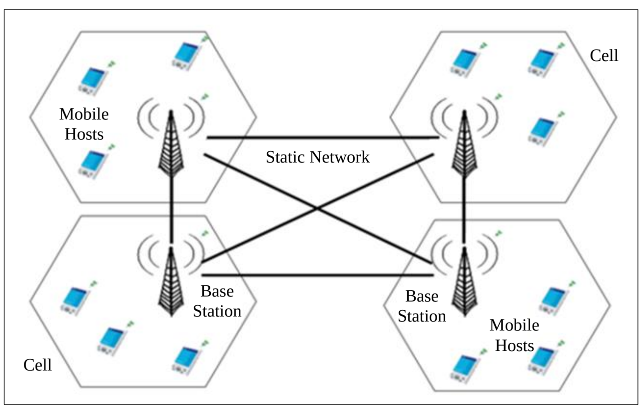
The Knowledge of the characteristics of radio waves in various propagation situations is essential for efficient network design and wireless communication system deployment [1-5]. Electro Magnetic (EM) wave strength and direction in a wireless channel are typically stochastic and unpredictable [2]. A comprehensive understanding of the channel phenomenon is crucial to ensuring good Quality of Service (QoS) and achieving high data transmission rates in radio access networks.

In cellular communication (see Figure 1), the propagation of EM waves over the air is seriously impacted by the conditions of the channel. The EM waves transmitted over the air can be affected by factors such as the contours of the Earth, obstacles, reflection, diffraction, scattering, and varying distances. These factors can obstruct EM wave transmission, causing attenuation or loss of power along the channel, generally called path loss.

The physical components of the propagation environment affect the effectiveness of a wireless communication system. The straight Line-of-Sight (LOS) for radio signal transmission is frequently obstructed in a real situation by structures, mountains, billboards, vegetation, cars, and other physical objects. Therefore, in Non-Line-of-Sight (NLOS) situations, sent radio signals usually arrive at their target receivers via various propagation methods. Transmitted electromagnetic waves undergo refraction when they move from one material with a different refractive index to another [3]. When big objects block the transmission channel, diffraction causes the radio wave to bend. When a radio signal hits an object whose dimensions are enormous relative to the signal's wavelength, like metallic surfaces on window frames or building rooftops, reflection occurs [5]. When an item is substantially smaller than the radio signal's wavelength, scattering causes the electromagnetic waves to scatter in various directions. Precipitation (hail, snow, rain, drizzle, sleet), suspensions (mist, fog), and dust particles can all result in scattering. Scattering is caused by suspensions (mist, fog), dust particles, and precipitation (hail, snow, rain, drizzle, sleet). Furthermore, radio waves can be absorbed through dense surfaces such as flooring, walls, plants, or trees.

Multipath propagation is a phenomenon that occurs in real-world urban propagation environments when multiple copies of a broadcast radio wave reach the receiver by distinct propagation mechanisms. This phenomenon causes signal fading at the receiver [3, 6-8]. Small-scale fading is the term used to describe the situation where the received signal strength rapidly varies over a brief period of time while the distance stays relatively constant [4]. On the other hand, large-scale fading also referred to as path loss occurs when the average received signal strength dramatically drops as the distance grows [7, 9–14]. Several propagation models have been created to calculate route loss in different conditions. Radio network engineers use these models to estimate radio coverage effectively, choose the best site for base stations, assign frequencies wisely, choose the best antenna, and conduct feasibility studies about interference.

**(a)**




**(b)**

**Fig. 1 A typical cellular network (a) Network nvironment [3], and (b) Network architecture.**

Conventionally, radio propagation models, according to the literature, are typically categorized as deterministic, semi-deterministic, or empirical. If the mathematical formulas for a path loss model are derived from theoretical physics rules and principles, the model is said to be deterministic. Virtual simulation tools have been created [15] to use deterministic models for precise path loss predictions. These techniques are effective within their limitations and do not require a thorough understanding of the propagation environment. Deterministic models, however, may not always ensure precise predictions, particularly in the presence of site-specific information regarding the propagation terrain.

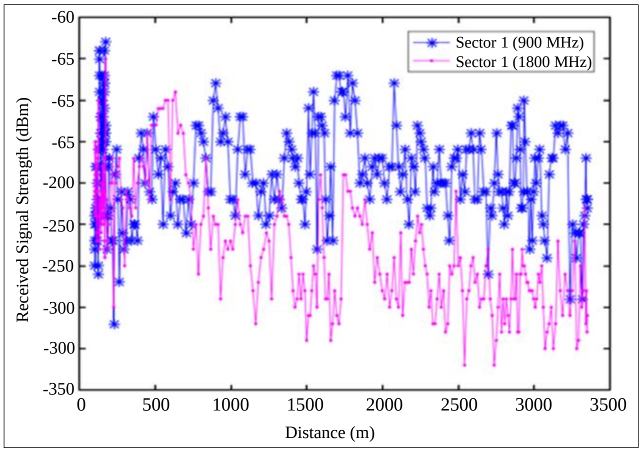
Deterministic models have a number of significant drawbacks, including computational complexity due to their requirement for large amounts of specific input data that may be difficult to collect. In contrast, measurement-based models, e.g. the Hata algorithm [5] and COST 231 algorithm [6], need fewer computational resources and are easier to use. However, their accuracy of prediction may not match that of deterministic models. Additionally, most measurement-based models do not adequately incorporate the effect of environmental factors on signal propagation, aside from distance and network parameters like transmission frequency and antenna heights [7]. These models' efficacy has been evaluated in various settings and frequency ranges.

Research has shown that existing models often exhibit significant prediction errors, particularly when used in environments different from those for which they were originally designed [4]. This highlights the need for ongoing assessment of these models' accuracy and the development more reliable approaches to enhance prediction precision. In a study by Popoola et al. [1], a measurement campaign was conducted to assess the received signal strength over a specific distance at Covenant University, Ota, Nigeria. However, the data from [1] has not been modeled for practical use by network and cellular communication engineers, emphasizing the need for mathematical characterising the dataset. Consequently, this paper presents the mathematical characterization of a GSM path loss dataset from Covenant University in Ota, Nigeria. The developed empirical propagation model utilizes a step-wise curve fitting to the path loss data and can be applied in the planning, designing, and optimising of cellular networks.

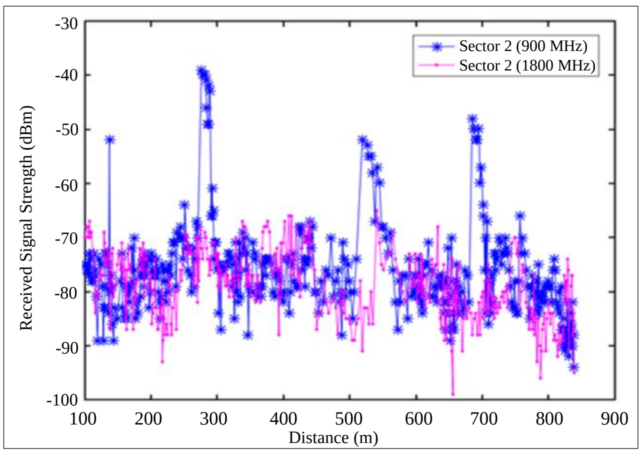
## 2. Materials and Methods

The variation of signal intensity concerning distance for both 900 MHz and 1800 MHz curves varies, implying that the EM wave variation depends on frequency. The distance considered for the signal strength measurement is 0 to 3.5 km for both 900 and 1800 MHz bands [1]. Furthermore, the next step is reading and studying curves to acquire the field strength data. The data is plotted and tabularized by Popoola et al. in [1] (see Figure 2). The terrain map of the measurement location is shown in Figure 3. The study area is situated at the $6^{0}29'15.22''\ N,\ 3^{0}08'07.15''\ E$. The area comprises open spaces, sporadic buildings, and rural vegetation. These measurements were obtained from a commercial base station on the Nigerian Lagos-Badagry Highway, operating at 900 and 1800 MHz over three separate routes. The graphs are functions of the Effective Radiated Power (ERP). Equation (1) transposes the power into the Effective Isotropic Radiated Power (EIRP), and the magnitude of the antenna's power gain is about 2.2 dB.

$$P_{t\ (dBW\ EIRP)} = P_{T\ \ (dBW\ \frac{ERP}{dipole})} + 2.2\ (dB) \qquad (1)$$




**(a)**

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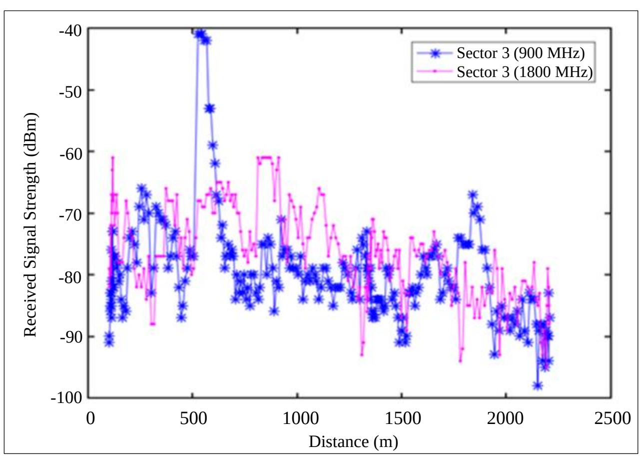


**(c)**

**Fig. 2 Signal strength profile against distance (a) Route 1, (b) Route 2, and (c) Route 3 [1].**

Where, $P_T = 10\log_{10}(1KW)\ dB$ is the computed power. As per reference [2], when the effective power transmitted is $P_t$ and the signal strength received ($E$) is measured in dBμV/m.

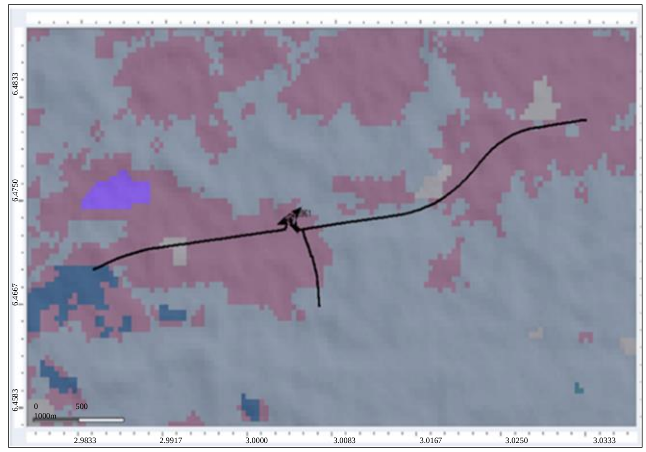

**Fig. 3 Digital terrain map where the drive test was conducted [1]**

These values can be converted to losses of propagation by,

$$L_p = P_T - \underbrace{[E + 20\log_{10}(\lambda G_i) - 156.76]}_{\text{Received Power } (P_r)} \quad (2)$$

Where $G_i$ is the antenna gain (isotropic) ratio. With the assumption that the antenna gain is zero, $G_i$ becomes one. $\lambda$ is the wavelength of the signal in meters, and $P_t$ is the received power with an isotropic feature. The mean of the wavelengths corresponding to the 900 and 1800 MHz are employed to compute the loss accordingly. It is equally good to note that in losses, the maximum and minimum wavelengths based on $20\log_{10}(\lambda)$ gives approximately 4.7 and 2.6 dB approximate for the corresponding 900 and 1800 MHz frequencies, while the $G_i$ is taken as one. Thus, for the equivalent 900 and 1800 MHz curves, the wavelength causes a total inaccuracy of 1.3 and 2.37 dB. The 900 and 1800 MHz mean wavelengths are 0.52 and 1.57 m, respectively. As such, the received power is computed, and the propagation loss is observed by its subtraction from the power received $P_T$.

### *2.1. Formulation of Propagation Loss*

This paper aims to mathematically model various variation loss curves observed via Equation (2). The propagation loss model should add the distance as a parameter. The log-distance model [2] has been developed to model path loss because the loss changes logarithmically per distance. Several models were evaluated using the Matlab curve fitting tool, and the models with the lowest error were compared to the data-based propagation loss changes per distance. The coefficient of determination ($R^2$) and Root Mean Square Error (RMSE) metrics weigh the expression findings. At the fixed base station height, the adjusted log-distance expression in Equation (3) agrees quite well with different curves for distances between 1.5 and 3.5 km.

$$L_p = G + \rho_1 d + \rho_2 \log_{10}(d) \quad (3)$$

Where, $G$ denotes the assumed constant, $\rho_1$ and $\rho_2$ are the coefficients of the expression, while $d$ denotes the distance observed in km.

### *2.2. 900 MHz Curve's Coefficient*

Here, the mean of $G$ is employed to ensure easy computation. Fixing G at 82 dB, the data is fitted using different spacings to obtain $\rho_1$ and $\rho_2$ using Equation (3). As such, the values of $\rho_1$ and $\rho_2$ have been computed at various spacing. Ensuring the model depends on the height of the antenna, $\rho_1$ and $\rho_2$ are examined with antenna height. Based on the literature, a log-based model and polynomial are considered. Based on [3], the power law algorithm derived from Equations (5) and (6) offer a significant fit for the fluctuations in coefficients with respect to the height of the antenna. We then selected the standard fit function given by Equations (5) and (6). Employing the Matlab toolbox responsible for curve fitting, a non-linear least squares (nLS) regression is performed using the data coefficient. Since nLS minimizes the added squared of the residuals [4], the problem of nLS is thus given as follows,

$$\lim_{\vec{\alpha}} \sum_{i=1}^{n} (y_i - F(x_i, \vec{\alpha}))^2 \quad (4)$$

Where $y_i$ denotes the response obtained. The fitted response is represented by $F(y_i, \vec{\alpha})$, the real and anticipated response difference is represented by $x_i$, and the unknown vector parameter is indicated by $\vec{\alpha}$. The curves and their corrected R-square values for correctness of fit are shown in Table 1. The correctness of curve fitting (adjusted *R-square*) values is depicted in Table 1. The values of $a, x, y, b, and\ u$ are in the nLS regression analysis using the Trust region approach. Table 2 displays the parameters' values with a confidence interval (CI) of 95%.

$$\rho_1 fit = \frac{x}{h^a} + y \quad (5)$$

Where $y$ stands for the constant for a specific curve relationship, the coefficient is represented by $x$, and $a$ for the rate of change of $\rho_1$ versus the antenna height ($h$).

$$\rho_2 fit = \frac{u}{h^b} \quad (6)$$

Where $u$ represents the coefficient, $b$ is the rate of change of $\rho_2$ against the antenna height ($h$).

### *2.3. 1800 MHz Curve's Coefficient*

Here, $G$ is approximately put at 92 dB to ensure a reduction in the complexity of the curve fits. $\rho_1$ and $\rho_2$ are recomputed using the same method as the 900 MHz curve. The changes of $\rho_1$ and $\rho_2$ against the antenna height is modelled mathematically as Equations (5) and (6) were employed in the case of 900 MHz, with modifications in the coefficient parameters. Technically speaking, it is accurate to state that the fit for the matching curve shows a discernible shift in the coefficients ($\rho_1$ and $\rho_2$) as antenna height increases. Modeling the loss, $\rho_1 fit = \rho_1$ and $\rho_2 fit = \rho_2$. After the computation of the $\rho_1 fit$ and $\rho_2 fit$ for the corresponding band, the loss expression is given as in Equation (3).

## 3. Proposed Propagation Loss Model and Analysis

This section presents the developed model for both the 900 and 1800 MHz bands by the substitution of the values of $\rho_1$ and $\rho_2$ into Equation (3). The individual value of $G$, $\rho_1$ and$\rho_2$ are computed as given in Section 2.1.

$$L_p = G + \underbrace{\left(\frac{x}{h^a} + y\right)}_{\rho_1} d + \underbrace{\left(\frac{u}{h^b}\right)}_{\rho_2} \log_{10}(d) \quad (7)$$

**Table 1. The adjusted R-square value for $\rho_1$ and $\rho_2$ fit**

| | 900 MHz | | 1800 MHz | |
|---|---|---|---|---|
| | $\rho_1 fit$ | $\rho_2 fit$ | $\rho_1 fit$ | $\rho_2 fit$ |
| Adjusted R-Square | 0.9987 | 0.9998 | 0.9994 | 0.9959 |

**Table 2. Associated values of parameter with $\rho_1$ and $\rho_2$ coefficient**

| | | 900 MHz | CI | | 1800 MHz | CI | |
|---|---|---|---|---|---|---|---|
| $\rho_1$ | $x$ | -5.210 | | | -2.717 | | |
| | $y$ | 0.461 | 0.451 | 0.471 | 0.741 | 0.723 | 0.777 |
| | $a$ | 0.787 | 0.775 | 0.799 | 0.433 | 0.419 | 0.447 |
| $\rho_2$ | $u$ | 126.4 | | | 143.1 | | |
| | $b$ | 0.345 | 0.344 | 0.345 | 0.355 | 0.355 | 0.351 |

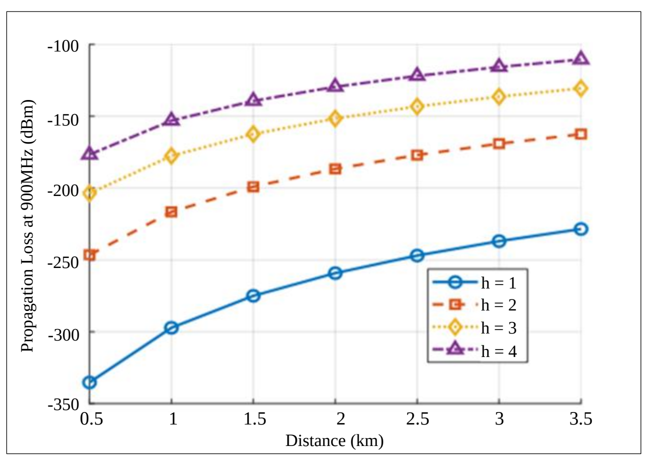


**Fig. 4 Prediction of propagation loss model versus distance at different mobile antenna heights for 900 MHz band (Equation 8)**

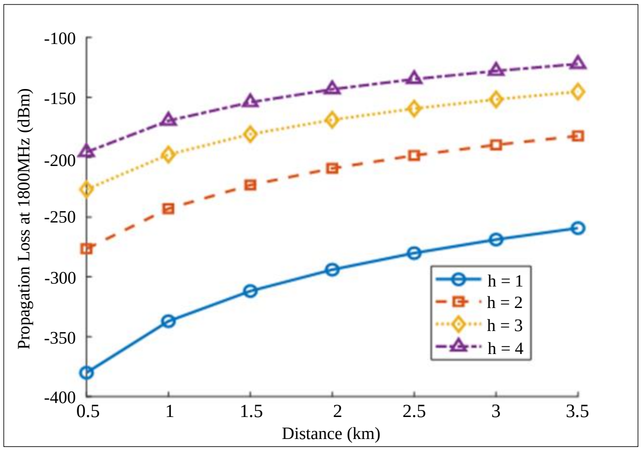


**Fig. 5 Prediction of propagation loss model versus distance at different mobile antenna heights for 1800 MHz band (Equation 9)**

Using Equation (7), the value of $G$ is 82 dB and 92 dB for 900 MHz and 1800 MHz bands, respectively. The parameter of $\rho_1$ and $\rho_2$ for the two bands are presented in Table 2. Hence, for 900 MHz, we have,

$$L_{p\ 900\ MHz} = 82 + \underbrace{0.460\left(1 - \frac{11.62}{h^{0.787}}\right)}_{\rho 1} d + \underbrace{\left(\frac{126.4}{h^{0.345}}\right)}_{\rho 2} \log_{10}(d) \quad (8)$$

In the same vein, the model for the 1800 MHz band is,

$$L_{p\ 1800\ MHz} = 92 + \underbrace{0.742\left(1 - \frac{3.768}{h^{0.433}}\right)}_{\rho 1} d + \underbrace{\left(\frac{143}{h^{0.357}}\right)}_{\rho 2} \log_{10}(d) \quad (9)$$

Therefore, Equation (8) $L_{p\ 900\ MHz}$ and Equation (9) $L_{p\ 1800\ MHz}$ are the developed propagation loss models for the 900 MHz and 1800 MHz bands. The models are empirical loss models based on the Covenant University, Ota, Nigeria data. The model obeys the terrain profile of the region in the southwestern part of Nigeria. The step-wise curve fitting of the data is used to create the model to develop a simple and easy-to-use propagation loss model applicable for 900 MHz and 1800 MHz. It also covers the distance between 0 to 3.5 km between the base station and the mobile station. Figures 4 and 5 provide the prediction of the developed model and give accurate knowledge of the radio wave propagation needed to plan, design, and optimize the radio network effectively. The propagation loss keeps increasing as the mobile station becomes farther from the base station. The current trend in machine-to-machine communication technologies and the internet of Things requires more smart devices and sensors to interconnect. Conversely, the capability of the current networks may be insufficient to meet the high demands of future mobile networks. One solution is to increase the cellular network's capacity by deploying base stations in the area. More base stations should be deployed to guarantee signal quality at all points within the coverage area.

## 4. Conclusion

In conclusion, an empirical propagation loss model at GSM frequencies (900 MHz and 1800 MHz) with a particular reference to the signal strength measurement campaign conducted in the Covenant University campus in Ota, Nigeria, has been proposed. In addition, the step-wise curve fitting applies not only to the developed approach but also to other domains with comparable or related data patterns. To estimate the change in the propagation loss with the mobile antenna height and draw conclusions based on science, a sizable number of data on the EM signal loss fluctuation with the height of the mobile antenna is needed. In the future, the developed mathematical expression can be extended to other frequency bands. The results may spur new development of mobile network planning, budgetary, design, and optimization in wireless communication.

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