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ARTICLE

Assessment of Empirical Models and the Impact of Atmospheric Parameters over GSM Channels in Zaria City, Nigeria

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ABSTRACT

This study evaluates the accuracy of empirical path loss models and examines the influence of atmospheric parameters on 2G and 3G GSM channels for MTN and 9-Mobile networks in Zaria City, Nigeria. The Root Mean Square Error (RMSE) values of four models COST-231, ECC-33, Plane Earth, and Ericsson were analyzed to determine model effectiveness in predicting path loss. Findings reveal that the Ericsson model is most accurate for 2G networks, making it ideal for network planning and optimization, while the COST-231 model performs best for 3G networks, underscoring the importance of selecting models suited to the specific network generation. In addition, the study investigates correlations between path loss and environmental factors, including Line of Sight (LOS), Received Signal Strength (RSS), temperature, humidity, elevation, and pressure. Results indicate a strong negative correlation between path loss and both RSS and pressure, and a strong positive correlation between path loss and both LOS and temperature, while humidity and elevation show moderate and weaker correlations with path loss, respectively. These findings emphasize the significant role of environmental parameters in signal propagation and highlight their critical importance in accurate path loss prediction and effective network planning in urban areas like Zaria City. This study provides a comprehensive reference for future network optimization efforts, offering insights into model selection and environmental considerations essential for enhancing GSM network performance in similar urban environments.

Keywords: Path Loss Models; GSM Channels; Zaria City; Nigeria; RMSE; Network Planning

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1. Introduction

According to Oseni, O.F., wireless communication has grown astronomically in terms of technology and data utilization [1]. The volume of data used on the internet is growing and is predicted to do so over the next few years. Since there is a growing and more diverse demand for services and service delivery, capacity and quality requirements are becoming necessities [2]. Thus, precise route loss planning is necessary for dependable and highly efficient wireless network design [3].

Path loss is the attenuation brought on by radio propagation, which includes antenna height, ground operation, TX-to-RX distance, and frequency. In addition, losses of empty space, diffraction, reflection, refraction, and others cause the path loss [4]. A signal from the transmitter antenna will experience multipath fading to the receiving antenna, which can cause constructive or destructive signals. Path loss is one of the most important factors in link budget analysis or wireless network planning [5].

Propagation modeling is one of the most important aspects of mobile wireless network planning. Various environmental conditions cause a different path loss resulting from radio wave propagation [6]. Accurate path loss modeling will be useful for planning, designing and implementation of telecommunications networks and for analyzing network coverage [1]. Common propagation models used by network engineers include Okumura, Hata, COST-231, COST-231-Hata, the ECC model, and the Ericsson model.

However, current propagation models often lack accuracy due to variations in environmental, terrain, and climatic conditions [7], and no single model is universally applicable to all regions. Selecting an appropriate propagation model for a specific area is challenging and depends heavily on the terrain characteristics of the location [2].

The signal strength between the mobile station and the base station is critical in the design of a cellular system. A base station is defined as one that produces enough signals to allow a mobile station to operate within its coverage area [8]. The route loss is a critical component of any propagation environment. Correct calculation of propagation losses can allow for correct selection of base station sites as well as precise frequency plan development. The propagation characteristic losses may be used to efficiently identify the field strength, interference and signal-to-noise ratio [9]. The growth of mobile cellular network has witnessed a lot of development leading to a high level of reliability [10].

In economic terms, resources such as signal strength and coverage are narrow, while the environmental factors such as temperature, pressure, and humidity act as external forces that impact the efficiency and availability of these resources. Similar to how supply and demand govern resource allocation in economics, variations in environmental conditions affect the supply of reliable signal propagation, leading to increased attenuation or losses. For instance, higher humidity and temperature can significantly increase signal absorption and reduce signal strength, equivalent to rising costs in an economic model that reduce resource efficiency. Thus, understanding these factors is essential for optimizing network resources and ensuring efficient service delivery [11]. One of the primary issues of both network users and network operators is the capacity of mobile networks to establish and maintain calls. Before reaching the mobile station, the transmitted signal passes through the atmosphere, encountering atmospheric variables such as temperature, pressure, and humidity, as well as ambient influences. Because of these air elements and ambient conditions, the signal experienced distortion and attenuation of signal strength, as well as path loss. Furthermore, signal fluctuation and distortion vary with distance [12].

In view of all the mentioned issues, this research work will focuses to study and to evaluate some selected empirical models which include COST-231, ECC-33, Plane earth and Ericsson models as well as the variation in received signal strength with respect to four major atmospheric parameters i.e. varying temperature, relative humidity and pressure [13].

1.1. Review of Related Literature and Basic Theory

Path loss models are critical tools in wireless communication, particularly in planning and optimizing cellular networks. Evaluating the accuracy of these models in specific environments helps in predicting signal coverage and quality, ensuring efficient network deployment. The literature on path loss models is extensive, with various empirical models being applied and validated across different geographical regions and frequencies. This review examines the performance of widely used empirical path loss models, particularly in urban environments, and their application to GSM networks [14]. Several studies have conducted comparative analyses of path loss models in various Nigerian cities, with a focus on evaluating their accuracy in predicting GSM signal behavior in urban environments.

A. Obot performed a comparative study on path loss models across different Nigerian cities, including Zaria, and concluded that the Ericsson model was the most accurate in predicting actual measured data, particularly in densely populated urban areas [15]. Similarly , conducted an analysis of RMSE values for different path loss models in urban and suburban settings, finding that the Ericsson model had the lowest RMSE values, confirming its suitability for urban GSM networks [16].

Nwoye, O.U. underscored the importance of accurate path loss modeling for effective GSM network planning in Nigerian cities [17]. Their study emphasized that models such as the Ericsson and ECC-33, when adjusted for local environmental conditions, can be highly effective in this context. Ayegba, A. investigated the performance of various path loss models in Abuja's urban environment and reported that while the ECC-33 model tended to overestimate path loss, the Ericsson model consistently provided the most accurate predictions across various terrains [18]. In another study, Aliyu, A.S. assessed the accuracy of multiple path loss models, including COST-231, ECC-33, and Ericsson, over GSM channels in Zaria [19]. Their findings revealed that the Ericsson model consistently exhibited the lowest RMSE values, indicating a better match with actual measurements compared to other models. Usman, A.U. highlighted a significant element in this research, stating that while atmospheric characteristics play a vital impact in signal intensity, the network is also affected by location and weather conditions [20]. They discovered that temperature has a negative relationship with the refractive gradient, but humidity has a positive relationship.

Sadiq, M.H. studied the path loss and impact of environmental factors such as temperature, humidity, and rainfall on GSM signal strength in Zaria [21]. The researchers collected signal strength data over various seasons, especially focusing on the dry season, and analyzed how these factors influenced path loss and signal attenuation. The results demonstrated that temperature and humidity variations had a significant impact on signal quality, with higher humidity leading to increased signal attenuation, especially in the dry season.

Finally, Dib, N. evaluated path loss models in urban areas and confirmed that the Ericsson model outperformed other models in terms of accuracy when validated against field measurements, reinforcing the importance of selecting appropriate models for optimizing network performance [22].

Another team of researchers has worked on path loss prediction which is of vital importance in GSM network design, planning, location of BTS, coverage area, frequency assignment and interference for effective cellular networks aimed at achieving effective signal values and levels between a transceiver and a mobile device. For example, Akinbolati, A. in their assessment of error bounds for path loss prediction models for TV white space usage in Ekiti State, Nigeria discovered that no single model gives an accurate prediction consistently based on the evaluation metrics [23]. However, according to their research the Electronic Communication Committee (ECC) 33 model provides better values for the overall metrics considered with RMSE values of 8.48 dB and 9.62 dB (between predicted and measured values) for Ekiti Suburban and Urban routes respectively.

Another research conducted by Akinbolati, A. revealed that path loss increases with an increase in transreceiver distances, however path losses were higher during wet compared to dry season's month [24]. The overall findings of this work will be useful for the accurate prediction of path losses (Okumura-Hata model and its choice for assessing path losses in this study) and the design of power budgets and links over digital terrestrial television and similar wireless channels on the UHF band [25].

According to Akinbolati, A., it was observed that path losses were higher during wet than dry season months [26]. The overall finding is useful for power budgeting that will enhance the quality of service of DTTV signal over Kano city using a statistical model (Okumura Hata model).

From the literature review, it was discovered that much of research work has already been done to identify the effect of atmospheric parameters on received signal strength (RSS) of wireless communication technologies and many path loss models have also been proposed but the main gap which was found in the research is that no one yet has optimized the received signal strength (for LTE, 2G and 3G technologies) with respect to the atmospheric variations. So keeping this aspect in mind this research work will focus on multi-objective optimization of the received signal strength for 2G and 3G with respect to varying input parameters.

The reviewed literature demonstrates that path loss and tropospheric variables play a crucial role in determining GSM signal propagation. Models like COST-231, ECC-33, and the Ericsson model are widely applied to predict path loss over different terrains, with environmental factors such as temperature, humidity, and precipitation further influencing signal quality in urban settings like Zaria City. Understanding these interactions is vital for efficient GSM network planning, optimization and ensuring reliable communication services in cities with varying climatic and geographical conditions.

1.2. The Concept of GSM Network Quality

GSM (Global System for Mobile Communications) network quality refers to the network's overall ability to provide its users with dependable and efficient voice and data services. Several important elements influence GSM network quality, including signal strength, voice quality, call success rate, data speed, and network coverage. These parameters are impacted by a variety of technological, environmental, and service-related variables [27]. It is a first step toward the digitalization era, in which operating this phone requires a network connection.

Because it is designed to give the user with as much mobility as possible, the number of mobile users is rapidly expanding. These networks can run into problems when the signal strength is affected by environmental factors. These atmospheric diversions might include changes in temperature, humidity, wind speed, and many other factors [12].

1.3. Factors that Affect Signal Strength Propagation

The major factors that affect the signal strength at any location are: the receiver antenna, the transmitter location, the height of the transmitter, the power of the transmitting base station, the carrier frequency and the topography of the terrain between the transmitter and the receiver in the signal path [28]. In a mobile communication system, radio wave propagation is influenced by three fundamental factors. According to Popoola, S.I., these processes are reflection, diffraction, and scattering [29].

1.4. Measured Path loss

Path Loss in radio communications is the attenuation of signal strength resulting from the influence of terrain and atmospheric components on the channel of communication. It can also be defined as the difference (in decibels) between the transmitted power and the received power.

It represents signal level attenuation caused by free space propagation, reflection, diffraction, absorption and scattering [30].

Measured Path loss can be defined as the measure of the average Radio Frequency (RF) attenuation suffered by a transmitted signal when it arrives at the receiver after traversing a path of several wavelengths. It is given as

$$\text{PL (dB)} = 10\, Log \frac{\text{Pt}}{\text{Pr}} \tag{1}$$

where P_t and P_r are the transmitted and received power respectively [31]. Path loss is used in the calculation of link budget of communication systems [26].

1.5. Predicted Path Loss Propagation Models

Path loss models represent a set of mathematical equations and algorithms that are used for radio signal propagation prediction in definite areas. According to E. J. Ofure, predicted path loss models have been classified as follows [32]:

(1) Deterministic Model

(2) Stochastic Model

(3) Empirical Model

Deterministic and Stochastic Models are more of theoretical models that predict transmission losses by mathematical and computational analysis of the path geometrical information of the terrain between the transmitter and the receiver, as well as the refractivity of the troposphere.

Empirical Models are based on measurements conducted in a given environment and the main benefits for the use of these standard path loss models are time and cost efficiency, despite its limited accuracy. Path losses on wireless channels are generally the resultant effects of reflection, refraction, diffraction, scattering, absorption and fading due to multipath amongst others [33]. This study focuses on empirical models, as it is based entirely on observations and measurements. The selected models for error bounds analysis are those approved by the International Telecommunications Union, Radio Study Group (ITU-R). These models were chosen not only for their standardized parameters but also for their adaptability to the environmental characteristics of the study location. Their relationships and applicability are further detailed in this paper.

1.6. Types of Empirical Models

1.6.1. Friis Transmission Equation or Free Space Model (FSPL): Path loss in free space defines how much strength of signal vanishes during propagation from transmitter to receiver with no atmospheric attenuation or multipath components. Free space model depends on frequency and distance [34]. It is calculated as:

$$L_{FSPL} = 32.45 + 20log_{10}(d) + 20log_{10}(f) \qquad (2)$$

1.6.2. COST-231 PATH LOSS MODEL: COST-231 Hata model is an empirical model used for calculating path loss in cellular mobile system. This model is an extension of the Okumura-Hata model designed to cover frequency ranges from 1700Mz to 2300MHz with receiving antenna heights up to 10m and transmitting antenna heights of 30m–200m. COST-231 Hata model contains correction factors for urban, suburban and rural areas [35].

The equation for COST-231 Hata path loss model is expressed as:

$$L(dB) = 46.3 + 33.9\ log_{10}(f) - 13.82\ log_{10}(h_t) + [44.9 - 6.55\ log_{10}(h_t)]log_{10}(d) - a(h_r) + C_m] \qquad (3)$$

where, d is the link distance in Kilometres, f_c is the frequency in MHz, h_t is the effective height of the transmitting antenna in meters, h_r is the effective height of the receiving antenna in meters, C_m is the correction factor and is defined 0dB for rural and 3dB for urban area.

1.6.3. Electronic Communication Committee (ECC-33) Model

The Electronic Communication Committee 33 model was developed by Electronic Communication Committee. This model is designed to predict path loss at higher frequencies up to 3 GHz [36]. This model was proposed based on the Okumura model and is given by:

$$L_{dB} = L_{fs} + L_{bm} - G_t - G_r \qquad (4)$$

where L_{fs} is the free space attenuation (dB), L_{bm} is the basic median path loss (dB), G_t is the transmitter antenna height gain factor, G_r is the receiver antenna height gain factors, which are defined as:

$$L(fs) = 92.24 + 20log_{10}(d) + 20log_{10}(f) \qquad (5)$$

$$L(bm) = 20.41 + 9.83log_{10}(d) + 7.89log_{10}(f) + 9.56[log_{10}(f)]^2 \qquad (6)$$

$$G_t = log_{10}\left(\frac{h_t}{200}\right)\{13.98 + 5.8[log_{10}(d)]\}^2 \qquad (7)$$

For medium size city,

$$G_r = [42.57 + 13.7log_{10}(f)][log_{10}(h_m) - 0.585] \qquad (8)$$

And for large city,

$$G_r = 0.759h_m - 1.862 \qquad (9)$$

where f is in GHz, d in km, h_t and h_m area in meters.

1.6.4. Plane Earth Model (LPE)

The free space model doesn't recognize the impacts of proliferation over the ground. At the point when a radio wave proliferates over ground, a part of the power will be reflected due to nearness of the ground and the receiver. The information needed for the calculation is the height, the distance of separation and the reflection coefficient of the earth. The path loss equation for plane earth model according to [30]:

$$L_{PE} = 4010\ log_{10} - 20\ log_{10}(h_1) - 20\ log_{10}(h_2) \qquad (10)$$

where f is the frequency in (MHz), d is the distance from the base station to the receiver in (km), h_1 and h_2 in (m) are the heights of the transmitting base station and receiving antenna respectively.

1.6.5. Ericsson Model

Ericsson is one of the major vendors in the world. The company has been researching propagation modeling [37]. The Ericsson model of path loss patching is as follows

$$PL = a0 + a1\log(d) + a2\log(hb) + a3\log(hb)\log(d) - 3.2(\log(11.75h))^2 + g(f) \tag{11}$$

$$g(f) = 44.49(\log(f_c) - 4.78(\log(f_c))^2 \tag{12}$$

where d is the distance between the BTS and users (km), hb is the height of the BTS (m), f is the frequency (GHz). The parameters of $a0$, $a1$, $a2$, and $a3$ are adjusted according to specific propagation conditions.

2. General Justification for Using Selected Models and Excluding Other Models

The selected models COST-231, Ericsson, ECC-33, and Plane Earth were chosen based on their suitability for predicting path loss in urban environments and their relevance to GSM channel performance analysis. The rationale for selecting these specific models over other similar models is as follows:

(1) Frequency Range Compatibility: The chosen models are optimized for GSM frequencies (900 MHz and 1800 MHz), which are the primary bands used in Zaria City. Other models may focus on lower (e.g., VHF) or higher (e.g., 5G) frequency bands [38].

(2) Urban Environment Suitability: Zaria City is an urban area with dense infrastructure, which requires models that account for the complexities of signal propagation in such environments [39].

(3) Empirical Validation: The selected models have been widely validated and recommended for similar studies in urban environments in developing countries, providing a reliable foundation for this research [40].

(4) Comparative Analysis: These models offer a broad spectrum of complexity, from simple (Plane Earth) to highly refined (Ericsson), allowing for comprehensive analysis and comparison [41].

2.1. Statistical Tools Used in the Research

This study employed only two statistical tools which are root mean square error (RMSE) and correlation analysis to evaluate the performance of the empirical models and quantify correlations between variables by analyzing the relationship between path loss, received signal strength (RSS), and tropospheric variables (temperature, humidity, and pressure) for GSM networks over Zaria City.

2.2. Root Mean Square Error (RMSE)

For more accurate comparative analysis in determining the best path loss prediction model for a macro cellular environment is to use the root mean square error (RMSE) approach. The Root Mean Square Error (MSE) compares the measured data with the data obtained from each of the empirical models to determine the minimum RMSE.

This is dependent on the prediction error of distance from the base station. The prediction Error is given by:

$$\varepsilon = (P_1 - P_m)^2 \tag{13}$$

where P_1 is the measured path loss at distance (km), P_m is the predicted path loss. From the above equation, the overall, RMSE for a given model (m) and a given data set (n) is defined as:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(P_1 - P_m)^2} \tag{14}$$

where n is the number of observations for a given set of data.

When the value of the RMSE is closer to zero, it means a better fit, but the acceptable RMSE value is between 6 and 7 dB for urban areas and 10 – 15 dB for suburban and rural areas.

The RMSE was used mainly to predict the error margin and to verify the accuracy of path loss models [23].

2.3. Correlation Analysis

Correlation analysis is a statistical method used to measure the strength and direction of the linear relationship between two variables. It is quantified using the correlation coefficient, which ranges from -1 to 1. A positive value indicates a direct relationship, a negative value indicates an inverse relationship, and a value near 0 implies little to no linear relationship. The correlation analysis highlighted the significant impact of atmospheric variables on signal propagation and a basis for network optimization [42].

3. Methodology

3.1. Study Location and Field Measurement

Zaria City is a prominent urban city located in the North West region in Kaduna state of Nigeria along the coordinates latitude and longitude of 11° 05′ N and 7° 42′ E respectively. It has a tropical savanna climate with warm weather year-round, characterized by limited rainfall of less than 1,120 mm per year, occurring primarily from April to September and a drier season from October to March [43]. The natural terrains in the study locations provide a diverse landscape for examining signal propagation and losses and also add significance to the research.

The research was conducted along key routes in Zaria City, focusing on three specific areas: Samaru along Zaria-Sokoto Road, GRA (Government Residential Area) along Queen Elizabeth Road and Dorowa Road extending to Kongo Campus. These locations were selected strategically to represent different parts of the city with varied population densities, urban infrastructure and terrain which are crucial factors in assessing the behavior of GSM signals. The combination of these locations (Samaru, GRA, and Dorowa Road to Congo Campus) ensures a comprehensive analysis of GSM network performance in Zaria City. Each site offers different environmental and urban characteristics which are critical to understanding the behavior of mobile signals under varying conditions such as building density, road traffic and atmospheric conditions.

Figure 1 depicts the digital map of Zaria City showing different routes of measurement within the city while **Table 1** and **Table 2** present the characteristics of the experimental station of MTN and 9-Mobile respectively.

Figure 1. Digital map of Zaria City showing study location.

Table 1. Transmission parameter characteristics for MTN base station in Zaria City.

S/N	Parameters	Route A	Route B
1	Frequency (MHz) 2G/3G	900/2115 MHz	900/2115 MHz
2	Base stations geographic coordinate	Latitude 11° 05′ N and Longitude 08° 32’ E	Latitude 11° 58’ N and Longitude 008° 32’ E
3	Antenna Gain (dB) 2G/3G	12/15	12/15
4	Power transmitted (dB)	36.04	36.04
5	Height of Base Station (m)	32	32
6	Height of mobile antenna, $h_{m\,(m)}$	1.2	1.2

Table 2. Transmission parameter characteristics for 9-Mobile base station in Zaria City.

S/N	Parameters	Route A	Route B
1	Frequency (MHz) 2G/3G	930/2175 MHz	930/2175 MHz
2	Base stations geographic coordinate	Latitude 11° 08′ N and Longitude 008° 34' E	Latitude 11° 62' N and Longitude 008° 34' E
3	Antenna Gain (dB) 2G/3G	12/15	12/15
4	Power transmitted (dB)	40.0	40.0
5	Height of Base Station (m)	35	35
6	Height of mobile antenna, $h_{m\,(m)}$	1.2	1.2

3.2. Instruments and Methods of Data Collection

The study evaluated path loss over selected GSM channels within Zaria City by collecting data through drive tests along designated routes, recording received signal strength (RSS), geographical coordinates, and environmental parameters. Key equipment included a weather station to monitor temperature, humidity, and atmospheric pressure, a GPS device for logging precise locations, distances, and elevation, and a spectrum analyzer for capturing RSS and frequencies. Data collection involved measuring RSS at 100 m intervals for micro-analysis and 1 km intervals for macro-analysis, while simultaneously recording environmental conditions and location data. Measurements were conducted across the selected urban routes with diverse terrains and building densities to ensure comprehensive coverage. The data were used to compare predicted and actual path loss values and assess the accuracy of four empirical path loss models COST-231, ECC-33, Plane Earth, and Ericsson using statistical analysis, including Root Mean Square Error (RMSE).

During the data collection at the base station, power received (Received signal) and key environmental features were recorded, including elevation, atmospheric parameters and surrounding obstructions, as shown in **Figure 2**.

Figure 2. Taking readings at the MTN transceiver base station (reference point).

4. Results And Discussion

In this section, four empirical models which include COST-231, ECC-33, Plane Earth, and Ericsson models were employed for path loss prediction. Statistical tools which include root mean square error (RMSE) and correlation analysis were also used for accuracy of the predicted path loss models and determination of relationship among atmospheric variables respectively.

4.1. Primary Methodology Result

Table 3 presents the mean path loss values from both measured and predicted data for MTN and 9-Mobile networks. The predicted values are derived from the COST-231, ECC-33, Plane Earth, and Ericsson models, indicating the extent of deviation from the measured path loss values.

Table 3. The mean values based on 2G of the measured and predicted path losses for the measurement routes.

Network	Measured Path loss (dB)	Predicted Path loss (dB)			
		COST-231	ECC-33	PLANE EARTH	ERICSSON
MTN	110.10	153.22	281.42	-14.73	117.71
9-MOBILE	110.96	152.99	279.09	-15.82	117.89

4.1.1. Analysis and Comparison of Table 5 (Measured and Predicted Path losses)

According to **Table 3**, Ericsson model closely matches the measured path loss values, making it the most suitable model for predicting path losses in this environment. The COST-231 model tends to overestimate path loss but is still more reasonable compared to ECC-33.

The ECC-33 model significantly overestimates path loss, which indicates it may not be appropriate for the specific terrain or frequency used in this study. The Plane Earth model yields unrealistic results, suggesting it is not reliable in this case. **Figure 3** illustrates a graph showing the calculated predicted path losses against distance based on MTN 2G.

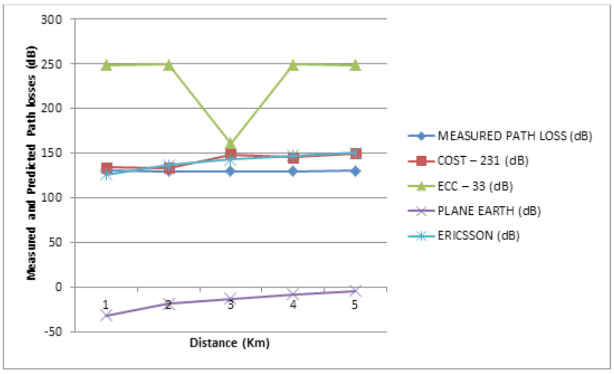

Figure 3. The graph of measured and predicted path losses against distance based on MTN 2G.

4.1.2. General Overview of the Graph

The graph compares distance (km) on the x-axis with path loss (dB) on the y-axis, plotting measured path loss alongside predicted values from COST-231, ECC-33, Plane Earth, and Ericsson models. The measured path loss serves as a benchmark to assess the accuracy of each model's predictions. COST-231 and Ericsson closely follow the measured path loss trends, with Ericsson performing slightly better overall. In contrast, ECC-33 significantly overestimates path loss, making it unsuitable for the urban 2G network, while the Plane Earth model produces unrealistic negative values, confirming its unsuitability. Overall, the Ericsson model demonstrates the best alignment with measured data, making it the most reliable choice for network planning and optimization in this context.

4.2. Robustness Test Result

The robustness test aims to assess the reliability and consistency of the empirical path loss models under varying conditions, particularly with respect to the influence of atmospheric parameters such as temperature, humidity, and pressure over GSM channels in Zaria City, Nigeria. This section evaluates the stability of the models and verifies their predictive accuracy by analyzing their performance across different datasets and environmental conditions. The primary metrics used for assessing robustness were the Root Mean Square Error (RMSE).

Table 4. Mean values of the root mean square error (RMSE) of the predicted path loss based on 2G.

Network	Root Mean Square Error (RMSE) Values			
	COST-231	ECC-33	PLANE EARTH	ERICSSON
MTN	17.66	54.98	35.12	6.00
9-MOBILE	16.5	52.73	36.41	5.00

Table 4 presents the Root Mean Square Error (RMSE) values for the predicted path loss using four different propagation models (COST-231, ECC-33, Plane Earth, and Ericsson) for MTN and 9-Mobile networks. These values reflect how closely each model's predictions align with the actual measured path loss values.

The RMSE values highlight that the Ericsson model is the most accurate, with minimal deviation from the measured path loss values for both MTN and 9-Mobile. In contrast, the ECC-33 model exhibits the highest errors, indicating its unsuitability for this scenario. The COST-231 and Plane Earth models have moderate RMSE values but are less accurate than Ericsson. Therefore, the Ericsson model is the most reliable for path loss prediction in this context.

Figure 4 and **5** illustrate a bar chats representing the root mean square error (RMSE) of the predicted path loss based on 2G for the MTN and 9-Mobile respectively.

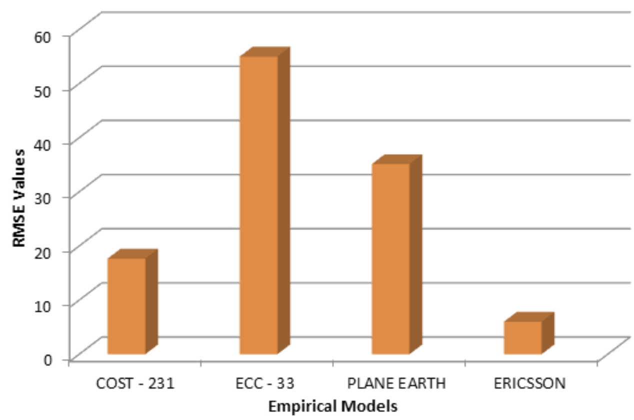

Figure 4. A bar chart representing the root mean square error (RMSE) values for MTN 2G.

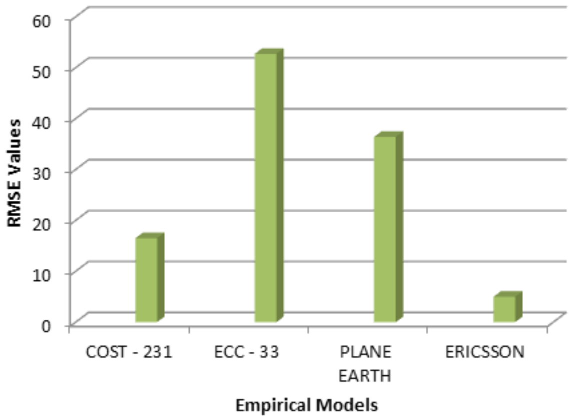

Figure 5. A bar chart representing the root mean square error (RMSE) values for 9-Mobile 2G.

4.2.1. Discussion of the Bar Chart (2G MTN)

The bar chart analyzing RMSE values for MTN 2G highlights the varying accuracy of four empirical models: ECC-33, Plane Earth, COST-231, and Ericsson. The Ericsson model, with the lowest RMSE of approximately 10, demonstrates the highest accuracy and reliability for predicting path loss, making it the best choice for this scenario. COST-231 performs moderately well with an RMSE of around 25, offering more accurate predictions than ECC-33 and Plane Earth. The Plane Earth model, with an RMSE of about 45 and ECC-33 model with the highest RMSE of approximately 60, show poor predictive performance. Overall, the Ericsson model stands out as the most reliable for estimating path loss, while ECC-33 should be used with caution.

4.2.2. Discussion of the Bar Chart (2G 9-Mobile)

The bar chart analyzing RMSE values for 9-Mobile 2G highlights the predictive accuracy of four empirical models: Ericsson, COST-231, Plane Earth, and ECC-33. The Ericsson model, with the lowest RMSE of 5.00 dB, demonstrates the best performance, showing a strong correlation between predicted and actual path loss values, making it the most reliable option for optimizing network coverage. COST-231, with an RMSE of 16.5 dB, provides reasonably accurate predictions but is less precise than Ericsson. The Plane Earth model, with an RMSE of 36.41 dB, shows moderate accuracy but still reflects substantial prediction errors, while ECC-33, with the highest RMSE of 52.73 dB, performs poorly, indicating significant deviations from actual measurements. These results highlight Ericsson as the most suitable model for predicting path loss and improving network performance for 9-Mobile 2G.

4.3. Comparison between Primary Methodology Result and Robustness Test Result

Table 3 presents the mean path loss values from both measured and predicted data for MTN and 9-Mobile networks, with predictions derived from the COST-231, ECC-33, Plane Earth, and Ericsson models. The comparison highlights the extent of deviation between the predicted and measured path loss values. To further evaluate accuracy, a robustness test shown in **Table 4** uses Root Mean Square Error (RMSE) as the statistical measure. Among the models, a lower RMSE value signifies a better fit between the predicted and measured values, indicating that the Ericsson model consistently demonstrates superior accuracy compared to the others for both MTN and 9-Mobile networks.

The results from the robustness test confirm the findings of the primary methodology. The Ericsson model is the most reliable for predicting path loss in this context, followed by the COST-231 model. The ECC-33 and Plane Earth models are less reliable due to high prediction errors and large deviations from the measured values.

4.3.1. Analysis and Comparison of Table 3 (Measured and Predicted Path losses)

(1) Measured Path Loss: The measured path loss

Table 5. The mean values based on 3G of the measured and predicted path losses for the measurement routes.

Network	Measured Path loss (dB)	Predicted Path loss (dB)			
		COST- 231	ECC-33	PLANE EARTH	ERICSSON
MTN	133.29	108.91	281.30	-19.79	142.2
9-MOBILE	131.59	109.46	279.89	-20.57	141.74

values for MTN (133.29 dB) and 9-Mobile (131.59 dB) are almost similar, indicating consistent signal attenuation for both networks along the measurement routes, but MTN showing a slightly higher path loss than 9-Mobile.

(2) Predicted Path Loss: COST-231 Model predicts a path loss of 108.91 dB for MTN and 109.46 dB for 9-Mobile while Ericsson Model predicted path losses are 142.2 dB for MTN and 141.74 dB for 9-Mobile, which are relatively close to the measured values, whereas ECC-33 Model predicts significantly higher path losses of 281.30 dB for MTN and 279.89 dB for 9-Mobile. This model's predictions are much greater than the measured values, suggesting it may not be suitable for this environment. Plane Earth Model predicts negative path loss values of -19.79 dB for MTN and -20.57 dB for 9-Mobile. These negative values are unrealistic, indicating that the Plane Earth model is not applicable or accurate in this context. **Figure 6** illustrates a graph showing the calculated predicted path losses against distance based on MTN 3G.

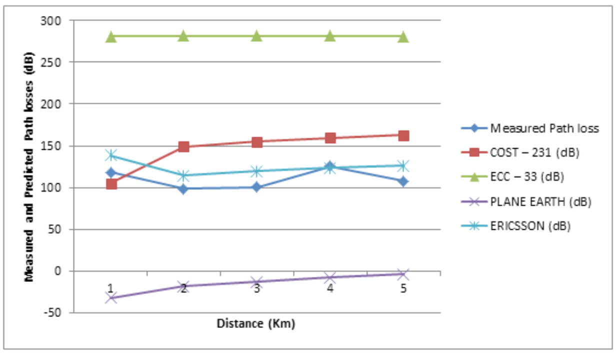

Figure 6. The graph of measured and predicted path losses against distance based on MTN 3G.

4.3.2. General Overview of the Graph

The graph of distance versus path loss for MTN 3G, with the x-axis representing distance (km) and the y-axis showing path loss (dB), includes one line for measured path loss and four lines for predicted path losses from the empirical models. The measured path loss values show minor fluctuations, indicating that signal loss may be influenced more by environmental factors than distance within the studied range. Among the models, COST-231 and Ericsson demonstrate better accuracy at larger distances, with COST-231 performing consistently well across the entire range. In contrast, ECC-33 overestimates path loss significantly, making it less suitable for the urban 3G network, while Plane Earth provides unrealistic negative path loss values, confirming its unsuitability. Overall, COST-231 emerges as the most reliable predictor for MTN 3G in urban or semi-urban environments, making it a strong candidate for network planning in similar regions.

4.3.3. Performance Evaluation of the Predicted Models

The performance evaluation of the predicted models was determined using root mean square error (RMSE) relation (equation 14) based on MTN and 9-Mobile 3G. The RMSE mean values are shown in **Table 6** below:

Table 6. The mean values based on 3G of the root mean square error (RMSE) of the predicted path loss.

Network	Root Mean Square Error (RMSE) Values			
	COST-231	ECC-33	PLANE EARTH	ERICSSON
MTN	3.36	55.94	57.86	9.32
9 – MOBILE	3.835	49.47	57.48	8.35

Table 6 presents the mean values of Root Mean Square Error (RMSE) for the path loss predictions from four empirical models COST-231, ECC-33, Plane Earth, and Ericsson for MTN and 9-Mobile networks. Lower RMSE values indicate higher prediction accuracy, while higher RMSE values show that the model deviates significantly from the measured path loss. The values reflect how closely each model's predictions align with the actual measured path loss values.

Figure 7 and **8** illustrate a bar chats representing the root mean square error (RMSE) of the predicted path loss based on 3G for the MTN and 9-Mobile respectively.

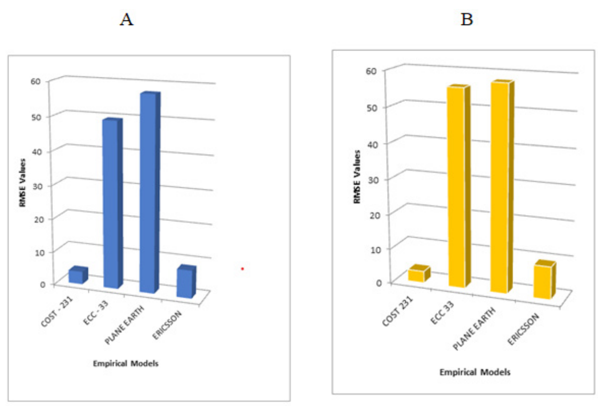

Figure 7. A bar chart representing the root mean square error (RMSE) values for MTN 3G.

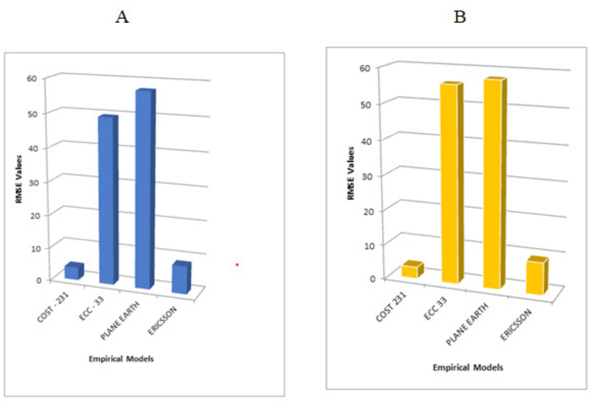

Figure 8. A bar chart representing the root mean square error (RMSE) values for 9-Mobile 3G.

4.3.4. Discussion of the Bar Chart and Analysis of RMSE Values (3G MTN)

The bar chart illustrates the Root Mean Square Error (RMSE) values for four empirical models COST-231, ECC-33, Plane Earth, and Ericsson used to predict path loss for MTN 3G. COST-231, with the lowest RMSE of 3.36 dB, is the most accurate and reliable model, reflected by its shortest bar. The Ericsson model, with an RMSE of 9.32 dB, also performs reasonably well but is less accurate than COST-231. ECC-33 has the second-highest RMSE, indicating relatively poor performance, though it slightly outperforms the Plane Earth model. Plane Earth, with the highest RMSE, demonstrates the least accuracy and is unsuitable for predicting path loss in this scenario. Overall, COST-231 is the most effective model for MTN 3G network planning in this context.

4.3.5. Discussion of the Bar Chart and Analysis of RMSE Values (3G 9-Mobile)

The bar chart analyzing RMSE values for 9-Mobile 3G highlights significant differences in the predictive accuracy of four empirical models: COST-231, Ericsson, ECC-33, and Plane Earth. COST-231, with the lowest RMSE of 3.8 dB, demonstrates the strongest correlation between predicted and actual path loss, making it the most reliable and effective model for capturing the propagation characteristics and environmental factors affecting 9-Mobile's network. The Ericsson model, with an RMSE of 8.35 dB, performs reasonably well but is less accurate than COST-231. ECC-33, with an RMSE of 49.41 dB, shows moderate accuracy but still reflects substantial prediction errors. The Plane Earth model, with the highest RMSE of 52.73 dB, performs poorly, indicating significant deviation from actual measurements and unsuitability for the specific environmental conditions. Overall, COST-231 is the most suitable model for optimizing coverage and minimizing dropped calls in 9-Mobile's network.

4.3.6. Comparison of RMSE Values of Predicted Path Losses for MTN and 9-Mobile Based on 2G and 3G Networks

The above comparison as presented in **Tables 4** and **6** highlights the accuracy of four predicted path loss models which are COST-231, ECC-33, Plane Earth, and Ericsson. RMSE values serve as a key metric to evaluate the alignment between predicted and measured path loss, with lower values indicating greater precision. For 2G networks, the Ericsson model consistently demonstrates the highest accuracy, making it the most suitable choice for planning and optimizing 2G network performance in urban areas like Zaria City.

For 3G networks, however, the COST-231 model emerges as the most reliable, offering better path loss predictions due to its lower RMSE values compared to the other models. This analysis emphasizes the variability in model performance across different network generations and the critical need to select models tailored to the specific technology. By aligning the choice of model with the network type, operators can achieve more accurate path loss predictions and improve network planning and optimization efforts in complex urban environments.

According to **Table 7**, the most significant relationships are observed between Path Loss vs RSS and pressure (strongly negative) and Path loss vs LOS and Temperature (strongly positive). The moderate and weak correlations are between Path loss vs Humidity and path loss vs elevation respectively which indicate some level of interaction, but not as pronounced. These findings are critical for understanding signal propagation in Zaria City and suggest that environmental factors must be carefully considered for accurate path loss prediction as well as effective network planning and optimization.

Table 7. Correlation coeffcients between Path loss and LOS, RSS, Temperature, Humidity, Elevation and Pressure in respect of GSM network (MTN and 9-Mobile).

	Path Loss	LOS	RSS	ELV	Temp.	Pressure	Humidity
Path loss	1						
LOS	0.89308	1					
RSS	-0.8340	-0.02951	1				
ELV	-0.17217	-0.34503	-0.0444	1			
Temp.	0.84075	0.579615	0.10188	0.205748	1		
Presssure	-0.79987	-0.59496	-0.13492	-0.35159	-0.96969	1	
Humidity	-0.51473	-0.33976	0.499447	0.396836	-0.24894	0.096639	1

4.4. Economic Implications of the Result

Accurate path loss prediction has significant economic value in wireless network planning. Reliable models like Ericsson reduce the cost of deploying and optimizing network facilities by minimizing signal degradation, improving resource allocation, and enhancing network performance. For network operators, accurate planning ensures optimal base station placement, reduces infrastructure costs, and improves consistent service quality. These results provide better customer experience and higher revenue generation if utilized, especially in urban areas like Zaria City where high population density increases demand for reliable network services.

Policy Implications and Practical Applications

The findings from this study provide significant insights for policymakers, network operators, and engineers working to improve network performance and coverage. The results have several practical applications and implications:

(1) Network Planning and Optimization: The Ericsson model, with the lowest RMSE values for both 2G and 3G networks, should be prioritized for path loss prediction in Zaria City and similar environments. Network operators can use this model to optimize cell tower placement and ensure reliable signal coverage in urban areas. For 3G networks, the COST-231 model also performs well, especially at larger distances. It can serve as a secondary option for planning in regions where the Ericsson model might not be feasible.

(2) Policy Formulation for Service Providers: Service providers and regulatory bodies should adopt policies encouraging the use of more accurate models like Ericsson for network expansion projects. This will help in optimizing resources, reducing costs, and improving the overall user experience.

These results underline the critical role of model selection and environmental factors in path loss prediction and network planning. The Ericsson and COST-231 models stand out as the most reliable for this environment, while other models like Plane Earth and ECC-33 require careful reconsideration. Adopting these findings in policy and practice will enable service providers to enhance network performance, reduce costs, and deliver better services to users in Zaria City and similar regions.

5. Conclusions

The assessment of empirical path loss models for MTN and 9-Mobile networks on 2G and 3G channels in Zaria City, Nigeria, highlights notable findings on model precision and environmental impacts on signal behavior. For 2G networks, the Ericsson model emerged as the most effective, showing the lowest RMSE values, making it ideal for urban network planning and optimization. Conversely, for 3G networks, the COST-231 model displayed the greatest accuracy, marking it as the optimal choice for path loss forecasting in this context. This distinction underscores the necessity of selecting models that align with the specific network generation to maximize accuracy.

Furthermore, analyzing the correlation between path loss and environmental factors such as Line of Sight (LOS), Received Signal Strength (RSS), temperature, humidity, elevation, and pressure shed light on atmospheric influences on signal propagation. A strong negative correlation exists between path loss and both RSS and pressure, while positive correlations with LOS and temperature further emphasize the impact of these factors. Moderate correlations with humidity and weaker ones with elevation also suggest interactions that, although less influential, remain relevant to network dynamics. These results reinforce the importance of considering environmental variables in planning and optimizing 2G and 3G networks in urban areas like Zaria City. By selecting models tailored to the network generation and integrating environmental parameters, network planners can enhance path loss prediction accuracy and optimize GSM network performance. This study serves as a valuable reference for future network planning, highlighting critical strategic factors essential for network enhancement in similar urban regions.

Author Contributions

M. S.: Methodology, software, writing—original draft preparation and funding acquisition. A. A.: Conceptualization, validation, supervision, project administration, writing review and editing as well as funding acquisition. I. B.: Resources, visualization and funding acquisition. N. A.: Formal analysis, investigation and funding acquisition. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

The data supporting the findings of this study is not publicly available due to privacy and ethical restrictions.

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Conflicts of Interest

The authors declare no conflicts of interest.

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