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Validation and Modification of the Stanford University Interim Path Loss Model for Very High Frequency Propagation in Calabar, Nigeria

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Abstract

This study focuses on the validation and modification of the Stanford University Interim (SUI) path loss model for Frequency Modulated (FM) signal propagation at 105.5 MHz within the Calabar environment. Empirical measurements of received signal strength were taken across twelve geographically diverse locations in Calabar, using a digital spectrum analyzer and GPS receiver to capture signal and positional data. The standard SUI model was applied to the collected data, and significant deviations were observed between the predicted and measured path loss values. A correction factor of 42.50 dB was subsequently introduced to account for the discrepancies. The modified SUI model yielded a Root Mean Square Error (RMSE) of 11.65 dB, indicating improved prediction accuracy compared to the unmodified version. However, this error margin still exceeds the International Telecommunication Union (ITU) threshold of 6 dB for acceptable path loss prediction accuracy. The findings demonstrate that while the modified SUI model performs better than the original, it remains insufficiently accurate for FM signal prediction in Calabar. The study highlights the necessity of developing or further refining propagation models based on local environmental conditions. It contributes to the broader discourse on region-specific path loss modelling and provides valuable insights for RF engineers, broadcasters, and researchers concerned with network planning and optimisation in Calabar.

Keywords: Path loss modeling; Stanford University Interim (SUI) model; Frequency Modulated (FM) signals; Very High Frequency (VHF); Radio propagation; Calabar

1. Introduction

Wireless communication has become an indispensable component of modern society, providing the foundation for broadcasting, mobile telephony, emergency services, and internet connectivity. Accurate prediction of radio signal attenuation is crucial for the effective design and optimization of wireless systems. This task is typically achieved through path loss modeling, which quantifies the reduction in signal strength as electromagnetic waves propagate through space [1-3]. Reliable models enable efficient frequency planning, interference management, transmitter placement, and assurance of quality of service (QoS) in communication systems [4-5].

Among terrestrial broadcasting services, Frequency Modulated (FM) radio remains one of the most widely used communication media, operating within the Very High Frequency (VHF) band (88–108 MHz) [4,6]. Ensuring robust and reliable FM coverage is therefore both a technical and developmental priority.

Several empirical path loss models have been proposed in literature [7-14], with the Stanford University Interim (SUI) model widely recognized for its simplicity and adaptability. Originally designed for broadband wireless systems in the 2–11 GHz range [15], the model has been extended to other frequency bands due to its flexible structure [16]. However, like most empirical models, the SUI model was derived under specific environmental conditions, mainly temperate

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regions with relatively uniform terrain, and thus requires calibration when applied to geographically and climatically distinct areas [17-18].

Calabar, Nigeria, presents a complex propagation environment due to its tropical monsoon climate [19-23]. These conditions significantly influence VHF signal propagation, often causing severe attenuation and deviation from predictions made by conventional models [6,24]. Existing studies indicate that the direct application of unmodified models in such environments leads to large prediction errors, resulting in inefficient spectrum utilization, poor coverage, and suboptimal broadcast service quality [11,25-26]. Despite the importance of FM broadcasting in Calabar, there is a lack of empirically validated or locally adapted propagation models for this frequency band and region [4].

This study addresses this gap by validating and modifying the SUI path loss model for FM signal transmission at 105.5 MHz in Calabar. Field measurements of received signal strength were conducted across twelve diverse locations, and the model was calibrated against empirical data. The modified model demonstrates improved prediction accuracy compared to the unmodified version, though further refinement is still necessary to meet the International Telecommunication Union's (ITU) 6 dB error threshold for acceptable path loss prediction accuracy.

By tailoring the SUI model to the unique propagation conditions of Calabar, this work contributes both practical and theoretical value. It provides network engineers with a more reliable tool for coverage planning, while also advancing the discourse on region-specific propagation modeling in tropical environments.

1.1. Overview of Stanford University Interim Model

This model was developed for fixed wireless access systems (FWA). It was developed for frequency bands below 11GHz. From its name, this model originated at Stanford University in the United States of America (USA) and covers a frequency range of 2.5 GHz to 2.7 GHz. The SUI models are divided into three different types: A (hilly terrains with moderate to heavy tree densities), B (hilly terrains with light tree densities), and C (flat terrains with light tree densities). The basic path loss equations with correction factor are presented in [15-16].

$$PL(dB) = A + 10y\log_{10}(d/d_0) + X_f + X_h + S \qquad \ldots\ldots\ldots\ldots \qquad (1)$$

for $d > d_o$

Where A is the free space path loss at reference distance; y is the path loss exponent; X_f is the frequency correction factor; X_h is the receiver's antenna height correction factor, d is the distance between the transmitter and the receiver, d_o = 100m and S is a log normally distributed factor used to account for the shadow fading due to trees and other clutter and has a value of 8.2dB and 10.6dB [27].

2. Materials and methods

The study adopts an experimental and analytical approach. It involves the collection of signal strength data from different locations within Calabar, followed by analysis using mathematical and statistical techniques to calibrate and validate the SUI path loss model.

2.1. Materials and Equipment

The following tools and equipment were used:

- A digital spectrum analyzer (GW-INSTEK) GSP-730 with a frequency range of 150 MHz - 3GHz was used in measuring the signal strength
- A hand-held Global Positioning System (GPS) device (GARMIN 78S) was used for the measurement of geographical coordinates (elevation, latitude, and longitude).
- A Laptop was used to collect and save the data measured via the spectrum analyzer.
- Signal strength was collected from the transmitter of the Cross River Broadcasting Corporation at 105.5 MHz.
- Values of antenna height and transmitting power were collected from the Technical Officer of CRBC, Calabar

2.2. Study Area and Measurement Locations

Measurements were taken across selected locations in Calabar, Cross River State. These include:

- University of Cross River State
- Calabar South Local Government Council
- Tinaba Business Resort
- State Secretariat, Calabar
- Atimbo Road
- Government Secondary School, Atu
- Good Luck Jonathan By-pass
- Scanobo Junction
- Calabar Municipal Local Government Council
- University of Calabar
- Watt market
- Marina Resort

These locations reflect varying terrain in Calabar.

2.3. Data Collection Procedure

Measurements of received signal strength and geographical coordinates were simultaneously taken at the twelve locations. Signals transmitted from the base station of Cross River Broadcasting Corporation at a frequency of 105.5 MHz were measured at Non Line-of-Sight (NLOS) distances at the different study routes with the base station as the reference point. The received signal strength was obtained at the receiver antenna at a height of 3.0 m.

2.4. Data Analysis

The measured signal strength data was converted to decibel (dB). The obtained value was then subtracted from the transmitting power of the base station. This was done to obtain the path loss. According to Ekah et al (2022), path loss is given as

$$P_L = P_T - P_R \quad \text{…………} \quad (2)$$

Where,
P_L = measured path loss
P_T = transmitting power of the base station (CRBC) = 68.451dB
P_R = measured power

The SUI path loss equation as obtained in equation (1) was used to obtain the predicted path loss values. The predicted path loss was compared to the measured path loss values via a graph for proper visualization. This was also validated by calculating the Root mean squared error of the predicted values. Where the value does not fall into the International Telecommunication Union (ITU) threshold of at least 6dB, a correction factor (C) was introduced to account for errors. Hence, equation (1) becomes

$$PL = A + 10y_{log}\left(\frac{d}{d_0}\right) + X_f + X_h + S + C \quad \text{…………} \quad (3)$$

On the addition of the correction factor, the values of the corrected SUI values were then compared to the measured path loss via a graph, and further ascertained by calculating the RMSE of the predicted SUI model. This result was then compared to the ITU-recommended threshold to validate the suitability of the SUI model in this study terrain. The results of this analysis are presented in the next section

3. Results

The analysis of the SUI model for path loss modelling in the Calabar environment has been achieved. Path loss values at strategic locations across Calabar have been obtained as shown in Table 1. The methods used in obtaining the SUI prediction model are also discussed in the various sections below.

3.1. Analysis of Measured Path Loss

Signal strengths at specific locations across Calabar were collected. Simultaneously, the distance between the transmitter and the receiver was measured for each location. The measured signal strength data was converted to decibels (dB). The obtained value was then subtracted from the transmitting power of the base station. This was done to obtain the path loss. These values are presented in Table 1.

Table 1 Table of Distance/Measured Path Loss

Distance (m)	Measured Path Loss (dB)
394	145.451
5172	141.451
6895	143.451
7902	146.451
11227	135.451
11865	145.451
12359	147.451
12679	146.451
14548	149.451
14700	143.451
16919	140.451
18219	148.451

3.2. Mathematical Analysis of the Standard University Interim Model

As stated in equation 1, the SUI path loss equation is given as

$$PL = A + 10y_{log}\left(\frac{d}{d_0}\right) + X_f + X_h + S$$

$$\text{But } A = 20\log\left(\frac{4\pi d_0}{\lambda}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

$$y = a - bh_b + \frac{c}{h_b} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

$$X_f = 6\log\left(\frac{f}{2000}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

$$X_h = -10.8\log\left(\frac{h_r}{2}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (7)$$

The sections below give a breakdown of the various components of the SUI Path Loss components.

3.3. Mathematical Analysis of Free Space Path Loss at the Reference Distance.

Calculating the wavelength (λ)

$$\lambda = \frac{c}{f} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (8)$$

Where c is the speed of light and f is the frequency of transmission

Here, $c = 3 \times 10^8 m/s$; $f = 105.5\ MHz$ = $105.5 \times 10^6 MHz$

Therefore, $\lambda = \frac{3\times 10^8}{105.5 \times 10^6} = 2.84m$

Substituting the value of λ into Equation 4

$$A = 20\log(\frac{4\pi \times d_0}{2.84}) \qquad \text{.................. (9)}$$

Where d_0 is the reference distance $= 100m$

Putting the value of d_0 into equation 9

$A = 20\log\left(\frac{4 \times 22 \times 100}{2.84 \times 7}\right) = 52.9dB$

3.4. Mathematical analysis of the path loss exponent for the Calabar environment

From equation 5, $y = a - bh_b + \frac{C}{h_b}$

Where $a = 4.6$; $b = 0.0075$; $c = 12.6$ and $h_b$which is the base station height $= 292.608m$

Substituting these values into equation 5 becomes;

$y = 4.6 - (0.0075 \times 292.608) + (\frac{12.6}{292.608})$

$y = 4.6 - 2.19456 + 0.04306 = 2.45$

3.5. Mathematical analysis of the frequency correction factor

From Equation 6

$$X_f = 6\log(\frac{f}{2000})$$

Where $f = 105.5MHz$

$X_f = 6\log\left(\frac{105.5}{2000}\right) = 6\log(0.05275) = -7.67dB$

3.6. Mathematical analysis of the Receiver Antenna Height Correction factor

From equation 7, $X_h = -10.8\log\left(\frac{h_r}{2}\right)$

But $h_r = 3m$

Putting the value of h_r into equation 7 gives

$X_h = -10.8\,Log\left(\frac{3}{2}\right) = -10.8\,Log\,1.5 = -1.90dB$

3.7. Obtaining the SUI Path Loss Model for Calabar

From equation 1, the SUl path loss model is given as

$$PL = A + 10y\log\left(\frac{d}{d_0}\right) + X_f + X_h + S$$

But $A = 52.9dB$; $y = 2.45$; $X_f = -7.67dB$; $X_h = -1.90dB$; $S = 8dB$

Substituting these values into equation 1 gives

$$PL = 52.9 + (10 \times 2.45)\log\left(\frac{d}{d_0}\right) - 7.67 - 1.90 + 8$$

This reduces to

$$PL = 51.32 + 24.5\ Log\ (\frac{d}{d_0}) \qquad \ldots\ldots\ldots\ldots (10)$$

Where d_0 = reference distance = 100m

3.8 Obtaining Path Loss Prediction Values for Measurement Locations

Substituting the values of d for each location into equation 10.

For location $A1, d = 14700m$

$$pL = 51.33 + 24.5 \log (\frac{14700}{2000})$$

$$pL = 104.4dB$$

For location $A2, d = 18219m$

$$pL = 51.33 + 24.5 \log (\frac{18219}{2000})$$

$$pL = 106.7dB$$

For location $A3, d = 16919m$

$$pL = 51.33 + 24.5 \log (\frac{16919}{2000})$$

$$pL = 105.9dB$$

For location $A4, d = 14548m$

$$pL = 51.33 + 24.5 \log (\frac{14548}{2000})$$

$$pL = 104.3dB$$

For location $A5, d = 12679m$

$$pL = 51.33 + 24.5 \log (\frac{12679}{2000})$$

$$pL = 102.8dB$$

For location $A6, d = 7902m$

$$pL = 51.33 + 24.5 \log (\frac{7902}{2000})$$

$$pL = 97.8dB$$

For location $A7, d = 394m$

$$pL = 51.33 + 24.5 \log (\frac{394}{2000})$$

$$pL = 65.9dB$$

For location $A8, d = 51729m$

$$pL = 51.33 + 24.5 \log \left(\frac{5172}{2000}\right)$$

$$pL = 93.3dB$$

For location $A9, d = 6895m$

$$pL = 51.33 + 24.5 \log \left(\frac{6895}{2000}\right)$$

$$pL = 96.2dB$$

For location $A10, d = 11227m$

$$pL = 51.33 + 24.5 \log \left(\frac{11227}{2000}\right)$$

$$pL = 101.5dB$$

For location $A11, d = 12359m$

$$pL = 51.33 + 24.5 \log \left(\frac{12359}{2000}\right)$$

$$pL = 102.6dB$$

For location $A12, d = 11865m$

$$pL = 51.33 + 24.5 \log \left(\frac{11865}{2000}\right)$$

$$pL = 102.1dB$$

The measured path loss values along with the obtained SUI prediction values for the various locations are presented in Table 2 and in a graphical form in Figure 1.

Table 2 Table of Measured/SUI predicted Path Loss values

Distance (m)	Measured Path Loss (dB)	SUI Predicted Path Loss (dB)
394	145.451	65.900
5172	141.451	93.300
6895	143.451	96.200
7902	146.451	97.800
11227	135.451	101.500
11865	145.451	102.100
12359	147.451	102.600
12679	146.451	102.800
14548	149.451	104.300
14700	143.451	104.400
16919	140.451	105.900
18219	148.451	106.700

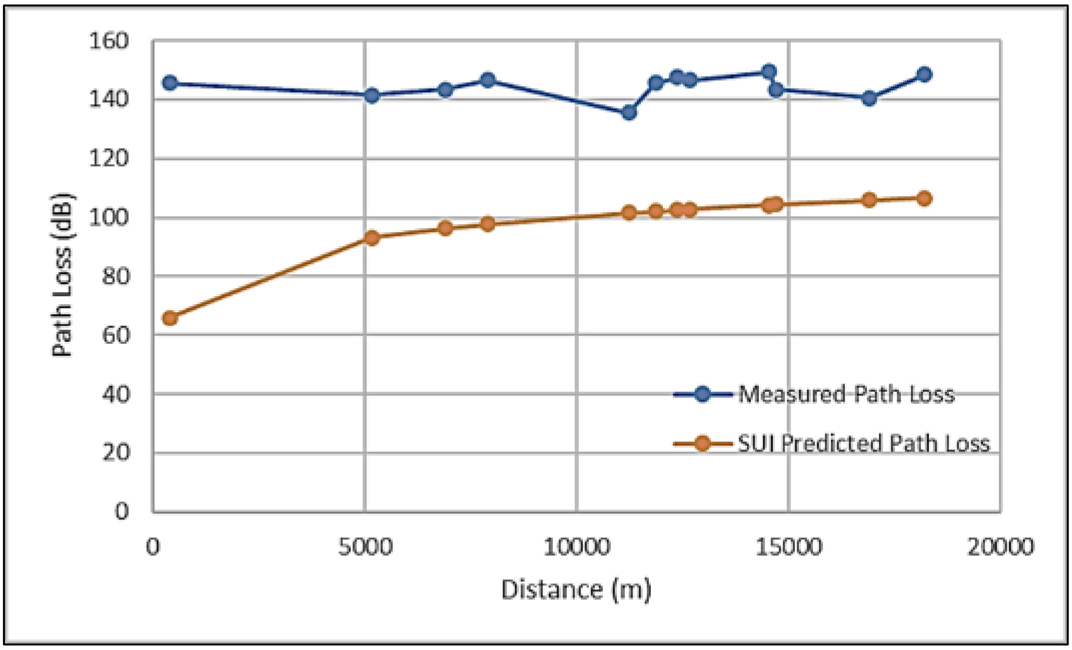

Figure 1 Graph of Path Loss against Distance for Measured/SUI Predicted values

As seen in Table 2 and Figure 1, the SUI predicted path loss values underestimated the measured path loss values. However, to predict the accuracy and reliability of the SUI predicted values, we calculated the Root Mean Square Error (RMSE)

Mathematically,

$$RMSE = \sqrt{MSE} \quad \ldots\ldots\ldots\ldots \quad (11)$$

Where MSE is the mean squared error

$$But\ MSE = \sum \left(\frac{Squared\ Errors}{N}\right) \quad \ldots\ldots\ldots\ldots \quad (12)$$

Where N=12

Calculating the mean squared error

$$MSE = \sum \left(\frac{Squared\ Errors}{N}\right)$$

Where N=12

Therefore, MSE = $\frac{26694.74}{12}$ = $222.456 dB^2$

Calculating RMSE

$$\text{RMSE} = \sqrt{2224.56} = 47.17 dB$$

The result of the RMSE is relatively high, and this shows that the SUI model is not suitable for path loss modeling in this environment.

3.8. Modification of the SUI Model for the Calabar Environment:

Since the SUI model is not suitable for Path Loss Modeling in Calabar, a correction factor (C) was introduced to account for the losses. This was earlier presented in equation 3. However, a breakdown of the SUI path loss model was presented in equation 10 as

$$PL = 51.32 + 24.5\ Log\ (\frac{d}{100})$$

Introducing the correction factor, C, into Equation 10

$$PL_c = 51.32 + 24.5\ Log\ \left(\frac{d}{d_0}\right) + C \qquad \text{.........} (13)$$

Where PL_c = corrected path loss

C = Correction factor

$$But\ C = \sum \left(\frac{measured\ path\ loss - Sul\ path\ loss}{N}\right) \qquad \text{............} \quad (14)$$

Where N is the number of measurements

From equation 4.12,

$C = \frac{510.02}{12} = 42.5dB$

Putting the value of C into Equation 13 gives

$$PL_c = 51.33 + 24.5\ Log\ \left(\frac{d}{d_0}\right) + 42.5 \qquad \text{................} \quad (15)$$

$$\text{Hence, } PL_c = 93.83 + 24.5\ Log\ \left(\frac{d}{d_0}\right) \qquad \text{................} \quad (16)$$

Putting the values of d and $d_0$into Equation 16

For $d = 14700m$

$$PL_c = 93.83 + 24.5 \log (\frac{14700}{2000})$$

$$PL_c = 146.922dB$$

For location $A2, d = 18219m$

$$PL_c = 93.83 + 24.5 \log (\frac{18219}{2000})$$

$$PL_c = 149.225dB$$

For location $A3, d = 16919m$

$$PL_c = 93.83 + 24.5 \log (\frac{16919}{2000})$$

$$PL_c = 146.922dB$$

For location $A4, d = 14548m$

$$PL_c = 93.83 + 24.5 \log\left(\frac{14548}{2000}\right)$$

$PL_c = 146.824dB$

For location $A5, d = 12679m$

$$PL_c = 93.83 + 24.5 \log\left(\frac{12679}{2000}\right)$$

$$PL_c = 145.354dB$$

For location $A6, d = 7902m$

$$PL_c = 93.83 + 24.5 \log\left(\frac{7902}{2000}\right)$$

$$PL_c = 140.331dB$$

For location $A7, d = 394m$

$$PL_c = 93.83 + 24.5 \log\left(\frac{394}{2000}\right)$$

$$PL_c = 108.408dB$$

For location $A8, d = 5172m$

$$PL_c = 93.83 + 24.5 \log\left(\frac{5172}{2000}\right)$$

$$PL_c = 135.823dB$$

For location $A9, d = 6895m$

$$PL_c = 93.83 + 24.5 \log\left(\frac{6895}{2000}\right)$$

$$PL_c = 138.889dB$$

For location $A10, d = 11227m$

$$PL_c = 93.83 + 24.5 \log\left(\frac{11227}{2000}\right)$$

$$PL_c = 144.055dB$$

For $d = 12359m$

$$PL_c = 93.83 + 24.5 \log\left(\frac{12359}{2000}\right)$$

$$PL_c = 145.084dB$$

For $d = 11865m$

$$PL_c = 93.83 + 24.5 \log\left(\frac{11865}{2000}\right)$$

$$PL_c = 144.643dB$$

The values of the measured path loss, SUI predicted path loss and the corrected SUI predicted path loss are summarized in Table 3 and are presented in Figure 2.

Table 3 Table of Measured path loss, SUI predicted path loss and the corrected SUI predicted path loss

Distance (m)	Measured Path Loss (dB)	SUI Predicted Path Loss (dB)	Corrected SUI Predicted Path Loss (dB)
394	145.451	65.900	108.408
5172	141.451	93.300	135.823
6895	143.451	96.200	138.889
7902	146.451	97.800	140.331
11227	135.451	101.500	144.055
11865	145.451	102.100	144.643
12359	147.451	102.600	145.084
12679	146.451	102.800	145.354
14548	149.451	104.300	146.824
14700	143.451	104.400	146.922
16919	140.451	105.900	148.416
18219	148.451	106.700	149.225

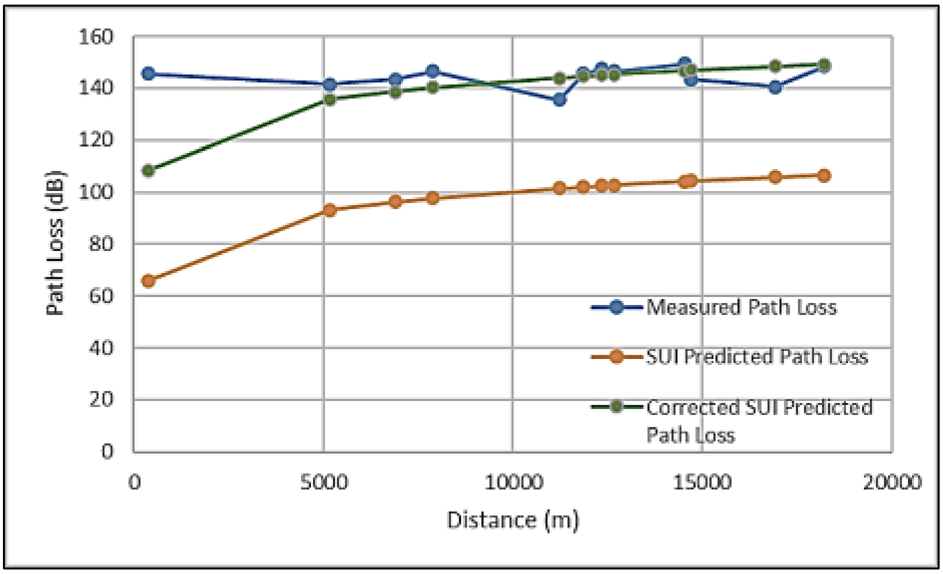

Figure 2 Graph of Path Loss against Measured/SUI/Corrected SUI Values

3.9. Suitability of the Corrected SUI Model for the Calabar Environment

To check for the suitability of the corrected SUI model, the RMSE value is calculated.

$$\text{Recall, RMSE} = \sqrt{MSE}$$

$$\text{But MSE} = \frac{1628.42}{12} = 135.70dB^2$$

$$RMSE = \sqrt{MSE} = \sqrt{135.70} = 11.65dB$$

The RMSE value of 11.65dB indicates a better agreement between the measured path loss and the corrected SUl path loss model. However, this does not conform to the ITU-recommended RMSE value of at least 6 dB.

4. Discussion of results

The findings from this study reveal that the unmodified Stanford University Interim (SUI) path loss model underestimates the actual path loss experienced during FM signal propagation at 105.5 MHz in Calabar. Across all twelve selected locations, there was a consistent deviation between the predicted and measured values, confirming that the standard parameters of the SUI model are not directly transferable to the Calabar environment. This observation aligns with the work of Akanni et al. [8], who highlighted the poor performance of standard models in Nigerian semi-urban settings and stressed the need for model modification tailored to local terrain and structural characteristics.

By introducing a correction factor of 42.5 dB, the modified SUI model significantly improved its predictive capability, as reflected by the reduction in Root Mean Square Error (RMSE) to 11.65 dB. While this represents a substantial improvement over the original model, it still exceeds the 6 dB threshold recommended for acceptable accuracy. Akinbolati and Ajewole [10] similarly observed that despite the enhancements made to standard models for digital terrestrial television in Nigeria, the error margins in tropical environments often remain above ideal thresholds, underscoring the challenges of signal prediction in such complex environments.

Additionally, this study supports findings by Adewumi et al. [9], who conducted empirical modelling of VHF path loss in building and vegetation-dominated channels. Their research demonstrated that environmental obstructions significantly affect signal attenuation and must be incorporated into any reliable prediction model. In the same vein, Akanni and Odepian [7], in their comparative analysis of VHF and UHF signals, noted that standard models often failed to capture the peculiarities of Nigerian urban propagation due to the lack of terrain-specific adaptation.

The results further reflect the observations made by Akinbolati et al. [25], who emphasised the importance of region-specific calibration of empirical models for digital terrestrial television broadcasting in rainforest zones. These authors confirmed that modified models based on field data outperformed generic ones in terms of accuracy. This is particularly relevant to the current study, where the modified SUI model, though not fully compliant with international standards, performed substantially better than its original version.

The study also echoes the conclusions of Ekah et al. [13], who found that frequency-modulated signals in southern Nigeria are strongly influenced by local atmospheric and environmental conditions. These influences, common to tropical coastal environments like Calabar, complicate signal propagation and reduce the effectiveness of empirical models developed in other climatic zones.

In addition, Akinbolati and Agunbiade [11] examined error bounds for path loss models and concluded that predictive accuracy is heavily influenced by local climatic conditions and geographical characteristics. Their findings support the need for model correction or redevelopment using in situ measurements, as carried out in the present study.

In conclusion, the experimental results reinforce the consensus from the literature that empirical path loss models must be modified with local environmental considerations to ensure acceptable prediction performance in tropical regions. While the modified SUI model showed marked improvement, the remaining error suggests that further enhancement, possibly through hybrid modelling techniques or the integration of AI-based methods as suggested by **Cavalcanti et al.** [14]**,** may be necessary for achieving optimal performance in environments like Calabar.

5. Conclusion

This study set out to evaluate the suitability of the Stanford University Interim (SUI) path loss model for Frequency Modulated (FM) signal propagation at 105.5 MHz in Calabar, Nigeria. Field measurements of received signal strength were collected from twelve geographically diverse locations across the city and compared with predictions from the standard SUI model. The analysis revealed that the unmodified SUI model consistently underestimated path loss values, confirming that the model's original parameters are not directly transferable to Calabar's tropical coastal environment.

By introducing a correction factor of 42.50 dB, the predictive performance of the model improved, reducing the Root Mean Square Error (RMSE) from extremely high values to 11.65 dB. Although this adjustment brought the model closer to measured values, the error margin remained above the International Telecommunication Union's (ITU) recommended threshold of 6 dB. These findings demonstrate that while the modified SUI model performs better than the original, it is not sufficiently accurate for reliable FM signal prediction in Calabar.

The results reinforce the broader consensus in the literature that empirical path loss models must be calibrated or modified based on local measurements to achieve acceptable prediction accuracy in tropical environments. They also highlight the unique propagation challenges posed by Calabar's climate, vegetation, and terrain, which significantly affect VHF signal behavior.

In summary, the study concludes that the SUI model, even in its modified form, is only partially suitable for FM path loss prediction in Calabar. Further research is recommended to incorporate additional environmental variables and explore hybrid or machine-learning-based modeling techniques. Such advancements will provide more robust and accurate tools for broadcasters, RF engineers, and policymakers to optimize network planning, ensure efficient spectrum usage, and improve service quality in Nigeria's coastal urban environments.

Compliance with ethical standards

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Disclosure of conflict of interest

No conflict of interest to be disclosed.

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