Investigation of path loss and modeling for digital terrestrial television over Nigeria

A. Akinbolati, M.O. Ajewole

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Abstract

Accurate prediction of path losses is a key factor in Digital Terrestrial Television (DTTV) to ensure Quality of Service (QoS). This study investigates the path losses of three Digital Terrestrial Television Base Stations (DTTBS) in Lagos, Kaduna and Katsina cities of Nigeria. The Received Signal Strength (RSS) of the DTTBS was measured at intervals along selected routes around the stations using a digital signal strength meter. So also, the transmitter-receiver distances of data points with their corresponding geographic coordinates and heights were measured using a hand held GPS receiver. Also measured concurrently were some of the location’s-based surface meteorological parameters such as temperature, atmospheric pressure and humidity, using a compact wireless weather station. In addition, the corresponding surface radio refractivity values along the routes were computed using the meteorological parameters recorded. Data were collected during dry and wet season months’ covering a period of three years. Path losses were calculated using Okumura-Hata model. Results for all the routes and seasons revealed that path loss increases with increase in trans-receiver distances, however path losses were higher during wet compared to dry season’s month. Path losses estimated were highest in Kaduna followed by Ikorodu-Lagos and least in Katsina. Average high positive correlation coefficients of 0.76, 0.75 and 0.74 were obtained between path losses and line of sight for Lagos (Coastal zone), Kaduna (Sudan Savannah) and Katsina (Sahel Savannah) respectively. In the same order, negative correlation coefficients of -0.72, -0.79 and -0.63 were obtained between path losses and RSS. In addition, Modified Okumura Hata Model(s) (MOHPL) that incorporates the effect of the specified tropospheric parameters were proposed. Results also revealed that path losses obtained by Okumura-Hata model increase with increase in LOS separation distance from the base station following a consistent exponential rise while the Modified Okumura-Hata Model (MOHPL) followed similar trend with few exceptions of crests and troughs depicting the influence of the incorporated location’s-based tropospheric parameters. Another finding is that Okumura Hata model under estimated the path losses associated with digital terrestrial television channel over the study locations. In order to ensure high reliability of power budgets and link’s design, the proposed models are recommended for use over the study locations. The overall findings of this work will be useful for the accurate prediction of path losses and the design of power budgets and links over digital terrestrial television and similar wireless channels on the UHF band.

1. Introduction

Accurate predictions of path losses are essential in wireless communications (Armoogum et al., 2010). Terrestrial path losses depend on terrain and atmospheric conditions of the troposphere (Akinbolati et al., 2016). Evaluation of losses is useful for radio wave propagation planning and equipment design by radio scientists and engineers. As the growth of wireless communications continues, it is very important to have the capability of determining optimum base stations’ locations and estimation of coverage areas (Sarkar et al., 2003). This can be achieved through estimation of path losses and modeling (Akinbolati et al., 2017). Analogue and Digital Terrestrial Transmission of signal on the UHF broadcast band is by space wave which propagates on Line of Sight (LOS) from the transmitter to the receiver through the troposphere. Thus, the signal received at locations away from the transmitter could be the direct transmitted wave, the reflected wave or the diffracted wave (Akinbolati et al., 2016; Kenedy and Bernard, 1992). This could be due to the effect of terrestrial objects on the propagation path, atmospheric components and terrain (Armoogum...
There is also the attenuation effect on UHF signal that can be caused by precipitation (Ajewole et al., 2014). Digital Terrestrial Television (DTTV) technology was first proposed by General Instrument Corporation (GIS) in 1990 and later adopted by the International Telecommunications Union leading to the world wide agreement on migration from Analogue Terrestrial Television Transmission (ATTT) to DTTT. This was premised on the quest to enhance Quality of Service (QoS) for terrestrial television Transmission and maximize frequency spectrum by harnessing the upper UHF bands (Channels 61 to 69; 790–862 MHz) for broadband services. DTTV is the transmission of digital signals from the television transmitter via a terrestrial transmitting antenna to the receiving antenna. The receiver antenna is connected to a Set Top Box (receiver) which converts the digitally transmitted signal to analogue signal for the analogue television to process and display. The medium of propagation for both analogue and digital terrestrial television is the troposphere, where most weather phenomena occur (Akinbolati et al., 2017; Boithias, 1987). It has therefore become expedient to carry out studies on path losses and modeling on DTTT channels in Nigeria now that the Nation will soon embrace total digital switchover. This has also become imperative because many literature texts have shown that existing empirical path loss models cannot fit in perfectly into all geographic locations across the globe due to differences in terrain and weather from the experimental study locations (Akingbade and Olorumunbi, 2013; Faruk et al., 2013; Nisiat et al., 2011). This premise forms one of the motivations for this study.

Propagation of radio signal in the troposphere is affected by many processes which include the variations of meteorological parameters such as air temperature, pressure, and humidity. These variations in weather parameters often result in refractivity changes (Oyedum and Gambo, 1994). Radio wave propagation is determined by the changes in the radio refractive index of air in the troposphere (Adedjii and Ajewole, 2008). These changes can lead to the abrupt changes in propagation direction of a radio wave propagating in the troposphere resulting in attenuation of signal. Based on this premise, studies on radio refractivity have become sacrosanct for radio engineers and scientists for the proper planning of radio links, power budget and coverage areas.

### 1.1. Surface radio refractivity and radio signal

The index of refraction (n) of air is always close to unity while the parameter used to describe its spatial and temporal variations is generally termed the radio refractivity \( N \), and defined by:

\[
N = (n - 1) \times 10^6
\]

It is a dimensionless quantity that depends on atmospheric parameters of pressure \( P \) (hPa), temperature \( T \) (K) and water vapour pressure \( e \) (hPa) (ITU-R, REC. P.453, 2003):

The surface radio refractivity \( N_s \) is expressed as:

\[
N_s = \frac{77.6}{T} (P + 4810 \frac{e}{T}) (N - \text{units})
\]

with the dry term of radio refractivity \( N_{dry} \) given by:

\[
N_{dry} = 77.6 \frac{P}{T}
\]

and the wet term, \( N_{wat} \) given by:

\[
N_{wat} = 3.732 \times 10^5 \frac{e}{T^2}
\]

where,

\[
e = \frac{H e_s}{100} \quad \text{(hPa)}
\]

and

\[
N_s = N_{dry} + N_{wat}
\]

where,

\[
e_s: \text{is the maximum (or saturated) vapour pressure at the given air temperature } t \text{ (°C)}
\]

\[
H: \text{the humidity (% R.H.)}
\]

\[
P: \text{is the atmospheric pressure (hPa)}
\]

\[
T: \text{is the temperature (K) and;}
\]

\[
e: \text{is water vapour pressure (hPa)}.
\]

Pressure \( P \) and water vapour pressure \( e \) decrease rapidly with height whereas temperature \( T \) decreases slowly with height (Ayantunji et al., 2011). Surface radio refractivity \( N_s \) has a high correlation with radio field strength values (Bean et al., 1966) while the surface refractivity gradient which depends on \( N_s \), determines the refractivity condition of the atmosphere which may result in a normal, sub-refractive, super refractive or ducting layer (Dairo and Kolawole, 2017) each of which has important influence on propagation of VHF, UHF and microwaves in the atmosphere (Oyedum and Gambo, 1994).

### 1.2. Research question

This study was designed to investigate the path losses associated with Digital Terrestrial Television (DTTV) over some selected climatic zones in Nigeria using the Okumura – Hata model. It equally aims at proposing Modified Okumura-Hata Path Loss Models by incorporating the effect of tropospheric parameters such as; elevation above sea level, temperature, pressure, humidity and surface radio refractivity to ensure optimum results.

### 2. Path loss prediction models

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 (Ravivier, 2004).

Path loss can also 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 (Sarkar et al., 2003):

\[
PL_{(dB)} = 10 \log \left( \frac{P_t}{P_r} \right)
\]

where \( P_t \) and \( P_r \) are the transmitted and received power respectively. Path loss is used in the calculation of link budget of communication systems. It is used for coverage areas prediction and optimization. It can equally be used to predict TV spatial white spaces for secondary users (Faruk et al., 2013).

Path loss prediction is the ability to accurately predict the attenuation effect of the channel of propagation on a radio signal. It is simply the prediction or calculation of the losses in power transmitted at the base station to the power received at the receiver. It is the losses associated with transmitted signal from source to destination. In wireless channels, there are different models that predict path loss. Some were derived in a statistical manner based on field measurements and others were developed analytically based on diffraction effects. Each model uses specific parameters to achieve reasonable prediction accuracy (Akingbade and Olorumunbi, 2013). The two major approaches to propagation modeling are the physical and the empirical models (Akingbade and Olorumunbi, 2013). Physical model makes use of physical radio waves principles such
as free space transmission, reflection or diffraction whereas empirical models make use of measurement data to validate a path loss equation (Armoogum et al., 2010; Sarkar et al., 2003).

### 2.1. Examples of empirical propagation models include

i. Friis Transmission Equation or Free Space Model (FSPL)

Friis transmission equation is a simplified path loss prediction model used in radio waves propagation. Radio and antenna engineers use the following simplified formula for path loss prediction between two isotropic antennas in free space (Kenedy and Bernard, 1992).

\[
L = 20 \log \frac{4\pi d}{\lambda} \tag{8}
\]

where \(d\) is the distance (Line of Sight, LOS) from the transmitter in meters, \(\lambda\) is the wavelength of the wave in m. The path loss, representing the attenuation suffered by the signal as it travels through the wireless channel is given by the difference of the transmitted and received power in dB and is expressed as:

\[
PL(dB) = 10 \log \frac{P_t}{P_r} \tag{9}
\]

ii. Plane Earth Model

This model incorporates the transmitting and receiving apparatus height, the distance of separation and the reflection coefficient of the earth. The path loss equation for plane earth model is given by (Ranvier, 2004):

\[
L_{PE} = 40\log_{10}(d) - 20\log_{10}(h_t) - 20\log_{10}(h_r) \tag{10}
\]

where \(d\) is the distance between transmitter and receiver in (km), \(h_t\) and \(h_r\) in (m) are the heights of the transmitting base station and receiver antenna respectively.

iii. Okumura Model

Okumura’s model is one of the most frequently used macroscopic propagation models. It was developed in 1968 from the result of large-scale studies conducted in and around Tokyo, Japan. The model was designed for use in the frequency range 200 up to 1920 MHz and mostly in an urban propagation environment (Okumura et al., 1968). Okumura’s model assumes that the path loss between the transmitter and receiver in the terrestrial propagation environment can be expressed as:

\[
L_{OKU} = L_{FS} + A_m(f, d) - G(h_t) - G(h_r) - G_{AREA} \tag{11}
\]

where:

- \(L_{OKU}\) is the median (i.e., 50th percentile) value of propagation path loss expressed in dB.
- \(L_{FS}\) is the free space propagation loss in dB.
- \(A_m(f, d)\) is the basic median attenuation relative to free space in dB.
- \(G(h_t)\) and \(G(h_r)\) are the base station and receiver height gain correction factor in dB respectively, and
- \(G_{AREA}\) is the gain in dB due to the type of environment.

European Co-operative for Scientific and Technical Research Team (COST 231) Model

This model is an extension of the Okumura - Hata model developed to cover a wide range of frequencies between (0.5–2 GHz), and it's used for medium to small cities (Mollel and Kisangiri, 2014). The expression for the model is:

\[
L_{dB} = 46.3 + 33.9\log_{10}(f) - 13.82\log_{10}(h_t) + [44.9 - 6.55\log_{10}(h_t)]\log_{10}(d) - \alpha(h_t) + C_n \tag{12}
\]

\(\alpha(h_r)\) receiver antenna height correction factor, while \(C_n = 0 \text{ dB}\) for medium-sized city and suburban areas and 3 dBfor urban areas.

v. ECC 33 Model

This model was developed by Electronic Communication Committee (ECC). It was extrapolated from original measurements by Okumura and modified such that it can closely represent a Fixed Wireless Access system. It is an appropriate model for the Ultra High Frequency (UHF) band, and according to recent recommendations of ITU-R, it can be used up to 3.5 GHz. This model was proposed based on the Okumura model and is given by (Abhayawardhana et al., 2005):

\[
L_{dB} = L_{FS} + L_{bm} + G_r - G_t \tag{13}
\]

where: \(L_{FS}, L_{bm}, G_r, G_t\) all in dB, are the free space attenuation, basic medium path loss, transmitter height gain factor and the receiver height gain factor, respectively, which are defined as:

\[
L_{FS} = 92.4 + 20\log_{10}(d) + 20\log_{10}(f) \tag{14}
\]

\[
L_{bm} = 20.41 + 9.83\log_{10}(d) + 7.89\log_{10}(f) + 9.56[\log_{10}(f)]^2 \tag{15}
\]

\[
G_r = \log_{10}(\frac{h_r}{200})\{13.98 + 5.8[\log_{10}(d)]^2\} \tag{16}
\]

For medium size city,

\[
G_r = [42.57 + 13.7\log_{10}(f)][\log_{10}(h_r) - 0.585] \tag{17}
\]

and for large city,

\[
G_r = 0.759h_r - 1.862 \tag{18}
\]

where \(f\) is in GHz, \(d\) in km, \(h_t\) and \(h_r\) in metres.

### 2.2. Okumura-Hata model (Hata, 1980) and its choice for assessing path losses in this study

Okumura-Hata, a globally acceptable model was used in this study to benchmark the new models due to the following advantages:

i. The model had been adjudged by ITU-R as a good model to benchmark new approaches on VHF/UHF channels (Armoogum et al., 2010; ITU- R, Rec. P.529-3, 1997).

ii. In addition, the study location (Nigeria) and the independent parameters of interest deployed into the models and can be easily deployed.

iii. The Hata model for urban areas, also known as the Okumura-Hata model is a developed version of the Okumura model and is the most widely used radio frequency propagation model for predicting the behavior of cellular transmissions in built up areas (Armoogum et al., 2010).

iv. The model can be used for both micro and macro cell outdoor prediction. This model is suited for both point-to-point and broadcast transmissions (Okumura et al., 1968).

Okumura-Hata models for urban and sub urban areas are formulated as:

\[
L_{urban} = [69.55 + 26.16\log f - 13.82\log h_t - \alpha(h_t)] \tag{19}
\]
For large city with the wave frequency of transmission $f \geq 400$ MHz,\
\[ a(h_m) = 3.2\log(11.75h_m)^2 - 4.97 \]  \hspace{1cm} (20)

$L_{\text{urban}}$ is the path loss in Urban Areas in dB, $h_m$ is the height of base station antenna in meters, $f$ is the frequency of transmission in MHz, $a(h_m)$ the antenna height correction factor and $d$, is the line of sight distance between the base and mobile stations in kilometer.

By specifications, Okumura-Hata model has the following range for optimum result:

- Carrier frequency: 150 MHz $\leq f \leq 1500$ MHz
- Base station height: 30 m $\leq h_b \leq 200$ m
- Mobile station height: 1 m $\leq h_m \leq 10$ m
- Distance between mobile and base station: 1 km $\leq d \leq 20$ km (Nizirat et al., 2011; Akingbade and Olorunmibi, 2013).

For sub urban area, it is given by:

\[ L_{\text{sub–urban}} = L_{\text{urban}} - \left[ 2\left(\log\left(\frac{f}{28}\right)\right)^2 - 5.4 \right] \text{ dB} \]  \hspace{1cm} (21)

3. Instrumentation and methods

This work was carried out in three Nigerian cities of Ikorodu-Lagos; Kaduna in Kaduna State and Katsina in Katsina State. These locations were chosen to represent the coastal, Sudan Savannah and Sahel Savannah climatic zones of Nigeria respectively. Ikorodu-Lagos and Kaduna represent urban cities while Katsina represents sub-urban based on Okumura-Hata's categorization of locations (Ranvier, 2004). Measurements of received signal strength and other parameters were carried out using three Digital Terrestrial Television Broadcasting Stations (DTTBS) sited in each of the study locations. Two routes of measurements were considered in urban cities of Ikorodu-Lagos and Kaduna because of their peculiar terrain and traffic congestion while three routes were considered in sub urban city of Katsina. Data were collected during wet and dry season months covering a period of three years (2016–2018). Table 1 presents the transmission parameters for each of the transmitting stations.

3.1. Equipment used for data collection and experimental arrangement

A digital signal strength meter was used to measure the signal strength while a mini weather station (model N96FY) was concurrently used to measure the surface atmospheric parameters. A GPS (GARMIN 78S) was used for the measurement of elevation, geographic coordinates and the LOS of the various data locations from the base station. Figure 1 presents the signal strength meter used for measurement campaign.

Table 1. Transmission parameters for the digital terrestrial television broadcasting stations (Akinbolati et al., 2020).

| S/N | Parameter | Transmitting Base Station |
|-----|-----------|---------------------------|
| 1   | Base station's location and geographic coordinates | Ikorodu – Lagos (Lat. 6°37'43'' N, Long. 3°31'42'' E) | Kaduna (Lat.10°32'16'' N, Long. 7°28'18'' E) |
|     |                                                      | Katsina (Lat.13°01'50'' N, Long. 7°32'51'' E) |
| 2   | Base station's transmitted power (kW)                | 2.20 | 2.30 | 2.20 |
| 3   | Base station's frequency (MHz)/Channel               | 658/44 | 714/51 | 530/28 |
| 4   | Height of transmitting antenna(m)                    | 182.5 | 182.5 | 182.5 |
| 5   | Height of mobile antenna AGL (m)                     | 1.5 and 3.0 | 1.5 and 3.0 | 1.5 and 3.0 |

Figure 1. Digital satlink signal strength meter (Akinbolati et al., 2020).

3.2. Method of data collection, computation and analysis

Measurements of RSS for the transmitting base stations (used as sources of signal) were carried out using different routes with each base station as reference point. Two sets of received signal strength were obtained for two specified receiver antenna heights of 1.5 and 3.0 m for each point. During the measurement campaign (drive test), LOS from each station was monitored using the GPS, which equally measures the geographic coordinates and the elevation above sea level. Concurrently, the weather station measures the surface weather parameters. Measurements were carried out at intervals of 1 km LOS up to about 20 km distance for each route in six phases covering dry and wet season months. In the coastal city of Lagos, data were collected in the months of June and November representing wet and dry season respectively, while in Sudan and Sahel savannah cities of Kaduna and Katsina, data were collected in the months of July and November representing wet and dry season respectively. Daily data were grouped according to routes and seasons and the average values used for analysis. The surface radio refractivity values corresponding to points of data collection were computed based on measured meteorological parameters using ITU-R refractivity equations as indicated in (2), (3), (4), 5 and (6) while path losses of the signal along different routes were computed using Eqs. (19), (20), and (21). The obtained data were analyzed during wet and dry season for all the transmitting base stations using necessary software. The proposed path loss models based on the measured data were derived using multiple regression analyzes.

For multiple regression analysis, given $k$ independent variables with $n$ observations $X_{11}, X_{12}, \ldots, X_{1n}, \ldots, X_{kn}$ in $n \times k$ vector and $n$ dependent observation $Y_1, Y_2, \ldots, Y_n$ in $n \times 1$ column vector, the multiple regression model is given as:

\[ Y = \beta_0 + \beta_1X_1 + \beta_2X_2 + \ldots + \beta_kX_k + \mu \]  \hspace{1cm} (22)

For ease of explanation, multiple regressions are preferably represented in matrix form (Akinbolati et al., 2018):
3.3. Performance metrics for the proposed model(s)

In order to evaluate the performance and the fitness of the proposed models for use over the study area, different metrics were employed. They are:

i. Coefficient of multiple determinations;
ii. Correlation coefficient;
iii. Standard deviation
iv. Prediction Error; and
v. Root Mean Square Error (RMSE)

RMSE measures the differences between values predicted by a hypothetical model and the observed values. It measures the quality of fit between the observed data and the predicted model. RMSE is the most apparent metric for analyzing error of predictive models (Nisirat et al., 2011; Faruk et al., 2013). Eqs. (28) and (29) present the prediction error and RMSE respectively.

\[ P_{e,d} = M_d - P_{d, \hat{d}} \]  

\[ \text{RMSE} = \sqrt{\frac{1}{n} \sum (M_d - P_{d, \hat{d}})^2} \]  

where, \( P_{e,d} \) is the prediction error at distance \( d \) (km) from the transmitter \( n \) is the number of observation for a given set of data \( M_d \) is the measured value at distance \( d \) (km) and; \( P_{d, \hat{d}} \) is the predicted value at distance \( d \) (km)

Generally, a RMSE value indicates a better fit when it is closer to zero (0) (Nisirat et al., 2011; Faruk et al., 2013). The acceptable RMSE for a path loss model should not exceed about 8 and 15 dB for urban and sub urban areas respectively (Blaunstein et al., 2003). Eq. (29) was used to compute the RMSE for each of the proposed models for wet and dry season months over the study area.

4. Result and discussions

In this section, Okumura-Hata model was used to compute the path losses along the routes of measurement for both dry and wet season months' over the study areas. Okumura-Hata model was chosen based on its globally acceptable status. The model had been adjudged as a good model to benchmark new approaches by the International Telecommunications Union (ITU-R, Rec. P.529, 1997; Armoogum et al., 2010) as earlier stated. The only limitation is that the model does not incorporate tropospheric parameters; which is one of the motivations for this work such that a modified version that incorporates some tropospheric parameters is obtained.

4.1. Assessment of path loss over Ikorodu - Lagos

Figures 2 and 3 depict typical plots for the Okumura – Hata path loss with distance for the two specified receiver antenna heights during dry and wet season months respectively in Ikorodu - Lagos. Generally speaking, the plots are similar irrespective of the routes, seasons and years of investigation, thus typical plots for 2017 and 2018 are presented. It was observed that path loss increases as LOS separation distance from the base station increases.

Average path loss of 120.54 dB and 118.05 dB were obtained when using receiver antenna heights of 1.5 and 3.0 m respectively during the dry period. For the wet season, average path loss of 121.90 dB and 119.21 dB were recorded when using receiver antenna heights of 1.5 and 3.0 m respectively. In all the routes and seasons, higher values of path losses were recorded for lower receiver antenna height of 1.5 m compared to the values recorded when using receiver antenna height of 3.0 m. The statistical analysis of data in Ikorodu-Lagos show that positive correlation coefficients of 0.77 and 0.75 with p-values based on \( \alpha \) (0.05) of 0.003 and 0.005 exist between Hata path loss and LOS from DTTBS during dry and wet season months' respectively. On the other hand, negative correlation coefficients of -0.72 and -0.71 with p-values of 0.080 and 0.010 were obtained between Okumura-Hata path loss and RSS for dry and wet season respectively while negative correlation coefficients of -0.57 and -0.52 with p-values of 0.054 and 0.081 were obtained between Hata path loss and elevation of data points for dry and wet season months' respectively. The implication of this is that the use of higher receiver antenna height reduces path losses on digital terrestrial television channel for the two seasons in Ikorodu-Lagos.

4.2. Assessment of path loss over Kaduna

Figures 4 and 5 depict typical Okumura-Hata path loss plots during dry and wet season months' respectively in Kaduna. Average path losses of 126.86 and 124.17 dB were recorded when using receiver antenna heights of 1.5 and 3.0 m during dry while 126.42 and 123.72 dB were recorded when using receiver antenna heights of 1.5 and 3.0 m respectively for the wet season months. However, there was no significant difference in path losses for the two receiver antenna heights of 1.5 and 3.0 m. This may be due to the fact that Kaduna being an urban centre with high rising congested buildings ranging from 3.0 to about 18.0 m with tall trees particularly in the following quarters of: Ungwai Rimi, Ahmadu Bello Way, State Secretariat, Government House Area, Nigerian Defence Academy (NDA) Area, Airport road amongst others. The high rising buildings with congested terrestrial features might have prevented the reception of the direct transmitted signal from the base station by both antennas. This was obvious and physically observed during the
measurement work. The signal received would primarily be the reflected or scattered signal (resulting from multipaths effect) as line of sight could not be established between transmitting and receiver antennas. This is the case for most subscribers in these areas. Therefore, for subscribers of DTTV in Kaduna city to access optimum signal level, their receiver antenna should be mounted as high as possible in order to establish line of sight link with the transmitting antenna.

Emphasis on statistical analysis shows that, low negative correlation coefficients of -0.29 and -0.30 with poor p-values of 0.315 and 0.324 were obtained between Hata path loss and elevation of data points (above sea levels) for dry and wet season months' respectively. These show that there is no dependable correlation between the pair of path loss and elevation of data points in Kaduna. This further confirms the impact of multipath effects on RSS in Kaduna city as earlier discussed. On the other hand, negative correlation coefficients of -0.78 and -0.79 with p-values of 0.030 and 0.010 were obtained between Okumura-Hata path loss and RSS for dry and wet seasons' months respectively.

4.4. Statistical analysis of data and modeling

Different statistical tools such as; mean, standard deviation, coefficient of correlation (R) and determination (R²) and Analysis of Variance (ANOVA) were employed to achieve optimum results. Multiple regressions were carried out using the proposed path loss models as dependent variables with location's - based LOS, elevation (ELV), humidity (H) and surface radio refractivity (Ns) as independent variables. The proposed path loss model is called Modified Okumura Hata Path Loss (MOHPL) in this study. In order to test the suitability of the derived models, error analyzes were also carried out on measured and derived models using Predicted Error (PE), Mean Square Error (MSE) and Root Mean Square Error (RMSE). Tables 2 and 3 present typical basic statistics of parameters during dry and wet season months respectively in Ikorodu-Lagos; while Tables 4 and 5 present same for Kaduna. Similarly, Tables 6 and 7 present the basic statistics of parameters during dry and wet season months respectively in Katsina. The Tables depict the evaluated mean values of some key parameters with their corresponding standard deviation. From the Tables, it was generally observed that; lower path losses were obtained for higher receiver antenna height of 3.0 m. In addition, highest values of surface radio refractivity were obtained in the coastal zone compared to other climatic zones as well as during wet compared to the dry season months.

The proposed models in this study was based on the analyzes of data obtained using the 3.0 m receiver antenna height. This was premised on
the fact that the antenna's height recorded lower path losses compared to the lower antenna height of 1.5 m. It is recommended that subscribers in the study locations should make use of 3.0 m as the minimum receiver antenna height so as to minimize losses. The proposed \( \text{MOHPL} \) model in Ikorodu-Lagos for dry season months with corresponding coefficient of multiple determination (\( R^2 \)) of 0.81 and p-value of 0.05 is as presented in Eq. (30) while \( \text{MOHPL} \) for wet season months with \( R^2 \) of 0.99 and p-value of 0.00 is as presented in Eq. (31).

\[
\text{MOHPL}_{\text{LG-DRY}} = 1492.364 + 9.363\text{LOS} - 2.689\text{ELV} - 0.050\text{Ns} - 0.184H \text{ (dB)}
\]

\[
\text{MOHPL}_{\text{LG-WET}} = 2267.075 + 3.365\text{LOS} - 1.187\text{ELV} - 4.453\text{Ns} + 0.871 \text{ (dB)}
\]

Where:

- \( \text{MOHPL} \): Modified Okumura-Hata Path Loss
- LOS: Line of Sight distance from DTTBS (km)
- ELV: Location based elevation above sea level (m)
- Ns: Location based surface radio refractivity (N-units)
- H: Location based humidity (%RH)
- DRY: Dry season
- WET: Wet season
- LG: Lagos city
- KD: Kaduna city
- KTN: Katsina city

4.5. Comparison of Okumura - Hata and Proposed Models (MOHPL)

Here, the proposed models were used to compute the expected path losses. Both Okumura - Hata and the Proposed Models were plotted against distance using the obtained tropospheric data. The comparison plots are similar for the three locations thus typical plots for two locations (Ikorodu-Lagos and Kaduna) are presented. Figures 8 and 9 present the typical comparison plots during dry and wet season months respectively in Ikorodu-Lagos and Kaduna. Table 9 presents the basic statistics obtained between the Okumura-Hata and proposed model.
Figure 4. Influence of LOS Distance from DTTBS on Path Loss in Kaduna for the two Specified Receiver Antenna’s Heights during Dry Season Months’ for (a) 2017 (b) 2018.

Figure 5. Influence of LOS Distance from DTTBS on Path Loss in Kaduna for the two Specified Receiver Antenna’s Heights during Wet Season Months’ for (a) 2017 (b) 2018.
Figure 6. Influence of LOS Distance from DTTBS on Path Loss in Katsina for the two Specified Receiver Antenna’s Heights during Dry Season Months’ for (a) 2017 (b) 2018.

Figure 7. Influence of LOS distance from DTTBS on path loss in Katsina for the two specified receiver antenna’s heights during wet season months’ for (a) 2017 (b) 2018.
during dry and wet season months over the study locations. The proposed models undulate with distance with typical crests (Points C) and troughs (Points T); depicting the influence of the location’s-based specified tropospheric parameters. On the other hand, the Okumura-Hata model maintains a fairly consistent exponential rise devoid of the effect of the terrain and tropospheric parameters of the data points. The implication is that; there are data points from the DTTBS whose path losses were either over or under predicted by the existing Okumura-Hata model, however the modified model has revealed the actual pattern taking into consideration the influence of the specified tropospheric parameters.

Results based on statistical analyses revealed that the proposed models are significant and reliable for use in the study areas. This is based on the standard deviation (SD), correlation coefficient and the RMSE.

### Table 2. Basic statistics of parameters for dry season months in Ikorodu-Lagos.

| Basic Statistics                            | Mean    | Standard Deviation | n  |
|--------------------------------------------|---------|--------------------|----|
| LOS distance from DTTBS (km)               | 4.589   | 3.428              | 12 |
| Okumura-Hata urban path loss (dB) at 1.5 m RxHt | 120.327 | 28.341             | 12 |
| Okumura-Hata urban path loss (dB) at 3.0 m RxHt | 117.637 | 28.341             | 12 |
| Elevation (ELV) of data points (m)         | 33.250  | 6.283              | 12 |
| Humidity (%RH)                             | 80.667  | 6.443              | 12 |
| Surface Radio Refractivity, Ns (N-Units)   | 398.150 | 5.244              | 12 |

### Table 3. Basic statistics of parameters for wet season months in Ikorodu-Lagos.

| Basic Statistics                            | Mean    | Standard Deviation | n  |
|--------------------------------------------|---------|--------------------|----|
| LOS from DTTBS (km)                        | 4.605   | 3.443              | 12 |
| Okumura-Hata urban path loss (dB) at 1.5 m RxHt | 119.857 | 29.962             | 12 |
| Okumura-Hata urban path loss (dB) at 3.0 m RxHt | 117.167 | 29.962             | 12 |
| Elevation of data points (m)               | 33.000  | 6.353              | 12 |
| Humidity (%RH)                             | 90.417  | 4.231              | 12 |
| Surface Radio Refractivity, Ns (N-Units)   | 402.258 | 1.860              | 12 |

### Table 4. Basic statistics of parameters for dry season months in Kaduna.

| Basic Statistics                            | Mean    | Standard Deviation | n  |
|--------------------------------------------|---------|--------------------|----|
| LOS from DTTBS (km)                        | 6.6072  | 4.6363             | 16 |
| Okumura-Hata urban path loss (dB) at 1.5 m RxHt | 126.8640| 27.2749            | 16 |
| Okumura-Hata urban path loss (dB) at 3.0 m RxHt | 124.1729| 27.2748            | 16 |
| Elevation of data points (m)               | 607.8750| 29.1179            | 16 |
| Humidity (%RH)                             | 42.3125 | 7.9391             | 16 |
| Surface radio refractivity (N-units)        | 304.6656| 9.9582             | 16 |

### Table 5. Basic statistics of parameters for wet season months in Kaduna.

| Basic Statistics                            | Mean    | Standard Deviation | n  |
|--------------------------------------------|---------|--------------------|----|
| LOS from DTTBS (km)                        | 6.626   | 4.634              | 16 |
| Okumura-Hata urban path loss (dB) at 1.5 m RxHt | 126.417 | 29.374             | 16 |
| Okumura-Hata urban path loss (dB) at 3.0 m RxHt | 123.727 | 29.374             | 16 |
| Elevation of data points (m)               | 607.813 | 28.992             | 16 |
| Humidity (%RH)                             | 73.438  | 6.229              | 16 |
| Surface radio refractivity (N-units)        | 375.877 | 1.390              | 16 |

### Table 6. Basic statistics of parameters for dry season months in Katsina.

| Basic Statistics                            | Mean    | Standard Deviation | n  |
|--------------------------------------------|---------|--------------------|----|
| LOS distance from DTTBS (km)               | 7.0207  | 4.33269            | 14 |
| Okumura-Hata sub-urban path loss (dB) at 1.5 m RxHt | 118.9275| 37.07668           | 14 |
| Okumura-Hata sub-urban path loss (dB) at 3.0 m RxHt | 116.3658| 36.37643           | 14 |
| Elevation of data points (m)               | 517.4286| 4.50153            | 14 |
| Humidity (%RH)                             | 32.5102 | 2.3769             | 14 |
| Surface radio refractivity (N-units)        | 301.2121| 21.69138           | 14 |
during the dry season while 122.25 and 117.64 dB with SD of 31.36 and 28.34 were obtained during wet season months. The evaluated correlation coefficients between measured and MOHPL in Ikorodu-Lagos during the dry and wet seasons are 0.897 and 0.998 respectively. Similarly, in Kaduna mean values of 126.18 and 124.17 dB with SD of 26.65 and 27.28 were obtained for proposed and measured models respectively during the dry season while 127.19 and 125.05 dB with SD of 31.22 and 30.54 were obtained during wet season months. Correlation coefficients between measured and MOHPL in Kaduna during the dry and wet seasons are 0.976 and 0.964 respectively. In Katsina, mean path loss values of 116.07 and 113.87 dB with SD of 31.53 and 31.05 were obtained for proposed and measured models respectively during the dry season while 120.40 and 117.80 dB with SD of 31.22 and 31.52 were obtained during wet season months. The evaluated correlation coefficients between

### Table 7. Basic statistics of parameters for wet season months in Katsina.

| Basic Statistics                        | Mean    | Standard Deviation | n  |
|----------------------------------------|---------|--------------------|----|
| LOS from DTTBS (km)                    | 8.375   | 5.835              | 14 |
| Okumura-Hata sub - urban path loss (dB) at 1.5 m RxHt | 115.605 | 28.701             | 14 |
| Okumura-Hata sub - urban path loss (dB) at 3.0 m RxHt | 112.911 | 28.700             | 14 |
| Elevation of data points (m)           | 524.286 | 10.702             | 14 |
| Humidity (%RH)                         | 77.929  | 5.650              | 14 |
| Surface radio refractivity (N-units)   | 358.494 | 9.278              | 14 |

### Table 8. Summary of the proposed models in a smart format.

| Location   | Parameter | MOHPL(dB) = k + aLOS + βELV + γNS + ρH |
|------------|-----------|----------------------------------------|
| Dry Season | k         | α           | β            | γ    | ρ    | k         | α           | β            | γ    | ρ    |
| Ikorodu-Lagos | -670.362 | 3.370       | 0.644        | 2.891 | -5.174 | 2605.601 | 12.941     | -0.114       | -8.265 | 8.357 |
| Kaduna     | -914.167  | -6.893      | -0.122       | 5.189  | -13.086 | -767.307 | 2.811      | 0.073        | 2.091  | 0.316 |
| Katsina    | 1492.364  | 9.363       | -2.689       | -0.050 | -0.184 | 2267.075 | 3.365      | -1.187       | -4.453 | 0.871 |

Figure 8. Comparison of Measured and Proposed (MOHPL) Path Loss Models for Ikorodu-Lagos during: (a) Dry Season Months’ (b) Wet Season Months’.
Table 9. Basic statistics of MOHPL and Okumura-Hata Path Loss models over the study areas.

| Location/Season         | Model      | Mean Path Loss (dB) | Standard Deviation | Pearson's Correlation Coefficient (P-value) |
|-------------------------|------------|---------------------|--------------------|---------------------------------------------|
| Ikorodu-Lagos/Dry season| MOHPL      | 118.47              | 23.75              | 0.897 (0.000)                              |
|                         | Okumura-Hata| 115.23              | 27.26              |                                             |
| Ikorodu-Lagos/Wet season| MOHPL      | 122.25              | 31.36              | 0.998 (0.000)                              |
|                         | Okumura-Hata| 117.64              | 28.34              |                                             |
| Kaduna/Dry season       | MOHPL      | 126.18              | 26.65              | 0.976 (0.000)                              |
|                         | Okumura-Hata| 124.17              | 27.28              |                                             |
| Kaduna/Wet season       | MOHPL      | 127.19              | 26.65              | 0.964 (0.000)                              |
|                         | Okumura-Hata| 125.65              | 30.54              |                                             |
| Katsina/Dry season      | MOHPL      | 116.07              | 31.33              | 0.999 (0.000)                              |
|                         | Okumura-Hata| 113.87              | 31.04              |                                             |
| Katsina/Wet season      | MOHPL      | 120.40              | 31.22              | 0.998 (0.000)                              |
|                         | Okumura-Hata| 117.80              | 31.52              |                                             |

Table 10. RMSE value between Okumura - Hata model and MOHPL over the study area.

| Study area/climatic zone | RMSE for dry season (dB) | RMSE for wet season (dB) | Mean RMSE (dB) |
|--------------------------|--------------------------|--------------------------|----------------|
| Ikorodu-Lagos/Coastal   | 12.50                    | 5.81                     | 9.16           |
| Kaduna/Sudan Savannah    | 6.40                     | 3.92                     | 5.16           |
| Katsina/Sahel Savannah   | 2.60                     | 2.35                     | 2.48           |
measured and MOHPL during the dry and wet seasons are 0.999 and 0.998 respectively.

In addition, it was observed that the mean values for the proposed model (MOHPL) were slightly higher than the existing Okumura-Hata model in all the study locations irrespective of the seasons. The deviation between the proposed and the standardized Okumura-Hata model ranges between 3-7 dB. This value cannot be overlooked particularly over a digital channel in order to minimize coverage failures. This implies that Okumura Hata Model under estimated the path losses associated with digital terrestrial television channel over the study locations. In order to ensure optimum planning of power budget and equipment design, the proposed models are recommended for use over the study location.

Furthermore, Table 10 presents the RMSE between Okumura Hata Model and MOHPL in the study areas. RMSE obtained during dry and wet season months in Ikorodu-Lagos are 12.50 and 5.81 dB respectively with mean value of 9.16 dB. These results are within the acceptable ranges according to Blaunstein et al. (2003) because Ikorodu-Lagos is partly urban and sub urban. Similarly, in Kaduna (an urban city) RMSE of 6.40 and 3.92 dB were obtained during dry and wet season months respectively with mean value of 5.16 dB. This is equally within the acceptable range for urban areas. Finally, RMSE of 2.60 and 2.35 dB were obtained during dry and wet season months respectively in Katsina with mean value of 2.48 dB. The overall RMSE values validate the proposed models to be fit and dependable for use over the study area.

5. Conclusion

In conclusion, the following results were deduced from this study amongst others:

(i) The evaluated Okumura-Hata path loss increases with increase in LOS separation distance from DTTBS irrespective of routes and seasons following a fairly consistent exponential rise while the Modified Okumura-Hata Model (MOHPL) followed similar trend with few exceptions of crests and troughs depicting the influence of the incorporated location’s-based tropospheric parameters. This underscores the need for high power transmitters or repeater stations over the study areas to ensure wider coverage and quality of service.

(ii) Path losses estimated were higher in urban compared to the sub urban cities and as well in the wet compared to the dry season’s months. The implication of this is that; the service providers on these channels should make deliberate efforts to compensate for the peculiar losses in urban cities, as well as during the wet season to ensure QoS.

(iii) Positive correlation coefficients of 0.76, 0.75 and 0.74 were obtained between path loss and LOS separation distance from DTTBS for the coastal, Sudan Savannah and Sahel Savannah climatic zones respectively. In the same order, negative correlation coefficients of -0.72, -0.79 and -0.63 were obtained between path loss and RSS. So also, negative correlation coefficients of -0.54, -0.30 and -0.51 were obtained between path loss and elevation above sea level of data points.

(iv) Modified path loss (MOHPL) models that incorporate the specified location’s-based tropospheric parameters were proposed for both seasons under study over Nigeria. The proposed models were tested practically and statistically and found to be dependable for use over the study areas.

(v) One of the key findings is that Okumura - Hata model under estimated the path loss associated with digital terrestrial television channel over the study locations. The deviation between the proposed and the standardized Okumura-Hata model ranges between 3-7 dB. This value cannot be overlooked particularly over a digital channel in order to minimize coverage failures.

(vi) This study has also revealed that the specified tropospheric parameters possess attenuation effects on the signal of digital terrestrial television over the study locations.

The overall findings of this work will be useful for the accurate prediction of path loss and the design of power budgets and link’s over digital terrestrial television and similar wireless channels on the UHF band.

5.1. Recommendation

In order to ensure optimum planning of power budget and link’s design over the study locations, the proposed models are recommended for use. It is equally recommended that DTTV subscribers should make use of 3.0 m as the minimum receiver antenna height in the sub urban areas while those in urban cities should raise their antenna as high as possible for optimum reception over the study locations so as to minimize path losses.

Declarations

Author contribution statement

A. Akinbolati: Performed the experiments; Analyzed and interpreted the data; Wrote the paper.
M. O. Ajewole: Conceived and designed the experiments; Wrote the paper.

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References

Abhayawardhana, V.S., Wassell, I.J., Crossby, D., Sellars, M.P., Brown, M.G., 2005. Comparison of Empirical Propagation Path Loss Models for Fixed Wireless Access Systems, 1. IEEE Vehicular Technology Conference, pp. 73–77, 2005. VTC 2005-Spring.

Aidedji, A.T., Ajewole, M.O., 2008. Vertical profile of radio refractivity gradient in Akure, South West Nigeria. Prog. Electromag. Res. C 4, 157-168.

Ajewole, M.O., Akinbolati, A., Aidedji, A.T., Ojo, J.S., 2014. Precipitation effect on the coverage areas of terrestrial UHF television stations in Osibo state, Nigeria. Int. J. Eng. Technol. 4 (9), 12-27.

Akinbolati, A., Akinsannmi, O., Efunshobo, K.R., 2016. Signal strength variation and propagation profiles of UHF radio wave channel in Osibo state, Nigeria. Int. J. Wireless Microwav. Technol. (IJWMT) 6 (4), 524-535.

Akinbolati, A., Ajewole, M.O., Aidedji, A.T., Ojo, J.S., 2017. The influences of meteorological parameters on digital terrestrial television (DTT) signal in the tropics, Int. J. Digit. Inf. Wireless Commun. 7 (3), 161–172.

Akinbolati, A., Ajewole, M.O., Aidedji, A.T., Ojo, J.S., 2020. Propagation Curves and Coverage Areas of Digital Terrestrial Television Base Stations in the Tropical Zone. Elsevier Heliyon 6 (3), e03599.

Akingbade, A.S., Olorunmibi, D., 2013. Path Loss Prediction Model For UHF Radiowaves Propagation in Akure Metropolis. Int. J. Eng. Technol. 4 (9), 524–535.

Abhayawardhana, V.S., Wassell, I.J., Crossby, D., Sellars, M.P., Brown, M.G., 2005. Comparison of Empirical Propagation Path Loss Models for Fixed Wireless Access Systems, 1. IEEE Vehicular Technology Conference, pp. 73–77, 2005. VTC 2005-Spring.

Aidedji, A.T., Ajewole, M.O., 2008. Vertical profile of radio refractivity gradient in Akure, South West Nigeria. Prog. Electromag. Res. C 4, 157-168.

Ajewole, M.O., Akinbolati, A., Aidedji, A.T., Ojo, J.S., 2014. Precipitation effect on the coverage areas of terrestrial UHF television stations in Osibo state, Nigeria. Int. J. Eng. Technol. 4 (9), 12-27.

Akinbolati, A., Ajoye, M.O., Aidedji, A.T., Ojo, J.S., 2017. The influences of meteorological parameters on digital terrestrial television (DTT) signal in the tropics, Int. J. Digit. Inf. Wireless Commun. 7 (3), 161–172.

Akinbolati, A., Ajewole, M.O., Aidedji, A.T., Ojo, J.S., 2020. Propagation Curves and Coverage Areas of Digital Terrestrial Television Base Stations in the Tropical Zone. Elsevier Heliyon 6 (3), e03599.

Akingbade, A.S., Olorunmibi, D., 2013. Path Loss Prediction Model For UHF Radiowaves Propagation in Akure Metropolis. Int. J. Eng. Technol. 4 (9), 524–535.

Akinbolati, A., Ajoye, M.O., Aidedji, A.T., Ojo, J.S., 2017. The influences of meteorological parameters on digital terrestrial television (DTT) signal in the tropics, Int. J. Digital Inf. Wireless Commun. 7 (3), 161–172.

Akinbolati, A., Ajewole, M.O., Aidedji, A.T., Ojo, J.S., 2020. Propagation Curves and Coverage Areas of Digital Terrestrial Television Base Stations in the Tropical Zone. Elsevier Heliyon 6 (3), e03599.
Bean, B.R., Cahoon, B.A., Samson, C.A., Thayer, G.D., 1966. A world class atlas of atmosphere radio refractivity Tech. rep. In: Institute for Telecommunication Sciences and Aeronomy, Boulder, Colorado, USA.

Blaunstein, N., Censor, D., Katz, D., Freedman, A., Matityahu, I., 2003. Radio propagation in rural residential areas with vegetations. Prog. Electromag. Res. 40, 131–140.

Bothians, L., 1987. Radio wave propagation, McGraw-Hill Inc. New York St. Louis an Francisco Montreal Toronto, pp. 10–105.

COST 231, 1991. Urban transmission loss models for mobile radio in the 900 and 1800 MHz bands (revision 2). In: COST 231 TD (90) 119 Rev. 2, The Hague, the Netherlands.

Dairo, O.F., Kolawole, L.B., 2017. Statistical analysis of radio refractivity gradient of the rainy-Harmattan transition phase of the lowest 100 m over Lagos. Nigeria J. Atmos. Solar Terr. Phys. 1–10.

Faruk, N., Ayeni, A.A., Adediran, A.Y., 2013. On the study of empirical path loss models for accurate prediction of TV signal for secondary users. Prog. Electromag. Res. B 49, 1–5.

Hata, M., 1980. Empirical formula for propagation loss in land mobile radio services. IEEE Trans. Veh. Technol. 29, 317–324.

ITU-R, 1997. Propagation Data and Prediction Methods Required for the Terrestrial Land mobile Services. Recommendation P.529-3.

ITU-R, 2003. The Radio Refractive index: its Formula and Refractivity Data. Recommendation P.453-9.

Kenedy, G., Bernard, D., 1999. Electronic communication system. In: McGraw-Hill/Macmillan, Singapore, pp. 80–85.

Mollel, M.S., Kisangiri, M., 2014. Comparison of empirical propagation path loss models for mobile communication. Comput. Eng. Intell. Syst. 5, 1–10.

Nisirat, M.A., Ismail, M., Nisirat, L., Al-Khawaldeh, S., 2011. A terrain correction factor for Hata path loss model at 900 MHz. Prog. Electromag. Res. C 22, 11–22.

Okafor, O.N., Agbo, G.A., 2012. The effect of variation of meteorological parameters on the tropospheric radio refractivity for Minna. Global J. Inc. (US) 1, 1–10.

Okumura, T., Ohmori, E., Fukuda, K., 1968. Field strength and its variability in VHF and UHF land mobile service, review Electrical communication laboratory, 16, 824–870. Oyedum, D.O., Gambo, G., 1994. Surface radio refractivity in northern Nigeria. Niger. J. Phys. 6, 36–40.

Ranvier, S., 2004. Path loss models, S-72.333 Physical layer methods in wireless communication systems. In: Radio Laboratory/TKK, 23 November.

Sarkar, Tapan K., Kyungjung Kim, Zhongji, Abdellatif of Medouri and Magdelena Salazar-Palma, 2003. A survey of various propagation models for mobile communications. IEEE Antenn. Propagat. Mag. 45 (3), 3–10.