Radio Frequency Propagation Studies for Digital Terrestrial Television Using Low-Cost Software Defined Radio

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Abstract:
Path loss measurement and modeling are necessary for selecting or developing suitable propagation models for specific radio environments. In this work, the signal power of six ultra-high frequency (UHF) digital broadcast transmitters was measured and variation of signal power was modeled. Measurements were obtained using a low-cost testbed made up of a global positioning system module and a Realtek software-defined radio (RTL-SDR) configured as a spectrum analyzer. The study was carried out in Nigeria's Adamawa and Bauchi States along twelve distinct routes. The path loss exponent, path loss intercept (determined by the mean free space attenuation), and log-normal shadowing variable for each route were determined. The average path loss exponents for the three transmitters in Adamawa, operating at 470, 522, and 538 MHz, are 1.71, 1.84, and 1.81, respectively. In contrast, for the transmitter in Bauchi operating at 634, 642, and 650 MHz, their respective average exponent values are 1.19, 1.18, and 1.21. A log-normal path loss model was developed and compared with the measured data and established empirical path loss models. In comparison to the empirical path loss models, the log-normal model offers a better root-mean-squared error performance. Additionally, a graphical comparison demonstrates that the Okumura-Hata model tends to overestimate the data whereas the log-normal model offers the best fit for the data. In contrast to the Okumura-Hata model, the Egli propagation model tends to underestimate the measured data.
Keywords: Path loss, log-normal shadowing, software-defined radio

1. INTRODUCTION

Propagation studies are an integral part of designing wireless communication systems for specific applications or environments. Analytical path loss models also known as foundational models are constructed from idealized propagation physics. Examples of these models include the Two-ray Ground Reflection model, the Flexible Path Loss Exponent Model, and the Friss Equation for free space between isotropic antennas. Even though these models are easy to develop, they are not appropriate for applications that require high accuracy. Other propagation modeling approaches based on statistical analysis, topography data, and machine learning are based on the measurement of received signal power. A classic measurement campaign that forms the basis of several path loss propagation models is the work of Okumura in [1]. In recent times, several path loss propagation studies have been carried out to meet specific requirements of various wireless communication networks in different environments. For example in [2], the researchers conducted propagation studies based on measurements in a rural area of South Korea to develop a path loss model that incorporates a diffraction component. Similarly, a path loss model that considers the effect of building diffraction and surface water reflection for propagation at 28 GHz frequency was proposed in [3]. Other research works such as [4] and [5] consider factors such as obstacles on roads, weather conditions and shadowing in specific environments for different applications. Several research endeavors in specific Nigerian states have focused on studying radio propagation for digital terrestrial television. In [6], the authors conducted path loss measurements for three digital terrestrial transmitters located in Kaduna, Katsina, and Lagos states. These researchers adjusted the Okumura-Hata model by using radio refractivity values measured along different routes. Authors in [7] specifically explored the suitability of the Okumura-Hata model for predicting path loss in Plateau state, Nigeria. Additionally, in [8], a log-normal path loss model was developed by researchers based on measurements taken along a specified route in Rivers state. The outcomes from these diverse Nigerian states underscore the variations in digital television signal behavior across dissimilar environmental settings.

These measurements are conducted using expensive spectrum analyzers or handheld signal strength meters. A viable and cost-effective alternative is to configure a software defined radio as spectrum analyzer for propagation measurement campaigns. Software-defined radio (SDR) refers to radio systems in which most physical layer functionalities such as carrier synchronization, equalization, interleaving, baseband modulation and demodulation are implemented in software using digital signal processing algorithms. The front end of the SDR captures radio frequency signals, down-converts them to baseband, digitizes them and outputs samples of the baseband signal across its USB interface[8]. Several studies such [9], [10] and [11] have indicated that SDRs can provide adequate radio signal measurement comparable to commercial radio frequency spectrum analyzers. In addition, SDR provides better flexibility for channel characterization in special applications such as communication links for implantable medical devices [12] and internet-of-things [13]. In particular, the Realtek software defined radio (RTL-SDR) is a low-cost device (costs less than $30) that can be used to receive any electromagnetic signal within the operating range of its tuner (25MHz – 1750 GHz) [8]. It can be configured as a spectrum analyzer using computer applications such as MATLAB, GNU Radio and Python programming language.

II. Methodology

This section discusses the methodology used for data collection and path loss modelling. Primary data was collected using a low-cost and flexible set-up consisting of a laptop computer, an RTL-SDR device and HiLetgo VK172 G-Mouse global positioning system module. Secondary details regarding the broadcasting transmitters' operational parameters were provided by the station operators. The operational parameters of the various digital television stations are presented in Table 1 and Table 2 for Adamawa and Bauchi States respectively.

TABLE 1: OPERATIONAL PARAMETERS OF DIGITAL TELEVISION TRANSMITTERS IN ADAMAWA STATE

Parameter	Transmitter 1	Transmitter 2	Transmitter 3
UHF Channel	23	27	29
Frequency (MHz)	490	522	538
Transmit Power (kW)	2.6	2.6	2.6
Antenna Height (m)	150	150	150
Latitude	9.3060	9.3060	9.3060
Longitude	12.4776	12.4776	12.4776

TABLE 2: OPERATIONAL PARAMETERS OF DIGITAL TELEVISION TRANSMITTERS IN BAUCHI STATE

Parameter	Transmitter 1	Transmitter 2	Transmitter 3
UHF Channel	41	42	43
Frequency (MHz)	634	642	650
Transmit Power (kW)	2.6	3.0	2.9
Antenna Height (m)	150	150	150
Latitude	10.3292	10.3292	10.3292
Longitude	9,8597	9.8597	9.8597

A. Measurement Set-up and Data Collection

The measurement equipment consists of a Realtek Software Defined Radio (RTL-SDR) device, an Omni-directional antenna, a Global Positioning System (GPS), and a laptop computer. MATLAB technical computing software was installed on the computer. The functional components of the experimental set-up are shown in Fig. 1.

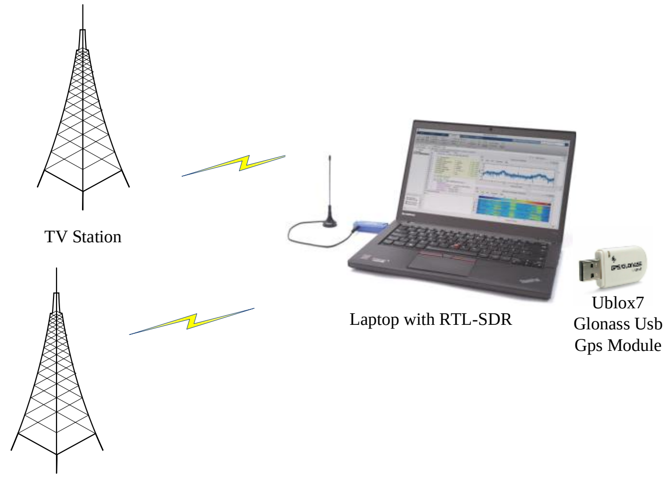

Fig.1. measurement set-up

The RTL-SDR device was connected to computer through a universal serial bus (USB) interface and configured using MATLAB’s communications toolbox support package. This hardware support allows the RTL-SDR to function as a standalone peripheral for streaming live radio frequency signals. The RF front-end of the SDR device is implemented using the Rafael R820T silicon tuner to downconvert radio frequencies (RF) to an intermediate frequency (IF) of 3.57 MHz [8]. Following this, the Realtek RTL2832U demodulator downcoverts the IF signal to baseband and use its on-board analog to digital converter (ADC) to sample the baseband signal. The in-phase and quadrature (IQ) samples undergo decimation in order to decrease the sampling rate of the signal that is transmitted over the USB (universal serial bus) interface of the RTL-SDR.

MATLAB’s communications system toolbox is used to stream the live IQ data after which the signal power level is estimated using digital signal processing algorithms. The functional block diagram of RF data acquisition and power estimation is shown in Fig. 2.

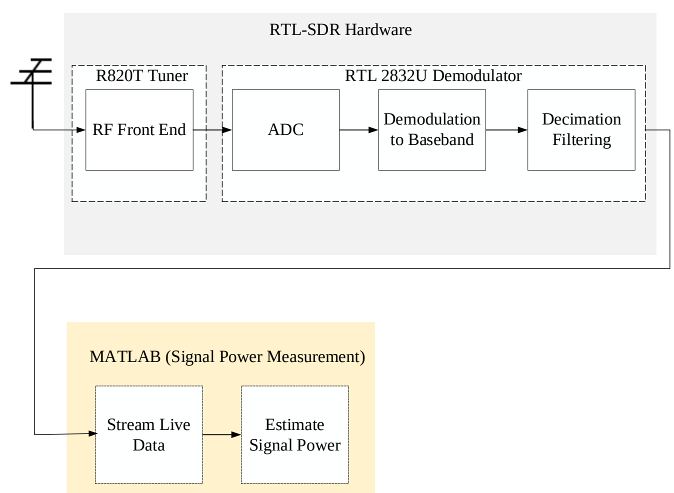

Fig. 2. block diagram of the software defined radio receiver chain

HiLetgo VK172 G-Mouse USB dongle was used to acquire the latitude, longitude, and elevation of each measurement location. The device is a global positioning system (GPS) receiver that provides a tracking sensitivity of -162 dBm with support for the world geodic system (WGS-84) coordinate system. The required data is streamed from the device using MATLAB navigation toolbox.

The propagation campaigns were carried out along major routes in Adamawa and Bauchi states of Nigeria. Measurements were taken at intervals of approximately 250 m while driving in a car at a speed of 30kilometers per hour. The measurement locations are shown on Google Maps base map in Fig. 3 and Fig. 4 for Adamawa and Bauchi States respectively.

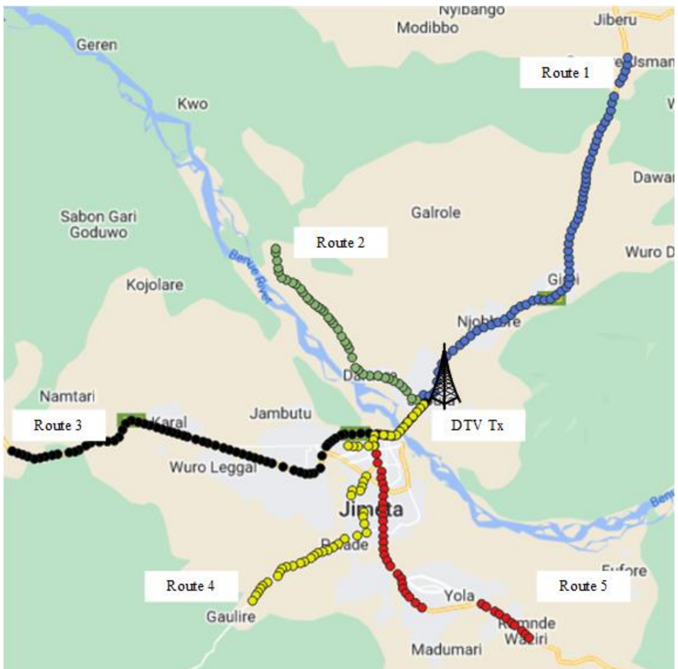

Fig.3. GPS points of measurement locations for Adamawa

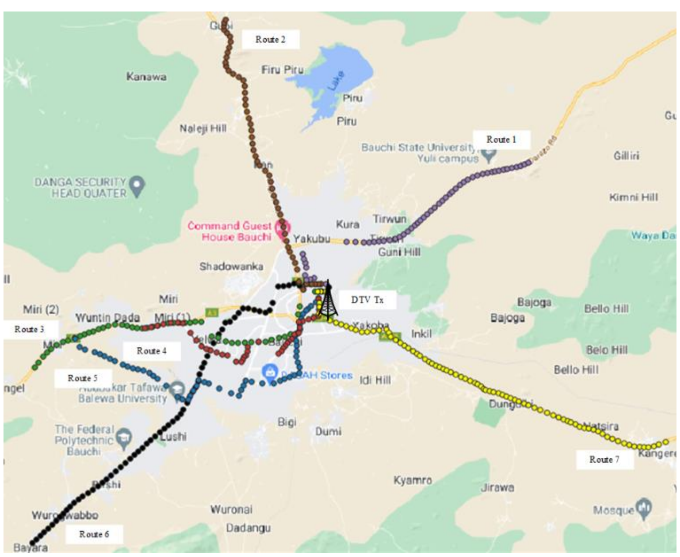

Fig.4. GPS points of measurement locations for Bauchi

Signal power and location data measurements are accomplished using an algorithm developed in MATLAB as shown in Fig. 5. The algorithm first configures the communication port and output format for the GPS module and the operational parameters of the SDR. An SDR gain of 29.7 dB was selected to provide adequate signal to noise ratio while avoiding overload and intermodulation from strong signals that might be present within the filter bandwidth of the dongle. The center frequency of the SDR is set to the operating frequency of the television transmitter for which measurement is to be taken. A resolution bandwidth of 125 Hz was determined for the spectrum estimator using a fast Fourier transform length of 16384 and an SDR sampling rate of 2.048 MHz.. At every specific measurement site, 1000 readings of the signal power level are taken, and an average value is subsequently calculated. The average signal power is recorded along with the latitude, longitude, and elevation of the location in a text file for post processing. After taking readings at ten (10) consecutive locations, the data collection process is paused to inspect the collected data before continuing with the drive test.

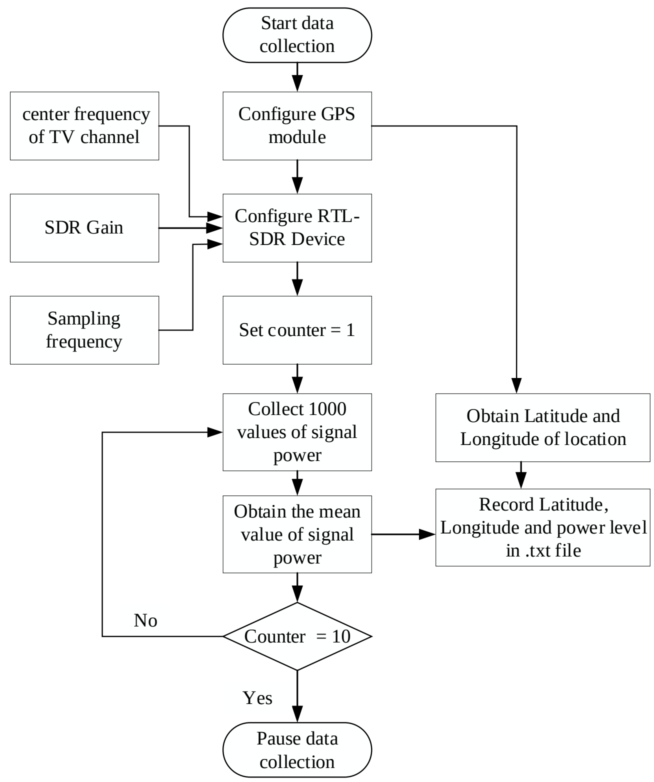

Fig. 5. Data collection procedure

B. Path Loss Modelling

Received signal power levels decrease with distance in a log-normal manner with the slope of the decline determined by the path loss exponent of the propagation environment. Assuming a fixed antenna height, the path loss of an environment can be expressed by log-normal distance path loss model expressed in (1) [9].

$$P_L(dB) = C + 10\eta log_{10}(d) + \chi_\sigma \quad (1)$$

Where:

$P_L(dB)$ = path loss (dB)
C = constant that depends on average free space channel attenuation and antenna characteristics
η = path loss exponent
d = separation distance between transmitter and receiver (km)
χ_σ = log-normal distributed random variable with a standard deviation σ

The separation of each measurement site from a given television transmitter is determined using the harversine formula of (2) [14].

$$d = 2rsin^{-1}\left(\sqrt{sin^2\left(\frac{\varphi_1 - \varphi_2}{2}\right) + \cos(\varphi_1)cos(\varphi_2)sin^2\left(\frac{\lambda_1 - \lambda_2}{2}\right)}\right) \quad (2)$$

Where:
d = distance between the transmitter and receiver (km),
r = radius of the earth in kilometers,
φ_1 = latitude of the TV transmitter
φ_2 = latitude of the measurement site
λ_1 = longitude of transmitter location (in radians)
λ_2 = longitude of measurement location (in radians)

The path exponent (η) and attenuation constant (c) in the log-normal path loss model correspond to the slope (b) and intercept (k), respectively, in the linear regression model described in equation (3) and depicted in figure 6.

$$y_i = k + bx_i \quad (3)$$

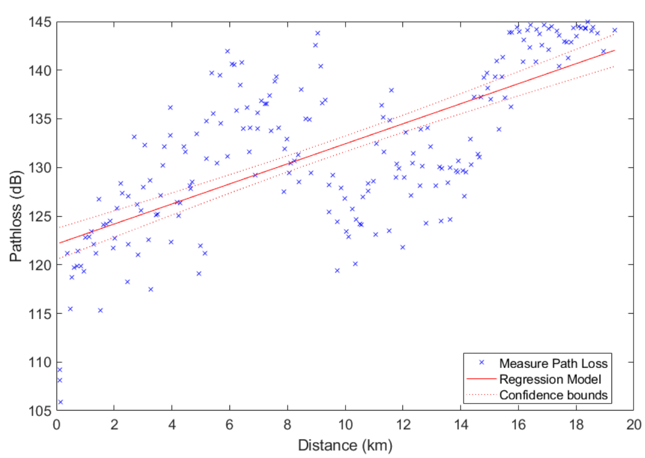

Fig.6. Linear Regression to formulate log-distance path loss model

The log-normal random variable of (1) accounts for random variations due to shadowing effects such as reflection, absorption and refraction of the radio signal within the environment. The standard deviation used to estimate the shadowing effect can be computed by comparing measured values at specific distances with predictions from (3). The path loss exponent, attenuation constant and standard deviation for the different routes in Adamawa and Bauchi States are averaged and substituted in (1) to give the log-normal path loss model of (4) and (5) respectively.

$$PL_a = \begin{cases} 111.89 + 17.1log_{10}(d) + \chi_{9.69} & f = 490 \\ 111.75 + 18.4log_{10}(d) + \chi_{10.12} & f = 522 \\ 111.26 + 18.1log_{10}(d) + \chi_{9.91} & f = 538 \end{cases} \quad (4)$$

$$PL_b = \begin{cases} 117.56 + 11.9log_{10}(d) + \chi_{7.73} & f = 634 \\ 117.14 + 11.8log_{10}(d) + \chi_{8.18} & f = 642 \\ 117.86 + 12.1log_{10}(d) + \chi_{8.43} & f = 650 \end{cases} \quad (5)$$

It is also necessary to compare the measured path loss data and log-normal path loss model with established empirical path loss models. The Okumura-Hata propagation is an established empirical model that is amenable to both broadcast and point-to-point communications. The Okumura-Hata model for urban cities is the basic variant and is given as:

$$PL_u = 69.55 + 26.16log_{10}f - 13.82log_{10}h_b - C_H + (44.9 - 6.55log_{10}h_b)log_{10}r \quad (6)$$

Where:
PL_u = path loss in urban areas (units in dB),
h_b =height of antenna base station (units in m),
f = frequency of transmission (units in MHz),
C_H = Antenna height correction factor and r =distance between transmitter and receiver (units in km).

The antenna correction for a small or medium-sized city is given as:

$$C_H = 0.8 + (1.1\log_{10}f - 0.7)h_r - 1.56log_{10}f \quad (7)$$

Where h_r is the height of the receiver antenna (m).
For suburban environments where man-made structures are not as dense and high as the urban environment, the Okumura-Hata Model is formulated as:

$$PL_{sub} = PL_u - 2\left(log_{10}\frac{f}{28}\right)^2 - 5.4 \quad (8)$$

Similarly, the Okumura-Hata model is amenable to transmissions in rural environments characterized by open spaces and no obstruction using the formula:

$$PL_{ru} = PL_u - 4.78(log_{10}f)^2 + 18.33(log_{10}f) - 40.94 \quad (9)$$

Another important empirical model is the Egli model, which is applicable for frequencies between 90 and 1000 MHz over irregular terrains [15]. The path loss equation for the Egli is given in (10).

$$PL(dB) = 20log_{10}(f) + 40log_{10}(r) - 20log_{10}(h_b) + \begin{cases} 76.3 - 10log_{10}(h_r) & h_r < 10\text{m} \\ 85.9 - 10log_{10}(h_r) & h_r > 10\text{m} \end{cases} \quad (10)$$

III. RESULTS AND DISCUSSIONS

The entire dataset of the measured signal power along all the routes is shown in Fig. 7. The distance has a negative correlation coefficient of -0.7125 with the measured signal power. This inversely proportional relationship is as expected since signal strength is known to attenuate with increase in distance between a radio transmitter and receiver.

Fig. 8 and Fig.9 provide a statistical comparison of the root-mean-square error for the log-normal model, the Okumura-Hata model, and the Egli model along selected routes in Adamawa and Bauchi states. The log-normal model provides a better RMSE performance as it was derived from measurements obtained from the study area. Similar results were obtained for the remaining four (4) routes in Adamawa State and six (6) routes in Bauchi State.

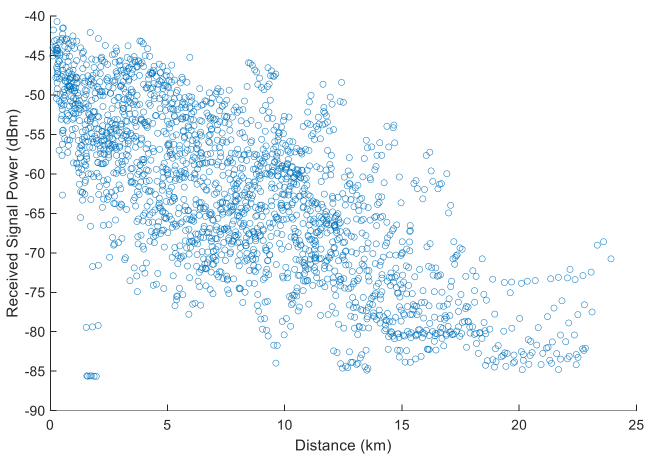

Fig.7. Variation of measured signal power with Distance

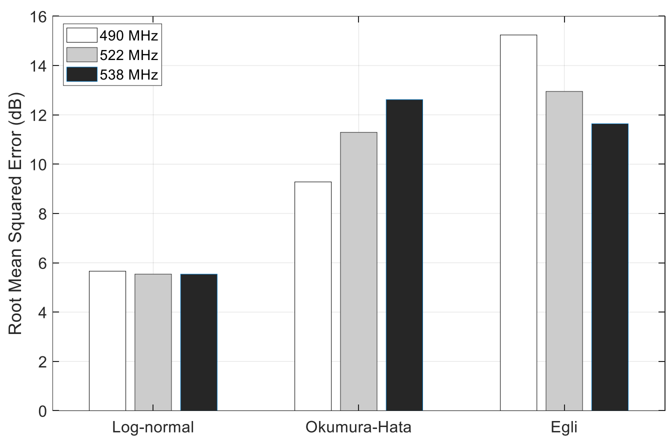

Fig.8: RMSE for measurements along route 3 in Adamawa

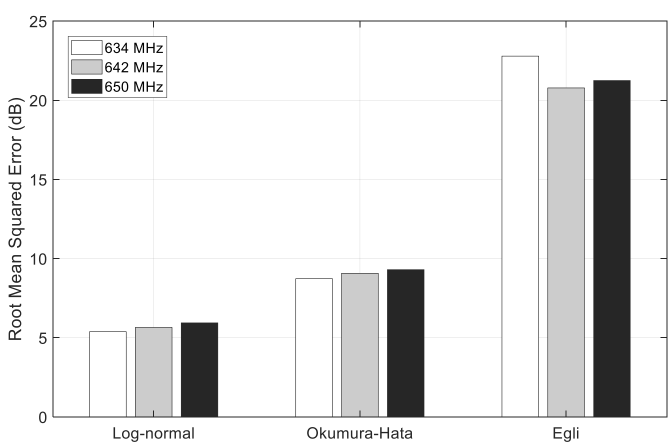

Fig.9: RMSE for measurements along route 3 in Bauchi

Graphical comparison of the measured data with the empirical measurements with the empirical measurements are provided in Fig.10 – Fig.15. The comparison shows while the Egli model tends to underestimate the data whereas the Okumura-Hata model tends to overestimate the data. The best fit is provided by the measurement-based log-normal model. The path loss exponent values calculated for Adamawa and Bauchi were relatively lower compared to those observed in Rivers State, as outlined in [8]. This difference primarily arises from the more urbanized landscape of Rivers State, characterized by numerous tall buildings. Additionally, the Okumura-Hata model underestimated the collected data in Rivers while tending to overestimate it in Adamawa and Bauchi States.

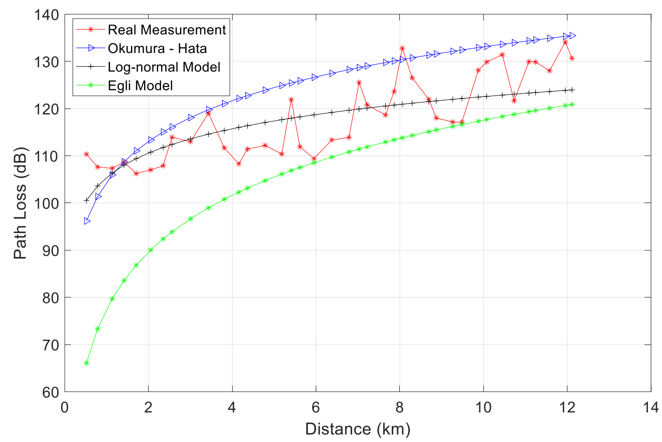

Fig.10. Comparison of measured data and empirical models for 490 MHz

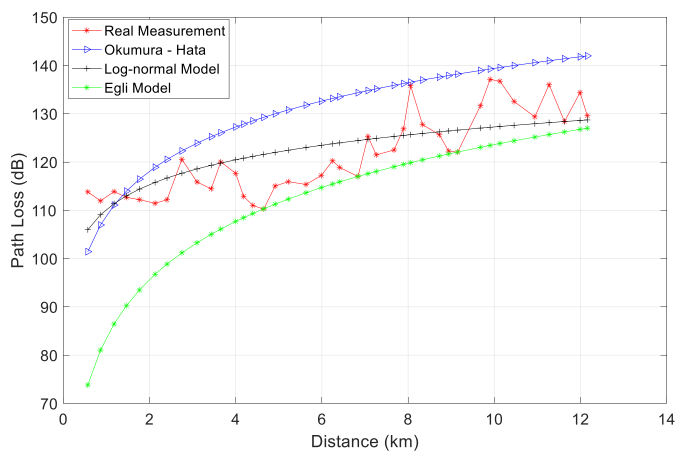

Fig.11. Comparison of measured data and empirical models for 522 MHz

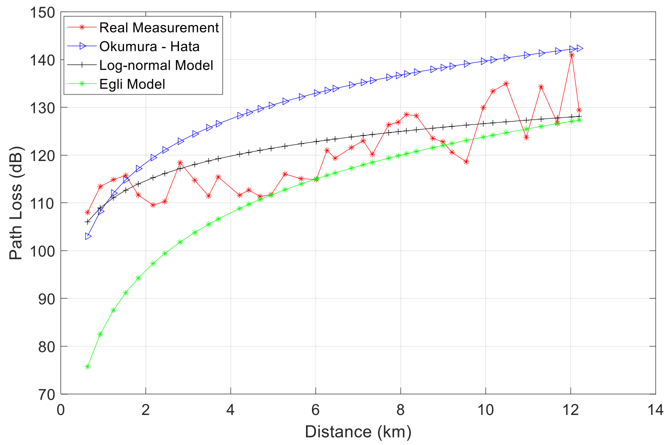

Fig.12. Comparison of measured data and empirical models for 538 MHz

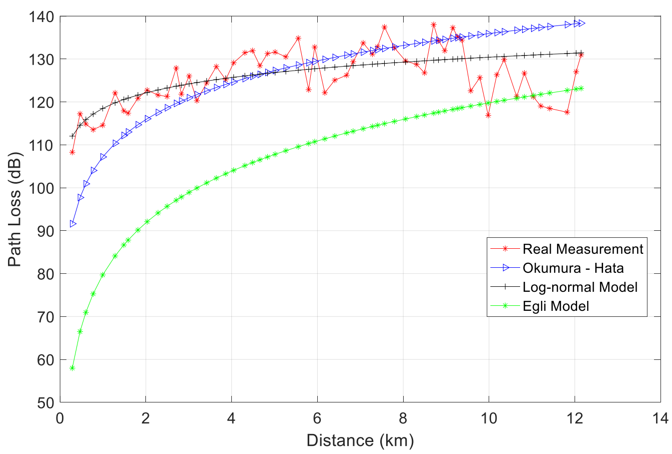

Fig.13. Comparison of measured data and empirical models for 638 MHz

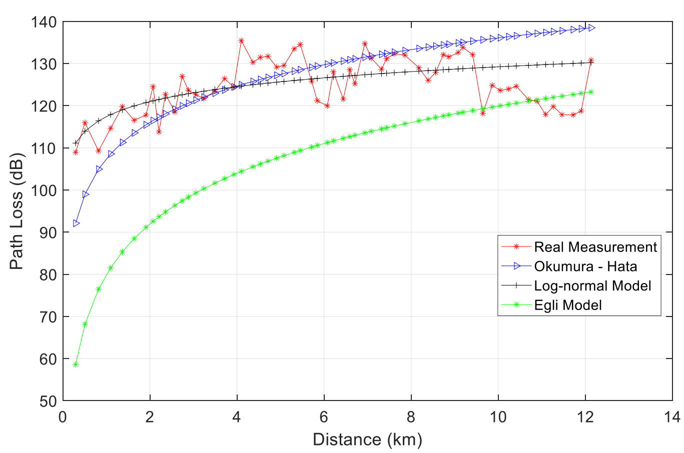

Fig.14. Comparison of measured data and empirical models for 642 MHz

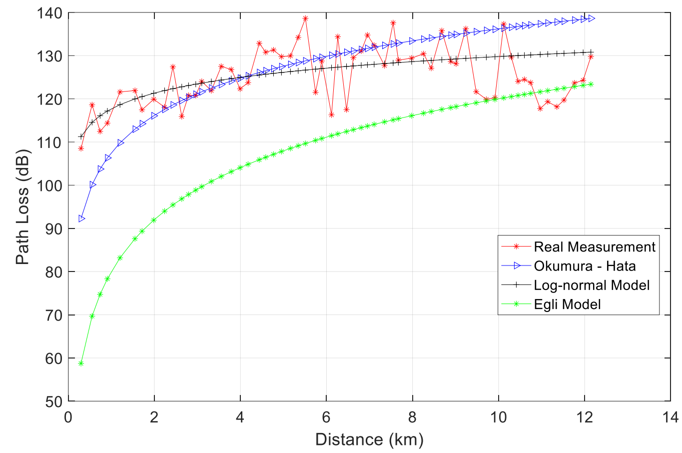

Fig.15. Comparison of measured data and empirical models for 650 MHz

IV. CONCLUSION

in this work, we measured the signal power levels of six different digital broadcasting transmitters along different routes in Adamawa and Bauchi states. This was accomplished using a low-cost software-defined radio, a GPS module, and a laptop. The measurement data obtained along twelve distinct routes in the study areas were used for radio frequency propagation studies. The propagation studies involved developing a log-normal path loss prediction derived from the path loss exponent, path loss intercept, and log-normal shadowing variable of the study area. In addition, the suitability of the Okumura-Hata and Egli models for the study area was also investigated.

The results obtained show that the log-normal model provides better performance in terms of root-mean-squared error performance. It also provides a better tracking of the measured path loss data. Considering cost-effectiveness, flexibility, and ease of use, the experimental set-up provides a veritable platform for developing active measurement-based path loss prediction models that provide better prediction accuracy. More extensive measurements at different antenna heights can be undertaken in future research works.

REFERENCE

[1] Y. Okumura, E. Ohmori, T. Kawano, and K. Fukuda, “Field strength and its variability in VHF and UHF land-mobile radio service,” *Rev. Commun. Lab.*, vol. 16, no. 9–10, pp. 825–873, 1968.

[2] J. Park, H.-B. Jeon, J. Cho, and C.-B. Chae, “Measurement-Based Close-In Path Loss Modeling With Diffraction for Rural Long-Distance Communications,” IEEE Wirel. Commun. Lett., vol. 12, no. 8, pp. 1334–1338, 2023, doi: 10.1109/LWC.2023.3273280.

[3] X. Liao, X. Li, Y. Wang, J. Zhou, T. Zhao, and J. Zhang, “Path Loss Modeling in Urban Water–Land Environments at 28 GHz: Considering Water Surface Reflection and Building Diffraction,” IEEE Antennas Wirel. Propag. Lett., vol. 22, no. 4, pp. 744–748, 2023, doi: 10.1109/LAWP.2022.3224155.

[4] S. Sung, W. Choi, H. Kim, and J.-I. Jung, “Deep Learning-Based Path Loss Prediction for Fifth-Generation New Radio Vehicle Communications,” IEEE Access, vol. 11, pp. 75295–75310, 2023, doi: 10.1109/ACCESS.2023.3297215.

[5] P. Kryszkiewicz, P. Sroka, M. Sybis, and A. Kliks, “Path Loss and Shadowing Modeling for Vehicle-to-Vehicle Communications in Terrestrial TV Band,” IEEE Trans. Antennas Propag., vol. 71, no. 1, pp. 984–998, 2023, doi: 10.1109/TAP.2022.3216472.

[6] A. Akinbolati and M. O. Ajewole, “Investigation of path loss and

modeling for digital terrestrial television over Nigeria," Heliyon, vol. 6, no. 6, pp. 1–15, 2020, doi: 10.1016/j.heliyon.2020.e04101.

[7] E. E. C. Igbonoba, "Investigated Performance of Okumura-Hata Model for Dvb-T2 Signal Propagation in Nigeria," Int. J. Recent Eng. Sci., vol. 2, no. 2021, pp. 10–15, 8AD.

[8] R. W. Stewart, K. W. Barlee, D. S. . Atkinson, and L. H. Crockett, Software Defined Radio Using MATLAB and Simulink and the RTL-SDR. Strathclyde Academic Media, 2015. [Online]. Available: www.desktopSDR.com

[9] D. P. Wright and E. A. Ball, "Highly Portable , Low Cost SDR Instrument for RF Propagation Studies," IEEE Trans. Instrum. Meas., vol. 69, no. 8, pp. 5446–5457, 2020, doi: 10.1109/TIM.2019.2959422.

[10] B. Reynders, R. N. Iyare, S. Rajendran, V. Volski, G. A. E. Vandenbosch, and S. Pollin, "Using Cheap RTL-SDRs for Measuring Electrosmog," pp. 1–3.

[11] A. Fanan, N. Riley, M. Mehdawi, M. Ammar, and M. Zolfaghari, "Comparison of Spectrum Occupancy Measurements using Software Defined Radio RTL-SDR with a Conventional Spectrum Analyzer approach," in 23rd Telecommunications Forum 2012, Serbia: IEEE, 2015, pp. 200–203.

[12] M. Manoufali, K. Bialkowski, A. T. Mobashsher, B. Mohammed, A. image of A. Abbosh, and A. Abbosh, "In Situ Near-Field Path Loss and Data Communication Link for Brain Implantable Medical Devices Using Software-Defined Radio," IEEE Trans. Antennas Propag., vol. 68, no. 9, pp. 6787–6799, 2020, doi: 10.1109/TAP.2020.2993106.

[13] N. El Hassainate, A. O. Said, and Z. Guennoun, "Communication Link Budget Estimation between Ground IoT Terminal and Cubesat 3U 's SDR," in IEEE International Conference on Internet of Things and Intelligence Systems (IoTaIS), 2022, pp. 172–178. doi: 10.1109/IoTaIS56727.2022.9975947.

[14] Captain HM Navigation School, "Admiralty Navigation Manal," Admir. Navig. Man., vol. 2, 1938.

[15] N. T. Surajudeen-Bakinde et al., "Path loss predictions for multi-transmitter radio propagation in VHF bands using Adaptive Neuro-Fuzzy Inference System," Eng. Sci. Technol. an Int. J., vol. 21, no. 4, pp. 679–691, 2018, doi: 10.1016/j.jestch.2018.05.013.

[16] B. I. Bakare, K. J. Biebuma, and S. Orike, "Analysis of Signal Attenuation in Digital Terrestrial Television (DTTV) Broadcasting," Eur. J. Electr. Eng. Comput. Sci., vol. 4, no. 4, pp. 1–8, 2020.