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Modeling the Distribution of Radiofrequency Intensities from the Digital Terrestrial Television (DTTV) Broadcasting Transmitters in Kampala Metropolitan; Uganda

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Authors' contributions

This work was carried out in collaboration among all authors. Author PO designed the study, performed the statistical analysis, wrote the protocol, managed the literature searches and wrote the first draft of the manuscript. Authors AK, TWI and WO managed the analyses of the study. All authors read and approved the final manuscript

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ABSTRACT

This study presents the modeling of the distribution of RF intensities from the Digital Terrestrial Television (DTTV) broadcasting transmitter in Kampala metropolitan. To achieve this, the performance evaluation of the different path loss propagation models and envisaging the one most suitable for Kampala metropolitan was done by comparing the path loss model values with the measured field Reference Signal Received Power (RSRP) values. The RSRP of the DTTV broadcasting transmitter were measured at operating frequencies of 526 MHz, 638 MHz, 730 MHz and 766 MHz using the Aaronia Spectran HF-6065 V4 spectrum analyzer, Aaronia AG HyperLOG 4025 Antenna at 1.5 m and 2.5 m heights, Aaronia GPS Logger, real time Aaronia MCS spectrum-analysis-software and a T430s Lenovo Laptop. On comparing the measured path loss values with the various path loss prediction model values, results showed that Egli and Davidson models are the

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most accurate and reliable path loss prediction models for the distribution of DTTV RF intensities in Kampala metropolitan, since their Root Mean Square Error values were the least for both routes.

Keywords: Radiofrequency intensities; path loss; empirical models; Reference Signal Received Power (RSRP); Root Mean Square Error (RMSE).

1. INTRODUCTION

In order to have a good estimate of Digital Terrestrial Television (DTTV) network signal coverage, the efficiency for total revolutionary switchover from analog to digital television signal transmission is dictated upon by signal pathloss and the use of the link budgeting [1-3]. This has caused a lot of anxiety amongst the media and the general public wanting to know the exact differences in quality of services between Analog Terrestrial Television (ATTV) and Digital Terrestrial Television (DTTV) broadcasting technologies. Because of this, researchers, scientists, and engineers have picked interest in researching about the modeling of the distribution of RF intensities from DTTV broadcasting transmitters in order to know the DTTV signal pathloss in different environments. With this, many DTTV network planners in different countries having different geographical settings find it easier to work on TV signal coverage planning, optimization and prediction by using empirical pathloss propagation models.

Fundamentally, TV signals always attenuate with distance which is the basis of these models [4,5]. For any environment, accurate optimization of pathloss is when the established pathloss models are subjected to empirical prediction with respect to the field measured Reference Signal Received Power (RSRP). Better optimization of the model depends on the calculated value of the Root Mean Square Error (RMSE) and a better fit for any propagation model is when its RMSE value is closer to zero. The acceptable RMSE value should not exceed about 6-7 dB for urban and 10- 15 dB for the sub-urban and rural areas [6].

Though there are other model optimization methods, like the composite function-based approach, adjustment of the original pathloss model coefficients [1,7,8], in this study, the RMSE approach was used alongside the field measured RSRP for the 20 km distance from the DTTV transmitter in the eastern and western sides of the transmitter. Since the RMSE is always positive and a value of zero never achieved, it out competes other methods in indicating a perfect fit of the data. With this advantage, RMSE enabled in coming up with a pathloss model that best describe the distribution of DTTV RF intensities in Kampala metropolitan; Uganda.

The RMSE approach is calculated as;

$$MSE = \sqrt[2]{\sum_{i=1}^{n} \frac{(P_{mi} - P_{ri})^2}{n}} \quad (1)$$

where P_{mi} is the measured RF intensity path loss in dB , P_{ri} is the predicted RF intensity path loss in dB and n is the number of measured data points.

The motivation for this work was to review, have a clear assessment of the existing models, choose the best model to achieve accuracy and minimize errors in relation to the measured RSRP so as to fit the distribution of RF intensity from the DTTV broadcasting transmitter in Kampala Metropolitan; Uganda.

2. PATH LOSS MODELS

RF intensity path loss models have been classified as empirical and theoretical models. The empirical path loss models are based on the achieved measurements done in a given environment while as the theoretical models predict signal losses by mathematical analysis of the path geometry of the environment between the receiving antenna and the transmitting antenna and the tropospheric refractivity [9].

2.1 Free Space Path Loss Model

The free space propagation model is used to predict received signal strength when the transmitter and receiver have a clear, unobstructed line-of-sight path between them [10]. In free space, the power, $p_r(d)$, received by the detector antenna placed at a lateral distance, d, from the base of the transmitter antenna is given by the Friis free space equation [10], equation 2.

$$p_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2} \quad (2)$$

Where, P_t, is the transmitted power, G_t, is the transmitter antenna gain, G_r, is the receiver antenna gain and λ is the wavelength.

The Friis free space equation shows that the received power falls off as the square of the Transmitter-Receiver (T-R) separation distance. The path loss, which represents signal attenuation as a positive quantity measured in dB, is defined as the difference (in dB) between the effective transmitted power and the received power, and may or may not include the effect of antenna gains [11].

The path loss for the free space model when antenna gains are included is given as;

$$PL(dB) = 10log\frac{P_t}{P_r} = -10log_{10}\left[\frac{G_t G_r \lambda^2}{(4\pi)^2 d^2}\right] \quad (3)$$

For known frequency of operation, this relationship is given as;

$$PL(dB) = -10\,log_{10}(G_t) - 10\,\,log_{10}(G_r) - 20\,log_{10}\left[\frac{(cx10^3)}{4\pi xfx10^6}\right] - 20\,log_{10}\left(\frac{1}{d}\right) \quad (4)$$

where c is the speed of light ($3x10^8 ms^{-1}$)

$$PL(dB) = -G_t - G_r + 32.44 + 20log_{10}d + 20log_{10}f \quad (5)$$

Where G_t and G_r are measured in decibels, d is the distance in kilometers and f is measured in MHz [12].

2.2 Okumura Model

The models derivation was based on extensive drive test measurements made in Japan for frequencies within 150 to 1920 MHz and further extended to the 3000 MHz frequency. The model is basically for macrocells with cells diameters in the range of 1 to 100 km for the base station antenna height kept in the range between 30-100 m [13]. The Okumura model takes into account several propagation parameters such as the type of environment and the terrain irregularity. Okumura came up with a set of curves which gives the median attenuation relative to free space (Amu), in an urban area over a quasi-smooth terrain with a base station effective antenna height of 200 m and a mobile antenna height of 3 meters. The path loss prediction formula according to Okumura's model is given as [14].

$$PL_{50}(dB) = L_F + Amu_{(fd)} - G_{h_t} - G_{h_r} - G_{Are} \quad (6)$$

$PL_{50}(dB)$ is the median value (i.e. 50^{th} percentile) of the path (propagation) loss, L_F is the free space loss. Amu is the value of the median attenuation relative to free space, G_{h_t} is the base station antenna height gain factor, G_{h_r} is the mobile antenna height gain factor, and G_{Are} is the gain or correction factor owing to the type of environment.

$Amu_{(fd)}$ and G_{Are} are determined by observing the Okumura curves. Since Kampala metropolitan is a quasi-open area; $Amu_{(fd)}$, is 20 dB for the 1.5 m receiving antenna height and 25 dB for the 2.5 m receiving antenna height while as, G_{Are} is 6 dB, from the Okumura curves.

Both $G_{(ht)}$ and $G_{(hr)}$ can be got using the following formulas;

$$G_{h_t} = 20log_{10}\left(\frac{h_t}{200}\right) for\ 100\,m > h_t > 30\,m \quad (7a)$$

$$G_{h_t} = 10log_{10}\left(\frac{h_t}{200}\right) for\ h_t\ < 30\,m \quad (7b)$$

$$G_{h_r} = 10log_{10}\left(\frac{h_r}{3}\right)\ for\ h_r \leq 3\,m \quad (7c)$$

$$G_{h_r} = 20log_{10}\left(\frac{h_r}{3}\right) for\ 10\,m\ \leq h_r \leq 3\,m \quad (7d)$$

The model is considered to be the simplest and most excellent in terms of accuracy in path loss prediction for most wireless systems in cluttered environment.

2.3 Hata Model

Valid from 150 MHz to 1500 MHz frequency band, path distance up to 20 km, extended to 100 km; for a transmitting antenna height of 30-200 m and a receiving antenna height of 1 m-10 m parameter ranges, the model as provided by Yoshihisa Okumura [15] is an empirical formulation of graphical path loss data. The Hata model is, basically, a set of equations based on measurements and extrapolations from the curves derived by Okumura. Hata presented the urban area propagation loss as a standard formula, along with additional correction factors for application in other situations such as suburban and rural.

The model assumes a direct line-of-sight path from transmitter (t) to receiver (r) but the actual path is obstructed by two hills. Hence, the prediction would be too optimistic.

The standard Hata formula for median path loss in urban areas is given as;

$$PL(urban)(dB) = 69.55 + 26.16log_{10}f - 13.82log_{10}h_t - a(h_r) + (44.9 - 6.55logh_t)log_{10}d \quad (8)$$

Where, f, is the frequency, h_t, is the effective transmitter antenna height (in m) ranging from 30 m to 200 m, h_r, is the effective receiver antenna height (in m) ranging from 1 m to 10 m, d is the transmitter-receiver antenna separation distance (in km), $a(h_r)$ is the correction factor for effective antenna height which is a function of the size of the coverage area and its given as;

$$a(h_r) = 0.8 + (1.1\, log_{10} f - 0.7)h_r - 1.56\; log_{10} f \quad (9a)$$

for small or medium sized cities and

$$\mathrm{a}(h_r) = \begin{cases} 8.29[log_{10}(1.54h_r)]^2 - 1.1 & for \quad f \leq 300MHz \\ 3.2[log_{10}(11.75h_r)]^2 - 4.97 & for \quad f \geq 300MHz \end{cases} \quad (9b)$$

for large cities.

To obtain the path loss in a suburban area, the standard Hata model formula in equation (8) is modified to:

$$L(dB) = L(urban) - 2\left[log_{10}\left(\frac{f}{28}\right)\right]^2 - 5.4 \quad (10a)$$

and to obtain the path loss in an open area, the equation below is used;

$$L(dB) = L(urban) - 4.78log_{10}f_c^2 + 18.33log_{10}f_c - 40.94 \quad (10b)$$

2.4 Hata-Davidson's Model

This is a derivation of the Hata's model and its accuracy is good with the first 20 km from the transmitting antenna and after this distance, the prediction errors become higher. According to [16] the predication error becomes obvious after the 20 km distance from the transmitter. Because of this, the model provides six correction factors which extend the range of distance to 300 km. The path loss expression equation for this model is given as,

$$PL(dB) = PL_{Hata}(dB) + A(h_r, d_{km}) - S_1(d_{km}) - S_2(h_t, d_{km}) - S_3(f_{MHz}) - S_4(f_{MHz}) \quad (11)$$

$PL_{Hata}(dB)$ is defined in 8

However;

$$A(h_r, d_{km}) = \begin{cases} 0 & for\; d < 20\; km \\ 0.62317(d-20)\left[0.5 + 0.15\log\left(\frac{h_t}{121.92}\right)\right] & for\; 20 \leq d < 64.38\; km \\ 0.62317(d-20)\left[0.5 + 0.15\log\left(\frac{h_t}{121.92}\right)\right] & for\; 64.38 \leq d < 300\; km \end{cases} \quad (12a)$$

Where,

$$S_1(d_{km}) = \begin{cases} 0 \; for\; d_{km} < 20\; km \\ 0 \; for\; 20 \leq d_{km} < 64.38\; km \\ 0.174(d - 64.38) for\; 64.38\; km \leq d_{km} < 300\; km \end{cases} \quad (12b)$$

$$S_2(d_{km}) = 0.00784\left|\log\left(\frac{9.98}{d}\right)\right|(h_t - 300) for\; h_t < 300\; m \quad (12c)$$

$$S_3(f_{MHz}) = \frac{f}{250\log\left(^{1500}/_{f}\right)} \quad (12d)$$

$$S_4(f_{MHz}) = \left[0.112\log\left(\frac{1500}{f}\right)\right](d-64.38) for\ d_{km} < 64.38\ m \quad (12e)$$

$A(h_r, d_{km})$ and $S_1(d_{km})$ are the distance correction factors, $S_2(d_{km})$ the base station antenna height correction factor while as $S_3(f_{MHz})$ and $S_4(f_{MHz})$ are the frequency correction factors.

This model suitably works in the frequency range between 30 MHz and 3GHz.

2.5 Co-operative for Scientific and Technical Research Committee (COST) 231-Hata Model

The model is very efficient in predicting the path loss of digital television signals in the frequency range of 500 MHz to 2000 MHz and it's an extension of Okumura-Hata model. The basic equation for path loss (in dB) due to this model [17] is given as;

$$PL(dB) = 46.3 + 33.9log_{10}(f) - 13.82log_{10}(h_t) - ah_m + [44.9 - 6.55log_{10}(h_t)]log_{10}d + C_m \quad (13)$$

where f is the frequency in MHz, d is the distance in Km between the transmitter antenna and the receiver antenna, h_t is the transmitter antenna height in meters, C_m is in decibels and its 0 for suburban or open environments and 3 for urban environments. The parameter ah_m is defined for urban environments as, [13].

$$ah_m = 3.20[log_{10}(11.75h_r)]^2 - 4.97 \quad (14a)$$

and for suburban or rural (flat) environments as,

$$ah_m = (1.1log_{10}f - 0.7)h_r - (1.5log_{10}f - 0.8 \quad (14b)$$

Where h_r is the height of the receiver antenna in meters above the ground level?

2.6 European Communication Committee (ECC-33) Path Loss Model

According to this path loss model [18], the path loss is defined as;

$$PL(dB) = A_{fs} + A_{bm} - G_t - G_r \quad (15)$$

Where, A_{fs} is the free space attenuator, A_{bm} is the basic median path loss, G_t is the transmitter antenna gain factor and G_r is the receiver antenna gain factor. They are individually defined as;

$$A_{fs} = 92.4 + 20\ log_{10}(d) + 20\ log_{10}(f) \quad (16)$$

$$A_{bm} = 20.41 + 9.83\ log_{10}(d) + 7.894\ log_{10}(f) + 9.56[log_{10}(f)]^2 \quad (17)$$

$$G_t = log_{10}\left(\frac{h_t}{200}\right)\{13.958 + 5.8[log_{10}(d)]^2\} \quad (18a)$$

and for medium city environments,

$$G_r = [42.57 + 13.7\ log_{10}(f)][log_{10}(\ h_r) - 0.585 \quad (18b)$$

where, f is the frequency in MHz, d is the lateral distance between the transmitting and the receiving antennas in Kilometers, h_t is the transmitting antenna height in meters and h_r is the receiver antenna height in meters. This model is applicable in the frequency range of 700 MHz to 3500 MHz.

2.7 Ericsson 999 Model

This model also stands on the modified Okumura-Hata model to allow room for changing in parameters according to the propagation environment. The model works in the frequency range of 150 MHz to1900 MHz. Path loss according to this model is given as;

$$PL(dB) = a_0 + a_1log_{10}(d) + a_2log_{10}(h_t) + a_3log_{10}(h_t)log_{10}d - 3.2\big(log_{10}(11.75h_r)\big)^2 + g(f) \quad (19)$$

where, $g(f) = 44.49log_{10}(f) - 4.78\big(log_{10}(f)\big)^2$ (20)

The values of a_0, a_1, a_2 and a_3 are constants but can be changed according to the environment. The default values given by the model are, $a_0 = 36.2$, $a_1 = 30.2$, $a_2 = 12.0$ and $a_3 = 0.1$, for an urban environment and $a_0 = 43.20$, $a_1 = 68.93$, $a_2 = 12.0$ and $a_3 = 0.1$, for the suburban environment and f is the frequency.

2.8 Egli Path Loss Model

The model was first introduced by John Egli in 1957 [19]. The path loss prediction due to this model is for frequency from 40 MHz to 900 MHz and linking range for the transmitting and receiving antenna must be less than 60 km. It was derived from real-world data on UHF and VHF television transmissions in several large cities. The formulas for the Egli's path loss prediction model are as below.

$$PL(dB) = 20log_{10}f + 40log_{10}d - 20log_{10}h_t + 76.3 - 10log_{10}h_r \;\; for\; h_r \leq 10 \quad (21a)$$

and

$$PL(dB) = 20log_{10}f + 40log_{10}d - 20log_{10}h_t + 85.9 - 10log_{10}h_r \;\; for\; h_r \geq 10 \quad (21b)$$

Where, h_t, is the height of the transmitter in meters, h_r, is the height of the receiver antenna in meters, d is the distance in meters between the transmitter and the receiver antennas and f is the frequency of transmission in MHz.

Many researchers from different countries (Nigeria, Saudi Arabia, Malaysia, India) have carried out similar research as detailed by [20-24]. In these studies, different RF intensity path loss propagation models have been analyzed. The model that best suits a particular environment for a particular country in terms of the lowest RMSE value is being selected out of the many, to give the best model which best describe the distribution of DTTV RF intensities. Though there are many known RF intensity path loss propagation models [25,26], this study only considered those with more than three parameters and are built to operate in the DTTV frequency range.

In Uganda, the little known about the distribution of RF intensities from DTTV in term of modelling is not well detailed. This study has come at the rightful time because it will help the DTTV regulator, Signet; know which model best describe the distribution of RF intensities in Kampala metropolitan so as to better DTTV signal propagation planning in relation to the environment.

3. METHODS AND MATERIALS

Radiofrequency intensity determination was performed by measuring the Reference Signal Received Power (RSRP) during the day hours. During the analysis, the study did not take into consideration the effects of environmental/weather conditions as well as addition signals from nearby towers, Doppler Effect, absorption, scattering, reflection and refraction of signals during the time of measurements.

3.1 Measurement Campaign

Routes for the measurement campaign were planned to include major accessible roads in the eastern and in the western parts of the transmitter. The eastern route was the Kampala-Jinja road and for this route, the frequency band considered was the sub 700 MHz frequency band and the channel frequencies set were the 526 MHz and the 638 MHz.

The western route was the Kampala-Mityana road and the frequency band considered was the 700 MHz frequency band with set frequencies of 730 MHz and 766 MHz

The reference distance used for the measurements is 1 km from the DTTV Transmitter. Transmitter to receiver distance was varied between 1 km to 20 km in steps of 1 km at receiver antenna heights of 1.5 m and 2.5 m for both routes. The transmitter-receiver distance was limited to 20 km, because according to Uganda, this distance from the capital city is the urban part of Kampala Metropolitan. At every measurement point, the RSRP was taken for two consecutive five minutes interval and then the mean value considered. The Google maps of the measurement routes are shown in Fig. 2.

For the Kampala Metropolitan environment, average inter-building distance is about 10 m and street width is about 6 m. Table 1 shows the parameter configuration of the transmitter that was used and Table 2 shows the parameter configuration of the spectrum analyzer on the MCS software during the measurement campaign.

The mean Reference Signal Received Power (RSRP) measured from the two routes was converted to the equivalent measured path loss values for further analysis. The measured path loss for each measurement location at a distance $d\ (km)$ is calculated using equation 22 [27,1].

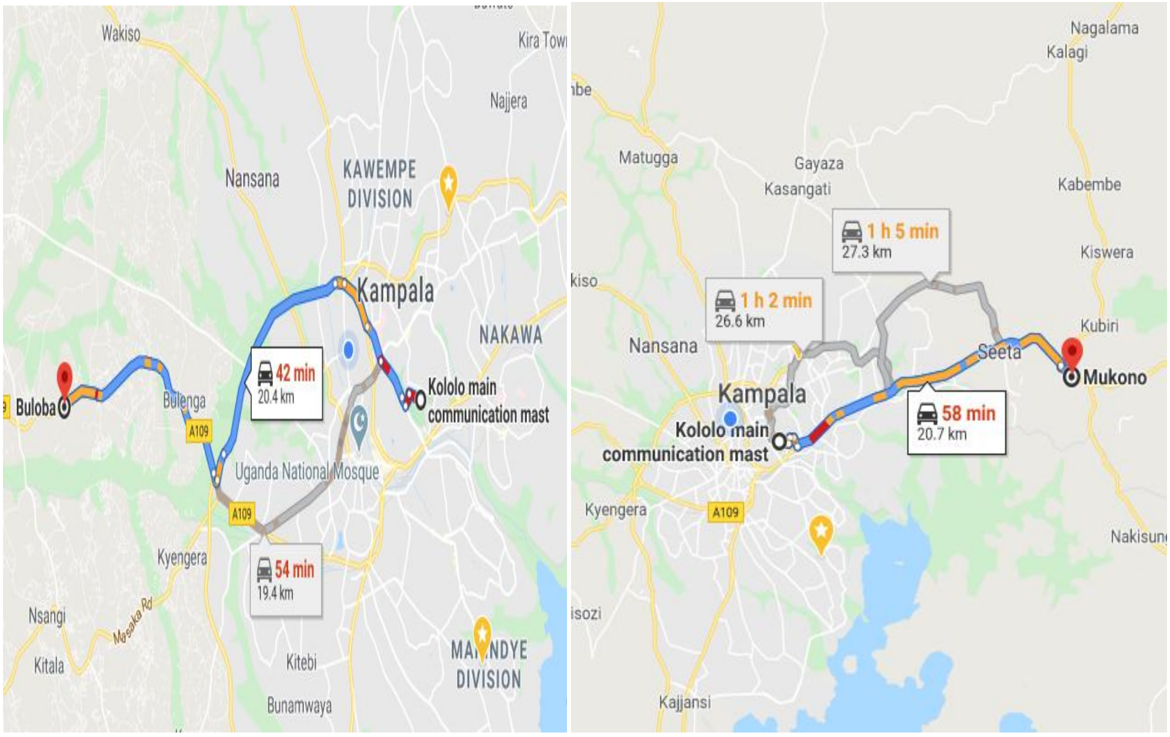
$$PL(dB) = P_T + G_T + G_R - L_{FC} - L_A - L_{CF} - P_R \quad (22)$$

where; P_T is the transmitter power in dBm, G_T is the transmitter antenna gain in dBi, G_R is the receiver antenna gain in dBi, L_{FC} is the feeder cable and connector loss in dB at the transmitter, L_A is the antenna body loss is in dB, L_{CF} is the combiner and filter loss in dB and P_R is the Reference Signal Received Power (RSRP) in dBm.

Using the values in Table 1 and putting them in equation 22, the equation becomes,

$$PL(dB) = 67.48 + 24.76 + 4 - 8 - 8 - 15.7 - P_R \quad (23a)$$

$$PL(dB) = 64.54\ (dBm) - P_R(dBm) \quad (23b)$$



(a) (b)

Fig. 1. Measurement routes from the DTTV transmitter: (a) is for the Western route and (b) is for the Eastern route

Table 1. Parameter configuration of the transmitter

Parameter	Value
Mast's base station's location	0°19'46.0"N, 32°35'41.0"E
Base station transmitter frequency range	470 MHz - 862 MHz
Frequencies considered	526 MHz, 638 MHz,730 MHz and 766 MHz
Maximum Transmitter Power	67.48 dBm
Transmitter Antenna gain	24.76 dBi
Height of Transmitting mast	350.0 m
Height of Transmitting Antenna	37 m
Height of receiving Antenna	1.5 m/ 2.5 m
Receiving Antenna gain	4 dBi
Feeder cable and connector losses	8 dB
Antenna body loss	8 dB
Combiner and Filter losses	15.7

Table 2. Parameter Configuration of the spectrum analyzer

Parameter	Value
Resolution Band Width	100 KHz
Video Band Width	100 KHz
Sweep time	100 ms
Detection type	RMS
Sample points	100
Attenuation factor	Auto
Reference level	-10
Unit	dBm

4. RESULTS AND DISCUSSION

The measured mean RSRP and the equivalent measured pathloss together with the GPS coordinates at each measurement location for the 1-20 km distance from the DTTV transmitter are as seen in Table 3 and Table 4 for the 1.5 m and 2.5 m receiving antennas for the western route.

From Tables 3 and 4, there is no uniform decrease in the value of the measured pathloss from the transmitter as theoretically expected. This is because different distances from the transmitter have different altitudes making some distances (with higher altitudes) which are far from the transmitter have higher measured pathloss values than some other distances which are nearer to the transmitter as, at the 8 km distance from the transmitter, the measured RF intensity path loss is higher than that at the 2 km from the transmitter, yet the 8 km distance is far from the transmitter than the 2 km distance, yet the 2 km distance is at a higher altitude than the 8 km distance.

It can be observed that there is a general decrease in the measured RF intensity path loss for all the path loss models as distance from the DTTV transmitter is increased. This observation is the same for the measured RF intensity path loss and the empirical propagation RF intensity path loss models for the selected frequencies in the sub 700 MHz and the 700 MHz frequency bands for the two routes.

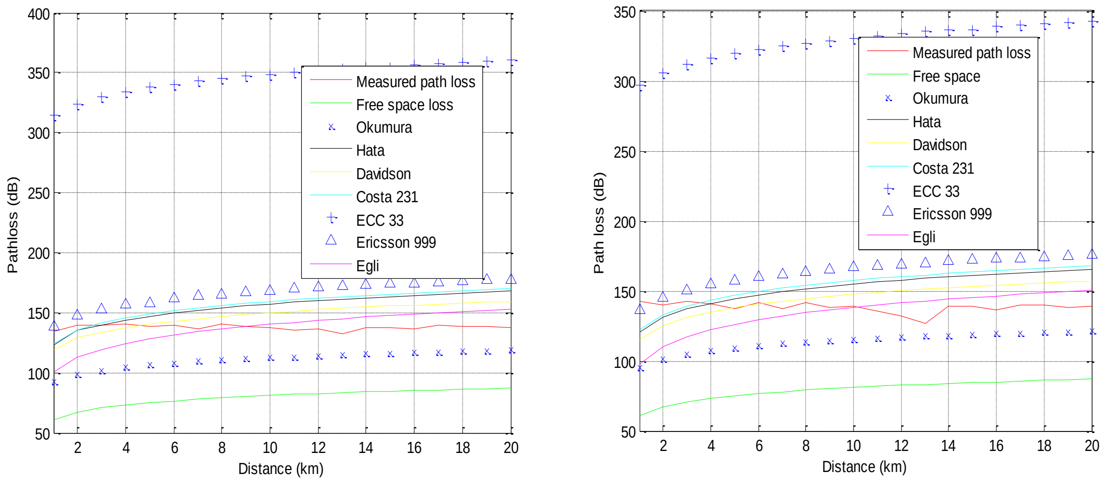
On comparatively studying the measured RF intensity path loss with various existing empirical propagation RF intensity path loss models, in order to select out the best one, the measured RF intensity path loss is compared with models such as, Free-Space, Okumura, Hata , Davidson's, Costa 231, ECC-33, Ericsson 999 and the Egli, models. From Figs. 2 and 3, for the western route, it's generally observed that the ECC-33 deviate too much from the measured path loss values. The Free-Space model is also less accurate because it has taken only the consideration that RF intensity becomes weaker as the distance increases because of diffraction of signal apart from the truth that there are many environmental factors that can affect RF intensities as they propagate from the transmitter. The path loss using Ericsson 999, Davidson's, Hata and Egli are much closer to each other and give better agreement with the measured RF intensity path loss values as compared to Okumura and Costa 231.

Table 3. Field measured RSRP and measure Path loss at 1.5 m receiving antenna height

d(km)	Measured RSRP (dBm) for 730 MHz	Measured Path loss (dB) for 730 MHz	Measured RSRP (dBm) for 766 MHz	Measured path loss (dB) for 766 MHz	Lat	Long	Alt
1	-69.7142432	134.25	-72.2156477	136.76	0.333206	32.58764	1203
2	-74.9625590	139.5	-74.7080645	139.25	0.33641	32.58268	1208
3	-75.3233405	139.86	-76.8795758	141.42	0.32993	32.57564	1022
4	-76.131885	140.67	-77.8410022	142.38	0.32762	32.56524	1247
5	-73.6362375	138.18	-70.9482635	135.49	0.32498	32.56106	1267
6	-75.2441426	139.78	-73.4098858	137.95	0.32856	32.55529	1201
7	-72.2151686	136.76	-77.954624	142.49	0.32187	32.54398	1185
8	-76.4673900	141.01	-77.7796706	142.32	0.32763	32.5355	1174
9	-73.9514557	138.49	-75.1248807	139.66	0.33047	32.53062	1180
10	-73.4127307	137.95	-75.1244784	139.66	0.32836	32.52505	1153
11	-71.4030284	135.94	-74.5077187	139.05	0.32227	32.52293	1155
12	-71.4725469	136.02	-68.0439530	132.59	0.31283	32.51354	1154
13	-67.8260035	132.37	-68.0374293	132.58	0.3193	32.5079	1187
14	-73.4574286	138.00	-75.1680418	139.71	0.32615	32.49944	1203
15	-72.8956196	137.44	-75.668498	140.21	0.33236	32.49368	1216
16	-72.1235000	136.66	-75.0935555	139.63	0.33338	32.48778	1257
17	-74.9461576	139.49	-75.8246677	140.36	0.33031	32.47983	1225
18	-74.3725584	138.91	-76.0815468	140.62	0.32682	32.47049	1182
19	-74.3096303	138.85	-75.5716813	140.11	0.32598	32.46112	1175
20	-73.3989354	137.94	-75.4139968	139.95	0.32246	32.45233	1201

Table 4. Field measured RSRP and measured Path loss at 2.5 m receiving antenna height

d(km)	Measured RSRP (dBm) for 730 MHz	Measured Path loss (dB) for 730 MHz	Measured RSRP (dBm) for 766 MHz	Measured path loss (dB) for 766 MHz	Lat	Long	Alt
1	-77.7199	142.26	-77.920609	141.46	0.333206	32.58764	1203
2	75.1837582	139.72	-74.596288	139.14	0.33641	32.58268	1208
3	-77.776498	142.32	-76.462686	141.00	0.32993	32.57564	1022
4	-76.044075	140.58	-78.114521	142.65	0.32762	32.56524	1247
5	72.7746500	137.31	-71.629755	136.17	0.32498	32.56106	1267
6	-77.163515	141.7	-77.604004	142.14	0.32856	32.55529	1201
7	-72.513465	137.05	-71.651501	136.19	0.32187	32.54398	1185
8	-77.526538	142.07	-80.947667	145.49	0.32763	32.5355	1174
9	-73.843995	138.38	-75.444426	139.98	0.33047	32.53062	1180
10	-74.587132	139.13	-75.298473	139.84	0.32836	32.52505	1153
11	-71.012761	135.55	-74.938715	139.48	0.32227	32.52293	1155
12	-67.439405	131.98	-68.158219	132.7	0.31283	32.51354	1154
13	-62.510237	127.05	-63.597938	128.14	0.3193	32.5079	1187
14	-74.159500	138.7	-75.248577	139.97	0.32615	32.49944	1203
15	-74.818179	139.36	-75.552056	140.09	0.33236	32.49368	1216
16	-71.972614	136.51	-75.568262	140.11	0.33338	32.48778	1257
17	-75.456740	140	-74.992511	139.53	0.33031	32.47983	1225
18	75.440282	139.98	-75.267024	139.81	0.32682	32.47049	1182
19	-73.942093	138.48	-75.233073	139.77	0.32598	32.46112	1175
20	-74.468951	139.01	-75.554542	140.09	0.32246	32.45233	1201



(a) **(b)**

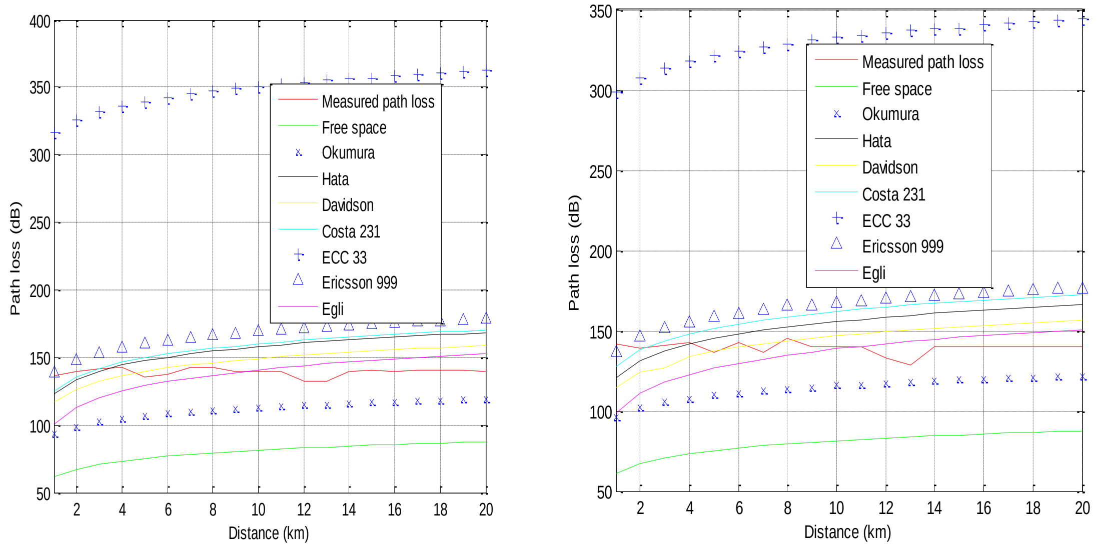
Fig. 2. Predicted and measured path loss along the Western route for the 730 MHz. The receiving antenna heights are 1.5 m for (a) and 2.5 m for (b)

As seen in Figs. 4 and 5, the observation is the same even for the Eastern route in the sub 700 MHz frequency band for the selected frequency values of 526 MHz and 638 MHz at 1.5 m and 2.5 m receiving antenna heights. That's, ECC-33 deviate too much from the measured path loss values and the Free-pace model is also less accurate as compared to other models.

Generally, for both frequency bands, sub 700 MHz band and 700 MHz frequency band, for the selected frequency values of 526 MHz and 638 MHz and 730 MHz and 766 MHz, respectively, for the receiving antenna heights of 1.5 m and 2.5 m, the path loss prediction using Ericsson 999, Davidson's, Hata and Egli are much closer to each other and give better agreement with the measured RF intensity path loss values as compared to Okumura and Costa 231.

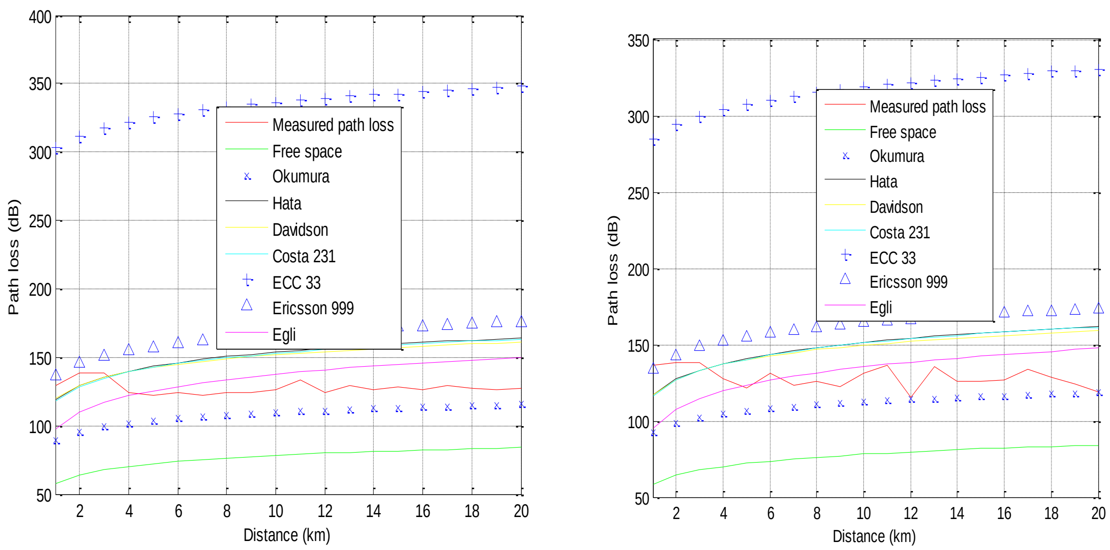
4.1 Selecting the Best Models

Since every environment has a path loss model which best describes the distribution of its RF intensities, the slight difference between these four models (Ericsson 999, Davidson's, Hata and Egli) can be made more clearer to find out which of the models best describe the distribution of radiofrequency intensities from the DTTV transmitter in Kampala metropolitan for the selected routes. This insight is obtained by computing the Root Mean Square Error (RMSE) associated by each model using equation 1.



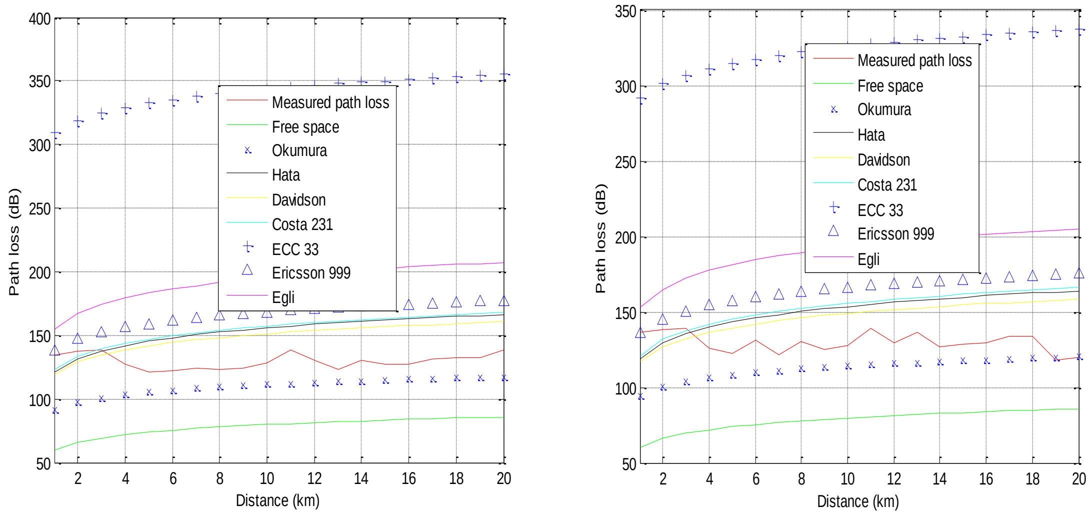
(a) (b)

Fig. 3. Predicted and measured path loss along the western route for the 766 MHz. The receiving antenna heights are 1.5 m for (a) and 2.5 m for (b)



(a) (b)

Fig. 4. Predicted and measured path loss along the Eastern route for the 526 MHz. The receiving antenna heights are 1.5 m for (a) and 2.5 m for (b)



(a) **(b)**

Fig. 5. Predicted and measured path loss along the Eastern route for the 638 MHz. The receiving antenna heights are 1.5 m for (a) and 2.5 m for (b)

By examining the RMSE in Tables 5 and 6, it's clearly observed that;

For the western route, for the 730 MHz frequency at the 1.5 m receiving antenna height, the minimum value of the RMSE is 14.085 and for the 2.5 m receiving antenna height, the minimum value of the RMSE is 14.381. These correspond to the RMSE of the predicted pathloss for the Egli and Davidson models respectively. The Egli and Davidson models, which satisfied the RMSE closest to zero, are taken as the best candidate for predicting the pathloss along the western route at the 730 MHz frequency at these receiving antenna heights. For the 766 MHz frequency at the 1.5 m receiving antenna height, the minimum value of the RMSE is 13.362 and for the 2.5 m receiving antenna height, the minimum value of the RMSE is 13.386. These correspond to the RMSE of the predicted pathloss for the Egli and Davidson models respectively. The Egli and Davidson models, which satisfied the RMSE closest to zero, are taken as the best candidate for predicting the pathloss along the western route at the 766 MHz frequency at these receiving antenna heights.

For the eastern route, for the 526 MHz frequency at the 1.5 m receiving antenna height, the minimum value of the RMSE is 14.085 and for the 2.5 m receiving antenna height, the minimum value of the RMSE is 18.140. These correspond to the RMSE of the predicted pathloss for the Egli model. Hence, Egli model, which satisfied the RMSE closest to zero, is taken as the best candidate for predicting the pathloss along the eastern route at the 526 MHz frequency at these receiving antenna heights. For the 638 MHz frequency at the 1.5 m receiving antenna height, the minimum value of the RMSE is 22.643 and for the 2.5 m receiving antenna height, the minimum value of the RMSE is 22.197. These correspond to the RMSE of the predicted pathloss for the Davidson model. Hence, Davidson model, which satisfied the RMSE closest to zero, is taken as the best candidate for predicting the pathloss along the eastern route at the 638 MHz frequency at these receiving antenna heights.

Table 5. Root mean square error for the western route

Model	RMSE at 1.5 m for 730 MHz	RMSE at 2.5 m for 730 MHz	RMSE at 1.5 m for 766 MHz	RMSE at 2.5 m for 766 MHz
Ericsson 999	30.044	28.629	29.424	28.059
Davidson	14.397	14.381	13.762	13.386
Hata	20.575	18.868	20.102	18.817
Egli	14.085	15.845	13.362	15.398

Table 6. Root mean square error for the eastern route

Model	RMSE at 1.5 m for 526 MHz	RMSE at 2.5 m for 526 MHz	RMSE at 1.5 m for 638 MHz	RMSE at 2.5 m for 638 MHz
Ericsson 999	35.589	36.618	37.117	36.511
Davidson	25.278	23.907	22.643	22.197
Hata	27.221	25.809	27.228	26.218
Egli	17.212	18.140	64.399	62.759

Since Egli and Davidson model satisfy the RMSE's closed to zero for both frequency bands along the two routes, they are taken as the best models for describing the distribution of RF intensities in Kampala metropolitan for the two receiving antenna heights.

5. CONCLUSION

In this present work, the measured RF intensity path losses along the western and the eastern routes of the DTTV transmitter in Kampala metropolitan have been compared against eight well know empirical models; Free space, Okumura, Hata, Davidson, Costa 231, ECC 33, Ericsson 999 and Egli. Results show that no single model is accurate for DTTV RF intensity distribution at all transmission distances. From the results, ECC and the Free-Space models overestimated the path loss for both the western and eastern routes. Ericsson 999, Davidson's, Hata and Egli are much closer to each other and give better agreement with the measured values as compared to Okumura and Costa 231.

On finding the RMSE of; Ericsson 999, Davidson's, Hata and Egli models, results showed that along the western route; Davidson model outperformed other contending models at the 2.5 m receiving antenna height at the 730 MHz and the 766 MHz frequencies since it had the lowest RMSE values while as at the 730 MHz and 766 MHz frequencies for the 1.5 m receiving antenna height, Egli outperformed other models because its RMSE values were the least.

Along the eastern route; the Egli model outperformed other contending models at the 526 MHz frequency because it gave the least RMSE values while as for the 638 MHz frequency, Davidson performed best by giving the least RMSE values, both models for the 1.5 m and 2.5 m receiving antenna heights.

Though both Egli and Davidson models give RMSE values which are for sub-urban and rural areas for the western route and for the eastern route, their RMSE values are beyond the accepted minimum values for urban or rural setting. Hence, according to Egli and Davidson model, though Kampala metropolitan is an urban area according to Uganda, these models RMSE values describe the distribution of RF intensity for Kampala metropolitan as a sub-urban and rural setting environment.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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