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A Simplified Path Loss Model For Classifying High Altitude Platform Station Propagation Environment

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Abstract:
The knowledge of the variability of a received signal at distant points to the Base Station (BS) is key for reliable and efficient radio signal transmissions. In consequence, developing a robust Path Loss Model (PLM) for determining the Path Loss (PL) between a High Altitude Platform Station (HAPS) and the User Equipment (UE) on the ground is crucial in positioning the HAPS. This paper presents a HAPS PLM for Ede environment. The PLM was developed based on some demographic data of the Ede land area. The parameters employed in the development of the PLM were buildings plots width, inter-building spacing, maximum building height, carrier frequency, HAPS altitude, PL exponent and elevation angles ranging from 10^0 to 90^0. The developed PLM was simulated for Line-of-Sight (LOS) and Non-Line-of-Sight (NLOS) scenarios at 2 GHz and 20 GHz. The PL values for Ede were compared with the PL values for Arlington (a suburban environment). For the LOS scenario, the same average PL value was obtained for both Ede and Arlington environments. However, for the NLOS scenario, at 2 GHz, the average PL values for Ede and Arlington were 149.0874 dB and 147.6406 dB, respectively. At 20 GHz, the average PL values for Ede and Arlington were 175.7631 dB and 173.7134 dB, respectively. The Root Mean Squared Error (RMSE) of the comparisons between Ede and Arlington PL values at 2 GHz and 20 GHz for NLOS condition were 1.4469 dB and 2.0498 dB, respectively. The results showed that the Ede environment is tending towards urban but can be better classified as a sub-urban environment based on the ITU-R classification standard. Thus, the findings in this study would serve as a useful reference for researchers and engineers of the HAPS communication system.

***Keywords**: High Altitude Platform Station (HAPS), Path Loss (PL), LOS, NLOS, radio propagation environment.*

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I. Introduction

High Altitude Platform Station (HAPS) systems are envisaged to play a significant role in the realization of beyond the Fifth Generation (5G) of mobile wireless communication network [1]. A HAPS is an airborne communication system that is positioned in the stratosphere, at an altitude of 17 km to 50 km above the earth's surface [2], [3]. Due to their low latency, ease of maintenance and cost effectiveness, HAPS networks are preferred over satellite networks for providing communication services to rural areas, locations requiring emergency network and difficult terrains [1],[3].

Emerging use cases of the HAPS systems include; serving as alternatives to terrestrial systems and ground stations for inter-satellite communications, and processing of data traffic of Unmanned Aerial Vehicle (UAV) and Internet-of-Things (IoT) [4], [5]. HAPS are mostly solar-powered, unmanned, remotely-operated, and usually quasi-stationary to have a constant Line-Of-Sight (LOS) with the ground [6],[7]. However, like every other Cellular Radio Access Network (CRAN), as the signal in the HAPS network travels over a distance, it experiences different propagation obstacles that result in the received signal power being significantly less than the transmitted signal power; this phenomenon is referred to as Path Loss (PL) [8],[9].

The reduction in the strength of the received signal could lead to errors in decoding the data sent by the transmitter; thereby degrading the Quality-of-Service (QoS) delivery of the network [8]. The knowledge of the variability of a received signal at distant points to the Base Station (BS) in a CRAN is key for reliable and efficient transmission [10]. In consequence, developing a robust Path Loss Model (PLM) for determining the PL between a HAPS and the User Equipment (UE) on the ground is crucial in positioning the HAPS. A PLM is also useful for the estimation of received signal strength (RSS), interference analysis, link budget design, and cell size estimation [11],[12]. A typical HAPS network is shown in Figure 1. The network can be expressed as a complete BS for ground receivers and as a relay for communication between a satellite and the ground stations.

A few PLMs for HAPS systems have been presented in the literature; and a PLM can be classified under any of empirical [8], deterministic [13] and stochastic [13],[14]. Hseih and Rybakowaski (2019) [15] presented a PLM for HAPS in two different environments (that is, dense urban and surburban) using their respective Path Loss Exponent (PLE) and clutter height. Comparisons were made between the two environments for 2 GHz and 20 GHz carrier frequencies under LOS and Non-Line-Of-Sight (NLOS) conditions. The simulation results revealed that the PLM for both environments reduces to the free-space path loss (FSPL) model for the LOS condition.

Li et al (2024) [16] proposed a PLM for a particular environment based on a beamforming algorithm and 3D propagation information. The developed model was shown to outperform the conventional 2D propagation information. A PLM based on Markov chain was presented by Zheng et al (2024) [17], and the model was shown to provide realistic channel profile. Bithas et al (2024) [18] employed the Beers–Lampert law to develop a PLM for HAPS system. The model was shown to give more accurate estimation of the path losses.

In general, the existence of multiple PL models implies that there is no PLM that perfectly characterizes every environment other than in which it was designed [19]. In other words, the path loss models for HAPS systems are site specific [16]. Thus, this paper develops the HAPS PLM for Ede environment. Ede is a town located in southwest Nigeria on coordinates 7°44'20" North and 4°26'10" East.

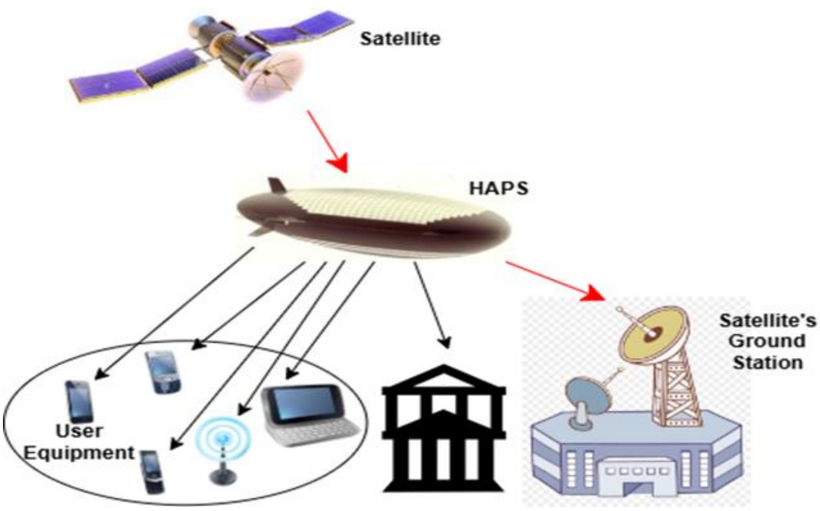

Figure 1. HAPS system assisting satellite and serving a cell of users' equipment

II. The HAPS Path Loss Model

The Path Loss (PL) modelling approach employed for satellite and terrestrial wireless systems was adopted in the development of the proposed HAPS path loss model (PLM) based on the standardized environmental parameters of the International Telecommunication Union Recommendation (ITU-R) as presented in Table no 1 (ITU-R, 2003). The parameters $\boldsymbol{\alpha_o}$, $\boldsymbol{\beta_o}$ and $\boldsymbol{\gamma_o}$ denote the ratio of built-up land area to the total land area, the mean number of buildings per unit area and a scale that describes the building heights distribution, respectively.

Table no 1: ITU-R parameters for propagation environments

	$\boldsymbol{\alpha_o}$	$\boldsymbol{\beta_o}$	$\boldsymbol{\gamma_o}$
Environment			
Suburban	0.1 – 0.29	750	8
Urban	0.2 – 0.49	500	15
Dense Urban	0.5 – 0.79	300	20
Highrise Urban	0.8	300	50

Path Loss Model for Ede Environment

The HAPS signal propagation in the Ede environment was modelled as ray tracing shown in Figure 2. The HAPS, representing the BS, is placed at an altitude of h_o from the surface of the earth to create a desired range of elevation angles of between 10^o to 90^o with the User Equipment (UE). It is assumed that building structures of different heights were placed at intervals to each other with a constant building width. The UEs (i.e. receivers) are located at different locations within the environment and are connected through LOS and NLOS links at different times. Clutter heights such as tall buildings and trees cause NLOS condition between the HAPS and a UE. The LOS condition is when there is no obstruction between the HAPS and the UE.

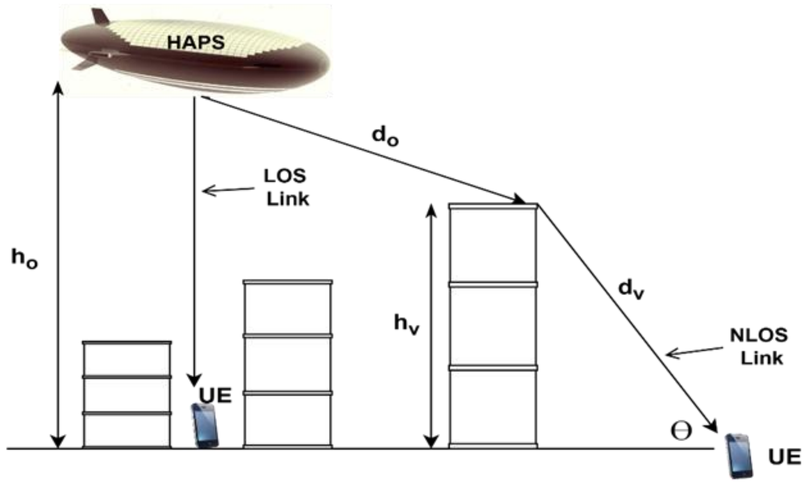

Figure 2. Ray tracing diagram depicting HAPS propagation in the Ede environment

Signal propagation below a certain height h_v is attenuated by the clutters with path loss exponent (PLE) denoted by m. Above this height, the signal from the transmitter follows free space propagation with $m = 2$. In the total propagation distance, only a small fraction distance d_v is affected by the buildings whereas the large part d_o is through free space. In other words, d_o is the transmission path for LOS whereas d_v is the transmission path for NLOS.

The building height, h, distribution is modelled as the Rayleigh probability density function (PDF), and is expressed as:

$$P(h) = \frac{h}{\gamma_o{}^2} e^{-\frac{h^2}{2\gamma_o{}^2}} \quad (1)$$

where $P(h)$ is the Rayleigh PDF, h is the building height in meters, and γ_o represent a scale that describe the building height distribution. The ratio of built-up land area to total land area, α_o, and the mean number of buildings per unit area, β_o, are obtained as follows [21]:

$$\alpha_o = NW^2/(1000D)^2 \quad (2)$$

$$\beta_o = N/D^2 \quad (3)$$

where D is the map area in kilometers for a square plot of land, N is the number of buildings inside the plot and W is the average width of the building.

The PL experienced by a j^{th} UE from a HAPS is given as:

$$PL_j = FSPL_j(f_c, d) + \xi_j \quad (4)$$

where $FSPL_j(f_c, d)$ is the free space PL as a function of the carrier frequency f_c and the direct distance d between the HAPS and the UE; ξ_j is the excess PL caused by NLOS link to the UE. The relationship between the elevation angle θ of the UE's antenna and the propagation distance for the NLOS condition is given as:

$$d_v = \frac{h_v}{\sin\theta}. \quad (5)$$

where h_v is the terrestrial clutter height.

For the Ede environment, $h_v = 13.2$ m (the height of the tallest building). Thus, arising from Equation (4), the HAPS PL model for Ede environment is given as:

$$PL^{Ede} = 10\log_{10}\left(\left(\frac{4\cdot\pi\cdot f_c\cdot d}{c}\right)^2\right) + 11.21(\mathrm{m} - 2) - 10\cdot\mathrm{m}\cdot\log_{10}\sin\theta. \quad (6)$$

where m is the PLE of the environment, f_c is the carrier frequency of the link, c is the speed of electromagnetic wave,

d is the direct distance between the HAPS and UE for LOS condition, and θ is the elevation angle. The constant value 11.21 in the second term of the equation is mainly due to terrestrial clutter height h_v. The third term of the equation accounts for the effect of θ. For LOS link, the $\mathrm{m} = 2$ and Equation (6) reduces to free space path loss.

Simulation of the Developed HAPS Path Loss Model

The developed PLM for Ede environment was simulated using MATLAB software package. The required demographic data were obtained from the Local Government Office in Ede. The system parameters and specifications are contained in Table no 2. The data were used to compute the propagation parameters α_o and β_o. Simulation was conducted for elevation angles 10^0 to 90^0 with a step size of 10^0, and at frequencies of 2 GHz and 20 GHz, which are considered for most mobile applications and fixed services, respectively [15]. Building walls were assumed to be reflective and the building edges diffractive.

Table no 2: Model simulation parameters

Parameter	Value
TX antenna height	20 km
RX antenna height	1.5 m
Carrier frequency	2 GHz, 20 GHz
PLE for 2 GHz	3.2
PLE for 20 GHz	3.7
TX and RX antenna gain	Isotropic
Building wall	Concrete
Minimum building height in Ede	6.5 m
Maximum building height in Ede	13.2 m
Area dimension of Ede	862 km^2
Average building width of Ede	17.5 m
Inter building Spacing in Ede	15.2 m
γ_o	[8, 15, 20]

Figure 3 represents the flow chart diagram for the simulation of the HAPS PLM for Ede propagation environment. After loading the system parameters, the simulation starts with the first elevation angle θ_1 to compute $log_{10}(\sin\theta_1)$ and the PL of Equation (6). The process was repeated for each elevation angle (θ_i) until the last elevation angle (90^0) was reached.

III. Results

The building height distribution of Ede was simulated via a curve fitting of Rayleigh PDF for three different values of γ_o as shown in Figure 4. The Rayleigh PDF was used to model the fading pattern over the building height distribution in Ede. The results showed that the maximum PDF value of 0.0529 that was obtained for the maximum building height in Ede (13.2 m) falls on the curve of γ_o = 8. The mean PDF values 0.019996, 0.019919, and 0.019118 were obtained for γ_o of 8, 15 and 20, respectively. The standard deviations for γ_o of 8, 15 and 20 were 0.026606, 0.013926, and 0.008658, respectively. The means and standard deviations decrease with increasing values of γ_o.

The computed values for α_o and β_o for Ede are compared with the ITU-R standard in Table no 3. The α_o and β_o values obtained for Ede were 0.28 and 930, respectively.

Calculated HAPS Path Loss for Ede Environment

Results of the computed logarithmic values of the elevation angles $log_{10}(\sin\theta)$ showed that the logarithmic values increase with the elevation angles; that is, from -0.7603 (for 10^0) to 0.0000 (for 90^0) as contained in Table no 4. Figures 5 shows the PL at 2 GHz for both LOS and NLOS. For LOS, at $\theta = 10^0$ (-0.7603), $\theta = 50^0$ (-0.1157) and $\theta = 90^0$ (0.0000), the PL was 154.8962 dB, 129.1128 dB and 124.483 dB, respectively. Similar trend was observed for the NLOS scenario, at $\theta = 10^0$, $\theta = 50^0$ and $\theta = 90^0$, the PL was 177.467 dB, 143.9487 dB and 137.9299 dB, respectively. Furthermore, the results show that the link with NLOS incurs more PL of about 22.57 dB than LOS at $\theta = 10^0$ and about 13.45 dB more PL than LOS at $\theta = 90^0$.

At 20 GHz for LOS condition, the PL at $\theta = 10^0$, $\theta = 50^0$ and $\theta = 90^0$, were 174.8962 dB, 149.1128 dB and 144.483 dB, respectively; whereas for NLOS, at $\theta = 10^0$, $\theta = 50^0$ and $\theta = 90^0$, the PL were 206.8715 dB, 170.1303 dB and 163.5327 dB, respectively. These results are also in agreement with those of 2 GHz in that the link with NLOS

incurs more PL of about 31.98 dB than LOS at $\theta = 10^0$ and about 19.05 dB more PL than LOS at $\theta = 90^0$.

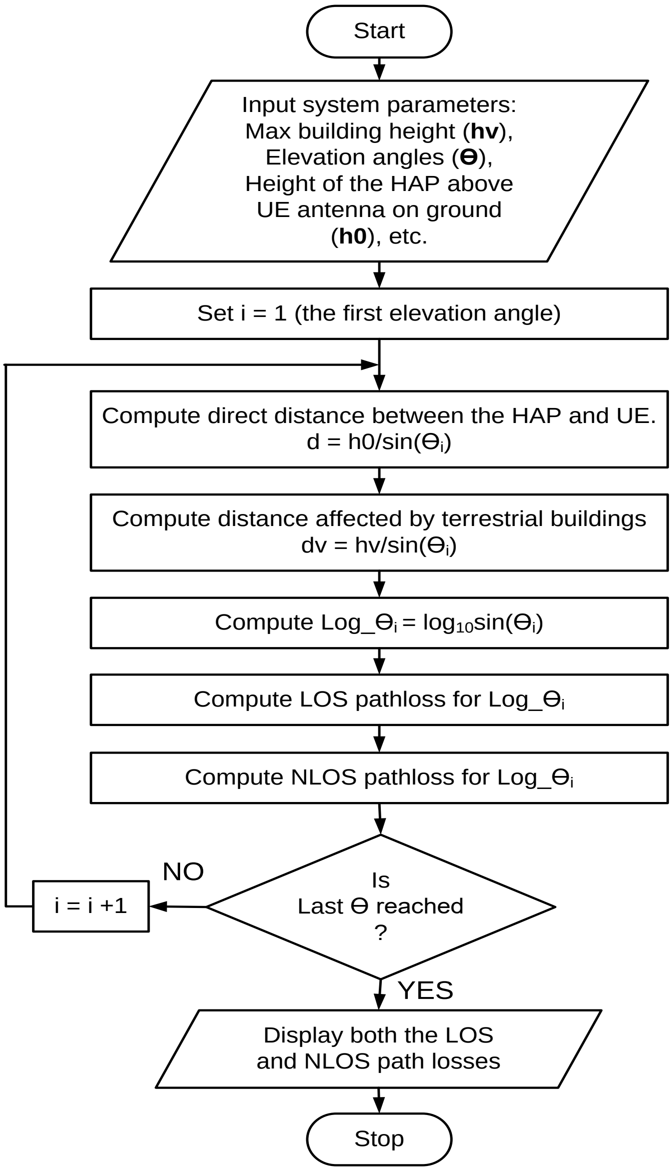

Figure 3. Simulation flow chart for the developed path loss model

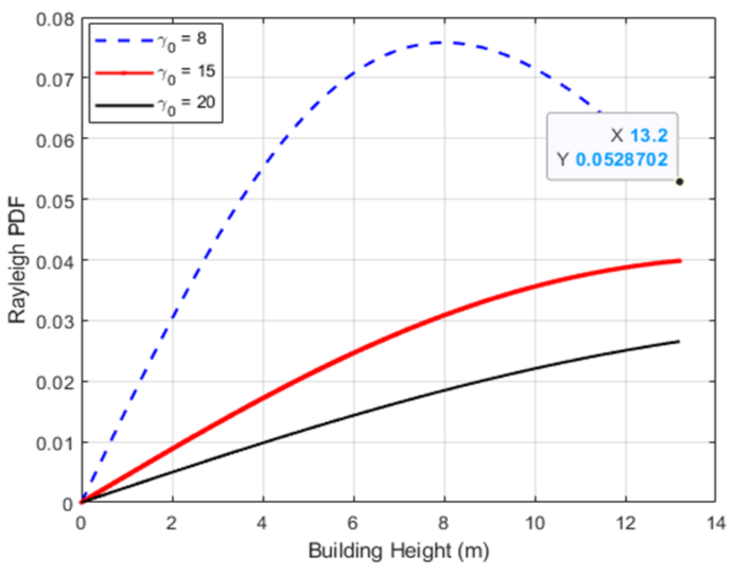

Figure 4. Rayleigh PDF for buildings heights distribution in Ede Environment

Table no 3. Building heights distribution parameters' values

Environment	α_0	β_0
Suburban (ITU-R)	0.1	750
Urban (ITU-R)	0.3	500
Dense Urban (ITU-R)	0.5	300
Ede environment	0.28	930

Table no 4. Elevation angle (θ) versus $\log_{10} \sin\theta$

θ	$\log_{10} \sin\theta$
10^0	-0.7603
20^0	-0.4659
30^0	-0.3010
40^0	-0.1919
50^0	-0.1157
60^0	-0.0625
70^0	-0.0270
80^0	-0.0066
90^0	0.0000

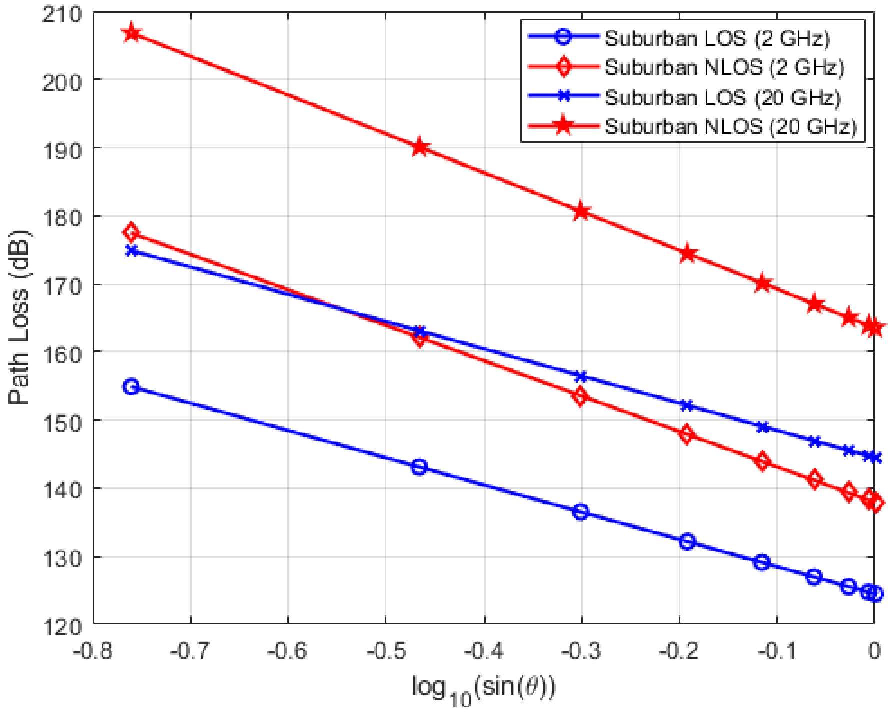

Figure 5. HAPS path loss for Ede environment at carrier frequencies 2 GHz and 20 GHz

Comparison Between Ede and Arlington Environments HAPS Path Losses

Comparisons between the calculated PL values for Ede and Arlington environments for LOS scenario are presented shown in Figure 6. Arlington environment, which has maximum clutter height of 10 m, was classified as a suburban environment in [15]. As expected for the LOS scenario, the same average PL value was obtained for both Ede and Arlington environments. The average PL values at 2 GHz and 20 GHz were 133.0657 dB and 153.0657, respectively. For the NLOS scenario, the PL results are presented in Figure 7. At 2 GHz, the average PL values for Ede and Arlington were 149.0874 dB and 147.6406 dB, respectively. At 20 GHz, the average PL values for Ede and Arlington were 175.7631 dB and 173.7134 dB, respectively. The Root Mean Squared Error (RMSE) of the comparisons between Ede and Arlington PL values at 2 GHz and 20 GHz for NLOS condition were 1.4469 dB and 2.0498 dB, respectively, as shown in Figure 8.

IV. Discussion

The Path Loss Model (PLM) for a HAPS system's propagation environment is advantageous for making informed decisions in the design and configuration of the system. The Rayleigh PDF provided insight into the signal impairment pattern over the building height distribution in Ede. Most of the buildings in Ede are more likely to fall under suburban (γ_o = 8) than urban or dense urban because the building height 8.0 m corresponding to the peak PDF, P(8.0) = 0.0758, is below the maximum building height in Ede (i.e. 13.2 m). The calculated α_o value reveals that Ede falls in-between suburban and urban. Furthermore, the calculated β_o value reveals that Ede is more of suburban than urban based on the ITU-R classification standard [20].

The path loss (PL) results reveal that a UE at a high elevation angle will experience a relatively lower PL compared to a UE at a lower elevation angle. Generally, PL decreases with increasing elevation angle for both LOS and NLOS scenarios. The PL values for the NLOS scenario are relatively higher than for the LOS scenario due to the presence of obstacles (such as buildings) between the HAPS and the UE, which invariably leads to signal attenuation. In addition, it was observed that the PL in LOS for 20 GHz is relatively higher than the PL in NLOS for 2 GHz at elevation angles greater than 10^o. This reveals that PL is directly proportional to the frequency of transmission. In other words, PL is significantly higher at relatively higher frequencies thereby making the signal to be more susceptible to absorption and scattering, thereby reducing the received signal strength.

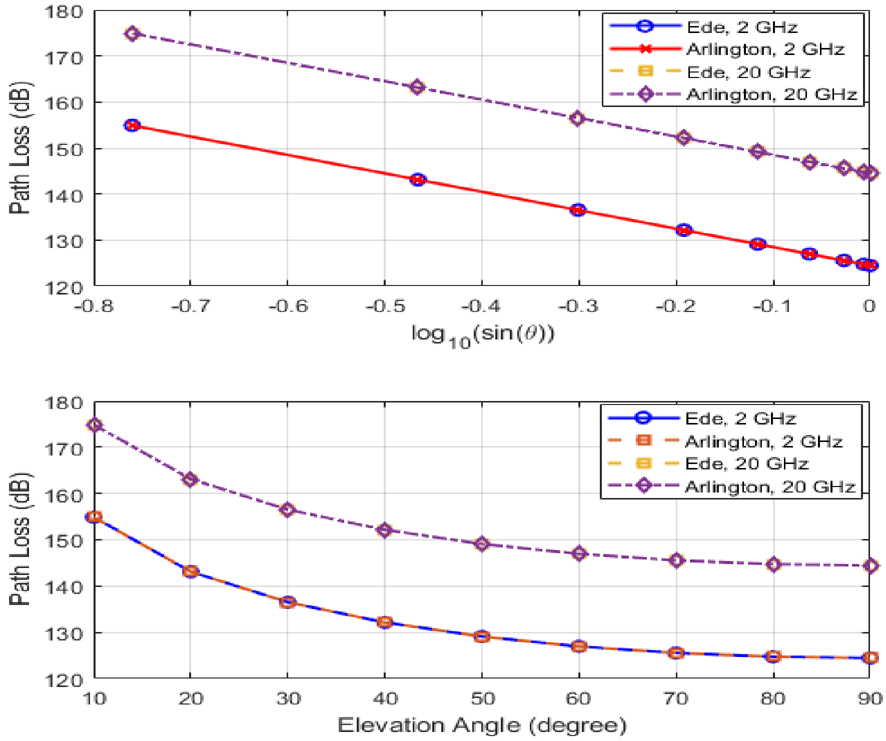

Figure 6. Comparison between Ede and Arlington for Line-of-Sight (LOS)

For the LOS scenario, irrespective of the type of propagation environment, PL is determined only by the FSPL model. However, it was observed for the NLOS scenario that with the same elevation angles and carrier frequencies, the PL for Ede is just slightly higher than the PL for Arlington (a suburban environment). The PL difference between Ede and Arlington for NLOS is due to the difference in cluttered heights of the environments.

V. Conclusion

This paper presents a HAPS path loss model (PLM) for Ede environment. The PLM was developed based on some demographic data of buildings in Ede. The developed PLM was a function of the HAPS carrier frequency, propagation distance, maximum building height, path loss exponent and elevation angle. The developed PLM was simulated at 2 GHz and 20 GHz carrier frequencies for both the LOS and NLOS scenarios at elevation angles from 10^o to 90^o . The results reveal that free-space PL model is sufficient for obtaining PL for LOS, and the PL for Ede agrees with the PL for Arlington in LOS. However, for NLOS, Ede environment gave relatively higher PL values compared to the Arlington environment (suburban) with RMSE values of

1.4469 dB and 2.0498 dB for 2 GHz and 20 GHz, respectively. The results showed that the Ede environment is tending towards urban but can be better classified as a sub-urban environment based on the ITU-R classification standard. Thus, the findings in this study would serve as a useful reference for researchers and engineers of the HAPS communication system technology.

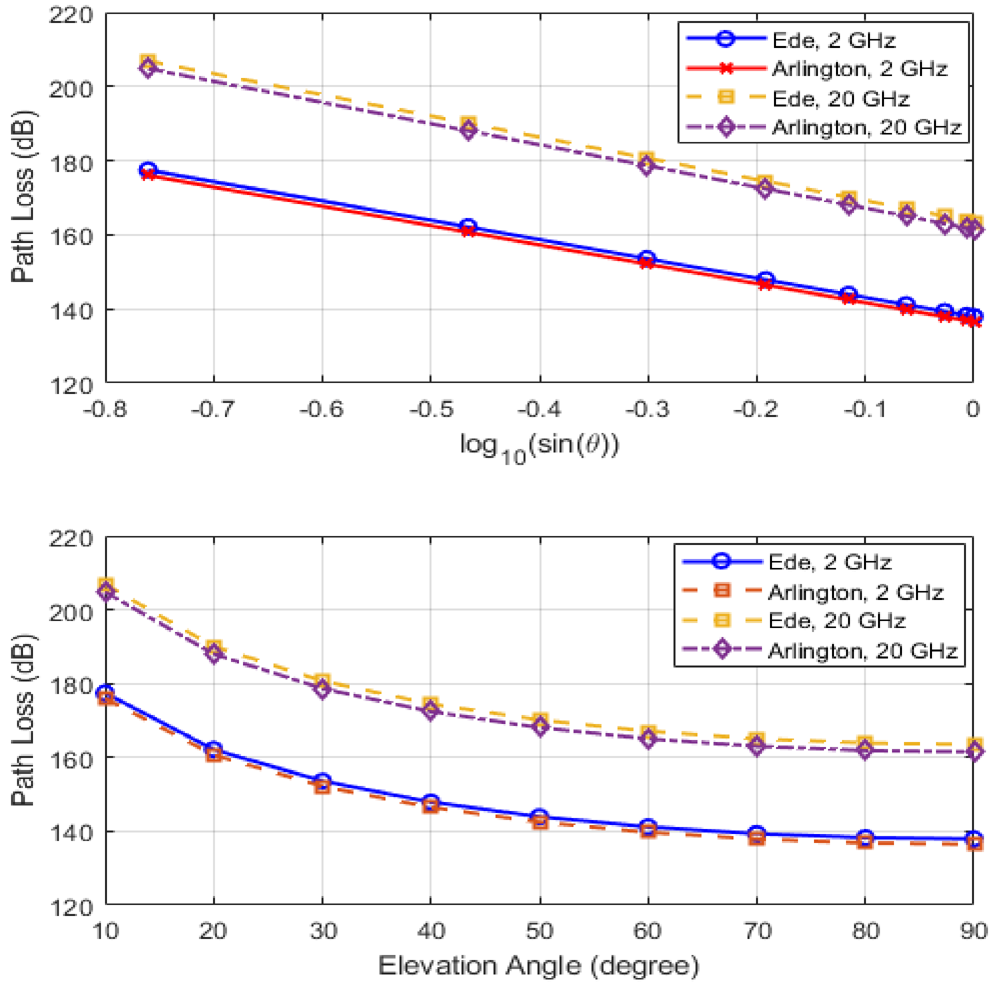

Figure 7. Comparison between Ede and Arlington for Non-Line-of-Sight (NLOS)

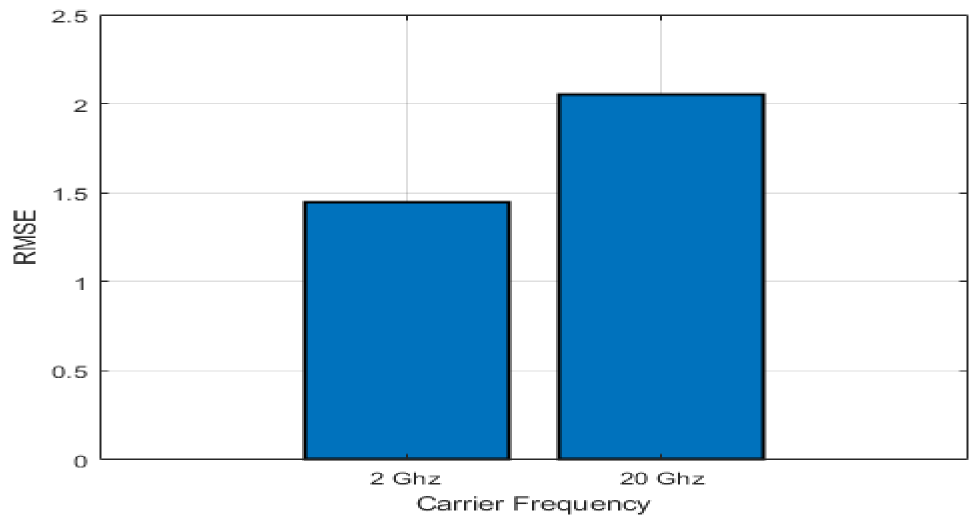

Figure 8. Root Mean Squared Error (RMSE) between Ede and Arlington Path Losses for NLOS scenario

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