Comparative Analysis of Terrestrial Rain Attenuation at Ku band for Stations in South-Western Nigeria

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Abstract - ***Rain is the most significant factor in radio propagation analyses and this has serious undesirable effects on rain attenuation on terrestrial point-to-point and point-to-multipoint radio communication systems for frequency bands above 10 GHz. One year daily rainfall data were collected from the Nigerian Meteorological Services (NIMET) for four stations in the South-Western region of Nigeria. The ITU-R model mostly over-estimated the measured data for $p \leq 0.1\%$ of time, while Abdulrahman and Silver Mello proposed prediction models generally over-estimated for $p > 0.1\%$ of time exceeded. Abdulrahman proposed prediction model was the best-performed model; it was closely follwed by Silver Mello and ITU-R models, respectively. The Moupfouma prediction model showed the worst perfomances of all the models investigated by largely over-estimating the measured data in all the four stations of interest. The poor performances of the ITU-R and Moupfouma prediction models may be attributed to the fact that the data used for the formulation of these models are mostly sourced from the temperate regions. This further accentuated the need for urgent review of the current ITU-R Recommendation P.530-13.***

Key Words: *Terrestrial, Rain attenuation, Rain rate, Path length, Prediction models.*

1. INTRODUCTION

Apart from being the major factor that influences satellite broadcast signals above frequency 10 GHz [1-5], it is nonetheless a key suspect in terrestrial point-to-point and point-to-multipoint radio signal transmission. Rain is the most significant factor in radio propagation analyses. Rain attenuation is usually described by statistical means [6]. The structure of rain drops can assume various shapes. It is spherical for small size cells, while it is considered oblate spheroidal or oblate distorted for medium and large size rain drops respectively. Rain attenuation is dependent on frequency, rain drop size distribution, drop shape ambient temperature and pressure [7]. Due to this great effect of rain attenuation on terrestrial point-to-point and point-to-multipoint radio communication systems for frequency bands above 10 GHz, several efforts have however led to the development of rain rate and rain attenuation models. These models do not give an accurate prediction of rain attenuation in tropical regions because the data used for the formulation of most of these prediction models were sourced from temperate regions, which predominantly experience solid precipitations. Therefore, more studies are needed in order to obtain a better rain attenuation prediction models that suite the tropical and equatorial climates. This will promote the establishment of reliable rain attenuation prediction methods for the tropics.

The International Telecommunication Union – Radio communication Sector (ITU-R) provides a model for predicting rain attenuation on any terrestrial radio link, but the model is encumbered since the prediction was founded on data collected from the temperate region. The methods for the prediction of rain attenuation in terrestrial links as recommended by the ITU-R are based on simplified models for the rain field affecting the propagation path. Another major setback is the assumption that the non-uniform rainfall along the propagation path can be modeled by an equivalent cell of uniform rainfall rate. The terrestrial prediction method as provided in ITU-R P.530-13 [8] assumes that an equivalent cylindrical cell of uniform rain can intercept the link at any position with equal probability. An effective path length is thus calculated as the average length of the intersection between the cell and the propagation path. Consequently, the effective path length was found be smaller than the actual path length [9], and this is the motivation that led to the introduction of a path reduction factor. This approach compensates for the non-homogeneity of rainfall and rain rates.

Rainfall of high intensity is difficult to record and measure experimentally, in addition to being highly variable from year-in, year-out. However, in system design, it is the highest rainfall rates that are of great interest. Short integration-time rainfall rate is the most essential input parameter in the prediction models for rain attenuation [10]. A rain event is not evenly distributed in an area; and the contribution of rain effect on a transmitted signal is such as to impede propagation of electric fields. Rainfall is structurally inhomogeneous in both vertical and horizontal direction of propagations. While it a fact that vertical variability negatively impacts only tropical climates where the 0^oC isotherm is high, horizontal variability affects all climates, particularly areas that experience heavy precipitations with its characteristic localized nature [11]. Rain attenuation prediction models generally take into account the inhomogeneity of rainfall by incorporating a path reduction factor, which features both path length and rainfall rate. The product of path reduction factor and the physical path length of a microwave link is the effective path length, defined as the intersection between the rain cell and propagation path. It is confirmed that the effective path length is often smaller than the actual physical path length leading to introduction of a path reduction factor [9, 12].

Several rain rate and rain attenuation prediction models abound in the literature. These include the revised version of the Crane's two-component model [13], Excell model [14], Bryant model [15], Flavin model [16], DAH model [17], simple attenuation model (SAM) by Stutzman and Yon [18], etc. According to Ajayi et al. [19], a methodological approach had been provided for estimating rain-induced attenuation from available rain statistics. In their work, the traditional method of moment of regression analysis was used for estimating the number of rain drop sizes and the results were compared with those obtained by using the log-normal distribution [20].

2. RESEARCH METHODOLOGY

Daily rainfall data were collected from the Nigerian Meteorological Services (NIMET) for four stations (Akure, Ile-Ife, Ilorin and Ikeja,) all in the South-Western region of Nigeria, for a period of one year (January to December 2010). Measurement setup at the meteorological station consists of the buck type rain gauge. The setup also comprises indoor and the outdoor units. The indoor unit consists of spectrum analyzer (trlytic), field strength meter (BK Precision 2640 GHz) and a satellite tracker. The obtained parameters like signal strength during clear air and other precipitations can then be recorded and analyzed. Rain rate data is collected from the weather station in the same geographical location where beacon signal is monitored.

Shown in Table 1 are the physical, spectral and climatological parameters for the stations for these four stations under study.

Table -1: Local climatological parameters for the stations

STATIONS	Longitude (^oN)	Latitude (^oE)	Annual Rainfall (mm)	$R_{0.01}$ (mm/h)
Akure (9.2km, 14.8GHz)	5.18	7.17	1485.57	104.2
Ile-Ife (15.2km, 14.8GHz)	5	7.5	1215.27	104.6
Ikeja (13.45km, 14.8GHz)	3.2	6.3	1425.21	101.9
Ilorin (8.9km, 14.8GHz)	4.5	8.5	1232.77	106.5

Chebil and Rahman's rain rate conversion method [21-22] was used to convert these hourly data into its equivalent one-minute rainfall rate values, as follows:

$$CF60 = \frac{R1(p)}{R60(p)} = ap^b \quad (1)$$

$$CF60 = ap^b + c * exp(dp) \quad (2)$$

Where a, b, c and d are regression coefficients derived from Segal proposed conversion model [23] using Gauss-Newton technique for the evaluation [21[. From (2), the following relationship was derived:

$$CF60 = 0.772 * p^{-0.041} + 1.141 * \exp(-2.57 * p) \quad (3)$$

Where $CF60$ is the rain rate conversion factor, defined as the ratio of rain rates $R1(p)$and $R60(p)$ for a given percentage of time p with an integration time of 1 min and 60 min, respectively. Although this model is applicable for the range $0.001\% \leq p \leq 1.0\%$ 0.001%, nonetheless, if $R60(p)$ is known, then $R1(p)$ can be derived as:

$$R1(p) = R60(p) * CF60 \quad (4)$$

2.1 Brief overview of relevant rain attenuation prediction models

The International Telecommunication Union - radio communication sector (ITU-R) model was adjudged the most widely accepted internationally for the prediction of rain effects on communication systems [24]; for this reason, most emerging models are compared against it for conformity and reliability; especially for cases where measured data are not available. However, recent researches have shown that some ITU-R models are only suitably reliable in certain geographical areas [25-27]. The performances of the following rain attenuation prediction models were investigated in the four locations studied in this work.

2.1.1 ITU-R

The method for the prediction of rain attenuation in terrestrial links as given in ITU-R Recommendation P.530-13 [8], was originally developed based on a simplified model that the spatio-temporal random variations of rain field is responsible for attenuation. The basic assumption in the method is on the premise that an equivalent cell with uniform rainfall rate and length d_0 randomly positioned in the great circle plane can represent the effect of the non-uniform rainfall along the propagation path. Assuming that this equivalent rain cell may intercept the link at any position with equal probability, then the expression for an effective path length is derived [7]. The effective path length is the average length of the intersection between the cell and path and it is represented as:

$$D_{eff} = d * r \quad (5)$$

$$r = \frac{1}{1+d/d_0} \quad (6)$$

$$D_{eff} = d * r = \frac{d}{1+d/d_0} \quad (7)$$

The diameter d_0 of the equivalent cell is empirically derived from experimental data, depending on the long-term point rainfall rate measured in the region of interest. The cell diameter d_0 is obtained from the long-term complementary cumulative probability distribution of the point rainfall rate, R (mm/h) measured in the link region. The rainfall rate exceeded at 0.01% of time $R_{0.01}$ is used to predict the corresponding value of rain attenuation, $A_{0.01}$.

$$A_{0.01} = \gamma_{0.01} * d_{eff} = k(R_{0.01})^{\alpha} * \frac{d}{1+d/d_0} \quad (8)$$

Where γ (dB/km) is the specific attenuation, obtained using the frequency and polarization dependent parameters k and α from Recommendation ITU-R P. 838-3 [28], and d is the actual path length.
Where

$$d_0 = 35 * \exp(-0.015 * R_{0.01}) \quad (9)$$

The attenuation exceeded for other time percentages, p, of an average year may be calculated from the value of $A_{0.01}$ by using the following:

$$A_{\%p} = 0.12 A_{0.01}\, p^{-(0.546+0.043\log_{10} p)} \quad (10)$$

The major draw-back of the extrapolation approach of (10) is that it does not perform well in tropical regions, especially at higher rain rates [29].

2.1.2 Moupfouma

The rain attenuation $A_{\%p}$ exceeded at $p\%$ of time is obtained from:

$$A_{\%p} = k\left(R_{\%p}\right)^{\alpha} * d * \delta(R_{\%p}, d) \quad (11)$$

Where $\delta(R_{\%p}, d)$ is the reduction factor for $p\%$ of the time, $R_{\%p}$ (mm/h) is the rain rate exceeded at the same time percentage, d (km) is radio path length. Parameters k and α are regression coefficients that is dependent on frequency, rain temperature, and polarization; and their values can be obtained from ITU-R P.838-3 [28].
To determine the effective propagation path length, d_{eff} there is need to define a reduction factor which accounts for the non-uniformity of rain on the entire propagation path. According to Moupfouma, path reduction factor at 0.01% of time for any terrestrial radio link is calculated as follows [29]:

$$\delta(R_{\%p}, d) = \exp\left(\frac{-R_{0.01}}{1+\zeta(d)*R_{0.01}}\right) \quad (12)$$

Where $R_{0.01}$ (mm/h) is the rain rate at 0.01% of time and $\zeta(d)$ is a parameter whose value depends on the actual radio path length.
Generally, the parameter $\zeta(d)$ must be less than zero, else $\delta(R_{\%p}, d)$ will be greater than the actual path length, d. That is, $\delta(R_{\%p}, d) \leq 1.0$. However, recent findings showed that this is not always the case [30-31].

2.1.3 Abdulrahman et al.

The relationship between path reduction factor and different link lengths was studied using multiple non-linear regression techniques. The concept of equivalent rain cell as proposed in the ITU-R P.530-13 [8] was adopted in the experimental data analysis. Based on the analysis, the relationship between d_0 and the corresponding rain rate, $R_{0.01}$ at 0.01% of time was investigated, and it was found that the former is dependent on the latter according to the following empirical relationship [30]:

$$d_0 = 2.6379 * R_{0.01}{}^{0.21} \qquad (13)$$

When (13) was combined with (6), it yielded

$$\delta(R_{0.01}, d) = \frac{1}{1 + d/2.6379 * R_{0.01}{}^{0.21}} \qquad (14)$$

Multiplying the Right Hand Side of (14) by the true path length, d produced the expression for the effective path length:

$$D_{eff}(R_{0.01}, d) = \frac{d}{1 + d/2.6379 * R_{0.01}{}^{0.21}} \qquad (15)$$

Therefore, the attenuation exceeded for other time percentages, p can be expressed as:

$$A_{\%p} = k(R_{\%p})^{\alpha} * D_{eff}(R_{0.01}, d)$$
$$= k(R_{\%p})^{\alpha} \frac{d}{1 + d/2.6379 * R_{0.01}{}^{0.21}} \qquad (16)$$

2.1.4 Silver Mello et al.

A modified method that addressed some of the problems found in the current ITU-R method but retains the general expression for d_{eff} (which is the basis of the model,) and uses the full rainfall rate distribution at the links region as input for the prediction of the cumulative distribution of rain attenuation was proposed by [7].
The dependence of the reduction factor on link parameters was investigated, using experimental data from concurrent long-term measurements of point rainfall rate and rain attenuation in terrestrial links available in the ITU-R databanks. A correction factor r_p was introduced to accommodate all percentages of time for available data with the expression:

$$r_p = \frac{A_p}{k R_p{}^{\alpha} * d} \qquad (17)$$

Where A_p and R_p are respectively the rain attenuation and the point rainfall rate exceeded at $p\%$ of the time.
It was found that r_p decreases with the path length and the point rainfall rate [7]. A power-law relationship was obtained for the equivalent cell diameter, d_0 as:

$$d_0 = 1.763 * R^{-0.244} \qquad (18)$$

The dependence of the effective rain rates on link parameters was also investigated, using experimental data from concurrent long-term measurements of point rainfall rate and rain attenuation in slant path links available in the ITU-R databanks, with only data from beacon measurements with concurrent measurements of rainfall rates considered. This resulted in (20).

$$R_{eff} = \left(\frac{A_p}{k * \frac{d}{1 + d/d_0}} \right)^{\alpha} \qquad (19)$$

After series of trials with different functions to obtain the best regression fit, the general expression for terrestrial rain attenuation prediction given in (20) was eventually arrived at.

$$A_p = k\left[1.736 R^{0.753+0.197/d}\right]^{\alpha} \frac{d}{1 + \frac{d}{119 R^{-0.244}}} \qquad (20)$$

One-minute rain rate and rain attenuation data from 64 links in 15 different countries for a period of 74 years was tested over terrestrial links and the results showed that the proposed model out-performed the ITU-R Recommendation P.530-13 [8] model for prediction of rain attenuation over terrestrial links [7].

3. RESULTS AND DISCUSSIONS

Results of the comparison for the ITU-R model and other relevant rain attenuation prediction models for terrestrial links for the four selected stations in the Nigeria South-Western geographical region were plotted. At the Akure Station, a glimpse at Fig. 1 seems to show that the ITU-R model presented the best performance. However, a careful observation of Figs. 2 and 3 reveals that indeed the ITU-R model closely matched the measured only within the limits $0.01\% \leq p \leq 1.0\%$ of time. At $p < 0.01\%$, it began to deviate from the measured (by over-estimation), while both the Silver Mello and Abdulrahman proposed models began to show closer matching.

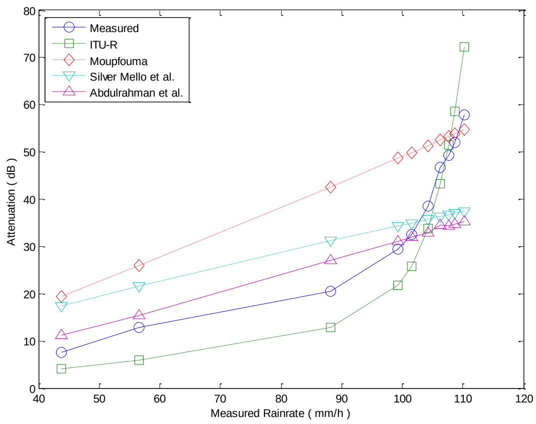

Fig -1: Comparison of rain rate and attenuation CDs for Akure

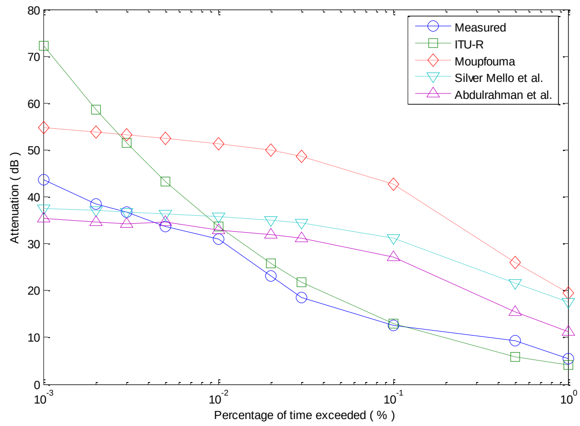

Fig -2: Comparison of rain attenuation CDs for Akure

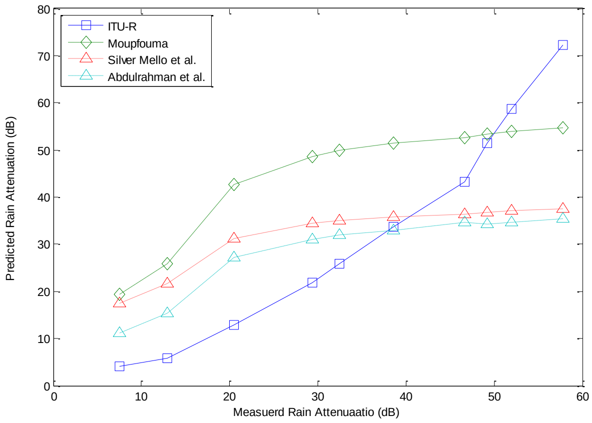

Fig -3: Predicted versus measured rain attenuation for Akure

The same pattern observed at the Akure station is replicated at the other three stations. The reason for this is that the four stations experience similar meteorological conditions. However, the degrees to which radio signals are attenuated vary slightly. For instance, the attenuation exceeded for Akure at 0.001% and 0.01% of time are 43.57dB and 33.69dB respectively, while it is 57.82dB and 38.54dB; 42.82dB and 29.12dB; 54.82dB and 34.0dB for Ile-Ife, Ilorin and Ikeja respectively. These can be seen in Figures 4 to12.

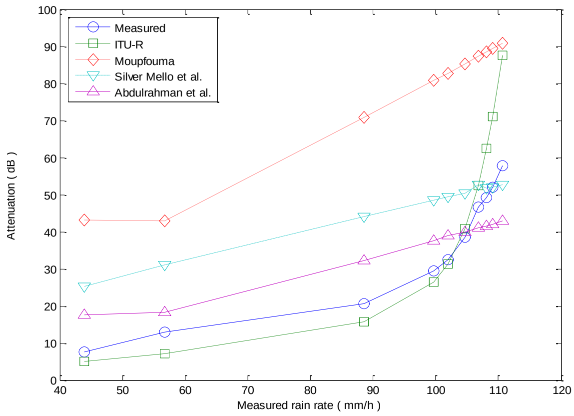

Fig -4: Comparison of rain rate and attenuation CDs for Ile-Ife

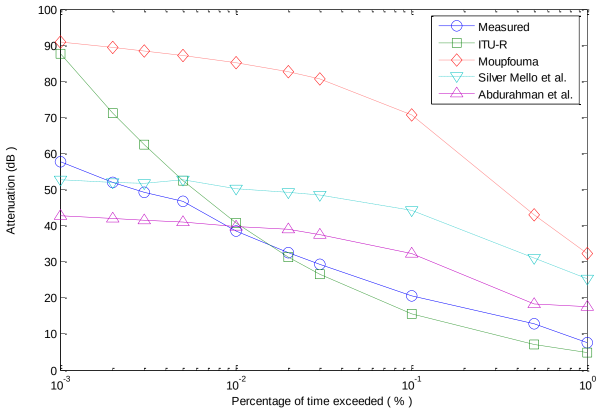

Fig -5: Comparison of rain attenuation CDs for Ile-Ife

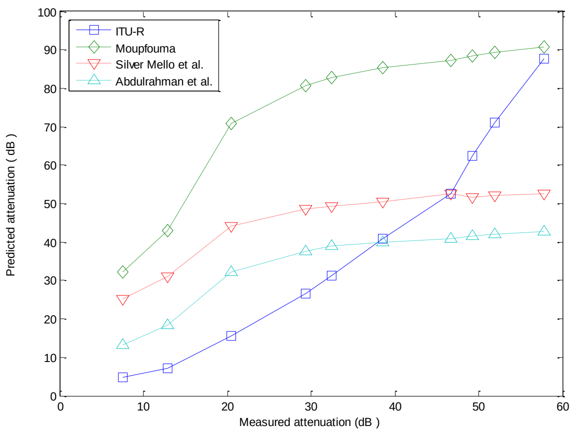

Fig -6: Predicted versus measured rain attenuation for Ile-Ife

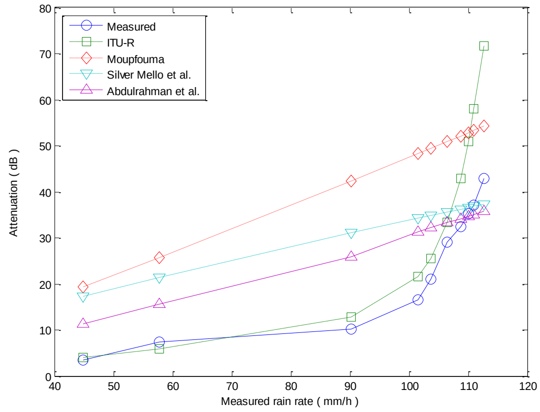

Fig -7: Comparison of rain rate and attenuation CDs for Ilorin

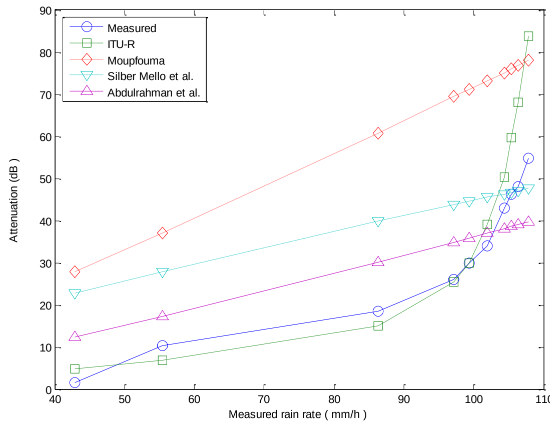

Fig -10: Comparison of rain rate and attenuation CDs for Ikeja

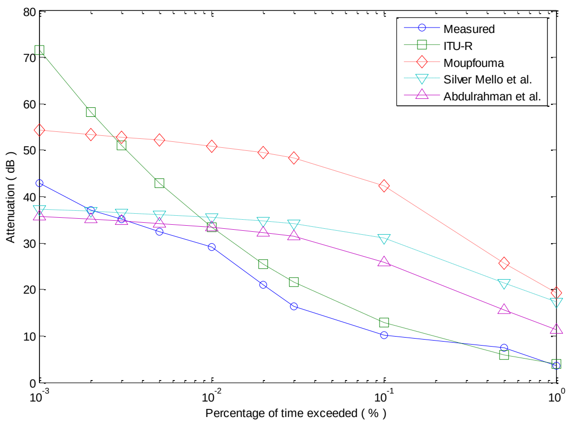

Fig -8: Comparison of rain attenuation CDs for Ilorin

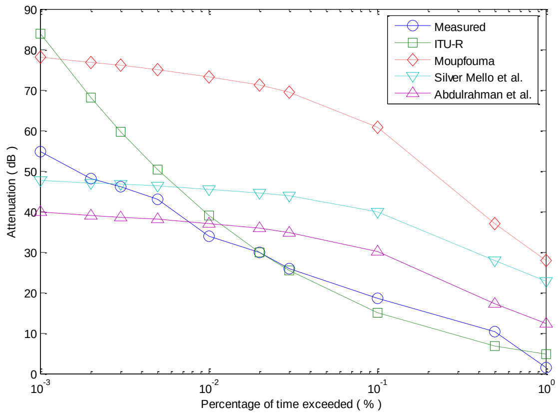

Fig -11: Comparison of rain attenuation CDs for Ikeja

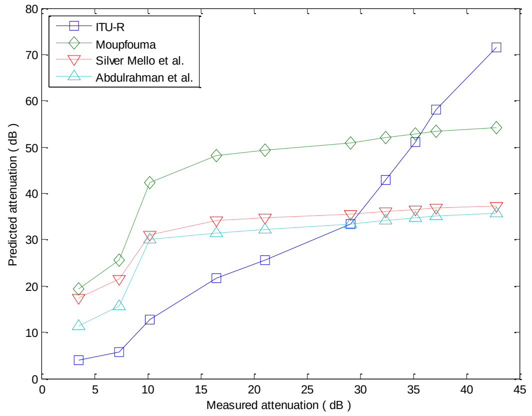

Fig -9: Predicted versus measured rain attenuation for Ile-Ife

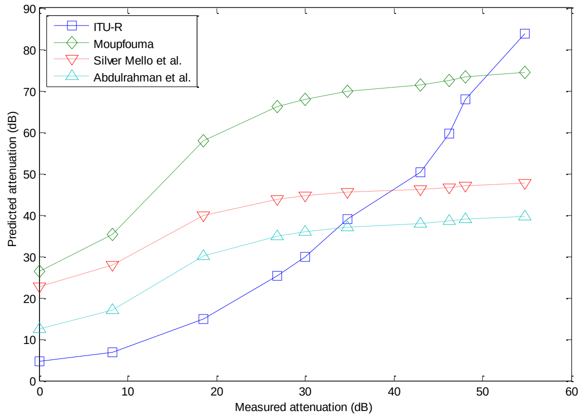

Fig -12: Predicted versus measured rain attenuation for Ikeja

Table 2 (see Appendix) presents the percentage mean, deviation and root-mean-square values for various percentages of time exceeded and for the respective rain attenuation prediction models of interest.
For Ikeja station, Abdulrahman model performed better than the other prediction models for $p \leq 0.01\%$, and was closely followed by Silver Mello for $p < 0.01\%$. The ITU-R prediction model exhibited the best performances for $p > 0.01\%$, which really is of no serious practical implication since the ITU-R recommended limits for commercial and millitary equipment are 99.99% and 99.999% of availability respectively. These trend was maintained for other stations.
The ITU-R model was generally observed to have over-estimated the measured data for $p \leq 0.1\%$ of time, while Abdulrahman and Silver Mello proposed prediction models generally over-estimated for $p > 0.1\%$ of time exceeded. The Moupfouma prediction model showed the worst perfomances of all the models investigated by largely over-estimating the measured data in all the four stations of interest under investigation.
According to the evaluation procedures adopted for comparison of prediction methods by the Recommendations ITU-R P.311-13 [32], the best prediction method produces the smallest values of the statistical parameters. Therefore, Abdulrahman proposed prediction model is overall best model and was closely follwed by Silver Mello and ITU-R models, respectively.

3. CONCLUSIONS

This paper presented the findings of the comparative analysis and study of terrestrial rain attenuation for four stations in the South-Western geographical region of Nigeria. Results of this study suggested that the ITU-R and Moupfouma prediction models over-estimated the measured data; with the Moupfouma proposed model showing the worst performances in all the stations of interest. Abdulrahman proposed prediction model exhibited the overall best performance and was closely follwed by Silver Mello and ITU-R models, respectively.
The poor performances of the ITU-R and Moupfouma prediction models may be attributed to the fact that the data used for the formulation of these models are mostly sourced from the temperate regions. On the other hand, the impressive performances of Abdulrahman and Silver Mello proposed prediction models can be ascribed to its data sources, which are Malaysia and Brazil, respectively; which are both tropical stations. This further emphasized the need for urgent review of the ITU-R Recommendation P.530-13 as it currently obtains.

REFERENCES

[1] T. Maruyama, Y. Shirato, M. Akimoto, and M. Nakatsugawa, "Service area expansion of quasi-millimeter FWA systems through site diversity based on detailed rainfall intensity data," *IEEE Transactions on Antennas and Propagation*, vol. 56, No. 10, pp. 3285–3292, 2008.
[2] A. D. Panagopoulos, P. D. M. Arapoglou, and P. G. Cottis, "Satellite communications at Ku, Ka, and V bands: Propagation impairments and mitigation techniques," *IEEE Communications Surveys & Tutorials*, vol. 6, no. 3, pp. 2-14, 2004.
[3] S. A. Kanellopoulos, A. D. Panagopoulos, C. I. Kourogiorgas, and J. D. Kanellopoulos, "Satellite and terrestrial links rain attenuation time series generator for heavy rain climatic regions," *IEEE Transactions on Antennas and Propagation*, vol. 61, no. 6, pp. 3396–3399, 2013.
[4] F. J. A. Andrade and L. A. Da Silva Mello, "Rain attenuation time series synthesizer based on the gamma distribution," *IEEE Antennas and Wireless Propagation Letters*, vol. 10, pp. 1381–1384, 2011.
[5] C. Kourogiorgas and A. D. Panagopoulos, "New physical-mathematical model for predicting slant path rain attenuation statistics based on inverse Gaussian distribution," *IET Microwaves, Antennas & Propagation*, vol. 7, no. 12, p. 970–975, 2013.
[6] J. S. Mandeep et al., "Modified ITU-R Rain Attenuation Model for Equatorial Climate'', *Proceeding of the 2011 IEEE International Conference on Space Science and Communication (Icon Space)*, pp. 89-92, 2011.
[7] L. A. R. Silva Mello and M.S. Pontes, "Unified Method for the Prediction of Rain Attenuation in Satellite and Terrestrial Links", *Journal of Microwaves, Optoelectronics and Electromagnetic Applications*, vol. 11, no.1, pp. 1-14, June 2012.
[8] Recommendation ITU-R P. 530-13, "Propagation data and prediction methods required for the design of terrestrial line-of-sight systems", *International Telecommunication Union*, 2009.
[9] R. M. D. Islam, A. Y. Abdulrahman and T. A. Rahman, "An improved ITU-R rain attenuation prediction model over terrestrial microwave links in tropical region", *EURASIP Journal on Wireless Communications and Networking*, no. 1, pp. 1-9, 2012.
[10] J. S. Ojo, M. O. Ajewole and S. K. Sakar, "Rain rate and rain attenuation prediction for satellite communication in Ku and Ka bands over Nigeria", *Progress on Electromagnetic Res. B 5*, pp. 207–223, 2008.
[11] J. W. F. Goddard, "Propagation in rain and cloud: Spatial temporal structure of rain," *Propagation of Radio Waves*, 2nd edition, The Institution of Electrical Engineers, IEE, U.K., 2003.
[12] A. Y. Abdulrahman, T. A Rahman, S. K. B. Abdulrahim, and M. Rafiqul Islam, "Empirically Derived Path

Reduction Factor for Terrestrial Microwave Links Operating At 15GHz In Peninsula Malaysia", *Journal of Electromagnetic Waves and Appl.,* vol. 25, pp. 23–37, 2011.

[13] R. K. Crane, "A two component rain model for the prediction of rain attenuation statistics", Radio Science, vol. 17, no. 6, pp. 371–1387, 1982.

[14] C. Capsoni, F. Fedi, C. Magistroni, A. Paraboni, and A. Pawlina, "Data and theory for a new model of the horizontal structure of rain cells for propagation applications," *Radio Sci.*, vol. 22, no. 3, pp. 395-404, 1987.

[15] G. H. Bryant, I. Adimula, C. Riva, and G. Brussaard, *"Rain attenuation statistics from rain cell diameters and heights,"* International journal of satellite Communications, vol. 19, no. 3, pp. 263-283, 2001.

[16] R. Flavin, "Rain Attenuation Considerations for Satellite Paths in Australia", *Telecommunication Research,* Vol. 16, no. 2, pp. 11-24, 1992.

[17] A. Dissanayake, J. Allnutt, and F. Haidara, *"A Prediction Model that Combines Rain Attenuation and Other Propagation Impairments along Earth-Satellite Paths,"* IEEE Transaction on Antennas and Propagation, vol. 45, no. 10, pg. 1549, 1997.

[18] W. Stutzman and K. Yon, "A simple rain attenuation model for earth-space radio links operating at 10–35 GHz", *Radio science,* vol. 21, no. 1, pp. 65-72, 1986.

[19] G .O. Ajayi, I. E. Owolabi and I. A. Adimula, "Rain induced depolarization from 1 GHz to 300 GHz in a tropical environment", *International Journal of Infrared and Millimeter Waves,* vol. 8, no. 2, pp. 177–197, 1987.

[20] A.Y. Abdulrahman, T. A Rahman, S. K. B. Abdulrahim, U. Kesavan, "Comparison of measured rain attenuation and ITU-R predictions on experimental microwave links in Malaysia*", International Journal of Microwave and Wireless Technologies,* vol. 3, no. 4, pp. 477–483, 2011.

[21] J. Chebil and T. A. Rahman, "Rain rate statistical conversion for the prediction of rain attenuation in Malaysia," *Electronics Letts*., Vol. 35, 1019–1021, 1999.

[22] J. Chebil and T. A. Rahman, "Development of 1 min rain rate contour maps for microwave applications in Malaysia Peninsula, "*Electronics Letts.*, Vol. 35, 1712–1774, 1999.

[23] B. Segal, "The Influence of Rain Gauge Integration Time on Measured Rainfall-Intensity Distribution Functions", *Journal of Atmospheric and Oceanic Technology*, pp. 662-671, 1986.

[24] A. I. O. Yussuff and N. H. H Khamis, "Modified ITU-R Rain Attenuation Prediction Model for a Tropical Station", *Journal of Industrial and Intelligent Information,* vol. 1, no. 3, pp. 155-159, 2013.

[25] K. S. Chen, C.Y. Chu, and Y. C. Tzeng, "A semi-empirical model of rain attenuation at Ka-Band in Northern Taiwan*," Progress in Electromagnetics Research M*, vol. 16, pp. 213-22, 2011.

[26] J. Chebil, "Rain rate and rain attenuation distribution for microwave propagation study in Malaysia," *Ph.D. dissertation, Dept. of Radio and Communications Engineering, Universiti Teknologi Malaysia,* 1997.

[27] A. Y. Abdulrahman, T. A Rahman, S. K. B. Abdulrahim, and M. Rafiqul Islam, "A new rain attenuation conversion technique for tropical regions," *Progress in Electromagnetics Research B*, vol. 26, pp. 53-67, 2010.

[28] Recommendation ITU-R P.838-3, "Specific attenuation model for rain for use in prediction methods", *International Telecommunication Union*, 2005.

[29] F. Moupfouma, "Electromagnetic waves attenuation due to rain: A prediction model for terrestrial or L.O.S SHF and EHF radio communication," *J. Infrared Milli. Terahz Waves*, Vol. 30, pp. 622–632, 2009.

[30] A. Y. Abdulrahman, T. A, Rahim, S. K. A. and Islam, M. R. U., "Empirically Derived Path Reduction Factor for Terrestrial Microwave Links Operating at 15Ghz in Peninsula Malaysia", *Journal of Electromagnetic Waves and Applications,* vol. 25, pp. 23–37, 2011.

[31] L. A. R. Da Silva-Mello, M. S. Pontes, R. M De Souza, and N. A. Perez-Garcia, "Prediction of Rain Attenuation in Terrestrial Links Using Full Rainfall Rate Distribution", *Elecronics Letters,* vol. 43, no. 25, pp. 1442-1443, 2007.

[32] Recommendation ITU-R P.311-13, "Acquisition, presentation and analysis of data in studies of tropospheric propagation", *International Telecommunication Union*, 2009

APPENDIX

Table -2: Comparison of mean error, standard deviation and RMS for different stations and prediction models

Station	Parameters	Model	0.001	0.002	0.003	0.005	0.01	0.02	0.03	0.1	0.5	1
AKURE	Mean	ITUR	0.0658816	0.0525461	0.040327	0.0285691	0.0091172	0.0116603	0.0181193	0.002422	-0.0372198	-0.0263356
		Abdulrahman et al	-0.0189183	-0.0097937	-0.0065461	0.0026922	0.0064938	0.0383579	0.0679286	0.1152773	0.0646544	0.1028826
		Moupfouma	0.0257093	0.040102	0.0453074	0.0559623	0.0662432	0.1159935	0.1629892	0.2380952	0.177343	0.2533396
		Silver Mello et al	-0.0139399	-0.0036658	0.0001904	0.0079593	0.0157651	0.0514072	0.0857909	0.1474364	0.1313506	0.217581
	Std	ITUR	0.3426667	0.3449634	0.3466044	0.347771	0.3488234	0.3487476	0.3484717	0.3489341	0.3469518	0.3479473
		Abdulrahman et al	0.5886408	0.5888632	0.5889083	0.5889385	0.5889089	0.5876942	0.5850141	0.5775526	0.585385	0.5798888
		Moupfouma	1.4286935	1.4283619	1.4282063	1.4278285	1.4273885	1.4242091	1.4195987	1.4089488	1.4178771	1.4062877
		Silver Mello et al	0.9840478	0.9841397	0.9841465	0.9841143	0.9840202	0.9828029	0.9804	0.97304	0.9753417	0.9597931
	RMS	ITUR	0.3362738	0.3409379	0.3442504	0.3465956	0.3487042	0.3485526	0.3480004	0.3489257	0.3449496	0.3469492
		Abdulrahman et al	0.5883367	0.5887818	0.5888719	0.5889324	0.5888731	0.5864411	0.581057	0.5659312	0.5818036	0.5706892
		Moupfouma	1.4284621	1.4277989	1.4274875	1.4267314	1.4258505	1.4194777	1.410211	1.3886855	1.4067427	1.3832802
		Silver Mello et al	0.983949	0.9841328	0.9841465	0.9840821	0.9838939	0.9814575	0.9766392	0.9618052	0.1380925	0.9348055
IFE	Mean	ITUR	0.0515467	0.0368946	0.0268862	0.0124663	0.0060902	-0.0036314	-0.0098258	-0.0236676	-0.0449188	-0.0344852
		Abdulrahman et al	-0.0259065	-0.0190522	-0.0155161	-0.0123328	0.0034489	0.0202936	0.0276319	0.0575254	0.0421765	0.1353862
		Moupfouma	0.0571227	0.0720199	0.0797739	0.0868752	0.1211833	0.1551253	0.1748003	0.2450757	0.2328698	0.3292817
		Silver Mello et al	0.0121768	0.0234506	0.0294388	0.0351324	0.0611302	0.0875944	0.1036367	0.1666775	0.2012448	0.3256205
	Std	ITUR	0.2923142	0.2945223	0.2956041	0.2965623	0.2967618	0.296802	0.2966616	0.2958792	0.2934057	0.2948142
		Abdulrahman et al	0.5095542	0.5098565	0.5099764	0.5100633	0.5102007	0.5098086	0.5094636	0.5069591	0.5084661	0.5095542
		Moupfouma	1.7721627	1.7716198	1.7712876	1.7709535	1.768937	1.7662841	1.7644456	1.7560642	1.7577244	1.7422391
		Silver Mello et al	1.4115385	1.4113962	1.411284	1.4111537	1.4102667	1.4088706	1.4077814	1.401716	1.397172	1.3735212
	RMS	ITUR	0.2877334	0.2922023	0.2943788	0.2963002	0.2966993	0.2967798	0.2964988	0.294931	0.2899469	0.2927903
		Abdulrahman et al	0.5088952	0.5095004	0.5097403	0.5099142	0.510189	0.5094046	0.5087137	0.5036847	0.5067139	0.4912393
		Moupfouma	1.7712418	1.7701553	1.7694902	1.7688213	1.7647812	1.7594589	1.7557657	1.7388787	1.7422304	1.7108391
		Silver Mello et al	1.4114859	1.4112014	1.4109769	1.4107163	1.4089412	1.4061449	1.4039615	1.3917709	1.3826027	1.3343657
ILORIN	Mean	ITUR	0.0671886	0.0565406	0.0448929	0.0322322	0.0147208	0.0211391	0.0316475	0.0254147	-0.0210856	0.0146303
		Abdulrahman et al	-0.0165022	-0.0054844	-0.0014503	0.0053545	0.014454	0.0528968	0.090862	0.1530506	0.1115997	0.2235716
		Moupfouma	0.0267473	0.0437297	0.050025	0.0606102	0.074906	0.134395	0.1933458	0.3145594	0.2485268	0.450665
		Silver Mello et al	-0.0128982	-0.0007795	0.0038458	0.0115668	0.0222384	0.0651164	0.1079636	0.2043531	0.1915396	0.3958727
	Std	ITUR	0.3644678	0.3662707	0.36788	0.3692047	0.3703166	0.3700057	0.3692553	0.3697366	0.3700087	0.3703201
		Abdulrahman et al	0.987077	0.9871997	0.9872139	0.9872004	0.9871091	0.9857967	0.9830246	0.9752788	0.9808867	0.9615659
		Moupfouma	2.0823061	2.0820187	2.0818769	2.0815957	2.0811303	2.0781367	2.0734829	2.0585836	2.0675949	2.0331294
		Silver Mello et al	1.5869863	1.5870385	1.5870341	1.5869966	1.5868829	1.5857023	1.5833622	1.5738271	1.5754379	1.5368724
	RMS	ITUR	0.3582212	0.3618803	0.3651305	0.3677951	0.3700239	0.3694013	0.3678966	0.3688621	0.3694074	0.370031
		Abdulrahman et al	0.986939	0.9871844	0.9872128	0.9871859	0.9870033	0.9843765	0.9788164	0.9631949	0.9745175	0.9352137
		Moupfouma	2.0821343	2.0815594	2.0812758	2.0807131	2.0797818	2.0737864	2.0644488	2.0344087	2.0526039	1.982553
		Silver Mello et al	1.5869339	1.5870383	1.5870294	1.5869544	1.5867271	1.5843647	1.5796771	1.5605036	1.563751	1.4850123
IKEJA	Mean	ITUR	0.0528611	0.0413544	0.02923	0.0168093	0.0150206	-0.00031	-0.0024923	-0.0191107	-0.0342349	0.2125665
		Abdulrahman et al	-0.0275387	-0.0187748	-0.0164091	-0.0116116	0.0089912	0.0195633	0.0341115	0.0621623	0.0657322	0.7241356
		Moupfouma	0.0358184	0.0523097	0.056958	0.0663535	0.1055971	0.1263533	0.1546962	0.2134915	0.2413146	1.6632979
		Silver Mello et al	-0.0131373	-0.0021487	0.0011449	0.0076116	0.0338941	0.04865	0.0684731	0.1153555	0.1698502	1.4099069
	Std	ITUR	0.7232958	0.7240449	0.7246356	0.7250301	0.7250693	0.7252248	0.7252206	0.7249731	0.7244164	0.6933734
		Abdulrahman et al	2.3143543	2.314442	2.31446	2.314489	2.3145007	2.3144355	2.3142668	2.3136832	2.3135846	2.1983225
		Moupfouma	5.4156772	5.415543	5.4154961	5.4153891	5.4147661	5.4143215	5.4135858	5.4115861	5.4104168	5.154055
		Silver Mello et al	4.514883	4.5149016	4.514902	4.5148957	4.5147749	4.51464	4.5143829	4.5134282	4.5117061	4.2891146
	RMS	ITUR	0.7213616	0.7228629	0.7240458	0.7248352	0.7249137	0.7252248	0.7252163	0.7241643	0.723607	0.6599865
		Abdulrahman et al	2.3141905	2.3143659	2.3144018	2.3144599	2.3144832	2.3143528	2.3140154	2.312848	2.3126506	2.0756323
		Moupfouma	5.4155587	5.4152904	5.4151966	5.4149826	5.4137363	5.4128469	5.4113751	5.4073732	5.4050325	4.878291
		Silver Mello et al	4.5148639	4.5149011	4.5149019	4.5148893	4.5146477	4.5143779	4.5138636	4.5119539	4.5085079	4.0507612