

*Full Length Research Paper*

# **Evaluation of simulated rain-based attenuation techniques at k-v frequency bands for satellite services under different modulation techniques over Southwestern Nigeria**

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Rain-based attenuation (RBA) is a major deteriorating factor affecting radio wave signals operating at microwave and millimetre wave bands for a typical Earth-Space Communication Link (ESCL). Although the international telecommunication union (ITU) recommended a standard model for predicting RBA along the terrestrial and ESCL, the technique underperforms in tropical environments. However, the model can be supported by appropriate modulation to enhance link performance. The present study assesses the performance of selected RBA models, namely the ITU, Moupfouma, and Garcia-López models based on rain types for K-V frequency bands over some selected locations in Southwestern Nigeria. Link performance was further tested based on different modulation scaling to minimize signal degradation. The result shows that Garcia-López and ITU models performed well at low rain rate  $R \leq 2$  mm/h but underestimated at higher rain rates (except thunderstorms rain type) at the high-frequency band. However, the Moupfouma model performed well for all the rain types irrespective of the selected frequency band, while the ITU model underestimated attenuation for  $R < 5$  mm/h (shower) and  $R > 30$  mm/h (thunderstorm) rain type from the K-V band frequency, Garcia Lopez underestimates the RBA value for  $R < 5$  mm/h and  $R > 5$  mm/h up to the Ka frequency band. Considering the modulation scaling on link performance shows that the bit-error-rate (BER) will severely degrade with a high rain rate compared to the low rain rate across different frequencies. The BER for 8-PPM outperforms the other types of modulation schemes that were used in this study. Overall results revealed that modulation technique DPSK with selective combining diversity gave a marginal improvement with the increase in link distance and operating frequency.

**Key words:** ESCL, rain attenuation models, modulation techniques, K-V frequency bands.

## **INTRODUCTION**

Southwestern Nigeria belongs to the tropical region with two dominant seasons: wet and dry. It has a minimum

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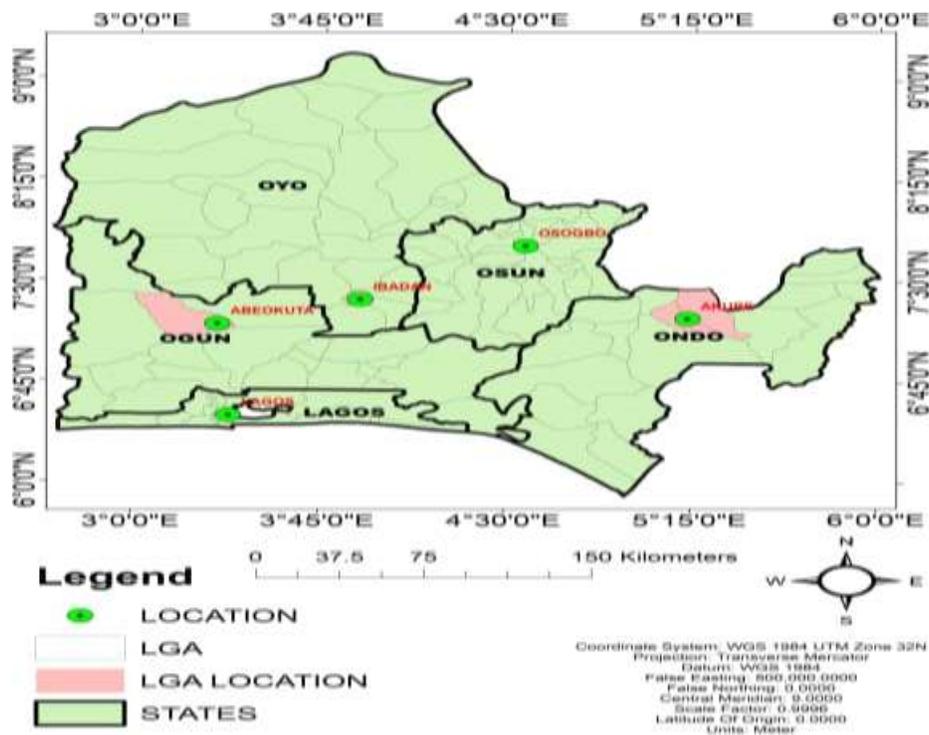


Figure 1. Map showing the study locations.

temperature of about 21°C and the temperature can be as high as about 34°C. The average annual rainfall is about 3000 mm. The southwest monsoon typifies the wet months and usually comes with the wind from the Atlantic Ocean while the northeast trade wind from the Sahara desert typifies the dry months (Ojo and Baiyegunhi, 2020; Faleyimu et al., 2013). As a result of the large volume of water in the atmosphere caused by heavy rain, the wet months experience significant degradation in terrestrial and satellite communication links most importantly at 10 GHz or more. Rain attenuation is a major source of impairment to signal propagation at microwave and millimeter-wave bands (Obiseye et al., 2014). Raindrop affects the transmission of signals in three major ways: the signal can be attenuated by absorption and scattering of the propagated waves, the polarity of the wave can be changed due to the irregular shape of the raindrop and the noise arises due to temperature can also be increased.

These three effects significantly reduced signal and become increasingly significant as the carrier frequency increases. At extremely low band (4-8 GHz), the effects may be minimal when compared with higher frequency band from Ka to V (Amaya et al., 2014). At such higher frequencies, signal degradation can be enormous such that it may be difficult to be compensated, especially at low availability needed lower frequencies (Robert, 2000; Afahakan et al., 2016).

Several rain-based attenuation models have been formulated by various researchers, including the standard ITU model. The present study assesses the performance of selected rain-based attenuation models, namely ITU, Moupfouma and Garcia-López models based on rain types for K-V frequency bands over some selected locations in Southwestern Nigeria (Figure 1). Link performance was further tested based on different modulation scaling to provide a marginal improvement on transmission links. Quantitative performance comparison of different modulation techniques (OOK, 8-PPM, and DPSK) based on parameters like the BER at different SNR levels and utilized bandwidth (Frequency range) was also carried out.

## Theoretical background

### *ITU rain-based attenuation (RBA) model*

The international telecommunication union (ITU-R 618-13, 2017) recommendation 618-13 (2017) is universally accepted as a standard model for use especially for regions with no measured data (Abayomi and Haji Khamis, 2012). The rain-based attenuation (RBA) is predicted based on:  $r_{0.01}$  which is the point rainfall rate at location of study for 0.01% of an average year, measured in mm/h,  $h_s$  for the location height in km, the angle of

elevation of the location  $\theta$  in: degrees, the latitude of the ground station  $\Phi$ , in degrees, the frequency of operation  $f$ , in GHz, and the effective radius of the earth  $R_E$  (8500 km). The steps involved in the calculation are as follows:

Step 1: Determination of the rain height  $h_R$ , as given in recommendation ITUR, 839-4, (2013).

Step 2: Determination of the slant path length and the horizontal projection. For  $\theta \geq 5^\circ$

$$L_s = \frac{(h_R - h_S)}{\sin \theta} \quad (1)$$

For  $\theta < 5^\circ$

$$L_s = \frac{2(h_R - h_S)}{\left(\sin^2 \theta + \frac{2(h_R - h_S)}{R_E}\right)^{\frac{1}{2}} + \sin \theta} \quad (2)$$

The horizontal projection is then expressed as:

$$L_G = L_s \cos(\theta) \quad (3)$$

If  $h_R - h_S \leq 0$ , then predicted rain attenuation for any time percentage is zero and the following steps are not required.

Step 3: Determination of  $r_{0.01}$  (with an integration time of 1 min).

Step 4: Calculation of the path attenuation, -specific attenuation  $\gamma$  (dB/km), is given as:

$$\gamma = aR^b \text{ in dB/km} \quad (4)$$

where  $a$  and  $b$  are regression coefficients which depend on the drop shape of the falling rain, rain drop density, polarization and frequency. These regression coefficients are computed by ITUR 838-3 (2007) as:

$$a = \frac{[a_H + a_V + (a_H - a_V)\cos^2 \theta \cos 2\tau]}{2} \quad (5)$$

$$b = \frac{[a_H b_H + a_V b_V + (a_H b_H - a_V b_V)\cos^2 \theta \cos 2\tau]}{2a} \quad (6)$$

where  $\tau$  is the polarization tilt angle relative to the horizontal and  $\theta$  is the path elevation angle. The polarization tilt angle  $\tau = 90^\circ$  for vertical polarization and  $\tau = 0^\circ$  for horizontal polarization while circular polarization is given as  $\tau = 45^\circ$ .

Step 5: Calculation of the horizontal reduction factor,

$$r_{0.01} = \frac{1}{1 + 0.78 \sqrt{\frac{L_G \gamma}{f}} - 0.38(1 - e^{-2L_G})} \quad (7)$$

$L_G$  is the horizontal projection as determined in Equation 3.

Step 6: Calculation of the vertical adjustment factor,  $v_{0.01}$ , for 0.01% of the time.

$$v_{0.01} = \frac{1}{1 + \sqrt{\sin(\theta) \left[ 31 \left( 1 - e^{-\frac{\theta}{1+x}} \sqrt{\frac{L_R \gamma}{f^2}} - 0.45 \right) \right]}} \quad (8)$$

$$\text{for } \xi > \theta, \quad L_R = \frac{L_G r_{0.01}}{\cos \theta} \text{ km} \quad (9)$$

$$\text{for } \xi \leq \theta, \quad L_R = \frac{h_R - h_S}{\sin \theta} \text{ km} \quad (10)$$

$$\text{and } \xi = \tan^{-1} \left( \frac{h_R - h_S}{L_G r_{0.01}} \right) \text{ degrees} \quad (11)$$

$$x = 36 - |\phi| \text{ degrees for } |\phi| < 36$$

$$x = 0 \quad \text{for } |\phi| \geq 36$$

Step 7: Computation of the effective path length as:

$$L_E = L_R v_{0.01} \text{ km} \quad (12)$$

Step 8: Calculation of the attenuation exceeded for 0.01% of an average year.

$$A_{0.01} = \gamma L_E \text{ (dB)} \quad (13)$$

Step 9: Estimation of the attenuation value for other percentages of exceedance in the range of 0.001 to 10%.

This is done by using the following expression:

$$A_p = A_{0.01} \left( \frac{p}{0.01} \right)^{-[0.655 + 0.033 \ln(p) - 0.045 \ln(A_{0.01}) - \beta(1-p) \sin \theta]} \quad (14)$$

where  $p$  is the percentage probability of interest and  $\beta$  is given as:

$$\beta = 0 \quad \text{if } p \geq 1\% \text{ or } |\phi| \geq 36^\circ \quad (15)$$

$$\beta = -0.005 (|\phi| - 36) \text{ if } p < 1\% \text{ and } |\phi| < 36^\circ \text{ and } \theta \geq 25^\circ \quad (16)$$

$$\beta = -0.005 (|\phi| - 36) + 1.8 - 4.25 \sin \theta \text{ if } |\phi| < 36^\circ \text{ and } \theta < 25^\circ \quad (17)$$

### García-López model

García-López et al. (1988) developed a RBA model for satellite links as an extension of the one proposed for terrestrial links, using measurements over satellite links in Europe, United States, Japan and Australia. For tropical regions, the values of the coefficients that are considered during the calculation of the attenuation are supplied separately (Parth and Rutvij, 2016).

RBA,  $A$  (dB) in a satellite link is obtained by:

$$A = \frac{KR_0^{\frac{\alpha}{2}} L_s}{\left[ a + \frac{L_s (bR + cL_s + d)}{e} \right]} \quad (18)$$

where  $L_s$  is the equivalent path length, in km given by:

$$L_s = \frac{H_R - H_s}{\sin \theta} \quad \text{for } \theta \geq 5^\circ \quad (19)$$

$$H_R = 4 \text{ km for } 0 < |\lambda| < 36^\circ \quad (20)$$

$$H_R = 4 - 0.075(|\lambda| - 36^\circ) \text{ km for } |\lambda| < 36^\circ \quad (21)$$

The coefficients  $a$ ,  $b$ ,  $c$  and  $d$  are constants generally area and can be empirically determined by regression techniques. The coefficient  $e$  is only a scaling factor. Taking  $e = 10^4$ , the world coefficients:  $a = 0.7$ ,  $b = 18.35$ ,  $c = -16.5$ , and  $d = 500$  (based on geographical area). For tropical climates,  $a = 0.72$ ,  $b = 7.6$ ,  $c = -4.75$ , and  $d = 2408$  (Parth and Rutvij, 2016).  $\lambda$  is the latitude of the earth station in degrees,  $R$  is the point rainfall intensity in mm/h,  $k$  and  $\alpha$  are the parameters depending on the frequency, polarization and elevation angle.

### Revised Moupfouma model

Moupfouma (2009) proposes that the actual relay path length can be multiplied with an adjustment factor " $\xi$ ". To obtain the equivalent propagation path length  $L_{eq}$  as:

$$L_{eq}(R_{0.01} L_T) = L_T \exp\left(\frac{-R_{0.01}}{1 + \xi(L_T) R_{0.01}}\right) \quad (22)$$

where  $(L_T) = -100$  for any  $L_T \leq 7 \text{ km}$  and  $\xi(L_T) = \left[\frac{44.2}{L_T}\right]^{0.78}$  for any  $L_T > 7 \text{ km}$ .

Therefore, the definition of rain attenuation is modified to:

$$A_{0.01} = KR_{0.01}^{\alpha} L_{eq}(R_{0.01}, L_T) \quad (23)$$

where " $L_T$ " is the space between two ground stations, while " $\xi$ " represents the non-uniformity of the rain on the

whole propagation path,  $R_{0.01}$  and  $A_{0.01}$  are the rainfall rate and path attenuation at 0.01% of the time,  $d = 2408$  (for tropical climate),  $e$  is a scaling factor given by  $10^4$  (Ojo et al., 2009).

The bit error rate (BER) for the three modulation techniques considered in this paper is given by the following equations:

$$BER_{OOK} = \frac{1}{2} \text{ERFC}\left(\frac{1}{2\sqrt{2}}\sqrt{SNR}\right) \quad (24)$$

$$BER_{N-PPM} = \frac{1}{2} \text{ERFC}\left(\frac{1}{2\sqrt{2}}\sqrt{SNR \cdot \frac{N}{2} \cdot \log_2(N)}\right) \quad (25)$$

$$BER_{DPSK} = \frac{1}{2} \text{ERFC}\left(\frac{1}{\sqrt{2}}\sqrt{SNR}\right) \quad (26)$$

## MATERIALS AND METHODS

### Instrumentation

The simulation of selected rain attenuation models over Abeokuta, Akure, Ibadan, Lagos, and Oshogbo in Southwestern Nigeria has been based on the rain rate data (categorized based on rain types) and other parameters presented in Table 1 as extracted from the Digital Video Broadcasting-second generation framing structure (DVB-S2x) over Geostationary Intelsat IS-17 satellite (66°E). The DVB-S2x is a channel bonding that combines several carriers increasing efficiency in direct-to-home applications (Rainer DVB-S2X Technology, 2019). The parameters extracted from DVB-S2x were utilized in the selected models, namely the ITU attenuation, Revised Moupfouma attenuation, and García-López attenuation models.

### System model

Testing the effect of rain on radio signals with link distance can be done by knowing the rain attenuation and corresponding rainfall intensity (Salem et al., 2016). In this paper, we focused on rain rates based on rain types and at specific frequencies for the K-V band shown in Table 2. In free space radio communication, the received power  $P$  can be expressed as:

$$P_r = P_t \tau_{tx} \tau_{rx} \frac{D^2}{(\theta L)^2} 10^{\frac{-\gamma L}{10}} \quad (27)$$

where  $P_t$  is the transmitted power,  $\tau_{tx}$  and  $\tau_{rx}$  are the transmitter and receiver efficiency, respectively.  $D$  is the receiver diameter,  $\theta$  is the divergence angle,  $L$  is the link distance and  $\gamma$  rain attenuation factor. The signal to noise ratio (SNR) can also be obtained using the following equation:

$$SNR = \frac{(R_0 P_r M)^2}{2qBM^{x+2}(R_0 P_r + I_D) + 2qI_L B + \frac{4kTBF}{R_{sq}}} \quad (28)$$

where  $R_0$  denotes the primary sensitivity of avalanche photodiode (APD),  $M$  is the APD gain,  $x$  is the excess noise factor,  $I_D$  is the

**Table 1.** Selected locations and link details.

Location	Abeokuta	Akure	Oshogbo	Lagos	Ibadan
Latitude (°N)	7.17	7.26	7.83	6.45	7.38
Longitude (°E)	3.43	5.21	4.58	3.47	3.93
Elevation Angle (Degree)	18.97	20.26	20.12	19.06	19.48
Azimuth Angle (Degree)	93.70	94.09	94.24	93.34	93.89
Slant Range (m)	39657	39533	39543	39648	39607
Satellite Delay (Up+Downlink) (ms)	264.40	263.60	263.60	264.30	264.00

**Table 2.** Rain types, corresponding rain rate, frequency band and range (Hall, 1980).

S/N	Rain type	Rain rate (mm/h)	Frequency bands	Range (GHz)
1	Drizzle	0.0 - 4.5.	Ku	12-18
2	Widespread	5.0 - 9.0	K	19-26
3	Shower	10.0-38.0	Ka	27-40
4	Thunderstorm	40.0-250.0	V	41-75

**Table 3.** Parameters for simulation (Freeman, 2002, 2007).

Parameter	Value
Wavelength (nm)	1550
Transmitter power (nW)	50
Transmitter divergence angle ( mrad)	2
Transmitter efficiency	0.5
Receiver efficiency	0.5
Receiver sensitivity ( dBm)	-20
Bulk dark current (nA)	0.05
Receiver diameter (m)	0.1
APD gain	100
Excess noise factor	0.5
Bandwidth (MHz)	25
Surface leakage current (mA)	1
System temp (K)	290
Noise figure (dB)	3
Equivalent resistor ( k $\Omega$ )	50

bulk dark current,  $I_L$  is the surface leakage current,  $q$  is the electronic charge,  $k$  is the Boltzman constant,  $B$  is the equivalent circuit resistance,  $F$  is the noise figure and  $T$  is the system temperature in Kelvin. The parameters assumed in this simulation are shown in Table 3.

## RESULTS AND DISCUSSION

### Rain-based attenuation with rain rate for drizzle rain type using ITU-R, Garcia-Lopez and Moupfouma models from K-V frequency bands

Since the aforementioned RBA above a specific

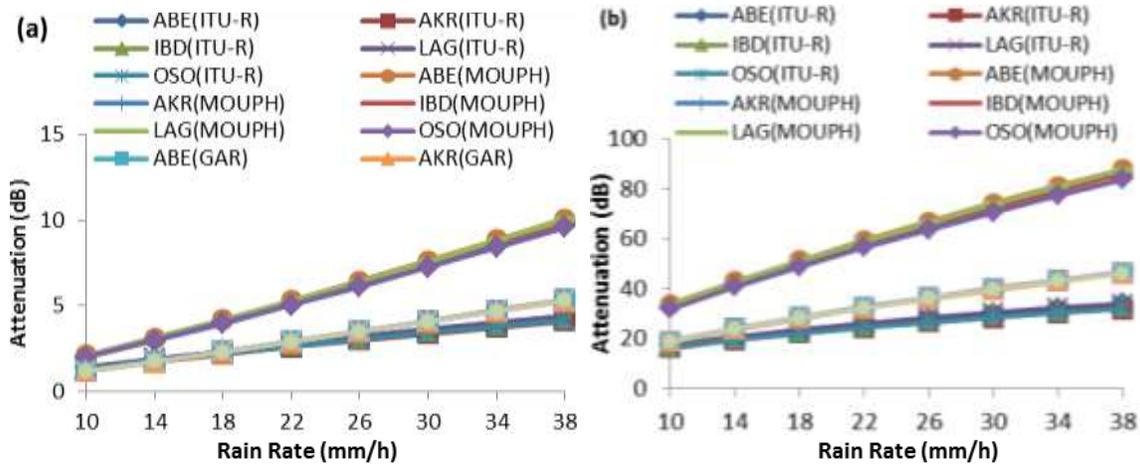
threshold frequency affects the line-of-sight (LOS) links, researchers have developed many models. However, the performance of each model largely depends on the parameters considered (Parth and Rutvij, 2016).

Figure 2a and b shows the variation of attenuation with rain rate for drizzle rain type using ITU-R, Garcia-Lopez, and Moupfouma models from Ku and V frequency bands. In Figure 2a, at 12 GHz and at a rain rate of 0.5 mm/h, ITU-R, Garcia-Lopez and Moupfouma models predict an attenuation of 0.06, 0.04, and 0.07 dB, respectively, for Abeokuta whereas, at  $R = 4.5$  mm/h, and attenuation of 0.65, 0.47, and 0.82 dB were predicted, respectively for the same location with minor variations across other locations. The variation of attenuation with rain rate follows a similar pattern for higher frequency as represented in Figure 2b with Garcia-Lopez model having the least value for RBA when compared with both ITU-R and Moupfouma models. In general, Figure 2a shows that in the downlink frequency of Ku-band, the response of all the tested models against RBA appears linear for the drizzle rain type. However, at the uplink frequency of V-band, ITU and Garcia Lopez model's response of RBA with rain rate is linear to about 2 mm/hr with low RBA value when compared with the value obtained using the Moupfouma model.

### Rain-based attenuation with rain rate for widespread rain type using ITU-R, Garcia-Lopez and Moupfouma models for K-V frequency bands

Figure 3a and b shows the variation of attenuation with rain rate for widespread rain type using ITU-R, Garcia-Lopez, and Moupfouma models for Ku and V frequency





**Figure 4.** Variation of attenuation with rain rate using ITU-R, Garcia-Lopez and Moupfouma models for shower rain type at (a) 12 GHz and (b) 75 GHz.

and Moupfouma models from K-V frequency bands. For example, in Figure 4a, at 12 GHz and at a rain rate of 10 mm/h, ITU-R, Garcia-Lopez, and Moupfouma models predict attenuation values of about 1.39, 1.19 and 2.09 dB, respectively, for Abeokuta, whereas, at a rain rate of 38 mm/h, attenuation of 4.38, 5.35, and 10.07 dB were, respectively, predicted for the same location with minor variations across other locations.

In general, the shower rain type at the downlink frequency of Ku-band follows the same trend as that of widespread and drizzles, although with the ITU model predicted low rain-based attenuation values at rain rate  $\geq 26$  mm/h and at a rain rate  $> 18$  mm/h. However, at V band frequency (Figure 4b), ITU and Garcia Lopez model's response of rain-based attenuation is linear to about 18 mm/h and thereafter gives a low rain-based attenuation value when compared with the value obtained using the Moupfouma model.

**Rain-based attenuation with rain rate for thunderstorm rain type using ITU-R, Garcia-Lopez and Moupfouma models for K-V frequency bands**

Figure 5a and b shows the variation of attenuation with rain rate for thunderstorm rain type using ITU-R, Garcia-Lopez, and Moupfouma models for Ku and V frequency band. It is observed from these figures that the rain rate exceeds 180 mm/h to about 250 mm/h only for Lagos because this location is located in the Coastal region and as such falls under the P-rain climatic zone (ITU-R P. 837-1, 1994). In Figure 5a, at 12 GHz and at a rain rate of 40 mm/h, ITU-R, Garcia-Lopez and Moupfouma models predicted rain-based attenuation values of about 4.57, 5.66, and 10.69 dB, respectively, for Abeokuta and

for a rain rate of 180 mm/h, the RBA values of about 14.11, 25.15, and 62.94 dB were respectively predicted for the same location, although there is a minor variation across other locations. However, ITU-R, Garcia-Lopez and Moupfouma models predicted about 17.67, 32.98 and 92.35 dB, respectively in Lagos at a rain rate of 250 mm/h.

Generally speaking, for thunderstorm rain type, the response of all the tested models with rain-based appears linear based on the different rain rate, although the ITU model still predicted lower attenuation values when compared with the remaining two models. The implication is that all the tested models appeared to perform well for higher rain rates irrespective of the frequencies of operation. However, considering the linear trends, the Moupfouma model performs better than the other two models.

**Attenuation and frequency response of ITU model**

Here, presents the frequency response on attenuation based on the ITU model. Based on previous discussion, there is the need to ascertain the level of responses of attenuation based on different frequencies using the ITU model. ITU model has been chosen among the other models because the model predicted lower attenuation values irrespective of the rain types.

Figure 6a and c shows the attenuation and frequency response for the ITU model at 2, 8, and 22 mm/h, respectively for the study locations. In general, Figure 6 shows that the ITU model produces a different trend in RBA for different rain rates. The results further show that, the ITU model produces reliable results for  $R \leq 18$  mm/h. However, at  $R > 20$  mm/h, the rain-based attenuation

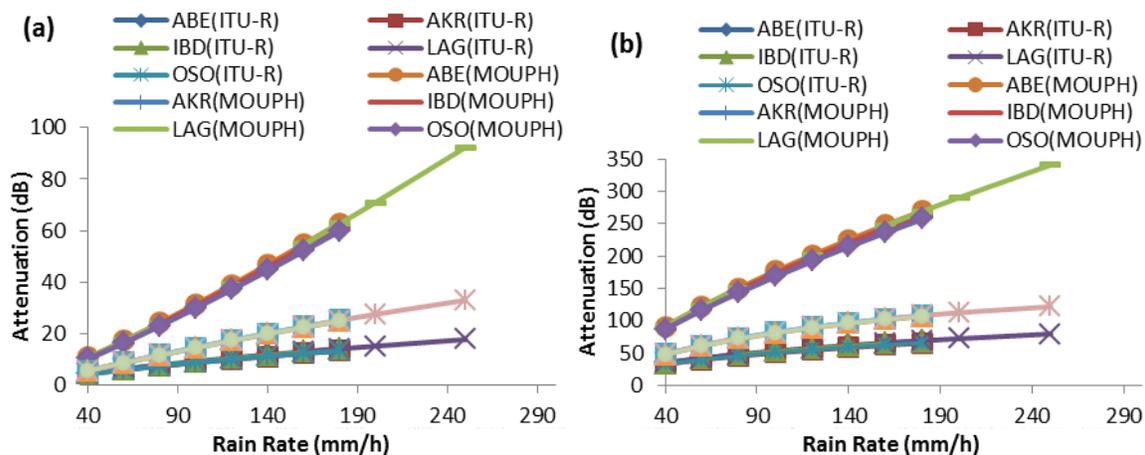


Figure 5. Variation of attenuation with rain rate using ITU-R, Garcia-Lopez and Moupfouma models for thunderstorm rain type at (a) 12 GHz and (b) 75 GHz.

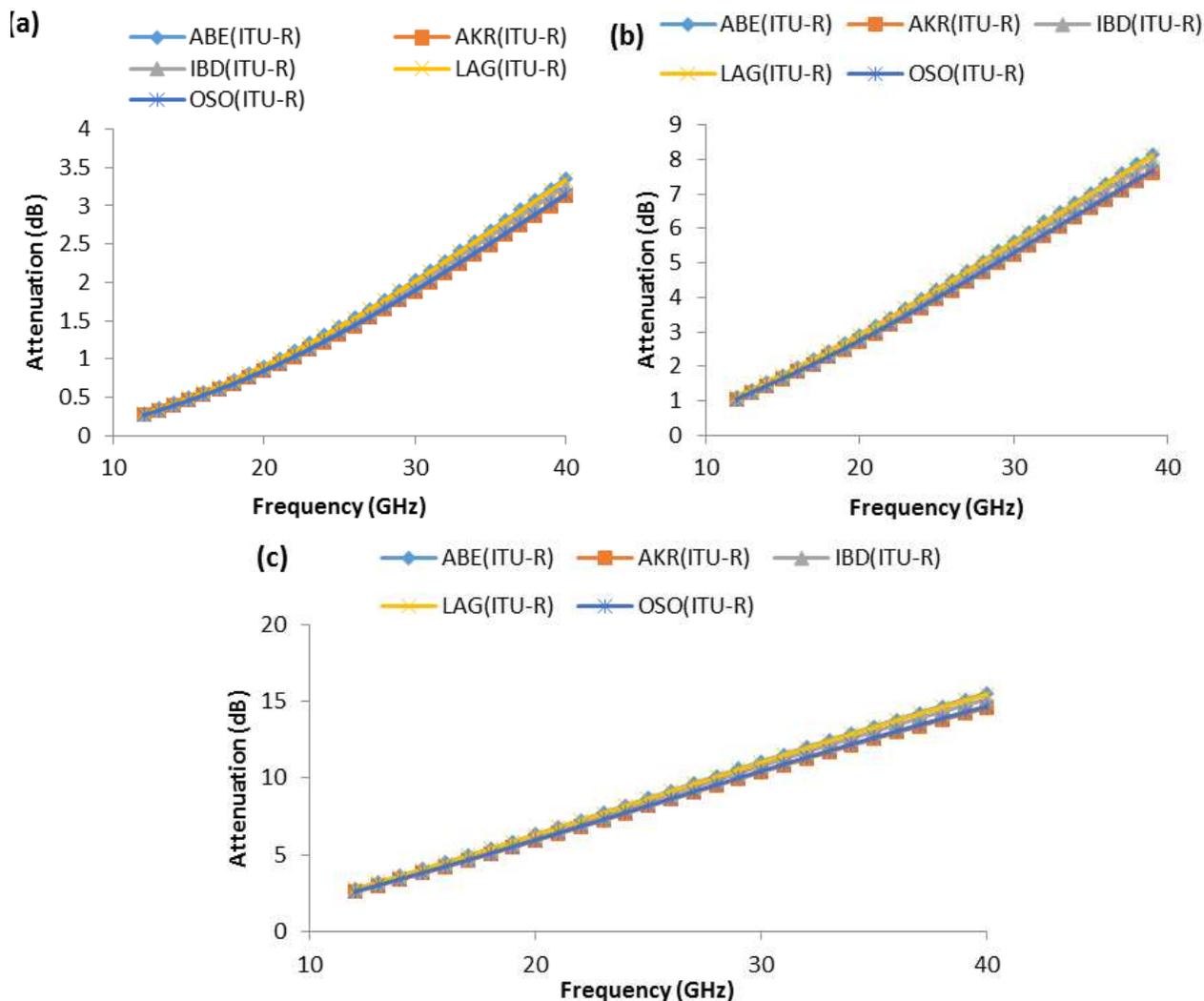


Figure 6. Attenuation and frequency response for ITU model at (a) 2 mm/h, (b) 8 mm/h, and (c) 22 mm/h.

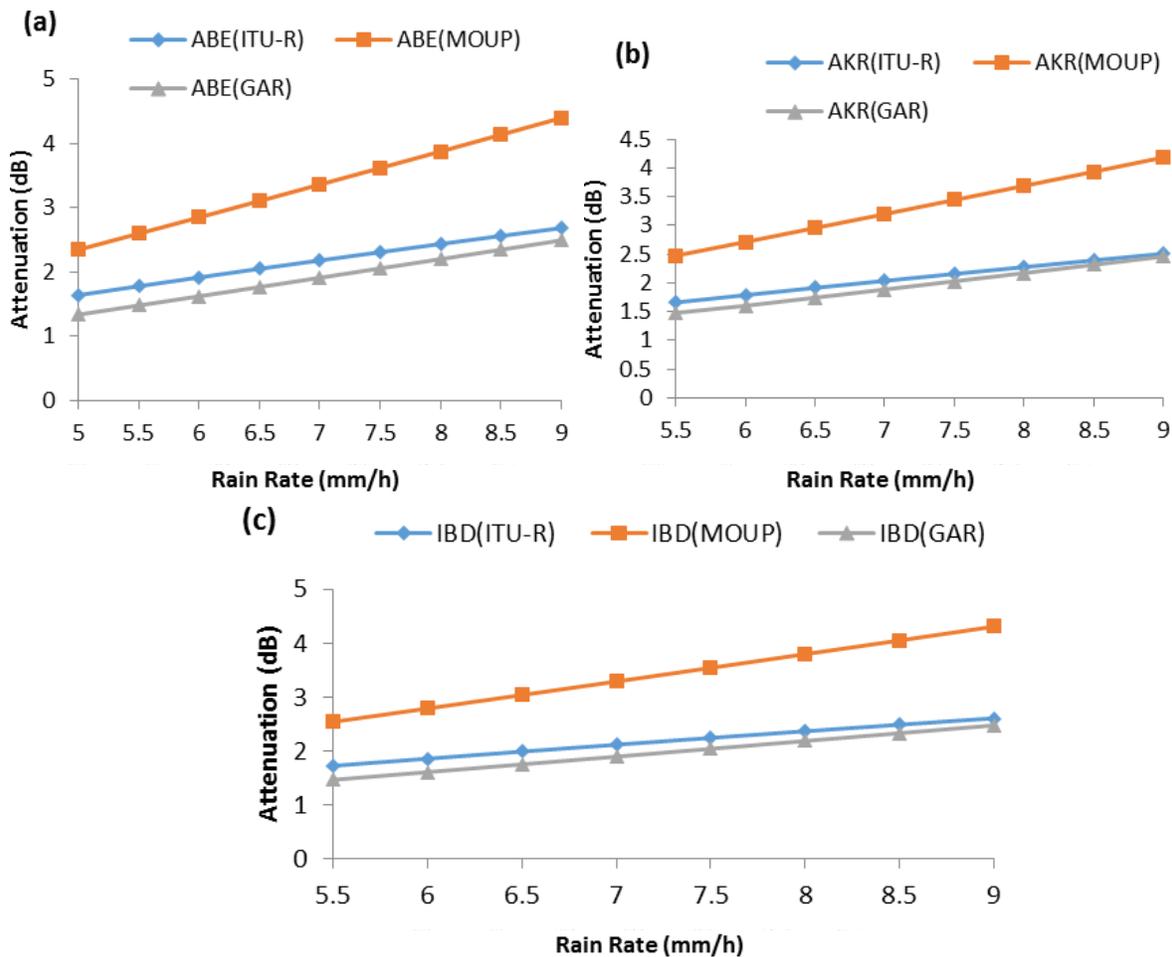


Figure 7. Simulation results based on different attenuation models from (a) Abeokuta, (b) Akure, and (c) Ibadan at 18 GHz for widespread rain type.

gives little increment. As frequency approaching 30 GHz, the rain-based attenuation decreases as R approaches 20 mm/h. It can be concluded that the ITU model is not suitable for higher frequencies above 30 GHz and higher rain rates. However, for system links operating in the Ku region, the ITU model produces reliable results.

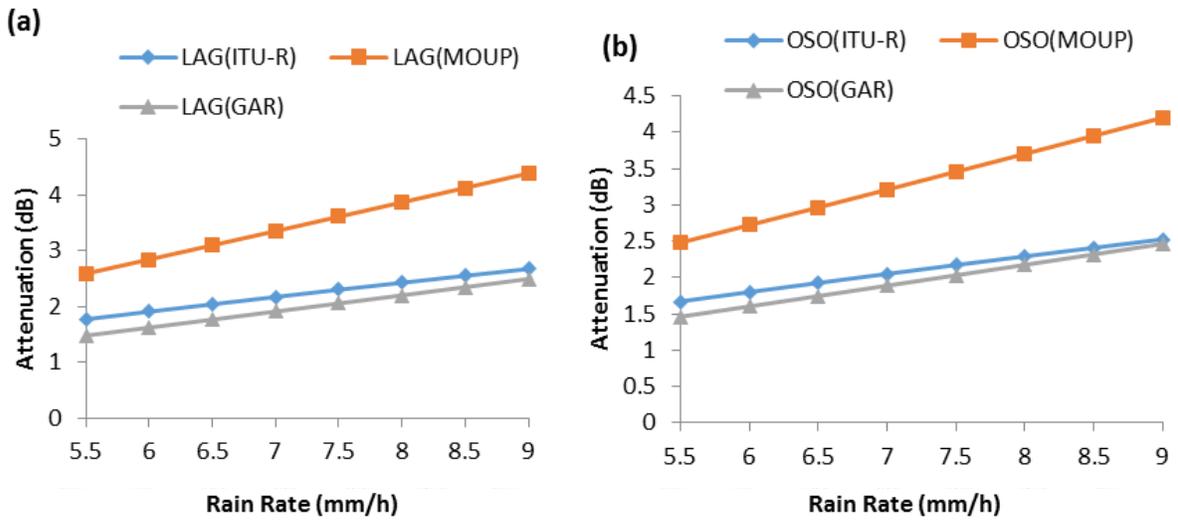
**Model comparative simulation results**

The results of the simulation based on the three models are presented here for the study locations at 18 and 30 GHz. The extent is to ascertain which of the models is preferable for each of the study locations. Comparative simulation results are as shown in Figures 7a to c and 8a and b for different rain-based attenuation models at 18 GHz for a typical rain type (widespread). Likewise, comparative simulation results are as shown in Figures 9a to c and 10a and b for different rain-based attenuation

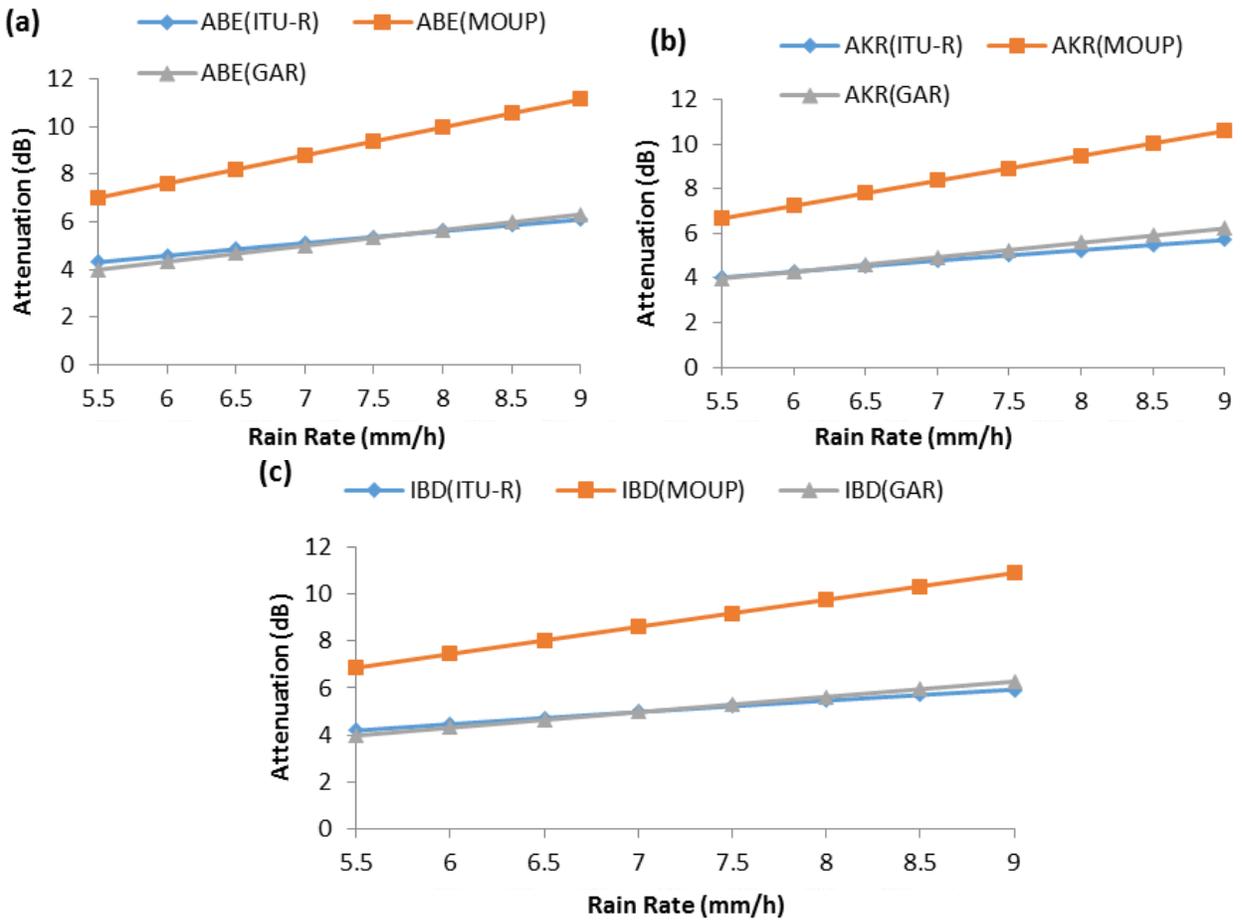
models at 30 GHz for widespread rain type. It can be seen that the ITU model performs poorly at higher frequencies as rain-based attenuation values decrease with increasing rain rates. The results also confirmed that the Moupfouma model performs excellently well regardless of frequency and rain rate type. This corroborated some earlier work from Nigeria and other tropical regions where the Moupfouma model has shown good performance in predicting rain-based attenuation (Fashuyi and Afullo, 2007; Ojo et al., 2009; Obiseye et al., 2014)

**Variation of received power, signal to noise ratio and bit error rate for the three modulation techniques**

Here, the effect of different rain rates on the received power, signal to noise ratio (SNR), and the bit error rate (BER) have been studied and the results are presented.



**Figure 8.** Simulation results based on different attenuation models from (a) Lagos and (b) Osogbo at 18 GHz for widespread rain type.



**Figure 9.** Simulation results based on different attenuation models from (a) Abeokuta, (b) Akure, and (c) Ibadan at 30 GHz for widespread rain type.

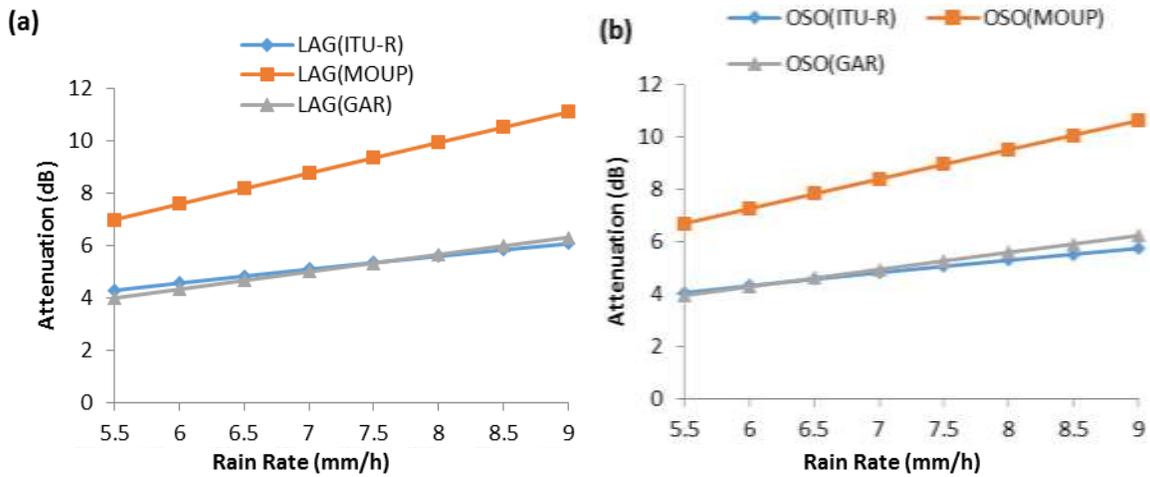


Figure 10. Simulation results based on different attenuation models from (a) Lagos and (b) Osogbo at 30 GHz for widespread rain type.

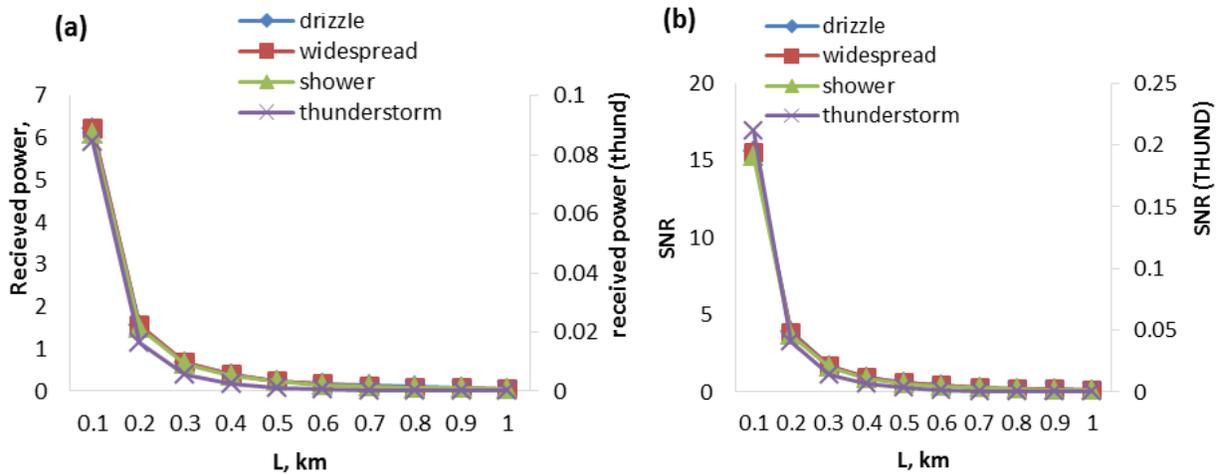


Figure 11. Variation of (a) Received power and (b) SNR in dB with link distance at 12 GHz

Figure 11a and b shows the variation of the received power and signal-to-noise ratio for the four different rain types at 12 GHz versus the link distance. The received power degrades with increasing link distance. This observation agrees with the power-law that states that the power density of a transmitted radio signal is inversely proportional to the square of link distance (Walter, 2007). It can also be observed that a high rain rate has a significant degradation of the received power as compared to a lower rain rate. In Figure 11a for instance, the received power for thunderstorm rain type at 12 GHz was recorded at 0.09 dB, and for drizzle rain type as 6.24 dB at 0.1 km.

Figure 11b presents results for the SNR versus the link

for the four rain rates. It can be observed that the rain types with a lower rain rate have a better SNR than rain types with higher rain rates. As link distance increases, SNR begins to degrade gradually. The SNR of a system can be expressed in terms of the ratio of signal to the noise level. A ratio bigger than 1 dB indicates that the signal is more than the noise as reported in the work of Choma et al., (2003). At 12 GHz and 0.1 km link distance, for example, the SNR for drizzle, widespread, shower, and thunderstorm were recorded at 15.59, 15.53, 15.25, and 0.211 dB, respectively. These results indicate signal levels will be very weak compared to the noise level during a thunderstorm rainfall while during a drizzle rainfall period, signal strength will be very strong. This

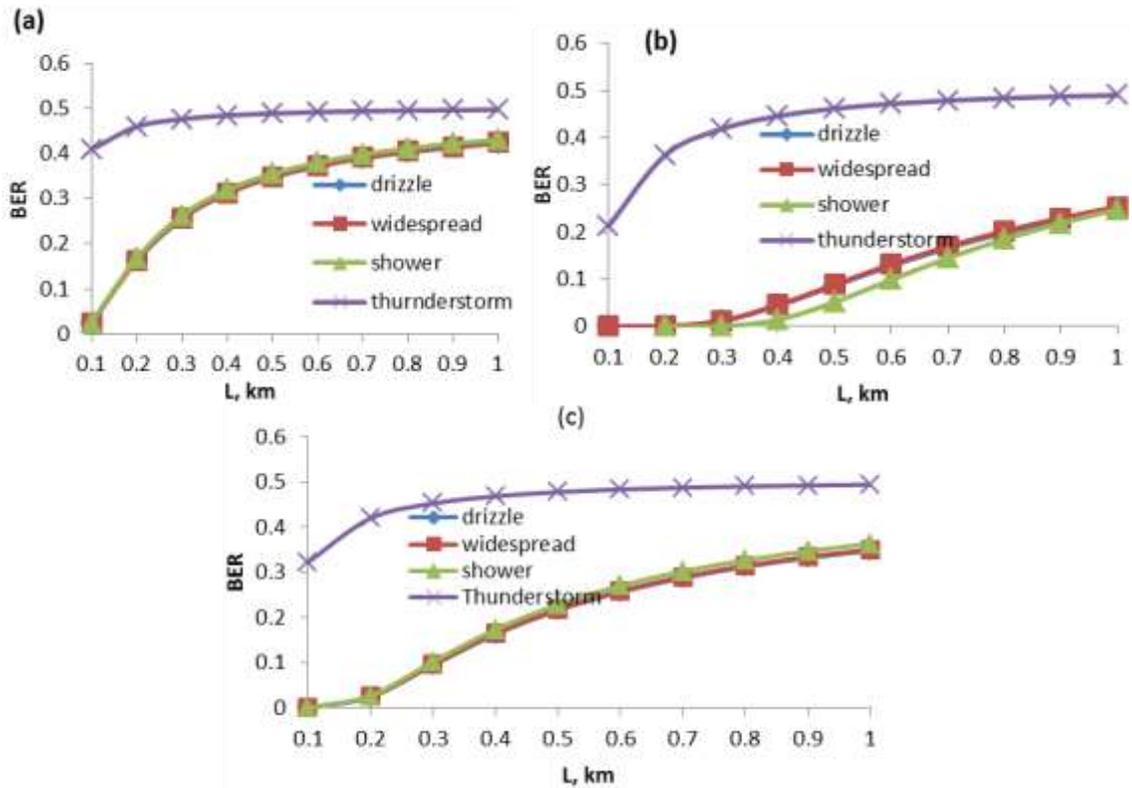


Figure 12. BER for different rain types using (a) OOK and (b) 8-PPM (c) DPSK modulation technique at 12 GHz.

result agrees with the result earlier obtained by Salem et al. (2016).

The BER (Bit Error Rate) for OOK modulation, 8-PPM modulation and DPSK modulation are investigated, and the results obtained are shown in Figures 12a to c and 13a to c at 12 and 30 GHz, respectively. The BER for all the modulation techniques with the lower rain rate (types) performs better than BER for a higher rain rate (type) for example thunderstorm. In Figure 12a for instance, it can be seen that at 12 GHz, the BER at OOK modulation for drizzle, widespread and shower rain type performs better than that of thunderstorm rain type typical result can also be observed for 30 GHz. As the link distance increases, the BER also increases for all rain types. In Figure 12b at 0.1 km, BER for drizzle, widespread, shower, and thunderstorm recorded were 0.02, 0.025, 0.03, and 0.409, respectively, and at 1 km, the BER at 8-PPM for drizzle, widespread, shower and thunderstorm rain type recorded were  $1 \times 10^{-11}$ ,  $2 \times 10^{-11}$ ,  $3 \times 10^{-10}$  and 0.29, respectively.

In Figure 14a to d, a comparison is made between OOK, 8-PPM, and DPSK modulation techniques for thunderstorm rain types at 12, 22, 30, and 50 GHz, respectively. At 12 GHz (Figure 14a) for instance, it can be seen that 8-PPM outperforms OOK and DPSK modulation techniques. At 0.1 km, the BER recorded

were 0.21, 0.32 and, 0.41 for 8-PPM, DPSK, and OOK modulation schemes, respectively. Similar results were obtained at 22, 30, and 50 GHz. At 22 GHz and 0.1 km link distance, BER recorded were 0.25, 0.34, and 0.42; at 30 GHz and 0.1 km link distance BER recorded were 0.27, 0.36, and 0.43; at 50 GHz and 0.1 km link distance BER was recorded as 0.3, 0.38, and 0.44 for 8-PPM, DPSK, and OOK modulation schemes, respectively. The result implies that with increasing frequency of propagation, the BER deteriorates. From Figure 14a to d, it can also be observed that the BER trend between the different modulation techniques becomes narrower as link distance increases. This observation agrees with the results gotten by Salem et al. (2016).

Figure 15a to d also presents the result of the selective combination (SC) diversity with OOK and DPSK modulation techniques for thunderstorm rain types at 12, 22, 30, and 50 GHz, respectively. Across all the frequency bands, it can be observed that a BER with SC diversity has slightly improved as compared to the case without SC most especially at higher link distance. For instance, at 50 GHz (Figure 15d) and 1 km, a BER of OOK with SC diversity was recorded as 0.25 as against 0.48 without SC diversity, making a difference of about 0.24. Likewise, a BER of DPSK with SC diversity was recorded as 0.249 as against 0.499 without SC making a

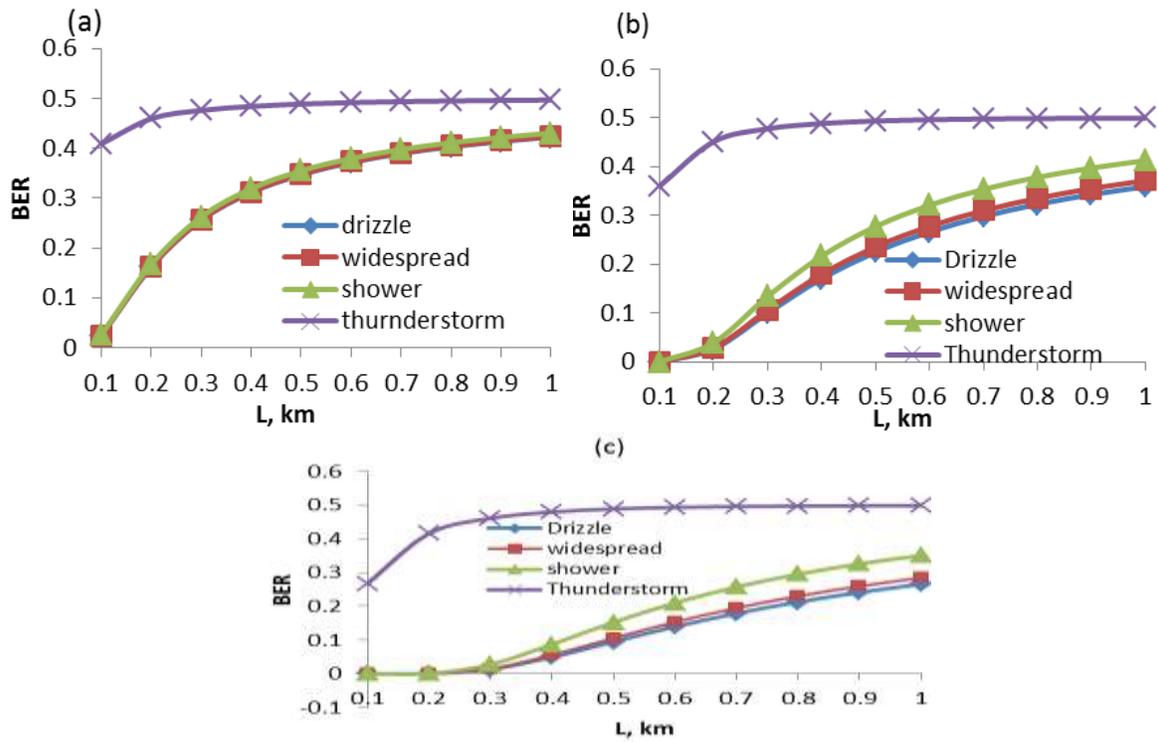


Figure 13. BER for different rain types using (a) OOK, (b) DPSK, and (c) 8-PPM modulation technique at 30 GHz.

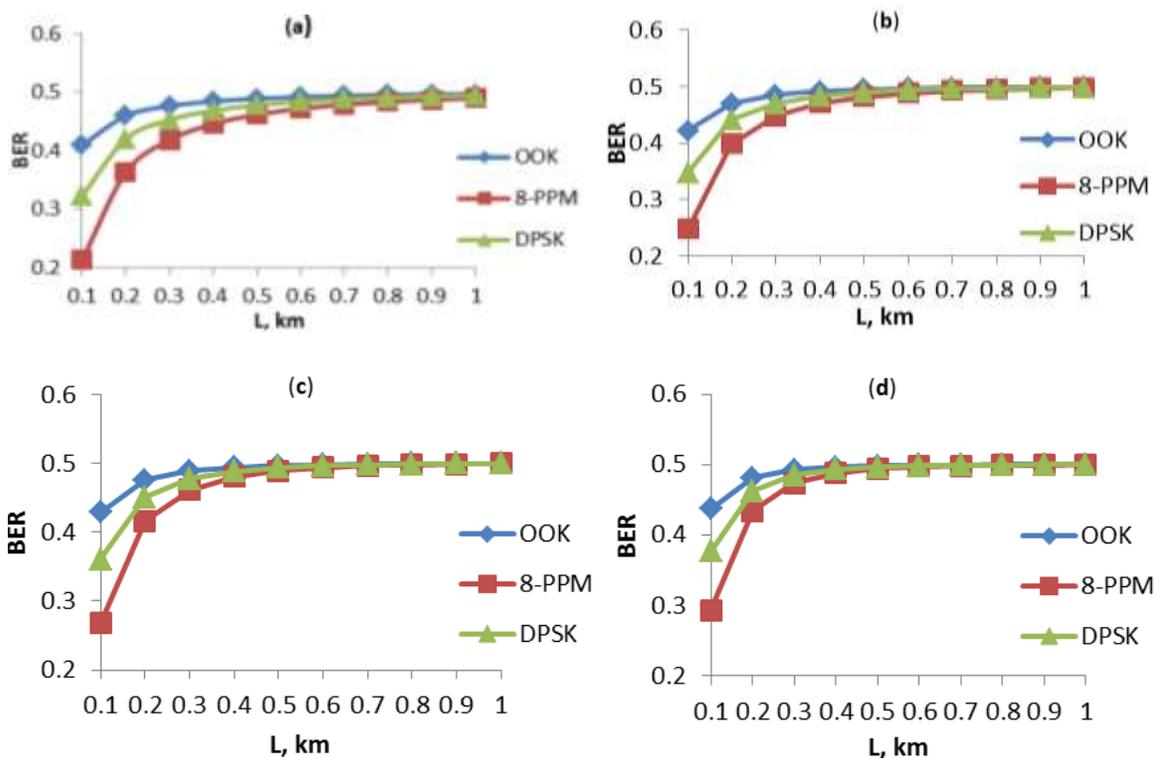
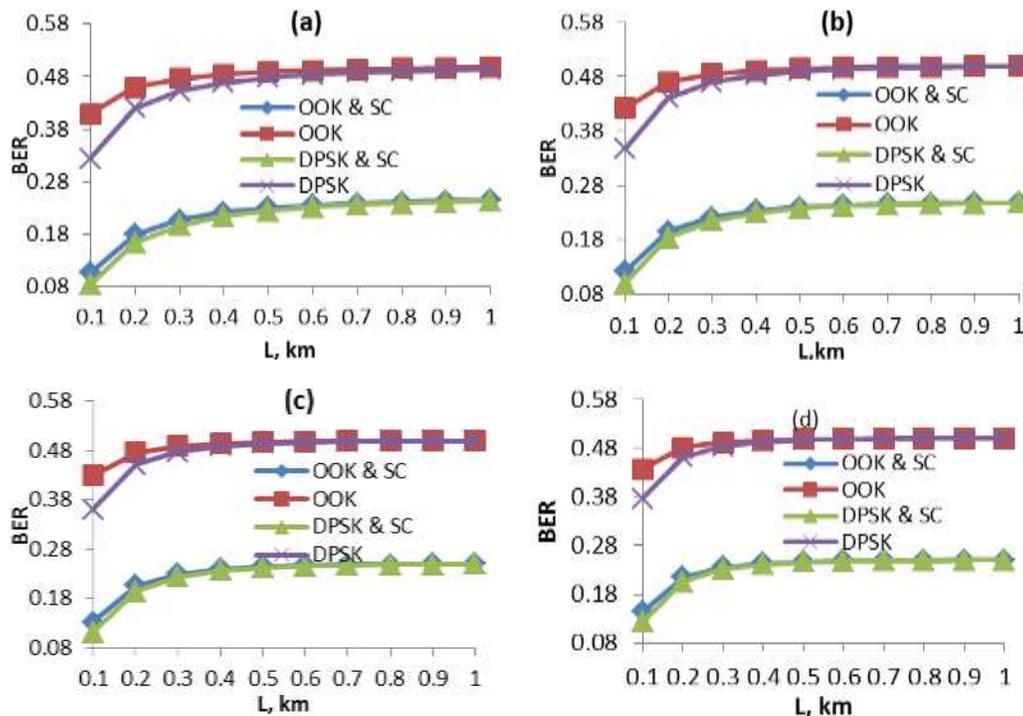


Figure 14. BER for OOK, 8-PPM and DPSK for thunderstorm rain type at (a) 12 GHz, (b) 22 GHz, (c) 30 GHz and (d) 50 GHz.



**Figure 15.** BER for OOK and DPSK with SC for thunderstorm rain type at (a) 12 GHz, (b) 22 GHz, (c) 30 GHz and (d) 50 GHz.

difference of about 0.25.

## Conclusion

The performance of three rain attenuation models, namely: ITU, García-López, and Moupfouma were analyzed using rain rate data based on rain types for K to V frequency over some selected locations in Southwestern Nigeria. It is observed that the García-López and ITU models performed well for drizzle, widespread, and shower rain types at a low rain rate of  $\leq 2$  mm/h but underestimated at higher rain rates (except thunderstorms rain type) especially at high-frequency bands. Moupfouma model on the other hand performed best across all the rain types from the K-V frequency band because the model was developed based on data from the tropical regions. The model also considered several parameters and coefficients, hence recommended for this region. The result can also be justified based on the previous works that Moupfouma performed suitably well and better, especially in tropical environments. The BER for all the modulation techniques with the lower rain rate (types) performs better than BER for a higher rain rate for example thunderstorm. Further results, especially at 12 GHz, show that the BER at OOK modulation for drizzle, widespread, and shower rain type performs better

than that of thunderstorm rain type. As the link distance increases, the BER also increases for all rain types. Overall results revealed that modulation technique DPSK with SC diversity gave a marginal improvement with the increase in link distance and operating frequency.

## CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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