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Adoption of site diversity to mitigate rain attenuation at KU and KA frequency bands

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Abstract

This work presented the adoption of site diversity technique on rain attenuation for Lagos State at 12 and 23 GHz. Site diversity is an effective technique to mitigate rain attenuation, especially in tropical region with high rainfall rate. This is because the probability of attenuation due to rain occurring simultaneously at all earth-space paths is very low compared with the probability of occurring on either individual slant paths. Local rainfall data at hourly integration time were sourced from Nigeria Meteorological Agency (NIMET), spanning a period of five years (January 2015 to December 2019) for three different stations in Lagos, Nigeria. One-minute rainfall rate distribution for these three selected earth stations (Ikeja, Marina and Ikorodu) were derived from the obtained hourly rain data for various percentages of time exceeded (that is, $0.001 \leq p \leq 1\%$). Site diversity technique was implemented by taking the Ikeja station as the reference site. ITU-R Hodge and Paraboni-Barbaliscia models were then applied in succession, to test the efficacy of each of these models. The results obtained showed that Paraboni-Barbaliscia model outperformed the ITU-R Hodge model along Ikeja-Marina and Ikeja-Ikorodu axes at 16.69 and 17.67 km respectively, and with improved link availabilities of 99.981% and 99.982% respectively at 0.1% of the time exceeded. Furthermore, single site diversity method presented higher attenuation exceedances compared to the joint site diversity approach, and this further accentuated the importance and effectiveness of considering adequate baseline site separation distances between the selected earth stations. Joint site diversity is therefore the recommended technique to mitigate against slant path signal outages resulting from equatorial and tropical rain precipitations.

Keywords: attenuation, fmt, joint diversity, site diversity, paraboni-barbaliscia, prediction models

Introduction

In recent years, satellite communication has become a demanding service due to advancing technology of wireless communication and broadband internet applications. Rain attenuation is one of the most significant limitations to the performance of satellite communication links, especially along the earth-space link; triggering interference and large variation in transmitted signal power, a typical phenomenon for electromagnetic waves 10 GHz [1]. Rain precipitation can be either stratiform rain (when low to medium rain fade are observed with large spatial homogeneity) or convective rain (with large rain rates which are associated with the inhomogeneity of rainfall) and are predominantly experienced in the tropics. This inhomogeneity of rainfall within the rain cells results in decorrelation of the attenuation of signals with dispersion along different paths.

Hence, strong propagation impairments have necessitated the need to incorporate techniques to mitigate the effects of propagation impairments, such as rain attenuation, in the design of telecommunication systems to operate at higher frequency bands [2-3]. Fade mitigation technique (FMT) has been employed to reduce the effect of rain attenuation on signals. Although a large number of FMTs exists, they can generally be grouped into three major categories: Power control technique (which is done by varying either the carrier power or the antenna gain when a fade occurs in order to increase the power flux on the link), adaptive transmission technique (which overcome rain attenuation either by using encoding technique or modulation technique to vary the way in which signals are processed or transmitted by the nodes of a satellite network whenever the link quality is degraded). However, both techniques ultimately have some disadvantages because it is inadequate to mitigate very large signal fade [4].

The third FMT is the diversity technique. It is the most efficient for modern satellite system operating at millimeter wave bands. Some of the available diversity schemes includes space diversity, orbital diversity, frequency diversity, time diversity and site diversity, amongst others. Space diversity (SD) employs two or more antennas to improve the quality or reliability of wireless link. Frequency diversity (FD) involves adaptively changing the propagating frequency to a lower frequency to overcome the effect of rain attenuation and then switching back to the original frequency after disruptive event [5]. Time diversity (TD) involves re-transmitting the information at the pre-allocated time slot. The shortcoming is that rain events have limited durations. In orbital diversity (OD), information is switched from one satellite to another. A major disadvantage of this technique is cost. Site diversity (SD) is one of the most effective methods to overcome large signal fades due to rain attenuation. It takes the advantage of the spatial structure of rainfall medium [6].

Spatial characteristics of the rainfall medium are exploited in SD by using two or more earth stations, with the believe that the probability of attenuation due to rain occurring simultaneously at all earth-space paths is very low compared with the probability of occurring on either individual slant paths. The earth stations are geographically dispersed but are terrestrially connected; hence each site offers less correlated propagation paths between the earth station and the satellite. Figure 1 depicts an example of a site diversity scheme. Site diversity technique links two or more earth stations receiving the same signal. The signal streams received at each station are sent to a named reference or base station, where these signal streams are processed using diversity combining techniques, such as, switched combining technique, which requires just a single collector radio between the various branches. Another method is the equal gain combining technique, in which the signals from all branches are consolidated to shape the output signal, with the intent of improving its signal to noise ratio (SNR) [7]. Hence, if the transmitted signal in a station is seriously encumbered, the system automatically switched to another station, and thus providing a sort of compensation to the effect.

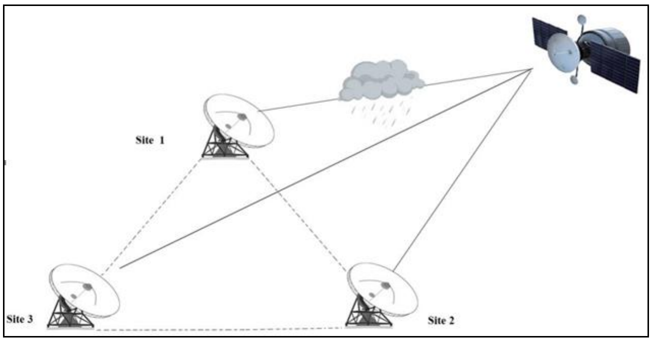

Fig 1: Site diversity scheme [1].

This paper presents the use of site diversity in the mitigation of rain attenuation at 12 and 23 GHz for Lagos, Nigeria. Rain attenuation prediction models can be classified into physical models and empirical or (regression) models. The former is founded on the consideration of the rain dynamics like rain cell structure and vertical structure of rain precipitation. EXCELL [8], Matricciani and Paraboni-Barbaliscia (P-B) [9] models are well known physical prediction models for site diversity performance. The Hodge [10] model is a regression model based on the regression fitting of the available rain attenuation statistics. The Paraboni-Barbaliscia and Hodge models have both been adopted by the current ITU-R recommendation [11] for predicting the site diversity gain. Since the ITU- R model is the intentionally accepted model, this paper shall test the locally derived rain data on the ITU-R Hodge and Paraboni-Barbaliscia models.

Literature Review

Several studies have been conducted to overcome the issue of rain attenuation based on site diversity technique. Most of the earlier studies on site diversity were performed in the temperate region, and only recently did propagation studies on site diversity for the Ku/Ka bands were undertaken the tropical region. Yussuff and Hamzat [12] studied the impact of SD as a FMT on rain attenuation at 12 GHz for Lagos, Nigeria and concluded that separation distance is a key factor to be considered when opting for site diversity as propagation impairment mitigation technique. It was also reported that efficiency starts to diminish and performance begins to suffer when the 20 km maximum separation distance threshold as recommended by ITU-R. Rec. P. 618-13 is exceeded. Yeo *et al* [13] in Singapore worked on SD gain at the equator and reported that ITU-R Paraboni-Barbaliscia model performs better than the ITU-R Hodge model. The study also revealed that triple-site diversity gain is better than two-site diversity gain, but inferred that the proper selection of sites in a double site diversity system yields more benefits compared to the implementation of a triple site diversity system. Furthermore, Semire *et al* [14] carried out performance analysis on site diversity using Hodge model and Panagopoulos model in south-east Asia. It was reported that the implementation of SD is a function of site separation distance between the diverse stations and the elevation angle of the slant-path. Again, Riza *et al* [15] studied the implementation of SD on Ka-band satellite in Indonesia. It was reported that SD improves the signal to noise ratio (SNR).

Model Description

The two selected models for study are ITU-R Hodge and Paraboni-Barbaliscia site diversity prediction models. They are briefly discussed in the following sub-sections.

ITU-R Hodge Model

The ITU-R site diversity gain model [16] is an empirically derived model that is based on the revised Hodge model. According to [17], diversity gain, G_{SD} (dB) is represented by a product of the various gains contributed by spatial separation G_d, frequency G_f, elevation angle G_θ and baseline dependent term G_β. The input parameters required are as follows:

$$G_d(d, A_s) = a(1 - e^{-bd}) \qquad (1)$$

$$G_{SD} = G_d(d, A_s).G_f(f).G_\theta(\theta).G_\varphi(\varphi) \qquad (2)$$

where $a = 0.78A_s - 1.94(1 - e^{-0.11A_s})$,

$b = 0.59(1 - e^{-0.1A_s})$,$G_f(f) = e^{-0.025f}$,

$G_\theta = 1 + 0.006(\theta)$ and $G_\varphi = 1 + 0.002(\varphi)$

Paraboni-Barbaliscia Model

The P-B method predicts $P_r(A_1 \geq a_1, A_2 \geq a_2)$ which is the joint probability (%) that the attenuation on the path to the first site is greater than a_1 while that to the second site is greater than a_2. $P_r(A_1 \geq a_1, A_2 \geq a_2)$, is the product of two joint probabilities. P_r is the joint probability that it is raining at both sites while P_a is the conditional joint probability of the attenuation exceeded at a_1 and a_2 respectively, (assuming that it is raining at both sites) simultaneously).

i.e. $P_r(A_1 \geq a_1, A_2 \geq a_2) = 100 \times \mathrm{Pr} \times Pa\%$ (3)

These probabilities are:

$$P_r = \frac{1}{2\pi\sqrt{(1-\rho_r^2)}} \int_{R_1}^{\infty} \int_{R_2}^{\infty} exp[-(\frac{r_1{}^2 - 2\rho_r r_1 r_2 + r_2{}^2}{2(1-\rho_r{}^2)})] dr_2 dr_1 \qquad (4)$$

Where $\rho_r = 0.7exp - \left(\frac{d}{60}\right) + 0.7exp[-\left(\frac{d}{700}\right)^2]$ (5)

and,

$$P_a = \frac{1}{2\pi\sqrt{(1-\rho_a{}^2)}} \int_{\frac{\ln a_1 - m\ln A_1}{\sigma \ln A_1}}^{\infty} \int_{\frac{\ln a_2 - m\ln A_2}{\sigma \ln A_2}}^{\infty} \exp[-(\frac{b_1{}^2 - 2\rho_a b_1 b_2 + b_2{}^2}{2(1-\rho_a{}^2)})] db_2 db_1 \qquad (6)$$

Where $\rho_a = 0.94exp - \left(\frac{d}{30}\right) + 0.06\exp[-\left(\frac{d}{500}\right)^2]$ (7)

$$P_k{}^{rain} = 100 \times Q(R_K) = 100 \times \frac{1}{2\pi} \int_{R_K}^{\infty} exp(-\frac{r^2}{2}) dr \tag{8}$$

i.e. $$R_K = Q^{-1}(\frac{P_K{}^{rain}}{100}) \tag{9}$$

The values of the parameters $m_{\ln A_1}$, $m_{\ln A_2}$, $\sigma_{\ln A_1}$, $\sigma_{\ln A_2}$ are determined by fitting each single-site rain attenuation, Ai, vs. probability of occurrence, P_i, to the log-normal distribution:

$$P_i = P_k{}^{rain}(\frac{lnA_1 - m_{lnA_i}}{\sigma_{lnA_i}}) \tag{10}$$

Materials and Methods

Monthly rainfall and measured attenuation data was sourced from Nigerian Meteorological Agency (NIMET) for three different, which were taken at the facilities of NIMET and consists of a buck-type rain gauge installed at the three locations of interest, to record rain exceedances at hourly integration time. The measurement setup at NIMET comprises indoor and the outdoor units. The indoor unit consists of spectrum analyzer, field strength meter and a satellite tracker. The obtained parameters, such as signal strength during clear air and other precipitations can then be recorded and analyzed. Rain rate data is collected from the weather station located at the premises of NIMET, situated in the same geographical location where signal from satellite at a downlink frequency of 12.437 GHz beacon and recorded. The outdoor equipment is a dish antenna with low noise block converter (LNBC), which was passed through a 3 dB splitter and fed into a digital receiver and a spectrum analyzer. The spectrum analyzer was set to 10.982 GHz and the video filter output of the spectrum analyzer was recorded and stored in a computer at a sampling rate of 1.0 Hz, using a data logger. A buck-type rain gauge rain gauge was installed at the measurement site to record the rain rate. This tipping bucket rain gauge has a sensitivity is 0.5 mm/min, with operating temperature range of -10 to 50 °*C*. It has a tipping accuracy of 100 %. Scintillations are removed with a low-pass filter by passing low-frequency signals while attenuating signals with frequencies above the cut-off frequency. A one-minute rainfall rate integration time will be derived using the empirical model produced by Chebil and Rahman [18]. The 1-minute rain rate for different percentage of time *p%*, ($0.001 \leq p \leq 1\%$) can be estimated by using only the average annual total rainfall. The rain rate R measured in millimetre per hour were recorded for different percentage probabilities, $\mathbf{P}$ indicating the reference (Ikeja) and diverse earth stations (Marina and Ikorodu) as shown in the Table 1. Chebil and Rahman's [18-19] proposed rain rate conversion model for conversion of these hourly data to the equivalent one-minute integration rainfall rate values as follows:

$$CF60 = \frac{R_{1(p)}}{R_{60(p)}} = ap^b \tag{11}$$

$$CF60 = \ ap^b + c * exp(dp) \tag{12}$$

Where a, b, c and d are regression coefficients derived from [20] using Gauss-Newton technique for the evaluation. From equation (23), the following relationship was derived:

$$CF60 = 0.772 * p^{-0.041} + 1.141 * \exp(-2.57 * p) \tag{13}$$

$$R_{1(p)} = \ CF60 * \ R_{60(p)} \tag{14}$$

Where CF_{60} is the ratio of rain rates $R_{1(p)}$ and $R_{60(p)}$ for a given percentage of time $\mathbf{P}$ with an integration time of 1 min and 60 min, respectively? $\mathbf{P}$ Lies between the constraints $0.001 \leq p \leq 1\%$. $R_{1(p)}$ Is the one-minute and $R_{60(p)}$ is the hourly integration rain rate data, respectively.

Table 1: One-minute rain rate for selected stations

Percentages of Time	0.001	0.002	0.003	0.005	0.01	0.02	0.03	0.1	0.5	1
Ikeja(mm/h)	141.1	139.0	137.7	136.0	133.3	129.8	127.0	112.9	72.4	56.1
Marina(mm/h)	155.8	153.5	152.1	150.3	147.3	143.4	140.3	124.7	80.0	62.0
Ikorodu(mm/h)	155.4	153.2	151.8	150.0	147.0	143.0	140.0	124.4	79.8	61.8

Moreover, the rain rate at different percentages of time were plotted using MATLAB and analysed. The diversity improvement factor, *I* given as the ratio of probabilities for a specific attenuation exceeded was subsequently obtained. From ITU-R. Rec. P.618-13 [5], the diversity improvement factor is given as:

$$I = \frac{P_1}{P_2} = \frac{1}{(1+\beta^2)} \cdot \left(1 + \frac{100.\beta^2}{P_1}\right) \approx \left(1 + \frac{100.\beta^2}{P_1}\right)$$

Where $\beta^2 = \ 10^{-4}.D^{1.33}$, D is the site separation distance in km, P_1 is the single-site time percentage for the single site attenuation and P_2 is the diversity time percentage for the single site time percentage P_1 and β is a parameter depending on link characteristics.

Results & Discussion

Figure 2 shows the cumulative distribution function (CDF) of single site attenuation and attenuation against rain rates for Ikeja, Marina and Ikorodu, respectively. From Figure 2 (a), it can be seen that at $0.001 \leq p \leq 1\%$ of the time exceeded, the single site attenuation for Marina and Ikorodu are higher than that of Ikeja. Also, in Figure 2 (b), it is observed that higher rain rates generated higher attenuation exceedances.

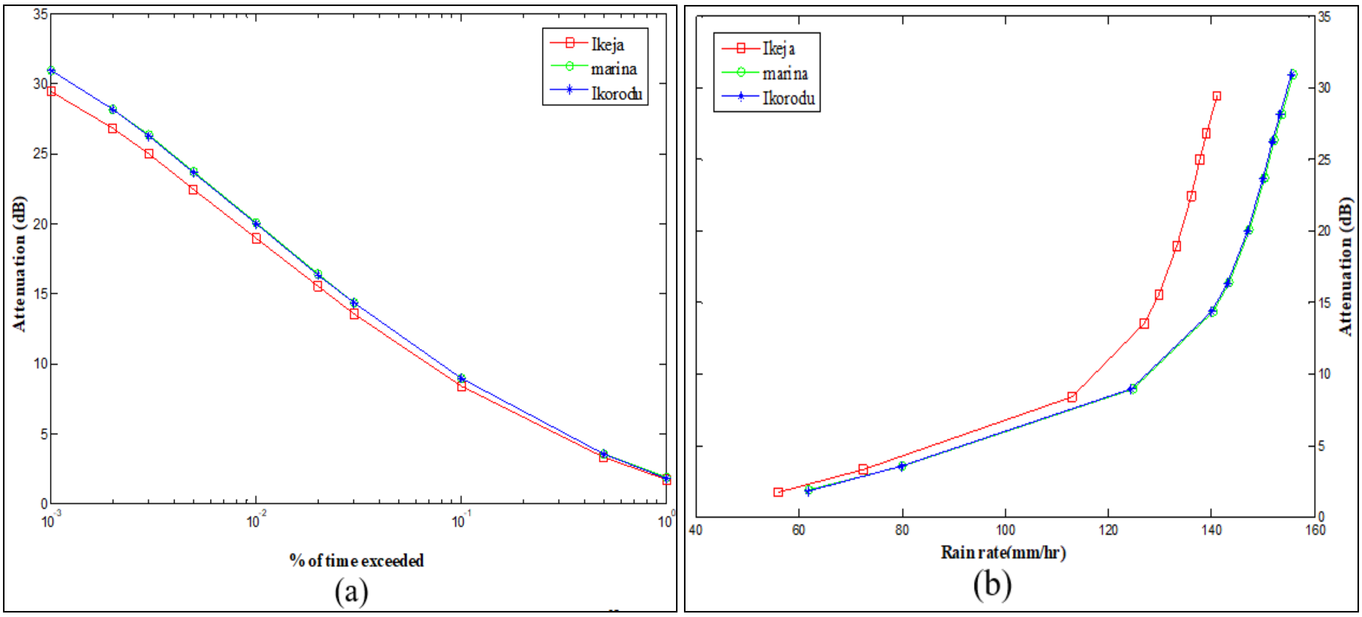

Fig 2: (a) CDFs of attenuation and (b) Attenuation against rain rate for Ikeja, Marina and Ikorodu at 12 GHz.

Figure 3 shows the comparison of site diversity gain of ITU-R and Paraboni-Barbaliscia models against (a) percentage of time (b) single site attenuation for Ikeja-Marina and Ikeja-Ikorodu at 12GHz. It is observed that P-B produced higher diversity gain compared to ITU-R model for site separation between Ikeja-Marina and Ikeja-Ikorodu.

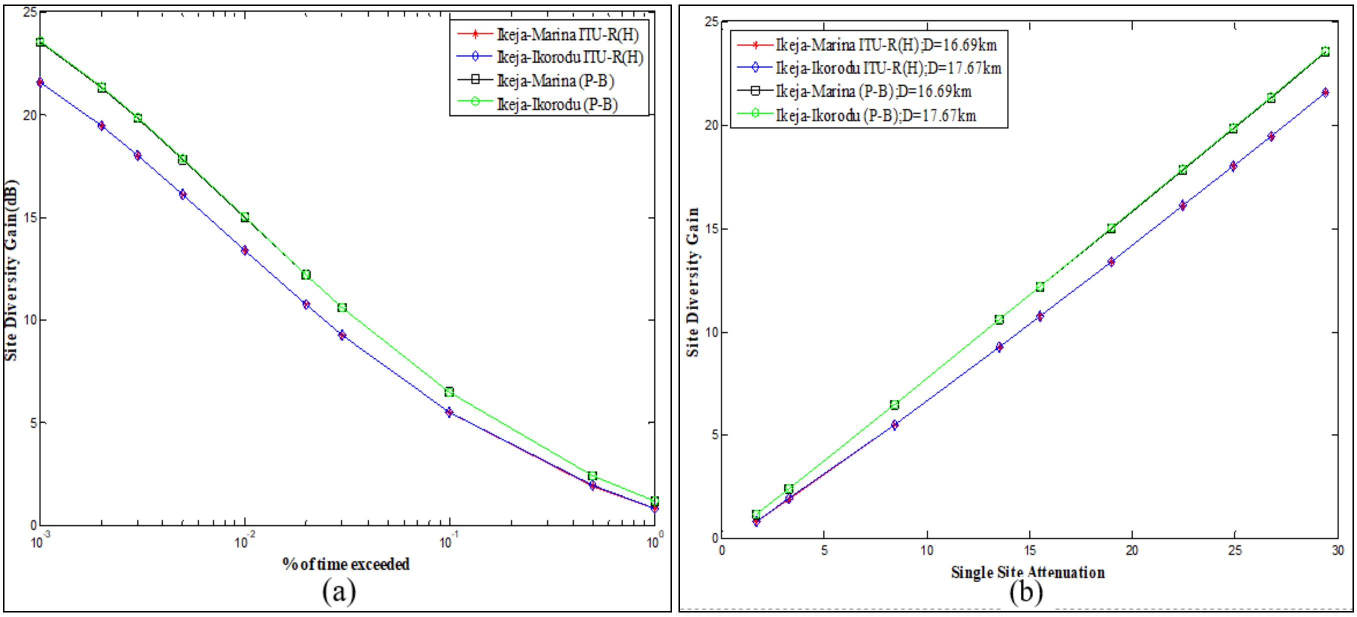

Fig 3: Comparison of site diversity gain of ITU-R and Paraboni-Barbaliscia models against (a) Percentage of time (b) Single site attenuation for Ikeja- Marina and Ikeja-Ikorodu at 12 GHz.

The comparison of joint site attenuation between the two predictions models are shown in Figure 4. Here, lower attenuation was presented when joint site diversity is implemented compared to single site, and this demonstrates the efficacy of site separation distance.

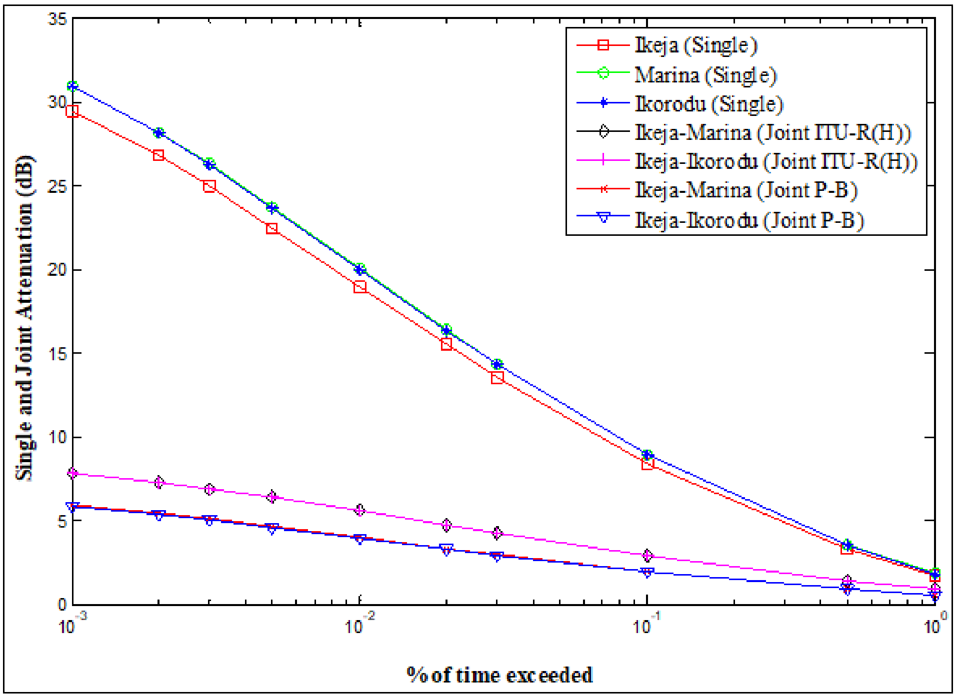

Fig 4: CDFs of single site attenuation and comparison of joint site attenuation of Paraboni-Barbaliscia and ITU-R models at 12 GHz

Furthermore, the plot also shows that the joint site attenuation using Paraboni-Barbaliscia model produced lower attenuation exceedances compared to the application of ITU-R(H) model, showing that P-B model is a better choice as site diversity FMT for slant path signals at 12 GHz. Displayed in Figure 5 are the CDF of single site attenuation and attenuation against rain rates for Ikeja, Marina and Ikorodu at 23 GHz. It can be seen that, the single site attenuation for Marina and Ikorodu are higher than that of Ikeja at $0.001 \le p \le 1\%$. It was also observed that the attenuation exceedances for Marina and Ikorodu are overlapped. Again, in Figure 6, the comparison of site diversity gains for ITU-R with P-B models against (a) percentage of time (b) single site attenuation in (Ikeja-Marina) and (Ikeja-Ikorodu) at 23 GHz was presented. It is observed that P-B generated higher diversity gain compared to ITU-R model for site separation of (Ikeja-Marina) and (Ikeja-Ikorodu).

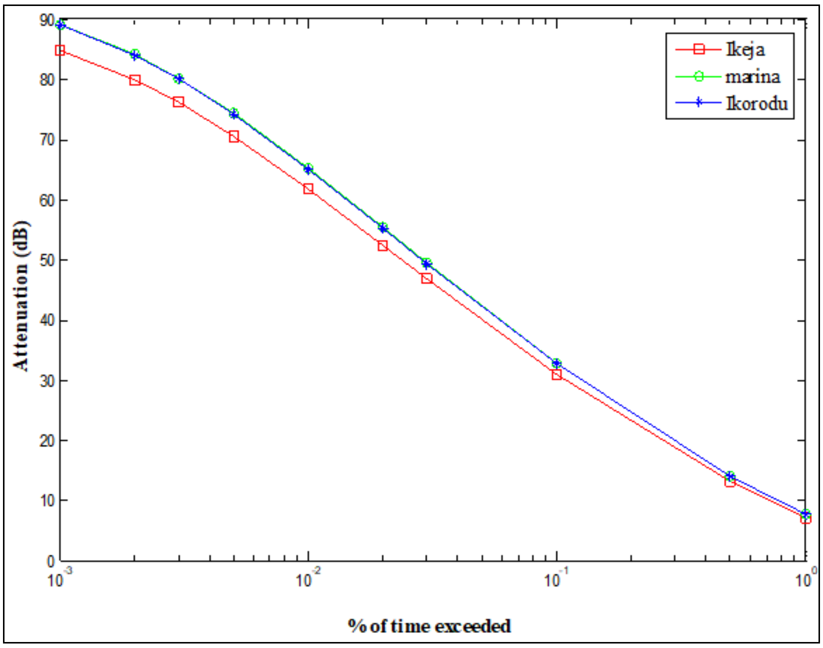

Fig 5: CDFs of attenuation for Ikeja, Marina and Ikorodu at 23 GHz.

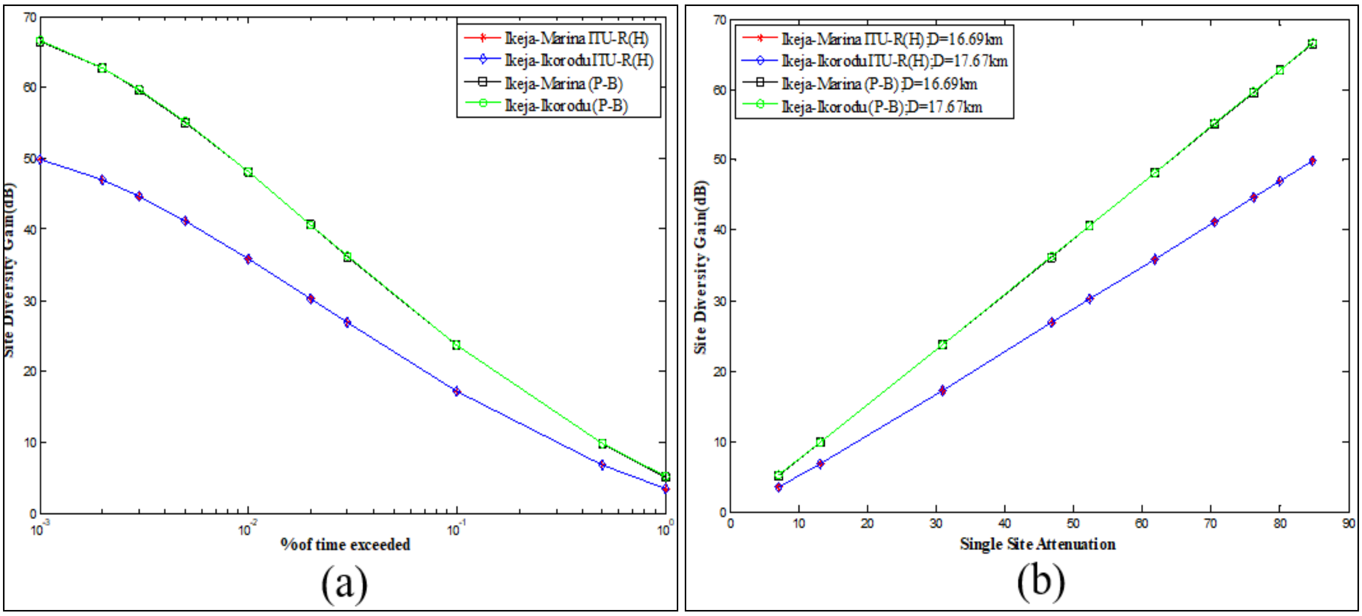

Fig 6: Comparison of site diversity gain of ITU-R model with Paraboni-Barbaliscia model against (a) Percentage of time (b) Single site attenuation for Ikeja-Marina and Ikeja-Ikorodu at 23 GHz.

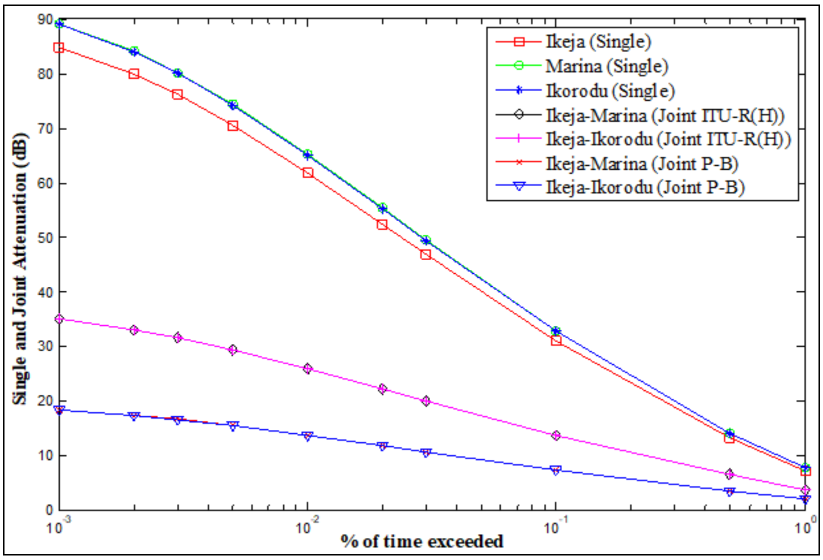

Fig 7: CDFs of single site attenuation and comparison between joint site attenuation of Paraboni-Barbaliscia and ITU-R models at 23 GHz.

The comparison of joint site attenuation exceedances between the two prediction models are shown in Figure 7. It also shows that joint site diversity implementation resulted in reduction of attenuation exceeded compared to when a single site is used. Furthermore, it is shown that joint site diversity with Paraboni-Barbaliscia model presented better performance than that of ITU-R (H) joint site diversity model for rainy effects on signals at 23 GHz for earth-to-space communication.

Table 2 shows the improved link availability for (Ikeja-Marina) and (Ikeja-Ikorodu) for various time exceeded. It is observed that the improved link availability slightly decreases with increased percentages of time exceeded.

Table 2: The improved link availability for distances 16.69 and 17.67 km

Probability	I1	I2
0.001	100.0000	100.0000
0.002	100.0000	100.0000
0.003	100.0000	100.0000
0.005	99.9999	99.9999
0.01	99.9998	99.9998
0.02	99.9991	99.9992
0.03	99.9980	99.9981
0.1	99.9809	99.9820
0.5	99.7290	99.7385
1	99.2970	99.3131

In Figure 8, the relationship between percentages of time exceeded for site separation of (Ikeja-Marina) and (Ikeja-Ikorodu) is presented. The relationship between P_1 and P_2 is a linear one.

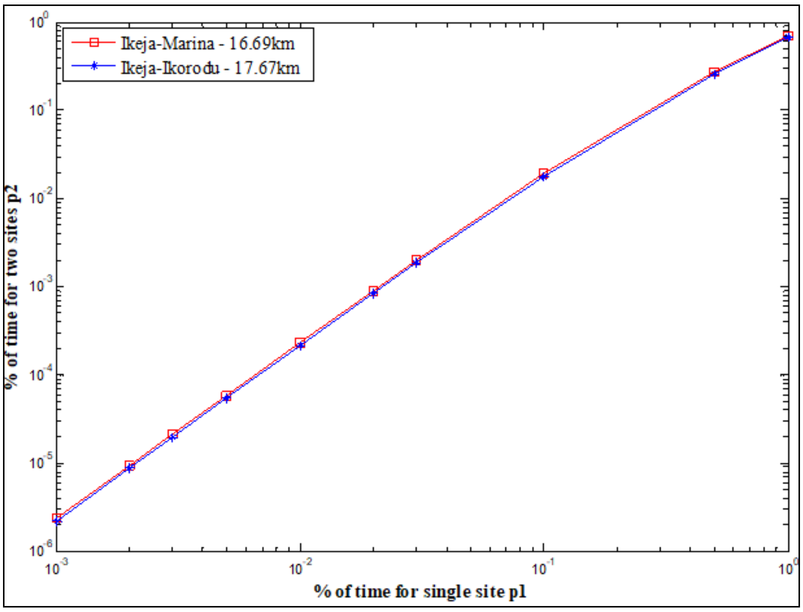

Fig 8: Relationship between percentages of time for site separations of (Ikeja-Marina) and (Ikeja-Ikorodu)

Hence, the improved link availability for distances 16.69 km (Ikeja-Marina) and 17.67 km (Ikeja-Ikorodu) for 0.1% of time exceeded are 99.981% and 99.982% respectively. Hence, site diversity provides improvement in both performance and availability of the system. Also, it is observed from Figures 4 and 7 that for both Ku/Ka bands, the joint site attenuation of Paraboni-Barbaliscia model gave lo wer values compared to the joint site attenuation of ITU-R (H) model. This shows that Paraboni-Barbaliscia model is effective compared to ITU-R (H) model. Furthermore, it is also observed from Figures 3 through 7 that the gap between the joint site attenuated value and site diversity gain generated by ITU-R (H) with that of Paraboni-Barbaliscia model for 12 and 23 GHz at 0.001% of time is 2.0 and 16.608 dB respectively, with Paraboni-Barbaliscia model generating higher diversity gain and lower attenuation values. Consequently, it is established that Paraboni-Barbaliscia model presented more effective way of mitigating against rain attenuation exceedances at millimeter wavebands, where fade due to rain precipitation is more pronounced.

Conclusions

In this work, the effectiveness of site diversity as a fade mitigation technique was studied both at 12 and 23 GHz. Using ITU-R(H) and P-B, it was observed that single site attenuation diversity technique tends to generate higher attenuation exceedances than joint site diversity method; thus substantiating the effectiveness of site separation distance, and also revealing that the spatial correlation dependence on rain attenuation has significant effect on potential utility of site diversity as a FMT for Ku/Ka frequency bands. Furthermore, the joint site diversity attenuation of Paraboni-Barbaliscia model presented lower attenuation exceedances compared to the ITU-R (H) joint site diversity attenuation model for both Ku/Ka bands. It was also observed that Paraboni-Barbaliscia model would be more effective when receiving signals at Ka-band compared to Ku-band. Therefore, it can be safely concluded that Paraboni-Barbaliscia model is the most suitable for reasonably predicting rain attenuation in Lagos, Nigeria, which is a tropical climatic geographical station with attendant high rain rates. This outcome could be useful in ensuring improved fade mitigation technique in the design of future earth-to-space links for satellite communications in tropical stations of the world, which is yet to be adequately provided for in the scheme of things.

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