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Rain fade impairment analysis for Earth-to-space radio links using site diversity techniques in Delta State, Nigeria

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Abstract

Site diversity is a fade mitigation technique that employs two or more spatially separated receiving stations to reduce the adverse effects of rain attenuation on satellite communication links. Its effectiveness is particularly important in tropical regions where intense convective rainfall frequently degrades Earth-to-space radio communications. This study investigates rain fade impairment and evaluates the effectiveness of site diversity for Ku-band Earth-to-space radio links in Warri, Delta State, Nigeria, a tropical coastal environment with high rainfall intensity. Rain rate and received signal level measurements collected during the peak rainy months of 2024 were analysed to generate cumulative distribution functions (CDFs) for rainfall occurrence and attenuation statistics. The study adopted the ITU-R P.618-11 and P.618-12 propagation models to estimate rain attenuation and diversity gain for both single-site and joint-site configurations. Results show that rain attenuation increases with rainfall intensity and becomes particularly severe for rainfall rates exceeding 70 mm/h. Maximum single-site attenuation values of 54.83 dB and 25.12 dB were observed during rainfall intensities of 200 mm/h in July and August, respectively. The application of site diversity reduced attenuation significantly, producing maximum diversity gains of 13.76 dB, 5.27 dB, 5.22 dB, and 4.10 dB for July, April, August, and October, respectively. Negative diversity gains observed at low rainfall intensities indicate periods of high spatial correlation between rain cells, during which diversity effectiveness is reduced. The findings validate the applicability of the ITU-R site diversity model under tropical convective rainfall conditions and provide localized propagation information for the design and optimization of reliable Ku-band satellite communication systems in the Niger Delta region of Nigeria.

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1. Introduction

Information can be transmitted between locations via space using electronic equipment called a satellite communication system in Earth's orbit [1]. The demand for advanced communication system services is increasing because of growing traffic and user numbers, necessitating an expansion of the capacity allocated to these services. At higher frequencies, signal loss due to atmospheric effects is a significant problem, particularly in tropical and subtropical regions. The two primary factors causing signal deterioration above 10 GHz are rain attenuation and gas absorption. Rain-related attenuation, mainly resulting from scattering and absorption processes, is the most common cause of signal degradation in both terrestrial and space systems [2–4]. Attenuation caused by rainfall must be carefully considered when designing Earth-to-space radio links in higher frequency bands. Rain attenuation increases the power requirements of transmitting equipment, raising the cost per transmission bit [5]. Path attenuation becomes a critical issue when Earth-to-space communication links above 10 GHz fail in tropical areas where moderate to high rainfall is common. In tropical regions, rain attenuation can lead to extended outages of satellite communication links. Power control and fade mitigation techniques are strategies used to offset this attenuation in an Earth-space link and maintain performance. Fade mitigation measures can be implemented effectively if rainfall-rate or rain-attenuation data are available for short-term forecasting. As rain attenuation hampers propagation, diversity techniques that consider time, site, and frequency are also examined [6]. This study focuses on the site diversity technique.

Rain fade is the term used to describe radio-signal absorption by precipitation. Because the signal travels through rain over a long distance, especially if the satellite dish has a low look angle, rainfall can induce rain fade at both the uplink and downlink sites. Mitigating the influence of rainfall on satellite communication links has been the focus of many studies in recent years [5]. Many researchers have produced models that are currently used by satellite communication operators. Most rainfall activities in these areas have a stratified structure, are typically light, and have a comparatively high rain-cell diameter. However, rain in Warri comes from convective rainfall cells, which have small diameters and frequently produce strong downpours that cause unpredictable shifts in signal amplitude, phase, polarization, and arrival angle. Hence, this study analyses rain fade impairment on Earth-to-space radio links using site diversity techniques.

Site diversity is the use of two or more receiving antennas to lessen or avoid the impact of rain on the downlink. The dependability of satellite communications is increased through site diversity. Furthermore, by utilizing the constrained extent and size of concentrated rain cells, site diversity enhances overall satellite-link performance. The operations centre compares the received signals from two or more sites and chooses the signal with the least attenuation. The use of more than two dispersed ground stations in a satellite communication link to reduce the impact of attenuation caused by rain over an extended period is sometimes referred to as a site diversity system [7–10]. When using the site diversity approach, several variables are considered, such as wind direction, baseline orientation angle, elevation angle, height, frequency, and site separation [11].

The issue of poor signal reception has not yet been fully addressed, despite earlier relevant research such as that of Islam *et al.* [12], who employed rain-intensity measurements to analyse site diversity gain for Earth-to-satellite communications in Malaysia. The study focused on two locations 37.36 km apart. In a year with 381 observations, ten rain events occurred simultaneously at both stations. Analysis of all overlapping rain events revealed three values of 6, 12, and 18 mm/h: 0.0162%, 0.00497%, and 0.000381%. The recommended model is used to translate measured rain-rate distribution to rain-attenuation distribution, which is then compared with predictions from the ITU-R, Hodge, Panagopoulos, and Semire models.

Fikih *et al.* [13] computed rain attenuation in tropical locations using an exponential drop-size distribution, accounting for numerous scattering and absorption effects. Rain attenuation can hinder radio transmission, especially in tropical locations with high rainfall rates, because it disperses and absorbs electromagnetic waves. Arijit *et al.* [14] explored diversity gain for rain attenuation over an Earth-space route in a tropical environment. Their findings propose a method for calculating diversity gain for a given site using propagation data acquired at a single station. This approach is crucial for estimating diversity parameters when multi-station data are not available. The rain-decay parameter, established in the Simple Attenuation Model (SAM), is used to calculate rain rate and subsequent rain attenuation at various distances from the single receiving site.

Rain attenuation in tropical regions is strongly influenced by the microphysical structure of convective rainfall systems. Convective rain cells are characterized by high rainfall intensity, large raindrop sizes, strong vertical air motion, and localized spatial distribution. These characteristics increase electromagnetic-wave absorption and scattering, particularly at frequencies above 10 GHz [15, 16]. At Ku-band frequencies, attenuation occurs mainly because of the interaction between incident electromagnetic waves and rain droplets whose sizes become comparable to the signal wavelength [17, 18]. Under intense tropical rainfall conditions, the cumulative scattering and absorption effects result in severe fading of Earth-space radio links. Consequently, tropical regions such as the Niger Delta experience significantly higher rain-induced signal degradation than temperate regions dominated by stratiform rainfall systems.

Rainfall events in Warri are mostly convective and extremely localized, leading to severe short-duration attenuation episodes, in contrast to research conducted in temperate regions where stratiform rainfall predominates. Despite being widely used for satellite-link construction, the performance of the ITU-R P.618 diversity model under the tropical convective rainfall conditions of the Niger Delta region remains insufficiently tested. The regional validation of the ITU-R site diversity prediction model using observed rain-rate and signal-attenuation data acquired in Warri, Delta State, Nigeria, is the main contribution of this work. The study determines the operating parameters under which site diversity becomes effective for Ku-band Earth-to-space radio communications and further explores the attenuation behaviour and diversity-gain features associated with isolated tropical rain cells.

2. Methodology

Rainfall and satellite-signal measurements were obtained in Warri, Delta State, Nigeria (latitude 5.52°N, longitude 5.75°E), a tropical coastal region characterized by intense convective rainfall. The experimental setup consisted of two receiving stations configured in a site-diversity arrangement with an inter-site separation of 20 km. The separation distance was selected based on ITU-R recommendations for achieving decorrelation between localized convective rain cells in tropical regions. The receiving stations operated on a Ku-band downlink frequency of 12 GHz with an elevation angle of 45°. The Ku-band frequency was selected because rain-attenuation effects become significant above 10 GHz, particularly in tropical climates. The elevation angle of 45° corresponds to the operational geometry of the satellite link within the study area and was maintained constant throughout the measurement campaign to ensure consistency in attenuation estimation.

Rainfall measurements were carried out using a Davis Vantage Vue weather station with a one-minute integration time. The instrument recorded rainfall rate in mm/h continuously during the observation period. Simultaneously, received signal-power measurements were obtained using a spectrum analyser and digital satellite signal meter connected to the Ku-band receiving antenna system. The measured rainfall data and corresponding received signal levels were collected for April, May, June, July, August, and October 2024, which correspond to the peak rainy season in Warri. These months were selected because they contain the highest convective rainfall occurrences responsible for severe rain-attenuation events in the study region.

The study adopted the ITU-R P.618-11 and P.618-12 propagation models to estimate rain attenuation and site diversity gain. Selection combining was assumed in the diversity system, where the receiving station with the minimum attenuation level was selected at each observation interval. Two concepts can be used to describe the performance of diversity. The diversity improvement factor is calculated by dividing the single-site time percentage by the diversity time percentage at the same attenuation level. The diversity gain is the difference in decibels between the single-site and diversity attenuation standards for a similar percentage of time. A diversity prediction algorithm was used for time percentages below 0.1%. The improvement factor of diversity, I, is given by:

$$I = \frac{p_1}{p_2} = \frac{1}{1+\beta^2}\left(1 + \frac{100\beta^2}{p_1}\right) \approx 1 + \frac{100\beta^2}{p_1}, \tag{1}$$

where p_1 is the single-site time percentage, p_2 is the diversity time percentage, and β is the link characteristic. Based on several experiments conducted in the 12 GHz band, β^2 varies mostly with the distance d between the stations and only marginally with the frequency and elevation angle. It was estimated as:

$$\beta^2 = 10^{-4} d^{1.33}. \tag{2}$$

The empirical expression below is used to compute the diversity gain, G (dB), between pairs of sites. The input parameters are described in Ref. [11]: d is the distance (km) between sites, A is the single-site path attenuation (dB), f is the frequency (GHz), θ is the elevation angle (degrees), and ψ is the angle (degrees) formed by the propagation path's azimuth with respect to the baseline between locations, with $\psi \leq 90°$. Gain contributed by spatial separation is given as

$$G_d = a\left(1 - e^{-bd}\right), \tag{3}$$

where $a = 0.78A - 1.94(1 - e^{-0.11A})$ and $b = 0.59(1 - e^{-0.1A})$. The frequency-dependent gain is

$$G_f = e^{-0.025f}. \tag{4}$$

The gain term based on the elevation angle is

$$G_\theta = 1 + 0.006\theta. \tag{5}$$

The standard-dependent term is

$$G_\beta = 1 + 0.006\beta. \tag{6}$$

The net diversity gain can be computed as

$$G_{\text{Net}} = G_d \times G_f \times G_\theta \times G_\beta. \tag{7}$$

With a distance D between the stations, the gain provided by a two-site diversity system may be computed as

$$G(D, A_S) = A_S(P) - A_J, \tag{8}$$

where A_J is the joint-site attenuation following selection combining, and A_S is the attenuation experienced by the single-site reference station. For this study, the frequency f is 12 GHz, the elevation angle is 45°, the distance D is 20 km, and ψ is 90°.

To evaluate the effectiveness of the site diversity system, statistical analysis was performed on the attenuation values obtained for both single-site and joint-site configurations. The percentage attenuation reduction due to diversity was estimated using

$$\text{Reduction (\%)} = \left(\frac{A_S - A_J}{A_S}\right) \times 100. \tag{9}$$

The attenuation exceeded for 0.01% of a mean year is obtained from

$$A_{0.01} = \gamma_R L_E \text{ (dB)}, \tag{10}$$

where L_E is the effective route length and γ_R is the specific attenuation. The estimated attenuation to be exceeded for other percentages of an average year, in the range of 0.001% to 5%, is determined by the rain fades to reach 0.01% for an average year [11]:

$$A_p = A_{0.01}\left(\frac{p}{0.01}\right)^{-(0.65+0.03\ln(p)-0.04\ln(A_{0.01})-\beta(1-p)\sin\theta)} \text{ (dB)}. \tag{11}$$

2.1. *Experimental configuration of the Earth-space link*

The Earth-space satellite link investigated in this study operated within the Ku-band frequency spectrum at 12 GHz. The receiving system consisted of two geographically separated receiving stations configured in a site-diversity arrangement within Warri, Delta State, Nigeria. The two receiving stations were separated by approximately 20 km to achieve attenuation decorrelation under localized rainfall conditions.

Each receiving station employed a parabolic dish antenna aligned toward the operational geostationary satellite with a fixed elevation angle of 45°. Horizontal polarization was maintained throughout the measurement campaign because of its common application in Ku-band satellite broadcasting systems. The received downlink signals were passed through a low-noise block downconverter (LNB) before being analysed using a spectrum analyser and digital satellite signal meter.

The received signal-power measurements were continuously monitored simultaneously with rainfall measurements to evaluate the relationship between rainfall rate and signal attenuation. The diversity-combining technique adopted in this work was selection combining, where the receiving station with the minimum attenuation level at any observation instant was selected as the effective diversity output.

Table 1: Rain fade and site diversity gain for April 2024.

Rain rate (mm/h)	Time exceeded (%)	$V_{0.01}$	$A_{0.01}$ (dB)	A_J (dB)	A_S (dB)	Gain (dB)
50	0.120	2.04	23.07	7.53	8.69	1.16
60	0.132	1.69	23.45	7.24	8.33	1.08
70	0.102	1.46	24.05	8.66	10.12	1.46
80	0.065	1.29	24.75	11.44	13.71	2.27
90	0.037	1.17	25.49	15.51	19.13	3.62
100	0.051	1.07	26.25	13.72	16.73	3.01
150	0.030	0.78	30.02	20.03	25.30	5.27

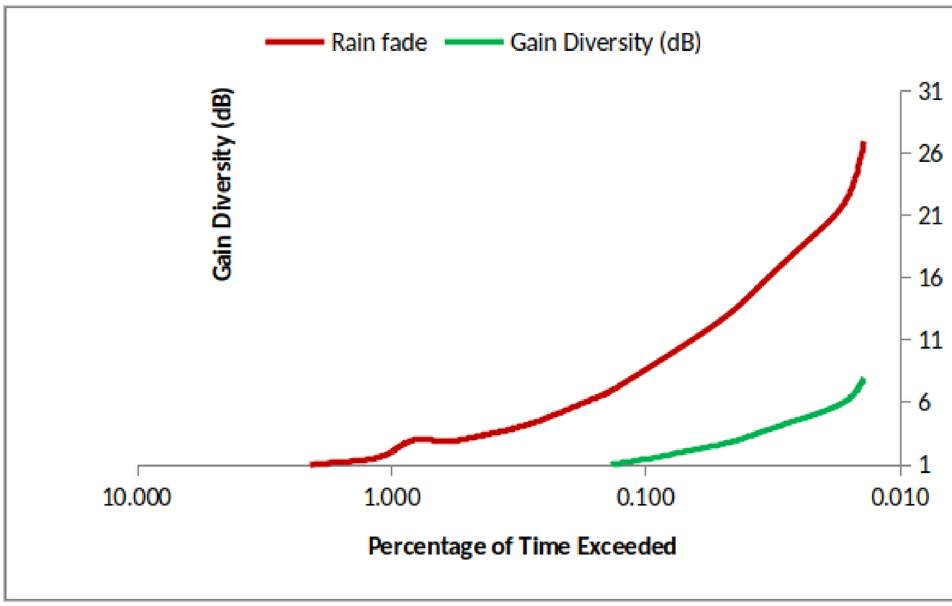

Figure 1: Gain diversity for May 2024.

3. Results

Table 1 presents the rain fade and site diversity gain for April 2024. Figures 1 and 2 show the gain diversity for May and June 2024, respectively. Tables 2–4 present the rain fade and diversity gain for July, August, and October 2024.

4. Discussion

Table 1 compares rain attenuation for the single-site and joint-site diversity configurations for April 2024. The results show that rain attenuation increased progressively with increasing rainfall rate from 50 mm/h to 150 mm/h. The maximum rain rate recorded during the month was 150 mm/h, corresponding to a rain fade of 20.03 dB at the joint site and 25.30 dB at the single site. The lower attenuation observed at the joint site confirms the effectiveness of the site diversity technique in mitigating rain-induced signal degradation. A maximum diversity gain of 5.27 dB was obtained at the highest rainfall intensity, indicating that the diversity system significantly reduced attenuation during severe convective rainfall events.

For July 2024, Table 2 compares the rain-attenuation values for the single-site and joint-site configurations under more intense rainfall conditions. The results indicate that attenuation increased rapidly as rainfall rate increased from

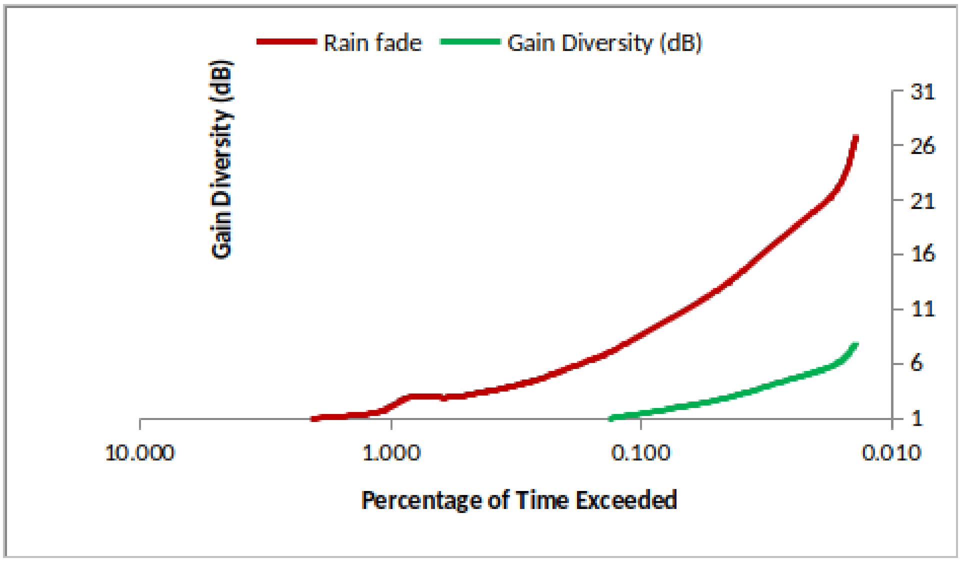

Figure 2: Gain diversity for June 2024.

Table 2: Rain fade and diversity gain for July 2024.

Rain rate (mm/h)	Time exceeded (%)	$V_{0.01}$	$A_{0.01}$ (dB)	A_J (dB)	A_S (dB)	Gain (dB)
50	0.984	1.70	23.43	1.66	1.48	-0.18
60	0.789	1.42	24.20	2.07	1.97	-0.09
70	0.549	1.23	25.11	2.87	2.96	0.09
80	0.271	1.09	26.08	5.03	5.59	0.56
90	0.146	0.98	27.07	7.86	9.10	1.24
100	0.076	0.90	28.06	11.88	14.29	2.41
150	0.014	0.65	32.82	29.50	38.50	9.00
200	0.007	0.53	37.20	41.07	54.83	13.76

Table 3: Rain fade and diversity gain for August 2024.

Rain rate (mm/h)	Time exceeded (%)	$V_{0.01}$	$A_{0.01}$ (dB)	A_J (dB)	A_S (dB)	Gain (dB)
50	1.644	1.70	23.43	1.06	0.77	-0.28
60	1.454	1.42	24.20	1.22	0.96	-0.26
70	1.356	1.23	25.11	1.35	1.10	-0.24
80	0.736	1.09	26.08	2.36	2.33	-0.03
90	0.565	0.98	27.07	3.03	3.15	0.12
100	0.382	0.90	28.06	4.23	4.61	0.38
150	0.238	0.65	32.82	6.91	7.92	1.00
200	0.049	0.53	37.20	19.90	25.12	5.22

50 mm/h to 200 mm/h. The highest rain rate recorded was 200 mm/h, which produced a rain fade of 41.07 dB at the joint site and 54.83 dB at the single site. The large attenuation difference between the two configurations demonstrates substantial attenuation mitigation due to spatial diversity. A maximum diversity gain of 13.76 dB was achieved at the peak rainfall intensity, suggesting that site diversity becomes more effective during highly localized rainfall events

Table 4: Rain fade and diversity gain for October 2024.

Rain rate (mm/h)	Time exceeded (%)	$V_{0.01}$	$A_{0.01}$ (dB)	A_J (dB)	A_S (dB)	Gain (dB)
20	0.731	6.53	30.38	2.76	2.82	0.06
25	0.463	4.20	25.43	3.32	3.50	0.18
30	0.343	3.16	23.74	3.88	4.18	0.31
35	0.266	2.57	23.14	4.52	4.97	0.45
40	0.192	2.18	23.03	5.60	6.29	0.69
45	0.174	1.91	23.16	6.02	6.81	0.79
50	0.134	1.70	23.43	7.16	8.22	1.06
60	0.095	1.42	24.20	9.08	10.65	1.57
70	0.067	1.23	25.11	11.39	13.65	2.26
80	0.032	1.09	26.08	16.85	20.94	4.10

where attenuation decorrelation between receiving stations is significant. However, negative diversity-gain values were observed at lower rainfall rates of 50 mm/h and 60 mm/h. This indicates that both receiving sites experienced nearly identical attenuation conditions during rainfall events, resulting in minimal diversity improvement due to spatial correlation of the rain cells.

Table 3 presents the attenuation characteristics for August 2024. Similar to the previous months, attenuation increased with increasing rainfall rate from 50 mm/h to 200 mm/h. At the maximum rainfall rate of 200 mm/h, the rain fade at the joint site was 19.90 dB, while the single-site attenuation reached 25.12 dB. A diversity gain of 5.22 dB was obtained under this condition, demonstrating that site diversity effectively reduced signal fading during intense rainfall periods. Negative diversity-gain values were also observed at lower rainfall rates between 50 mm/h and 80 mm/h. This behaviour suggests that during low-intensity rainfall events, the attenuation levels at both receiving stations were highly correlated, thereby reducing the effectiveness of the diversity system.

The attenuation results for October 2024, presented in Table 4, also show that rain fade increased progressively with increasing rainfall rate from 20 mm/h to 80 mm/h. Under this condition, the joint-site attenuation was 16.85 dB, whereas the single-site attenuation was higher at 20.94 dB. The corresponding diversity gain was 4.10 dB, confirming that the site diversity technique provided attenuation improvement during moderate-to-heavy rainfall conditions. The observed attenuation behaviour agrees with the expected propagation characteristics of Ku-band Earth-to-space links operating under tropical convective rainfall environments. The diversity gain obtained across the different months confirms the effectiveness of site diversity as a fade mitigation technique for Earth-to-space radio communication links in the tropical coastal environment of Warri, Delta State, Nigeria. Figures 1 and 2 further illustrate the relationship between percentage of time exceeded and diversity gain for May and June 2024, respectively.

5. Conclusion

The results demonstrate that attenuation increases nonlinearly with rainfall rate, which agrees with the ITU-R prediction framework for Ku-band propagation under tropical rainfall conditions. The observed escalation in attenuation beyond approximately 70 mm/h indicates the dominance of convective rain cells with high liquid water content and strong scattering effects. The diversity gain observed during high-rainfall periods validates the effectiveness of spatial diversity in mitigating rain-induced fading in tropical satellite links. Maximum diversity gains of 13.76 dB and 5.22 dB were observed in July and August, respectively, at 200 mm/h rain intensity, indicating substantial attenuation reduction under severe rainfall conditions.

Negative diversity-gain values observed at low rain rates during July and August suggest that attenuation at both receiving stations became highly correlated under weak rainfall conditions. This behaviour indicates that site diversity becomes ineffective when rain cells simultaneously affect both receiving sites with nearly identical attenuation characteristics. Such behaviour has also been reported in tropical propagation studies where localized convective cells exhibit overlapping spatial coverage during low-intensity rainfall events.

Overall, the attenuation trends predicted using the ITU-R model are consistent with measured rainfall characteristics in Warri, thereby supporting the applicability of the ITU-R P.618 framework for tropical Earth-space link analysis with appropriate regional validation.

Data availability

Data will be made available upon reasonable request from the corresponding author.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

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