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Investigation of the Performance of Site Diversity through Rain Gauge Measurements in South-South Nigeria

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Abstract

Site diversity is an effective technique to mitigate rain attenuation, especially in regions where rainfall rates are high. The South-South region of Nigeria is characterized by the tropical rain forest climate, exhibiting high rainfall rates almost all year round. This paper investigates the performance of site diversity technique in the South-South Nigeria at Ka-band frequency of 20 GHz. Rainfall data obtained from the Nigerian Meteorological Agency (NIMET) over a period of five years (2010 to 2014) were analysed to derive the one-minute rainfall rate distribution for four selected earth stations (University of Uyo, Uyo; Akwa Ibom International Airport, Uyo; Margaret Ekpo International Airport, Calabar; and Port Harcourt International Airport, Port Harcourt) within the South-South Nigeria. The link parameters of NigComSat-1R were used with the ITU-R model for rain attenuation to estimate the rain attenuation distribution through an annual cumulative distribution and percentage of outage time between 0.01 to 100 %. Site diversity (SD) was implemented, taking University of Uyo as the reference site. The results obtained shows that the SD gain between the University of Uyo and Port Harcourt International Airport is higher than the SD gain recorded between University of Uyo and Margaret Ekpo International Airport. This is consistent with the fact that longer distances between the earth stations yield higher SD gain.

Keywords: Rain Rate; Rain Attenuation; Cumulative Distribution; Site Diversity.

1 Introduction

Rainfall is the most severe cause of attenuation of electromagnetic waves of frequencies above 10 GHz [1]. It constitutes one of the most fundamental limitations on the performance of communication links, giving rise to large variations in the received signal power [1,2]. Strong propagation impairments have made it necessary to incorporate techniques which aim to mitigate the effects of propagation impairments such as rain attenuation in the design of telecommunication systems to operate at Ka and V-band frequencies. These techniques are referred to as fade mitigation techniques (FMTs). Some of these fade mitigation techniques have been proposed and are in existence [3]. These include power control, adaptive-wave and diversity techniques. This research would dwell on a diversity technique known as site diversity (SD), which has been known to be more efficient [2].

Site diversity makes use of the spatial characteristics of the rainfall medium by using two or more earth stations to exploit the fact that the probability of attenuation due to rain occurring simultaneously on the various earth-space paths is significantly less than the relevant probability occurring on either individual path [4]. The earth stations in a site diversity based communication system are geographically separated but terrestrially connected to each other, such that each site offers less correlated propagation paths between the earth station and the satellite. This 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 so as to improve its signal to noise ratio (SNR) [3]. Hence, if the transmitted signal is severely impeded in one site, another earth station is used to compensate this effect.

2 Review of Related Works

Most of the initial studies on site diversity were performed in the temperate region. Just recently, propagation studies on site diversity for the Ku and Ka bands have been reported over the tropical region. In 2001, analysis of site diversity performance was done in Singapore [5]. This research was carried out with a separation distance of 12.3 km and a non-conventional base line orientation of 4°.

Otung and Nagaraja [6] conducted another study in South England, providing a detailed analysis of site diversity as well as the spatial correlation of rain attenuation, which gave rise to a greater efficacy of site diversity for fade mitigation in the summer and a larger sensitivity to baseline orientation in non-summer periods. Nagaraja and Otung, [7] went ahead to propose an empirical model for statistical prediction of site diversity gain on earth-space propagation paths, incorporating 46 months of rain radar data in South England. The model performed with an overall root-mean-square (rms) error of 1.87 dB computed over a wide variety of link configurations with elevation angles ranging from 10o to 50o and transmission frequencies from 16 to 50 GHz.

In South-East Asia , Semir and his coauthors performed an analysis of beacon and weather radar data for the simulation and performance of site diversity technique [6], examining the effects of site separation distance, frequency of operation, elevation angle, and baseline angle on site diversity. It was discovered that site diversity gain depends greatly on site separation distance and elevation angle and it is less dependent on frequency and baseline angle of the site diverse stations.

3. Methodology

3.1. Description of the Rainfall Data

Rainfall data for Akwa Ibom International Airport (AKIA), Margaret Ekpo International Airport (MEIA) and Port Harcourt International airport (PHIA) were obtained from the Nigerian Meteorological Agency (NIMET) for a period of five years. Rainfall data for the University of Uyo (UNIUYO) was obtained from the University of Uyo weather station also for a period of five years.

The rainfall accumulation data retrieved from both data bases show daily rainfall volume (measured in mm), obtained using tipping bucket rain gauges. Monthly and annual rainfall accumulation was obtained from the rainfall data; an average value of annual rainfall accumulation was obtained over five years for each station. A summary of the rainfall data obtained for each site is presented in Table 1.

Table 1. Statistics of rainfall accumulation for the study area over a period of five years.

	ANNUAL RAINFALL ACCUMULATION (mm)			
Year	UNIUYO	AKIA	MEIA	PHIA
2010	2848.8	3172.8	3071.5	2837
2011	2930.9	3968.8	3487.2	2049.9
2012	3835.1	4651	4070.7	2842.2
2013	2867.5	4494.1	3506.4	2513.2
2014	3027.7	4267.8	3286.9	2322.4
Average	3102	4110.9	3484.5	2512.9

3.2. Rain Rate Distribution

The study of the performance of site diversity requires one minute rain rate data, which is not easily obtainable in the tropical and subtropical regions. However, the yearly rainfall accumulation statistics that were obtained may be incorporated with a model for converting the available rainfall data to the equivalent one minute rain rate cumulative distribution. For this reason, various models have been proposed. This research however, makes use of the Chebil rain rate model and the Moupfouma model for rainfall distribution [9] to derive the one minute rainfall distribution for the region under study.

The Chebil and Rahman, [10] rain rate model allows for the usage of long-term mean annual rainfall accumulation M to compute the point rainfall rate $R_{0.01}$, for the location of interest. This model uses the power law relationship expressed as:

$$R_{0.01} = \alpha M^{\beta} \tag{1}$$

where α and β are regression coefficients.

Chebil has made a comparison between some models based on measured values of $R_{0.01}$ and M in Malaysia, Indonesia, Brazil, Singapore and Vietnam. He showed that his model is the best estimate of the measured data [11]. The regression coefficients are defined as:

$\alpha = 12.2903$ and $\beta = 0.2973$

The Moupfouma and Martins model [9] has been suggested from recent analysis to be good for both tropical and temperate regions [12]. According to Moupfouma and Martins [9], one-minute rain rate cumulative distribution is the probability, $P(R \geq r)$ that one minute rainfall intensity, R (mm/hr) exceeds a threshold value, r (mm/hr) for a fraction of time. The model is expressed as:

$$P(R \geq r) = 10^4 \left(\frac{R_{0.01}}{r+1}\right)^b \exp(\mu[R_{0.01} - r]) \tag{2}$$

where μ governs the slope of the rain rate cumulative distribution and depends on the local climatic conditions and geographical features. For the tropical and sub-tropical regions, μ and b are approximated using the Equations (3) and (4).

$$\mu = \frac{4 \ln 10}{R_{0.01}} \exp\left(-\lambda \left[\frac{r}{R_{0.01}}\right]^{\gamma}\right) \tag{3}$$

where $\lambda = 1.066$ and $\gamma = 0.214$

$$b = \left(\frac{r - R_{0.01}}{R_{0.01}}\right) \ln\left(1 + \frac{r}{R_{0.01}}\right) \quad (4)$$

Thus, the Moupfouma model requires three input parameters; λ, γ, and $R_{0.01}$. the first two parameters have been provided. When estimating $R_{0.01}$, the Chebil's model becomes suitable [11].

Thus, making use of the combination of the Chebil and refined Moupfouma models, the 1-minute rain rate cumulative distribution was determined from the long-term mean annual rainfall data obtained from Table 1. The cumulative distribution of rain rates for all four sites is presented in Figure 1. Rain rates were plotted for other percentages of time ranging from 0.001 % to 1 % of an average year. This corresponds to 5.26 minutes to 87.72 hours of exceedance of the one–minute rainfall rate in an average year.

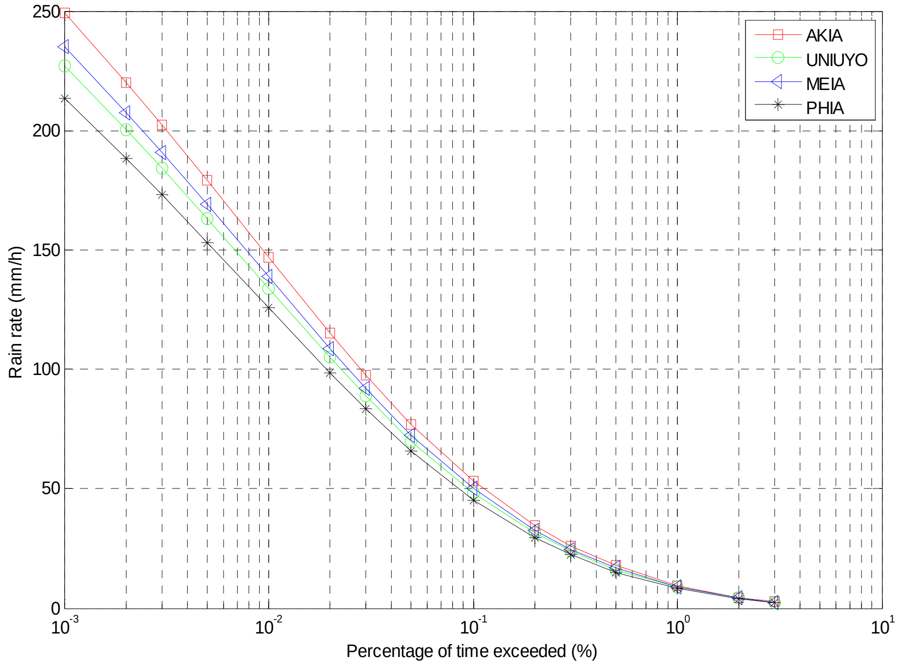

Figure 1. Cumulative distribution of rainfall rates for the study area.

It can be seen from Figure 1 that AKIA has the highest rain rate distribution at 0.01 % of outage time with 147.14 mm/h, MEIA has 138.75 mm/hr, UNIUYO has 133.97 mm/h and PHIA has 125.82 mm/h. From the measurements of rainfall rates that have been obtained, it was observed that the rainfall maps issued by the ITU underestimate the rainfall rate cumulative distribution for this region.

3.3. Rain Attenuation Distribution

Numerous models for predicting rain attenuation are available for different geographical and climatic conditions. The ITU-R model [13] which is widely accepted for the prediction of rain attenuation [14] was used to obtain the rain attenuation distribution in this research. The ITU-R model is semi-empirical and often employs the local climatic parameters at a desired probability of exceedance [15]. The input local climatic parameters include: point rainfall rate for 0.01 % of an average year ($R_{0.01}$) in mm/hr; height above sea level of the earth station (H_s:) in km; elevation angle (θ) in degrees; latitude of the earth station ($\emptyset$) in degrees; operating frequency (f) in gigahertz and effective radius of the earth (Re) in kilometres. The cumulative distributions of rain attenuation were obtained at a Ka band frequency of 20 GHz and a NIGCOMSAT 1-R orbital position of 42.5°. Other earth station parameters are summarized in Table 2.

The cumulative distribution of rain attenuation for all four sites is presented in Figure 2, rain attenuation values were plotted for other percentages of time ranging from 0.001 % to 1 % of an average year. The long-term attenuation obtained was found to be 50.29 dB for UNIUYO, 48.92 dB for AKIA, 49.29 dB for MEIA, and 45.33 dB for PHIA. These values were computed at 0.01 % of time exceedance (unavailability).

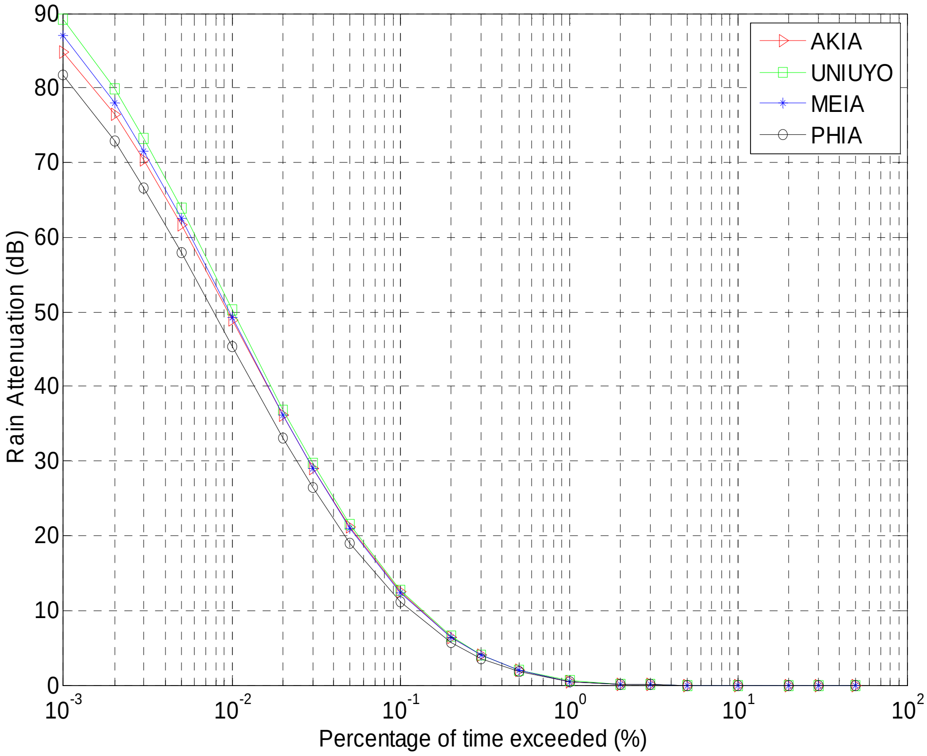

Figure 2. Cumulative distribution of rain attenuation at 20 GHz

A quality check of attenuation time series was conducted by comparing its Cumulative distribution with a Cumulative distribution predicted using the ITU-R model for rain attenuation [13] and its statistical rain rate at 0.01 % of an average year for the reference station using the experimental data available from the ITU-R databank. The data provided a good agreement with an RMSE of 0.074.

Table 2. Earth Station Parameters.

Parameters	(AKIA)	(MEIA)	(PHIA)	(UNIUYO)
Longitude (°E)	8.085736	8.34696	6.950289	7.918825
Height above sea level (m)	51.2	62.3	29	66
Distance from Satellite (km)	37099.4	37082.02	37182.87	37175.4
Elevation angle (degrees)	49.67	49.94	48.38	48.49
Azimuth (degrees)	97.08	97.08°	96.97	96.98

3.4. Site Diversity Implementation

An implementation of the site diversity technique requires the parameters known as joint site attenuation and site diversity gain to be computed. Joint site attenuation is the minimum attenuation between the instantaneous rain attenuations of the reference site and the diversity site [16]. It is obtained using a joint attenuation time series A_j, (dB) as follows:

$$A_{Jref,i} = \min[A_{ref}(t), A_i(t)] \quad (5)$$

where: $A_{ref}(t)$ and $A_i(t)$ are the instantaneous rain attenuation values at the reference and diversity stations respectively (i = 1,2,3,……n, n being the number of diversity stations).

This link performance is usually measured using the site diversity gain. SD gain is the difference in link attenuation for a given percentage of time between the single link A(dB), (single site attenuation) and the joint site diversity configuration A_j(dB), (joint site attenuation) [16, 17].

$$G_{SD} = A_i - A_{jref,i} \quad (6)$$

Joint site attenuation was computed with UNIUYO taken as the reference site; this was done by computing the minimum instantaneous values of rain attenuation between UNIUYO and each other site (using the rain attenuation distribution obtained for each site). A program was written in MATLAB to implement the joint attenuation in each case. A CDF was plotted for the single site attenuation and the joint site attenuation. The values that were obtained at 0.01 % of time and 20 GHz frequency are 48.92 dB, 49.29 dB and 45.33 dB with diversity sites taken as AKIA, MEIA and PHIA respectively.

Site diversity gain was determined for the three cases of joint attenuation that had been obtained, and CDFs were plotted. The values of gain obtained at 0.01% of time and at 20 GHz are 1.37 dB, 1.00 dB and 4.96 dB with diversity sites taken as AKIA, MEIA and PHIA respectively. The joint site attenuation obtained for 0.01 % of time, their corresponding SD gains and their distances from the reference station are summarized in Table 3.

Table 3. Joint site attenuation and SD gain at 20 GHz

Parameters	UNIUYO-AKIA	UNIUYO-MEIA	UNIUYO-PHIA
Joint Attenuation (dB)	48.92	49.29	45.33
SD gain (dB)	1.37	1	4.96
Distances apart (km)	21.1	48.22	117.29

The cumulative distribution of SD gain is presented in Figure 3.

3.5. Site Diversity Performance

The diversity gain cumulative distribution presented in Figure 3, it is observed that diversity gain is significantly higher at lower time percentages which corresponds to higher level of rain attenuation. Also, SD gain is dependent on site separation distance. The results obtained shows that a gain of at least 4.96 dB is attainable in the tropical rain forest climate of the South-South Nigeria, this translates to an improvement in the link margin of at least 15 %. It should be noted that this analysis was performed for a worst case scenario, where all diversity earth stations experience rainfall simultaneously. This scenario exhibits only a very minimal probability of occurrence.

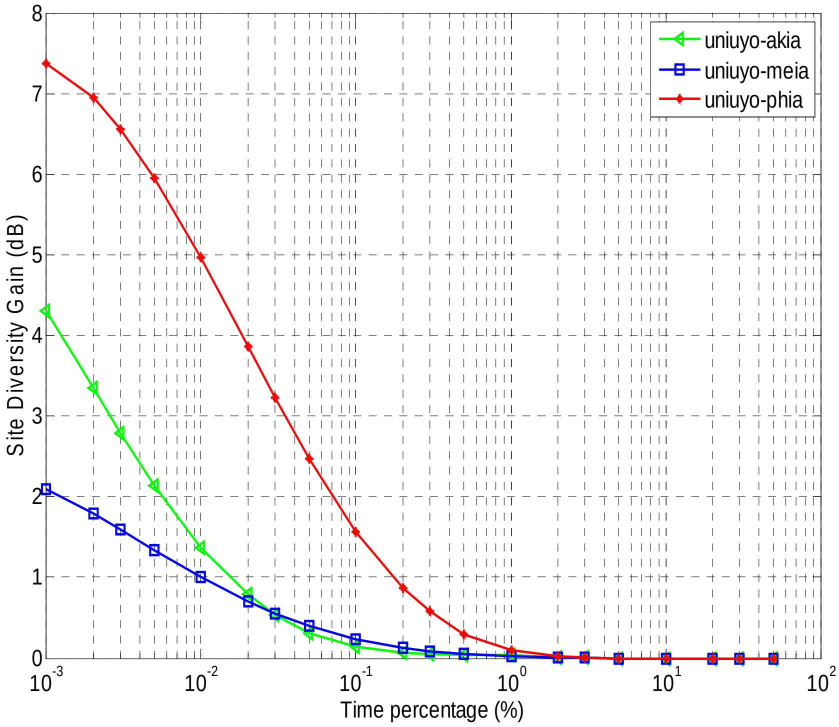

Figure 3. CDF of site diversity gain at 20 GHz

4. Results and Discussions

The viability of the procedure used in the implementation of SD was checked by comparing the cumulative distributions computed for each three diversity sites with an existing prediction model. Site diversity prediction models include the empirical models and the physical models. Empirical models use the effective path length and rainfall rate using the information from various data bases within a given climatic zone. The core benefits of these models is that the mathematical expressions used to describe them are quite simple. The physical models describes the properties of rain all the way along the propagation path, these methods are theoretical models (analytical models) which presents the physical behaviour involved in the attenuation process. In this case, not all the input parameters are required for analysis. The SD models proposed by Hodge [18], Goldhirsh [19], Alnutt and Rogers and ITU-R are empirical models while the Capsoni model and the Mass and Matricciani model are physical models.

Recent researches have shown that the Hodge [18] and the ITU-R models provide more reliable results. The experimentally obtained results from this research would therefore, be compared with the ITU-R site diversity prediction model. The necessary site parameters were inputted into the ITU-R site diversity model [13] and the resulting SD gain was plotted alongside the measured SD gain at the three diversity earth stations. Figure 4 shows a comparison between the ITU-R predictions and the measured data between 0.01 % and 1 % of outage time.

It is observed that the ITU-R model overestimates the site diversity gain for the South-South region of Nigeria. Therefore, the Hodge and ITU-R models are inappropriate models for site diversity prediction in the tropical climate of the South-South Nigeria; other prediction models may be developed to be adaptable to this region.

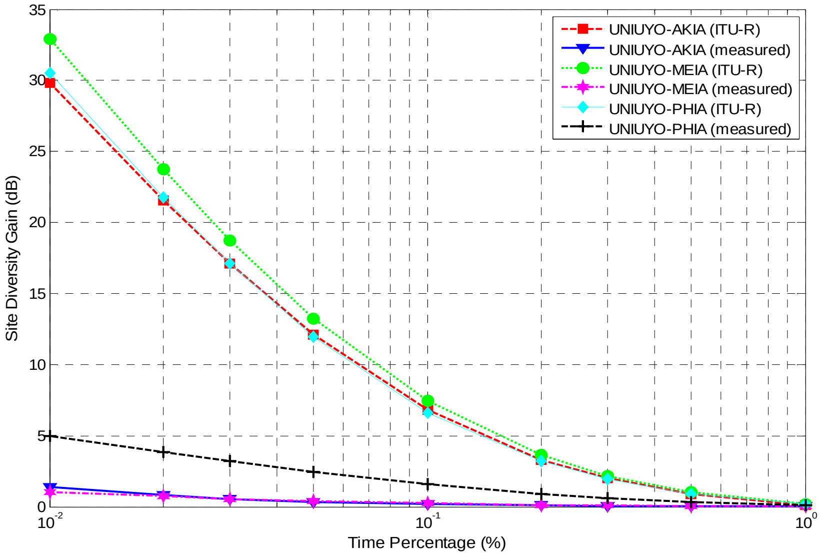

Figure 4. Comparison between experimental SD gain with the ITU-R prediction model.

5 Conclusion

The analysis of SD performance through rain gauge measurements in South-South Nigeria has shown that a considerable improvement in link margin is attainable despite the very high rate of rain attenuation. Furthermore, SD technique would be more effective in mitigating rain attenuation when it is configured with more diversity earth stations. However, a suitable prediction model becomes necessary for the study area, since the ITU-R predictions do not agree with the experimental data.

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