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Performance Evaluation of A Modified Time Diversity Gain Model For Rain Fade Mitigation In South-South Nigeria

Uduak M. Udongwo[1], Kufre M. Udofia[2], Akaninyene B. Obot[3]
[1,2,3]*Department of Electrical/Electronic and Computer Engineering, University of Uyo, Uyo, Nigeria*
Corresponding Author: Uduak M. Udongwo

ABSTRACT : *Satellite communication systems utilizing frequencies above 10 GHz are known to experience strong propagation impairments due to rain especially in regions where rainfall rates are high. South-south Nigeria is characterized by the tropical rain forest climate which exhibits high rainfall rates virtually all year round. Therefore, in order to compensate for the propagation impairments on earth-space communication link at Ka-band frequencies of 20 and 30 GHz, time diversity (TD) is presented in this paper. Rainfall data obtained from Nigerian Meteorological Agency (NIMET) over a period of five (5) years for four (4) selected earth stations were analyzed to derive one-minute rainfall rate distribution. The link parameters of Nigerian Communications Satellite (NigComSat-1R) were incorporated with the International Telecommunications Union Radiowave (ITU-R) model for rain attenuation to estimate the rain attenuation distribution through an annual cumulative distribution, and outage percentages of time between 0.01 to 100 %. The TD gain was computed taking the Akwa Ibom International Airport (AKIA) as the reference site. Results obtained from these analyses were used to develop a prediction model for the TD gain using regression analysis based of two parameters, the effective attenuation and time delays. The proposed model was compared with other models, namely Matricciani, Fukuchi and Nakayama, and the ITU-R models.*

KEYWORDS : *Satellite communication, fade mitigation technique, diversity technique, time diversity, time delay*

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I. INTRODUCTION

The continued demand for huge data rate to support multimedia services such as high quality real-time audio and video streaming in telecommunication systems has led to the usage of frequencies higher than 10 GHz [1]. Such frequency bands though are able to provide larger bandwidths and higher data rates to the users with notable drawbacks, heavy precipitation severely degrades the performance of satellite communication system particularly in tropical region [2].

Strong propagation impairments have made it necessary to incorporate techniques which aim to reduce the effects of propagation impairments such as rain attenuation in the design of telecommunication systems that operate at Ka and V band frequencies. According to [3], these techniques which are referred to as fade mitigation techniques (FMTs) are already in existence and they include; power control, adaptive – wave and diversity techniques.

As stated by [4], several diversity reception schemes have been thoroughly investigated in the past to mitigate rain fading in fixed/broadcast satellite communication systems operating above 10 GHz. These schemes have been shown to offer significant performance improvement. Some diversity techniques include [2, 4, 5]: site diversity (SD), orbital diversity (OD) or satellite diversity (Sat D), frequency diversity (FD), time diversity (TD) and polarization diversity (PD). These FMTs produce significant diversity gains but their use is limited due to specific technical and other factors [6]. As highlighted by [7], the main limitation of SD comes from cost consideration since additional earth stations and terrestrial connections enabling the processing of the jointly received signals are required. In OD, limitations are imposed by the switching procedure between the satellites, as well as by the waste of satellite bandwidth [8]. Finally, FD is rather expensive, requiring dual reception at the earth terminals [2].

II. TIME DIVERSITY TECHNIQUE

A. Time Diversity Overview

Time diversity is a fade mitigation technique, which works by retransmitting the same information with an acceptable time delay [9]. The receiver is able to collect and later on use the information gathered during good propagation conditions via any of the diversity combining methods such as maximal ratio combining (MRC), selective combining (SC) or equal gain combining (EGC) [3]. TD is suitable for applications such as video-on-demand (VoD), email, and data transfer process that do not require real-time communication [10]. The motivation for TD as a feasible fade mitigation technique is based on the fact that rain events are usually short-lived [11].

According to [2], a major advantage of TD when compared with other diversity techniques is that it does not require additional equipment or complicated synchronization procedures, since it utilises only a single satellite link and a single reception unit. The implementation is realistic, practicable, and inexpensive, and is less challenging compared to other diversity techniques.

B. Rain Data Analysis

For an effective assessment of rain attenuation in a satellite-earth link, determination of the temporal long-term time series (year-to-year) variations of rain events is required due to non-uniform distribution and its characteristics in South-south Nigeria. The analysis of rain characteristics in the region was performed using data obtained from NIMET for the four study sites (AKIA, University of Uyo (UNIUYO), Margaret Ekpo International Airport (MEIA) and Port Harcourt International Airport (PHIA)) to compute the cumulative rain rate and attenuation for each site being under studied. The cumulative distribution of rain rates for all four sites is presented in Fig 1. Rain rates were plotted for percentage unavailabilities 0.001 % to 1 % of an average year. These correspond to 5.26 minutes to 87.72 hours of percentage exceedances of the one–minute rainfall rate in an average year.

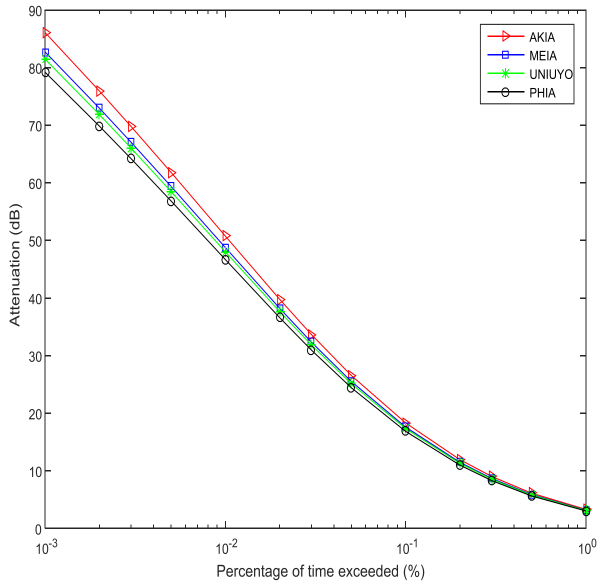

Fig 1: Rain attenuation CDF a 20 GHz

The cumulative distributions of rain attenuation for the four sites at 20 GHz are presented in Fig 2. Rain attenuation values were plotted for percentages of time ranging from 0.001 % to 1 % of an average year. The long-term attenuation obtained at 20 GHz frequency for the sites were found to be 48.03, 50.76, 48.77 and 46.69 decibels (dB) respectively for UNIUYO, AKIA, MEIA, and PHIA. These values were computed at 0.01 % of time exceeded (unavailability). From the computed values, rain attenuation affected AKIA the most also equally evident from the computed rain rate values in Fig 1.

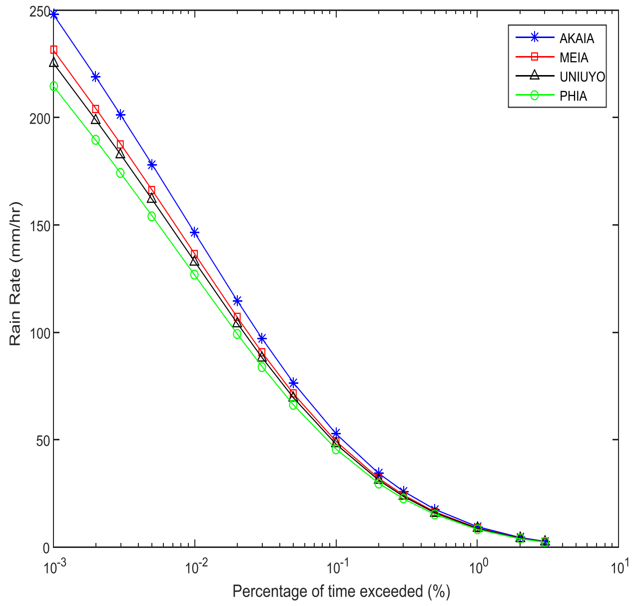

Fig 2: Cumulative distribution of rainfall rates for four sites

III. TIME DIVERSITY GAIN

TD gain is a key performance index for evaluating TD as a FMT. It is defined as the difference in dB between the cumulative distributions of rain attenuation at a time instant, and that with a defined time delay between transmissions [14]. In order to implement TD technique in a communication link, the effective attenuation is first determined. This is because for signal retransmission to be carried out, the difference between the initial attenuation and attenuation value from the delayed signal must be compared to ascertain the limits.

For signal retransmission, the time delay is Δt, while $\delta t = t + \Delta t$ refers to the total time shift per rain attenuation sample. The joint statistics of rain attenuation at both the initial and retransmitted signal are log-normally distributed [12]. The probability density of rain attenuation, $A(t)$ for a satellite to earth link is given by:

$$p\{A(t) > a\} = 1 - p\{A(t)\} \quad (1)$$

From the TD model developed in [13] for an equatorial climate, the joint distribution for $A(t)$ and $A(\delta t)$ is deduced as:

$$p[A(t) \geq a, A(\delta t) > a] = 1 - p[\min\{A(t), A(\delta t)\}] \quad (2)$$

where $A(t)$ is the rain attenuation time series at time, t; A_T is the attenuation time series with a delay of Δt ; A is the fade margin.

Similarly, we have that

$$p[A_T \geq A(t)] = 1 - p[\min\{A(t), A(\delta t)\}] \quad (3)$$

This is the percentage time exceeded for an effective or minimal attenuation, and is described by the function:

$$A_T = A_{eff} = \min\{A(t), A(\delta t)\} \quad (4)$$

Effective attenuation, A_T is the minimum of the two instantaneous attenuation values with time delay, Δt.

Mathematically, TD is expressed as;

$$G(P) = A_0(P) - A_{td}(p) \quad (5)$$

where $G(p)$ is the diversity gain, A_0 is the attenuation without time delay and A_{td} is the attenuation with time delay.

IV. PROPOSED TIME DIVERSITY MODEL

The proposed time diversity model is a modification of the Fukuchi and Nakayama model [5] which was adapted to the South-South region of Nigeria. It was derived based on the rain attenuation measurements from AKIA, MEIA, UNIUYO and PHIA. A regression analysis was carried out and a fitting was obtained on the numerical values derived from rain attenuation and time diversity measurements. Time diversity was modelled as a function of rain attenuation, cumulative time percentage and time delay of two data contents or broadcasts as examined in the succeeding subsections.

A. Model of Time Diversity Gain as a Function of Effective Rain Attenuation

In the derivation of the model of TD gain as a function of rain attenuation, data values of diversity gain were regressed with respect to the values of rain attenuation, *A*, at 0.01%-time percentage and at a frequency of 20 GHz using the linear relation of the form:

$$G_{0.01} = aA_{0.01} \quad (6)$$

The coefficients of regression for the four study sites are presented in

Table 1.

Table 1: Coefficients of Regression for Single Site Attenuation Dependence

Stations	***a***	***b***
AKIA	0.3601	-0.2201
MEIA	0.3619	-0.2122
UNIUYO	0.3619	-0.1714
PHIA	0.3633	-0.1680

a. Model of Time Diversity Gain as a Function of Time Percentage

ITU-R recommended equation was modified to obtain Equation (7) for predicting the attenuation over various percentage of cumulative time for an average year as a function of $A_{0.01}$ and cumulative percentage of concern p:

$$A_p = 0.12A_{0.01}p^{(0.546+0.0431 \log p)} \quad (7)$$

$$0.001[\%] \leq p \leq 1[\%]$$

Another equation for predicting the time diversity gain from rain attenuation and cumulative time percentage can be derived from Equation (8):

$$G(A_{0.01},p) = bA_{0.01}p^{(0.546+0.0431 \log p)} \quad (8)$$

b. Model of Time Diversity Gain as Function of Time Delay

Fukuchi and Nakayama [15] gave a linear relationship between TD gain, $G(T_d)$ and time delay, T_d modified as follows:

$$G(T_d) = c \log T_d + d \quad (9)$$

$$(1[min] \leq T_d \leq 60[min])$$

where *c* and *d* are coefficients of regression as presented in

Table 2 for the four study sites.

Table 2: Coefficients of Regression for Time Delay Dependence

Stations	*c*	*d*
AKIA	1.5994	0.2794
MEIA	1.6386	0.2862
UNIUYO	1.5628	0.2902
PHIA	1.7771	0.3032

The proposed model is expressed as follows;

$$G = G(A_{0.01},p,T_d) = G_{0.01}.G(A_{0.01},p).G(T_d) \quad (10)$$

$$G(A_{0.01},p,T_d) = \alpha A_{0.01}(\log T_d + \beta)p^{(0.546+0.0431 \log p)}$$

$$(0.001[\%] \leq p \leq 1[\%]),(1[min] \leq T_d \leq 60[min])$$

The coefficients α and β was derived by least of squared fitting method using data from the four sites with root mean squared error (RMSE) values below 0.0067. They are:

$$\alpha = 0.0221 \pm 0.001$$

$$\beta = 0.1751 \pm 0.046$$

The procedure of least squares fitting for finding the coefficients in Equation (10) is such that 0.01% of cumulative time percentage is used to find the slope at each T_d from 1 to 60 minutes for the four sites.

c. Performance Evaluation of the Proposed Model

The proposed model was compared with experimental results to determine its level of accuracy. This was done by inputting the various site parameters of each earth station into the mathematical expression of the proposed model, the results obtained were plotted alongside the experimental results for each site as presented in Fig 3.

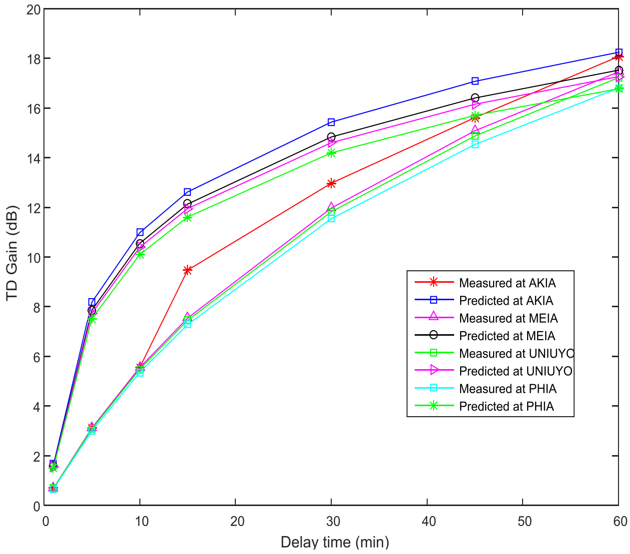

Fig 3: Evaluation of proposed model using measured data for the four sites

Further evaluation as presented in Fig 4 to Fig 7 was done by comparing the performance of the proposed model with two existing models (Fukuchi and Nakayama, and Matricciani) using measured rainfall data for the study areas.

A comparison of RMSE and percentage errors for UNIUYO sites is summarized in Table 3.

Table 3: Performance evaluation of TD gain prediction models at 0.01 % of time

TD Prediction Models	UNIUYO	
	RMSE	ε (%)
Proposed Model	0.5172	2.2837
Fukuchi and Nakayama-2004	11.6368	80.7719
Matricciani-2006	0.5467	5.9167

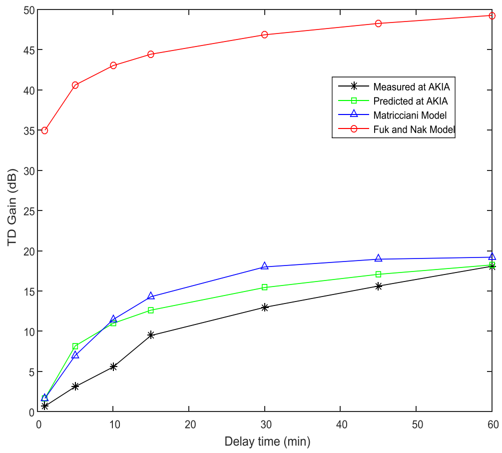

Fig 4: Performance evaluation of existing models in comparison with the predicted model and experimental results measured at AKIA

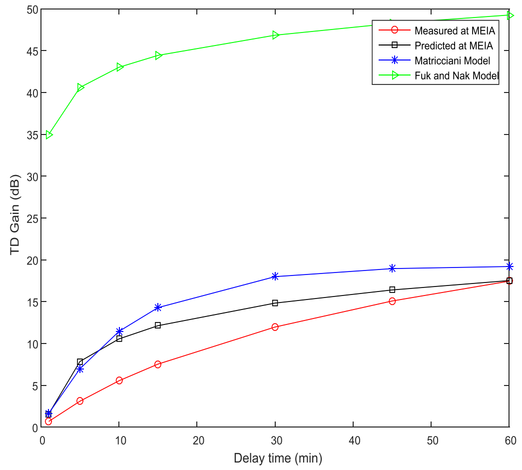

Fig 5: Performance evaluation of existing models in comparison with the predicted model and experimental results measured at MEIA

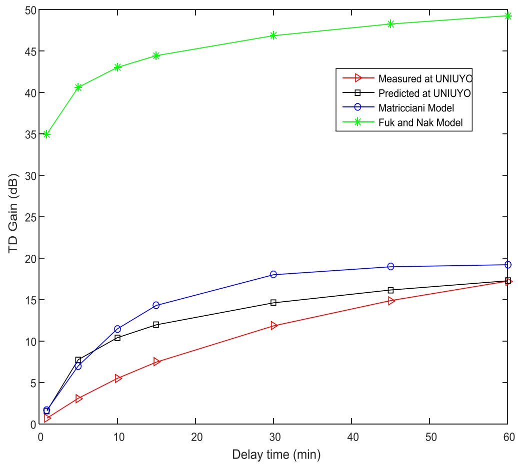

Fig 6: Performance evaluation of existing models in comparison with the predicted model and experimental results measured at UNIUYO

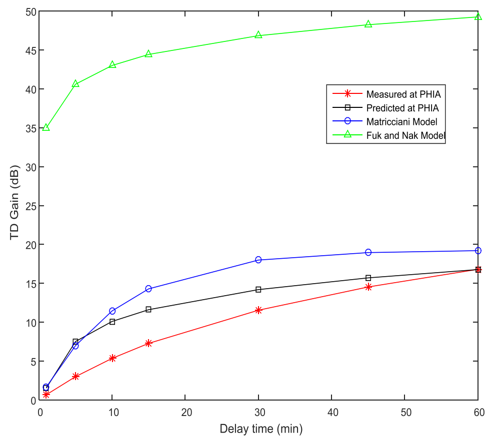

Fig 7: Performance evaluation of existing models in comparison with the predicted model and experimental results measured at PHIA

V. CONCLUSION

The paper focused on the TD technique as an effective rain FMT for South-south Nigeria based on data from four selected sites. The implementation of this diversity technique was carried out using measured rainfall data obtained from NIMET for the sites.

It was observed from Fig 2, Fig 3, Fig 4 and Fig 5 that the prediction models were in agreement at time percentages above 0.5 %. However, deviations were observed at time percentages below 0.5 % of outage time. The other TD prediction models (Fukuchi and Nakayama, and Matricciani) were observed to overestimate TD gain for the studied region at percentages of time below 0.5 %. The possible reasons for this overestimation include the followings:

i. Predictions were carried out using rainfall statistics from other regions that may possess different rainfall characteristics from this study area;
ii. Predictions were carried out at frequency ranges in the Ku-band where rain attenuation is less severe; and
iii. Predictions were done at different time delays, which included delays above 60 minutes.

It was observed from Table 3 that prediction errors were significantly reduced with the proposed TD model. This is an indication that the proposed model can better predict TD gain for this region.

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