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Research Article

EFFECTS OF RAIN ATTENUATION ON SATELLITE COMMUNICATION LINK

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ABSTRACT
Rain attenuation is a major challenge to microwave satellite communication especially at frequencies above 10 GHz, causing unavailability of signals most of the time. Rain attenuation predictions have become one of the vital considerations while setting up a satellite communication link. In this study, rain attenuation models, cumulative distribution curves and other analytical tools for successful prediction of rain attenuation are presented. A three year Rain rate data was obtained from the Nigeria Meteorological Agency (NIMET) database in addition to experimental data. Of the three prediction models used in the study, Ajayi model gave the range of values closest to the experimental data. A correctional factor was determined as 1.0988 and used to modify the Ajayi model. This modification to Ajayi's model enabled its rain attenuation values conform more closely to the experimental result.

Keywords: correctional factor, cumulative distribution curve, outage rain rate, prediction model, rain attenuation, satellite communication.

INTRODUCTION

Rainfall intensity along terrestrial path is inhomogeneous in space and time and the raindrops have a non-spherical shape and thereby cause the attenuation on the horizontally polarized wave to be greater than the attenuation of the vertically polarized waves. The attenuation, due to these rain particles, is non-uniform and can only be statistically or experimentally determined from the rain rate measurements. The consequences of this rain attenuation are as follows:

- Loss of signal strength at the receiver.
- Wastage of transmission power in a bid to overcome this form of attenuation.
- Total loss of signal at the receiver in extreme cases.
- Unavailability of the satellite link for a great percentage of the time [1, 2].

Rain attenuation, because of the statistical variation in rainfall rates, is given as a probabilistic value which is often expressed as a rainfall rate exceeded for a certain percentage of the time. Therefore, in designing a satellite communication service system in a given area, it is often required that such experiment amidst other forms of analysis, should be carried out to ensure the least effect of rain attenuation and other forms of losses to that communication set-up.

This paper is aimed at studying rain attenuation, as it affects satellite communication links; to determine its nature and its possible effects on the propagation of satellite signals.

It will enable the designer to determine some technical parameters that are pertinent in the design process. The result of this investigation will also enable the communication system designer to determine the following:

- The optimum transmitting power in which rain attenuation will have the least effect.
- Whether it is economically feasible to Set-up such a system in the area in question.
- Determine the optimum microwave transmission frequency at which there will be the least effect of rain attenuation.

The experimental measurement data used in this study was carried out in Akwakuma, Owerri in Imo State, Nigeria. Owerri city lies in the south-eastern part of Nigeria. The area is located in the latitude 5.28° (5° 19'53'') North of the equator and longitude 7.03° (7° 4'30'') East of the Greenwich Meridian.

GENERAL OVERVIEW OF RAIN ATTENUATION

Rainfall is a major cause of signal degradation for radio-communication systems operating at centimeter and millimeter wave bands, especially in the tropical region environment [5]. Determination of attenuation due to rainfall plays a significant role in the design of earth-satellite radio link at frequencies above 10 GHz [3, 4].

Rain attenuation of satellite signals do not simply affect the end users' resulting performance, it also affects the cost. Rain attenuation causes a greater power requirement from the transmitting units which hence leads to a higher cost per bit of transmission [5, 6].

In the determination of the statistical distribution of rain attenuation, many years of recording with sophisticated equipments like disdrometer, sensor rain gauges, power meters etc. are necessary to obtain the long-term rain attenuation statistics [5, 7]. Rain intensity measurements have been performed for many years in many countries hence their data is readily available for many places.

Consequently, in designing a satellite communication service system in a given area, it is often required that such an experiment, amidst other forms of analysis, should be carried out to ensure the least effect of rain attenuation and other forms of losses to the communication structure. However, from the economical point of view, it is not feasible to conduct measurement in one place every time a satellite receiver for communication services will be installed. It is usually very expensive and time consuming to conduct such an experiment and research. A minimum of one year data is needed to reveal the true effect of rain attenuation on satellite signals. Therefore, it is not only unfeasible but also impractical to carry out a one-year measurement and experiment, in advance, whenever a satellite telecommunication service is to be designed. With regards to this, many methods have been developed and employed to convert the available measured data in one geographical location to conform with the climatic and rainfall characteristics of the present location but this is not as accurate as using a locally measured data [8, 9, 10].

METHODOLOGY

An evaluation of the impact of rainfall on the propagation of earth-satellite signals operating in the Ku microwave frequency band is carried out. Considering the horizontal and vertical non-uniformity of rain structure, we therefore need a long period of measurement data to describe the seasonal variation of rainfall intensity. For a successful prediction of rain attenuation, the cumulative distribution of rainfall intensity obtained from long term measurements (at least 3-years data) is required. This research study is designed in such a way that raw data is retrieved from the Nigerian Meteorological Agency (NIMET). The data to be collected is rainfall rate data (mm/h) for a 3-year period (2010–2012). This data includes average monthly rainfall rate for the 3-year period, hourly rainfall rate for some selected months (highest rainfall intensity month, two average months and the least month) within the 3-year period. The data will then be processed using statistical means to find the probability of exceedance of each of the rainfall rate value in the data. A graph of rainfall rate against exceedance probability will be plotted. The value with the least probability of exceedance is determined and this value will be inputted into the available rain attenuation models to determine its corresponding rain attenuation value. The experiment will be carried out which will be used to determine a direct relationship between different values of rainfall rate and their corresponding values of rain attenuation. The results of the experiment will be used to compare with the result obtained using rain attenuation models. Then after proper analysis, a correction factor would be suggested to the model and hence a new model would emerge. The modified rain attenuation model would now be used as our working model. A 'Rain attenuation' – 'Rain rate' graph would be plotted using data obtained from the model, the experiment and the working model [11, 12, 13, 14].

The rainfall rate data retrieved from NIMET'S database shows hourly rainfall rate data. The rainfall rate data is measured in millimetre per hour (mm/h). The data covers a period of three years from 2010–2012. The long period data was to ensure an accurate prediction of rain attenuation. This is to make sure that the highest and the lowest possible rain rate expected in that region is not over-estimated or under-estimated. The 3-years data reveals the average rainfall rate for each month. The second data collected from NIMET reveals the hourly values of rainfall rate within some selected months. The second data would be used for comparison purposes. The exceedance probability of each value in the data is computed and is used to plot the cumulative distribution curve or Exceedance curve. The highest value of rain rate recorded in the experimental data and its corresponding value of rain attenuation is noted. This rainfall rate value is inputted in the three available rain attenuation models and the model that gives the closest value to the measured value will be selected as our active model. The different values of rainfall rate recorded during the experiment are loaded into the model and their corresponding model values of rain attenuation are also noted [15, 16]. A table is thus computed, showing the different rainfall intensity value, their experimental value for rain attenuation and their corresponding model value for rain attenuation. The two set of values are compared and used to suggest a correctional factor to the model. This correctional factor is used to modify our active model to yield a new model.

The working model

The working model is now used to generate the corresponding values of rain attenuation, by inputting the different values of rain rate into the working model. The different values of rain attenuation obtained are noted and then a graph of rainfall rate against rain attenuation is plotted for the different data sets. Finally, the cumulative distribution curve/exceedance curve for the rain attenuation values is plotted for the data.

RAIN ATTENUATION MODELS

The ITU-R model

The ITU-R method in the report 564-4 uses the concept of effective path length by means of a reduction factor. The method consists of the following procedure, which is proposed to calculate the long-term statistics of the slant path rain attenuation at a given location for frequency up to 30GHz (and provisionally for higher frequencies). This method involves several steps, which are presented below.

Step 1: The effective rain height h_e (km) is calculated from the latitude of the earth station, ϕ, as given by the following formulas.

$$h_R = 5.0 \text{ for } 0^o \leq \phi < 23^o \quad (1a)$$

$$h_R = 5.0 - 0.075(\phi - 23) \text{ for } \phi \leq 23^o \quad (1b)$$

Step 2: The slant path length L_s, below the freezing rain height is obtained, for antenna elevation angle $\theta > 5^o$, the slant path length, L_s (km) below the freezing rain height, h_R is given as,

$$Ls = \frac{(h_R - h_s)}{\sin\theta} \text{ for } \theta > 5 \quad (2)$$

where: h_s – the height of the earth station above the mean sea level, km.

For antenna elevation angle $\theta \leq 5^o$, a more accurate formula should be used which is given as:

$$Ls = \frac{2(h_R - h_s)}{(\sin^2\theta + \frac{2(h_R - h_s)}{R_e})^{1/2} + \sin\theta} \text{ for } \theta \leq 5^o. \quad (3)$$

where: R_e – effective radius of the earth = 8500 km.

Step 3: The horizontal projection of the slant path length L_G (km) is found.

Step 4: Obtain the characteristic length of rain cell given by

$$L_o = 35e^{(-0.015R)} \quad (4)$$

where: R – rainfall rate value.

Step 5: Obtain the reduction factor, r given by,

$$r = \frac{1}{1 + \frac{L_G}{L_D}} \quad (5)$$

Step 6: Obtain the specific attenuation Y(dB/km) using the rain rate measurement data. This is contained in more details in Rec. ITU-R P.838-3.

Step 7: Finally, the rain attenuation is calculated using the expression below,

$$A = \gamma L_s r \quad (6)$$

Ajayi method

This method was proposed by Ajayi as described in [17, 18, 19]. The path reduction factor in the ITU-R prediction method converts a physical path length to an equivalent length along which the rain rate can be assumed constant. Since it turned out that the conversion process does not necessarily always lead to a reduction in path length, Ajayi modified the ITU-R method by introducing two reduction factors, the horizontal reduction factor and the vertical reduction factor.

The Ajayi method is broken down into steps for simplification.

Step 1: The height of the freezing level during rain,

$$hf_R = 5.0 \text{ for } 0^o \leq \theta < 23^o \quad (7a)$$

$$hf_R = 5.0 - 0.075(\theta - 23) \text{ for } \theta \geq 23^o \quad (7b)$$

The two reduction factors used here are the horizontal reduction factors, r_h and vertical reduction factor, r_v.

Step 2, 3, 4 and 5 remain unchanged, i.e. still the same procedure as that of the ITU-R method.

Step 6: The horizontal reduction factor, r_h can be calculated using,

$$r_h = \frac{1}{1+L_G{}^{0.002}(R)^{1.01}} \quad (8)$$

Step 7: The vertical reduction factor r_v can be similarly calculated using,

$$r_v = \frac{1}{1+\frac{h_{FR}}{5+0.4\emptyset^{1.5}}} \quad (9)$$

Step 8: The effective path length, L_e through the rain can be evaluated from the triangle above by applying sine rule.

$$L_e = \frac{r_h \, x \, L_G}{Cos\ \varepsilon} \quad (10)$$

where: $\varepsilon = \tan^{-1}\left(\frac{h_{FR} r_v}{L_G r_h}\right)$ (11)

Step 9: The value of specific attenuation (dB/km) is evaluated

$$\gamma = KR^a$$

Step 10: The value of rain attenuation is calculated, using the equation below.

$$A = \gamma L_e r \quad (12)$$

Dissanayake-Allnutt model

This method was developed by Dissanayake and Allnutt in their work [19]. The conversion of the physical path length to the effective path length as implemented in the ITU-R method does not always lead to an accurate reduction in path length. Therefore in the Dissanayake Allnutt method, the conversion factor is called the Adjustment Factor instead of reduction factor.

Dissanayake and Allnutt included two adjustment factors, in their proposed method, namely horizontal path adjustment factor and vertical adjustment factor. The horizontal path adjustment factor takes into account the inhomogeneity of rain along the propagation path horizontally, while the vertical adjustment factor take into consideration the vertical inhomogeneity of the rain. The two adjustment factors were devised by using available slant path attenuation measurement data. The derivation of these adjustment factor is beyond the scope of this paper, thus only the end results of the derivation will be included.

Step 1: The freezing height h_{fR} during rainy condition is given by,

$$h_{fR} = 5.0 \text{ for } 0 \leq \phi < 23^o \quad (13a)$$

$$h_{fR} = 5.0 - 0.075(\phi - 23) \text{ for } \phi \geq 23^o \quad (13b)$$

Step 2: The slant path length for elevator angle greater than 5^o is

$$Sin\emptyset = \frac{h_{FR} - h_s}{L_s} \quad (14)$$

$$L_s = \frac{(h_{FR} - h_s)}{\sin\emptyset} \quad (15)$$

Step 3: Find the specific attenuation γ, using the ITU-R method,

$$\gamma = KR^a$$

Step 4: The horizontal path adjustment factor, r_h is calculated,

$$r_h = \frac{1}{0.628 + 0.194\sqrt{\gamma L_s}} \quad (16)$$

Step 5: Similarly, the vertical adjustment factor r_v is calculated,

$$r_v = \frac{1}{1+\sin\theta\ (1.282\sqrt{L_s} - 2.871} \text{ for } \theta > 23^0 \quad (17)$$

$$r_v = 1\text{-}0.5 \sin\theta \text{ for } \theta = 0^o \quad (18)$$

For latitudes between 0^o and 23^o, a linear interpolation between equation (13a) and (13b) is suggested.

Step 6: Calculate the horizontal projection L_G of the slant path as in the ITU-R method.

$$L_G = L_s \cos\theta$$

Step 7: Calculate the effective horizontal projection of the effective slant path length.

$$L_{Ge} = r_h L_G \quad (19)$$

Step 8: Calculate the effective slant path length, L_e

$$\sin\varsigma = \frac{h_{FR}}{Le} \quad (20)$$

$$\text{or } L_e = \frac{L_{Ge}}{\cos\varsigma} \quad (21)$$

where: $\varsigma = \tan^{-1}\left(\frac{h_{FR}}{L_{Ge}}\right)$ (22)

Step 9: Calculate the rain attenuation

$$A = \gamma\ L_e\ r_v \quad (23)$$

EXPERIMENT

The result of the experiment and data collected from the experiment will serve as sources of primary data which will enable us to adjust the existing rain attenuation models to suit the present environment. The aim of this experiment is to physically measure the magnitudes of raininduced attenuation and also measure the magnitude of point rainfall rate at that instant and possibly establish some form of relationship between the two parameters by adjusting the existing rain attenuation models. The experiment will also enable us to determine the outage rain attenuation and the outage rainfall rate.

The experiment is designed in such a way as to measure the average signal strength under normal propagation condition and note the signal strength. Then the signal strength is also measured during rainy conditions while taking note of the rain rate value of that rainfall. Then rain attenuation is computed as,

$$\text{Rain Attenuation} = \begin{pmatrix}\text{signal strength under}\\ \text{normal propagation}\\ \text{condition}\end{pmatrix} - \begin{pmatrix}\text{signal strength}\\ \text{under}\\ \text{rainy condition}\end{pmatrix}$$

This procedure was repeated for different rain events while taking note of their different measured rain rate value. The different rain rate values and their corresponding rain attenuation value were tabulated. The receiving antenna used is parabolic reflector antenna and the instrument used for measuring the signal strength is Digital Radio Frequency Power Meter. Rainfall rate was measured using a rain gauge and the timing was achieved using a digital stopwatch incorporated in a mobile phone. The tabulated values of rain rate and their corresponding rain attenuation value will thus be used for further analysis.

Instrumentation

Instruments used to carry out this experiment include the following:

- Parabolic reflector antenna having a specific known gain.
- Compass.
- Radio frequency power meter.
- Coaxial cable port connector.
- Connecting cable (coaxial cable).
- Rain gauge.
- Stopwatch timer.

Parameters pertinent to this experiment also include (Table 1).

Table 1. Table of value for experimental parameters

S/N	Parameter	Value
1	The satellite in space	Astra 2B (Multi TV Satellite) at 28.2° East
2	Frequency of the down link signal	12.527 GHz
3	Polarigation of the signal	Horizontal
4	Antenna elevation angle	42°
5	Latitude of site	5.28° North
6	Longitude of site	7.03° East
7	Height of antenna	2.9 m
8	Altitude of site	91.44 m
9	Antenna gain	35 dB
10	Antenna diameter	0.6 m

RESULTS AND DISCUSSION

Experimental Results

The result of the experiment conducted is presented in the Table 2. The rain attenuation values are measured and recorded in db and the rainfall rate is measured in mm/h. The signal power, Q measured under normal condition (absence of rainfall) was recorded as 52.5 dB.

Table 2. Experimental result for rain rate and rain attenuation

S/N	Rain rate	Rain attenuation value (Q–P)	Measured signal power during rainfall (P)
1	154	15.62	36.88
2	150	15.68	36.82
3	142	15.60	36.90
4	136	15.64	36.86
5	128	15.42	37.08
6	120	15.12	37.38
7	112	14.54	37.96
8	104	14.07	38.43
9	92	13.10	39.40
10	86	12.39	40.11
11	72	10.73	41.77
12	64	9.62	42.88

Observation

Rain attenuation increases as rainfall rate value increases. At a rain rate value of 112 mm/h and above, there is total outage of reception (i.e. there is useful output at the destination of the receiver's output). The rain attenuation corresponding to this rain rate value as seen from the above table is 14.54 dB. This rain rate value and rain attenuation will be called Outage rain rate value and Outage rain attenuation value.

Cumulative distribution curve (Exceedance Curve) of rain attenuation was plotted for the four different months studied earlier to determine the probability of exceedance value and to estimate the chances/probability that there will be an outage that month. Since rainfall rate varies in a highly unpredictable manner, very long period of data is usually required for this estimation to be able to account for long-term variability in the rain rate within the years and thereby making the prediction process more accurate. However, for the purpose of this research, the moderate period of data used will suffice.

The highest rain rate value measured is tested to be 154 mm/h on the different models to see which model gives the closest value of rain attenuation to the measured value attenuation.

Evaluation of rain attenuation values using the available rain attenuation models

ITU-R model

Using ITU-R model, g = 9.884 dB/Km

$A = gL_s r = 9.884 \times 6.1015 \times 0.4338 = 26.16$

Rain attenuation = 26.16 dB

Ajayi method

g = 9.884 dB/Km

$A = gL_e r = 9.884 \times 3.3115 \times 0.4338$

A = 14.2 dB

Rain attenuation = 14.2 dB

Alnutt – Dissanayake model

$A = gL_e = 9.884 \times 5.4323 \times 0.70485 = 37.84$ dB

A = 37.84 dB

Comparison of rain attenuation values obtained from the different models

From the MATLAB program written, the rain attenuation corresponding to different rain rate values has been computed for different rain attenuation models, what is shown in Table 3. A comparison is made between different models and rain attenuation values obtained from the experimentation (Table 4).

Since Ajayi model has its rain attention values closest to the experimental results, the Ajayi model will be chosen as our working model.

The values marked by asterisk are correctional factors whose values are similar, i.e. whose values are more consistent than the others. These values would be averaged to find the mean correctional factor which would be used to modify the Ajayi model.

Mean value of f =

$$\frac{1.0983 + 1.9954 + 1.0998 + 1.1012 + 1.0978 + 1.0982 + 1.0997 + .0961}{8}$$

Table 3. Rain attenuation comparison table for different rain attenuation models

S/N	Rainrate	ITU-R	Ajayi	Disanayake	Measured
1	154	26.1637	14.2222	37.8431	15.62
2	150	26.2361	14.2615	36.6966	15.68
3	142	26.2442	14.2659	34.4192	15.60
4	136	26.1253	14.2013	32.7252	15.54
5	128	25.7936	14.0210	30.4862	15.42
6	120	25.2591	13.7305	28.2708	15.12
7	112	24.5202	13.3288	26.0802	14.54
8	104	23.5787	12.8170	23.9159	14.07
9	92	21.8000	11.8501	20.7226	13.10
10	86	20.7545	11.2818	19.1516	12.39
11	72	17.9499	9.7573	15.5596	10.73
12	64	16.1452	8.7763	13.5581	9.62

Table 4. Comparison of Ajayi, model with experimental result

S/N	RAIN RATE	AJAYI model	Measured	Suggested correctional factor (f)
1	154	14.2222	15.62	1.0983*
2	150	14.2615	15.68	1.0995*
3	142	14.2659	15.60	1.0935
4	136	14.2013	15.54	1.0942
5	128	14.0210	15.42	1.0998*
6	120	13.7305	15.12	1.1012*
7	112	13.3288	14.54	1.0978
8	104	12.8170	14.07	1.0909*
9	92	11.8501	13.10	1.1055
10	86	11.2818	12.39	1.0982*
11	72	9.7573	10.73	1.0997*
12	64	8.7763	9.62	1.0961*

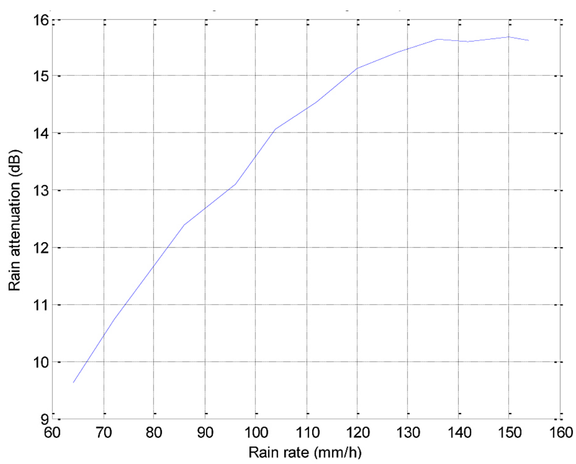

Fig. 1. Graph of rain attenuation against rain rate using the experimental measured values

$$\frac{8.7906}{8} = 1.0988$$

The correction factor to be used = 1.0988

For Ajayi; $A = \frac{3.1907R^{1.169}e^{-0.015R}}{35e^{-0.015R}+4.5343}$

$$\text{Modified Ajayi model} = \frac{1.0988 x 3.1907 x R R^{1.169} e^{-0.015R}}{35e^{-0.015R}+4.5343}$$

$$\text{Modified Ajayi model} = \frac{3.495R^{1.169}e^{-0.015R}}{35e^{-0.015R}+4.5343}$$

Table 5. Rain attenuation values using modified Ajayi model

Rain rate	Measured	AJAYI model	Modified AJAYI model
154	15.62	14.2222	15.6275
150	15.68	14.2615	15.6708
142	15.60	14.2659	15.6756
136	15.64	14.2013	15.6046
128	15.42	14.0210	15.4065
120	15.12	13.7305	15.0873
112	1.54	13.3288	14.6459
104	14.07	12.8170	14.0836
96	13.10	11.8501	13.4036
86	12.39	11.2818	12.3966
72	10.73	9.7573	10.7215
64	9.62	8.7763	9.6435

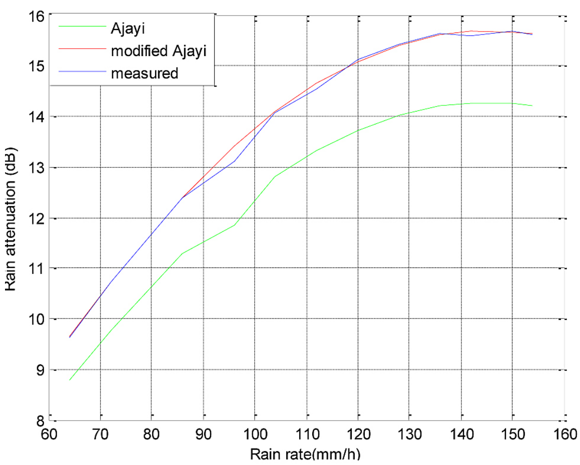

Fig. 2. Graph of rain attenuation against rain rate using, Ajayi, modified Ajayi and measured

Plotting of cumulative distribution curve (exceedance curve) of rain attenuation for different months using the modified Ajayi model

The MATLAB program for computing rain attenuation values is used to compute rain attenuation corresponding to different hourly rainfall

Table 6. Rain attenuation values of hourly rainfall rates in the month of August 2010

Rank	Rain rate	Frequency	Exceedance probability	Rain attenuation
1	154	2	0.0027	15.6275
2	152	4	0.0081	15.6525
3	150	1	0.0094	15.6708
4	149	7	0.019	15.6774
5	147	6	0.027	15.6856
6	146	7	0.036	15.6871
7	145	9	0.048	15.6869
8	143	5	0.055	15.6812
9	140	2	0.058	15.6592
10	138	9	0.070	15.6356
11	137	4	0.075	15.6210
12	135	6	0.083	15.5864
13	134	8	0.094	15.5663
14	133	7	0.103	15.5444
15	131	8	0.114	15.4949
16	130	10	0.128	15.4673
17	129	12	0.144	15.4378
18	128	7	0.153	15.4065
19	125	13	0.170	15.3011
20	124	6	0.179	15.2621
21	122	8	0.189	15.1785
22	121	2	0.192	15.1785
23	118	6	0.200	14.9884
24	117	3	0.204	14.9360
25	115	5	0.211	14.8257
26	114	7	0.220	14.7677
27	110	5	0.227	14.5166
28	109	4	0.232	14.4491
29	108	6	0.240	14.3797
30	106	3	0.244	14.2353
31	105	1	0.246	14.1604
32	104	4	0.251	14.0836
33	101	2	0.254	13.8421
34	98	3	0.258	13.5843
35	96	7	0.267	15.4036
36	93	2	0.270	13.1193
37	88	4	0.275	12.6114
38	84	1	0.277	12.1754
39	80	5	0.283	11.7143
40	75	5	0.290	11.1044
41	68	4	0.295	10.1924
42	65	3	0.300	9.7825
43	58	3	0.303	8.7884
44	55	2	0.306	8.3442
45	51	1	0.307	7.7421

rates of each month. The exceedance probability corresponding to the rain attenuation is also evaluated. A graph of rain attenuation against exceedance probability gives a cumulative distribution curve of rain attenuation. The shape of these curves will be used to estimate the likeliness or the probability or the chances that there will be an outage in a particular month.

In Figure 3, the rain attenuation value is the outage rain attenuation value which is 14.64 dB. This value was judged using two criteria; the exceedance probability of this rain attenuation value relative to other exceedance probabilities. The region of the graph in which this rain attenuation value occurs i.e. whether it occurs in region of high probability of occurrence or it occurs in region of low probability of occurrence. The region of high probability of occurrence is the region (point on the curve) having small gradient value relative to other regions, while the region of low probability of occurrence are the regions having high gradient value (more steep) relative to other regions. Then a decision is made using the points below:

- If the rain attenuation value has high probability of exceedance as well as lies in the regions of high probability of occurrence, this signifies a very high probability of outage that month.
- If the rain attenuation value has a high probability of exceedance but lies in the region of low probability of occurrence, this signifies a high probability of outage that month
- If the rain attenuation value has a low probability of exceedance but lies in the region of high probability of occurrence, this signifies a low probability of outage that month
- If the rain attenuation value has a low probability of exceedance and also lies in the region of low probability of occurrence, this signifies a very low probability of outage that month.

In Figure 3, it is observed that the rain attenuation value of interest, 14.64 dB has a high probability of exceedance lies in the region of high probability of occurrence hence there is a very high probability of outage in the month of August, 2010.

From Figure 4, the Outage rain attenuation value 14.64 dB has a high probability of exceedance relative to other excedance probability but however lay in the region of low probability of occurrence, hence there is high possibility/probability of outage that month.

Looking at figure 5, it is seen that the outage rain attenuation value, 14.64 dB has a low probability of exceedance relative to the exceedance probabilities but lay in the region of high probability of occurrence, hence there is a low probability of outage this month.

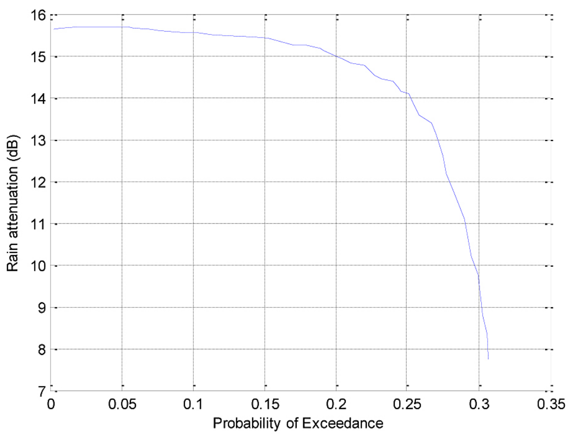

Fig. 3. Cumulative distribution curve (exceedance curve) of rain attenuation for the month of August, 2010

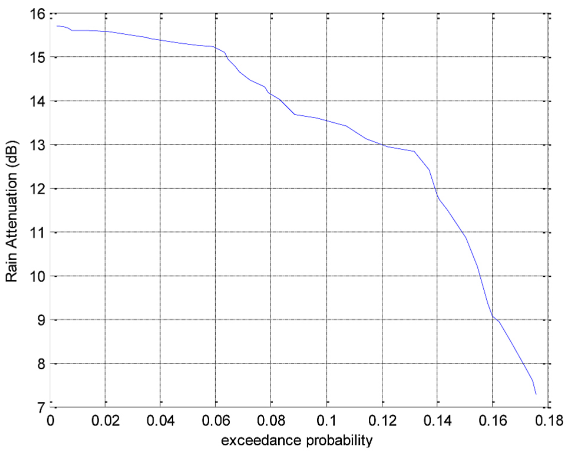

Fig. 4. Cumulative distribution curve of rain attenuation for the month of May 2012

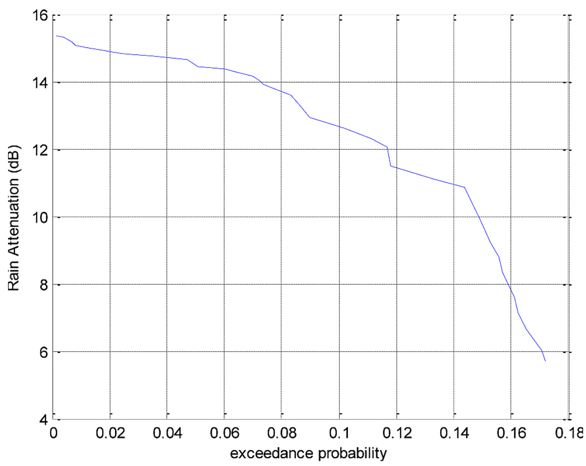

Fig. 5. Cumulative Distribution Curve of rain attenuation for the month of October 2010

Table 7. Rain attenuation values of hourly rainfall rates in the month of May, 2012

Rank	Rain rate	Frequency	Exceedance probability	Rain attenuation
1	144	2	0.0027	15.6849
2	142	2	0.0054	15.6756
3	138	1	0.0067	15.6356
4	136	1	0.0081	15.6046
5	135	4	0.0134	15.5864
6	134	6	0.0215	15.5663
7	132	4	0.0268	15.5206
8	130	4	0.0322	15.4673
9	129	2	0.0349	15.4378
10	128	1	0.0362	15.4065
11	125	8	0.0470	15.3011
12	124	5	0.0537	15.2621
13	123	4	0.0591	15.2213
14	120	3	0.0631	15.0873
15	117	1	0.0644	14.9360
16	114	2	0.0671	14.7677
17	112	1	0.0685	14.6459
18	109	3	0.0725	14.4491
19	107	4	0.0779	14.3084
20	105	1	0.0792	14.1604
21	103	3	0.0832	14.0049
22	99	4	0.0886	13.6721
23	98	6	0.0966	13.5843
24	96	8	0.1074	13.4036
25	93	5	0.1141	13.1193
26	91	6	0.1221	12.9212
27	90	7	0.1315	12.8196
28	86	4	0.1369	12.3966
29	81	2	0.1400	11.8319
30	80	1	0.1409	11.7143
31	78	2	0.1436	11.4747
32	75	3	0.1477	11.1044
33	73	2	0.1503	10.8505
34	68	3	0.1544	10.1924
35	62	3	0.1584	9.3621
36	60	1	0.1597	9.0763
37	59	2	0.1624	8.93319
38	56	3	0.1664	8.4925
39	52	4	0.1718	7.8939
40	50	2	0.1745	7.5896
41	48	1	0.1758	7.2822

Table 8. Rain attenuation values of hourly rain fall rates in the month of October 2010

Rank	Rain rate	Frequency	Exceedance probability	Rain attenuation
1	126	1	0.0013	15.3381
2	125	2	0.0040	15.3011
3	122	2	0.0067	15.1785
4	120	1	0.0081	15.0873
5	118	3	0.0121	14.9884
6	117	4	0.0174	14.9360
7	115	5	0.0242	14.8257
8	114	7	0.0349	14.7677
9	112	8	0.0470	14.7677
10	109	7	0.0564	14.4491
11	108	3	0.0604	14.3797
12	107	2	0.0631	14.3084
13	105	5	0.0700	14.1604
14	103	2	0.0725	14.0049
15	102	1	0.0738	13.9244
16	100	3	0.0779	13.7580
17	98	4	0.0832	13.5840
18	95	2	0.0859	13.3106
19	91	3	0.0899	12.9212
20	88	9	0.1020	12.6114
21	85	7	0.1114	12.2868
22	83	4	0.1168	12.0225
23	78	1	0.1181	11.4747
24	76	7	0.1275	11.2292
25	75	4	0.1329	11.1044
26	73	8	0.1436	10.8505
27	66	4	0.1490	9.9203
28	61	3	0.1530	9.2197
29	58	2	0.1557	8.7864
30	55	1	0.1570	8.3442
31	50	3	0.1611	7.5896
32	47	1	0.1624	7.1275
33	44	2	0.1651	6.6594
34	40	4	0.1705	6.0277
35	38	1	0.1718	5.7091

In Figure 6, it is clearly seen that the rain attenuation value, 14.64 dB has a low probability of exceedance relative to other exceedance probabilities and lies in the region of high probability of occurrence, hence there is a very low probability of outage this month.

Table 9. Rain attenuation values of Hourly rainfall rates in the month of November, 2011

Rank	Rain rate	Frequency	Exceedance probability	Rain Alttenuation
1	132	1	0.0013	15.5206
2	127	1	0.0027	15.3733
3	122	1	0.0040	15.1785
4	117	1	0.0054	14.9360
5	114	1	0.0067	14.7677
6	109	1	0.0081	14.4491
7	105	2	0.0107	14.1604
8	104	1	0.0121	14.0836
9	102	2	0.0148	13.9244
10	101	1	0.0161	13.8421
11	97	1	0.0174	13.4948
12	91	1	0.0188	12.9212
13	83	1	0.0201	12.0625
14	81	3	0.0242	11.8319
15	79	1	0.0255	11.5952
16	77	1	0.0268	11.3527
17	74	1	0.0282	10.9781
18	60	1	0.0295	9.0763
19	53	1	0.0309	8.0449
20	46	1	0.0322	6.9721
21	45	1	0.0336	6.8161
22	41	3	0.0376	6.1863

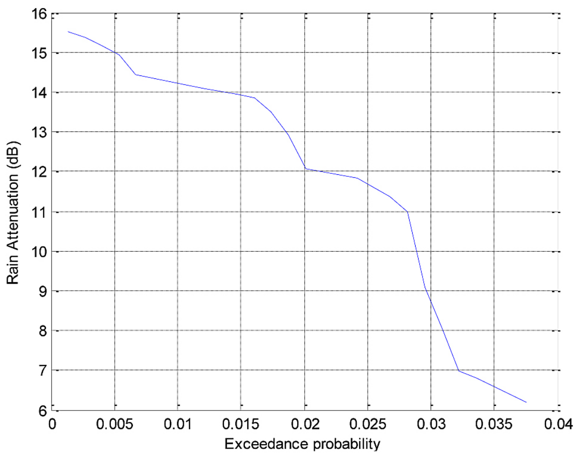

Fig. 6. Cumulative Distribution Curve of rain attenuation for the month of November 2011

Estimation of availability of the satellite link for the different months

The estimation of availability of the satellite link using the available data it is not very accurate because of lack of data showing the period for each rain rate value. Therefore, because of this constraint, the estimation of this availability is not very accurate but only serves to give us a value close to the actual value.

$$Availability = \frac{Total\ period\ of\ availability}{\text{Total period of time}} * 100\%$$

Table 10 shows four different months studied and their estimated availability measured in percentage of the total period of time.

CONCLUSION

Rain attenuation is caused as a result of absorption of part or all of the signal's radiation power by the raindrop. This absorption is as a result of scattering effect (diffraction and refraction) of the rain drop to the signal. Rain attenuation is prevalent at frequencies above 10 GHz and increases with frequency. This is because as frequency increases, the signal wavelength decreases and approaches the size of a rain drop and hence giving the rain drop more scattering and absorption capabilities to the signal. At a particular frequency, rain attenuation increases exponentially with increasing rain rate values because, the higher the rainfall rate, the higher the rain drop size (rain drop diameter). Hence, it is more its scattering effect on the signal, because as the rain drop size increases, it tends to approach the wavelength of the signal.

The month of August, 2010 is characterized by very high intensity rainfall rates with a very high probability of outage. This means that outage is very likely to occur this month and hence has a very low availability of 78%. The month of May, 2012 characterized by moderately high intensity rainfall rates, has a high probability of outage and a low availability of 93%. For October 2010,

Table 10. Table of availability for the different months studied

S/n	Month, Year	Outage rain Events (hr)	Non outage rainevents (hr)	Non-rain Events (hr)	Total period of availability (hr)	Total period of time (hr)	Availability
1	August, 2010	164	65	515	580	744	77.965%
2	May, 2012	51	80	613	693	744	93.15%
3	October, 2010	33	93	618	711	744	95.56%
4	November, 2011	5	23	692	715	720	99.31%

it is characterized by low intensity rainfall rates, has low probability of outage and hence has a high availability of 96%. The month of November, 2011 characterized by very low intensity rainfall rates has very low probability of outage, hence the outage is not very likely to occur in this month and so consequently has a very high availability of 99%. Therefore, the higher the probability of outage in a month, the lower is its expected availability.

The outage rain rate was found to be 112 mm/h and also the corresponding outage rain attenuation was also found to be 14.54 dB. Since the outage rain attenuation value is 14.54 dB and the highest possible rain attenuation (i.e. highest recorded rain attenuation) is 15.0756 (as predicted by the model) therefore, in link budget analysis, an extra power of (15.6756 – 14.54 = 1.1356) dB is needed for the downlink signal so as to compensate for rain attenuation losses. By doing this, the probability of outage of each of the month will enormously decrease and their corresponding availabilities will also increase. By doing this we can achieve a satellite link having the availability of 99.9% in an average year.

High gain antennas (having high efficiency and high directivity) should be used in area characterized by high intensity rainfall and having heavy rain attenuation. Parabolic reflector antennas having gain of 35–40 dB is recommended for use so as to compensate for the negative effects of rain attenuation in satellite communication links. More so, antenna having large effective area should be used.

Though reasonable amount of work was done on this topic, there is still a lot of room for improvement. There is a need for long period of data showing the period of each rain rate value so as to enable us to accurately estimate the availability of the satellite communication link.

There is serious need for a model or equation which will enable us calculate the specific numerical value of outage probability of a given rain attenuation value by simply inputting it’s exceedance probability and the gradient of the point or region of the curve where that value occurs instead of using relative and comparative values.

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