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Estimation of the Long-Term Propagation Losses Due To Rain On Microwave Satellite Links Over Jos, Nigeria

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Abstract
This paper presents the estimation of long term propagation losses due to rain on microwave satellite links over Jos. Data were retrieved from the National Space Research and Development Agency (NASRDA) Abuja, Nigeria. The data collected was rainfall rate (mm/h) for theperiod of three year (2015–2017) over Jos. Results were obtained based on the exceedance distribution frequency of percentage time (%) and cumulative distribution of one- minute rain rate which revealed that higher rainfall rate (above 100 mm/hr) account for about 0.01 and 0.001% time ofexceedance and it is during such times that maximum propagation losses due to rainfall is significant and can be best estimated.

1. Introduction

Satellite communication is the method of sending information from one locationto another using a transponder. Satellite communication finds its applications in Radio broadcasting, TV broadcasting, voice communications, and Internet applications such as providing Internet connection for data transfer, Global Positioning System (GPS) applications, and Internet surfing. As shown in Figure 1, communication via satellite is applied in three main areas: fixed satellite, mobile satellite and broadcast satellite services (Giuliano, *et al*., 2008).

Fixed Satellite Services (FSS) uses ground equipment at set locations to transmit and receive satellite signals**.** FSS satellites support the majority of our domestic and international services, from international Internet connectivity to private business networks.Mobile satellite services (MSS) uses a variety of transportable receiver and transmitter equipment to provide communication services for land mobile, maritime and aeronautical customers.Broadcast satellite services (BSS) offers high transmission power for reception using very small ground equipment. BSS is best known for direct-to-consumer television and broadband applications such as DIRECTV. In addition, satellite communication offer great advantages in delivering multicast and broadcast traffic because of its intrinsic broadcast nature. The utilization of satellite to complement terrestrial mobile communications has enhanced its performance so that its acceptance in the mass market is gaining increasing support, as it may well be the cheapest and most efficient (Akhondi and Ghorbani, 2005).

Figure 1: Satellite communication.

Source:(Odedina, 2010).

Satellite communication is normally thought of as a robust means of communication, not sensitive to environmental impacts. This perception is not totally accurate. Satellite communication is affected by the environment in which it operates. Environmental effects on satellite communication can be divided into:

i. Effects on the space element (i.e. the satellite)

ii. Effects on the ground element (i.e. the Earth station)

iii. Effects on the signals propagating through the Earth's lower and upper atmosphere (Ogherohwo*et al*., 2017).

Electromagnetic wave propagation includes everything that can happen to an energy radiated from a transmitting antenna to a receiving antenna. It includes the radiating properties of both antennas such as gain, power, directivity and polarization. It also includes free space attenuation of radio wave with distance in addition to factors such as refraction, reflection, noise interference, diffraction, atmospheric absorption and scattering. Propagation is therefore dependent upon the properties of all transmission and boundary media (Ogherohwo*et al*., 2017).

The troposphere is the most important region of the atmosphere for VHF and UHF radio waves propagation. It is the lower layer of the atmosphere surrounding the earth that extends to a height of approximately 10 km above the sea level. All weather on earth occurs in the troposphere during normal conditions. The temperature decreases as height increases, and generally drops with increased altitude at about 10^{o}C per km until the tropopause is reached. VHF/UHF and microwave signals can travel distances beyond the horizon under certain atmospheric conditions. Depending on the state of condition in the atmosphere, radio propagation between the transmitter and the receiver may occur by the mechanisms of scattering, reflection, refraction, diffraction, absorption, polarization and tropospheric ducting (Dissanayake, 2002: Odedina, 2010).

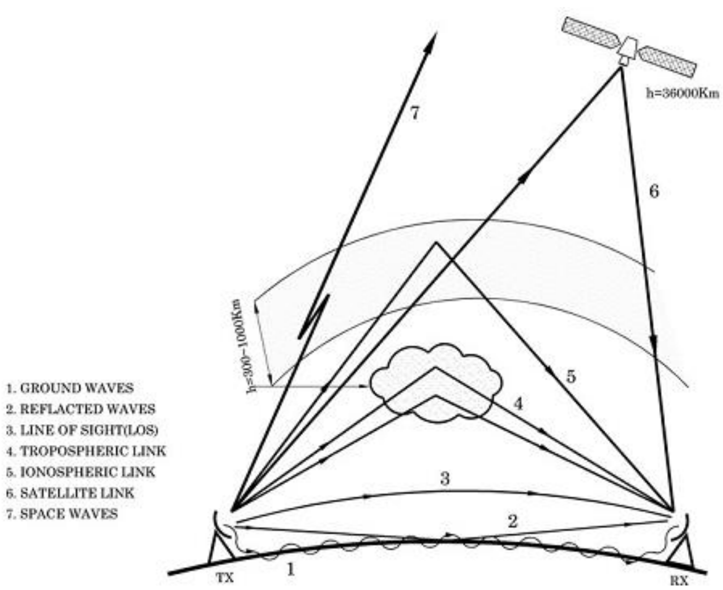

Figure 2: Mode of signal propagation

Source:((Abdullah *et al*., 2012).

Different types of radio links may be propagating between the transmitter and the receiver radio units as shown in Fig. 2. The main types of radio links are:

1. Ground waves commonly used for AM broadcasting, radio-navigational aids and short-wave radio systems.
2. Reflective waves producing multipath links along with the main route which are common in UHF and microwave radio links including FM broadcasting in TV networks as well.
3. Line of sight (LOS) links used in terrestrial microwave, UHF, and radar networks.
4. Tropospheric links for point-to-point telecommunications by refracting/reflecting waves through the troposphere layer and using over-horizon tropo-scatters.
5. Ionospheric links employed for long-distance telecommunications using reflection from ionosphere D, E, and F layers in medium frequency, high frequency and public audio broadcasting networks.
6. Satellite links for communications between satellites and ground stations with a distance ranging from several hundred up to around 40,000 km.
7. Radio links for space telecommunications between ground and spacecraft stations.

The effects of the earth's atmosphere on radio waves propagation between earth and space platforms have been a matter of constant concern in the design, development and performance of satellite communication systems. Most especially systems operating at frequency above 10 GHz, the problems become more acute because at this frequency and above, communication links can be adversely affected by rain, clouds, and fog. Rain and cloud which cause several decibels of attenuation have been identified to be major cause of visualimpairment atmicrowave frequency and is the limiting factor in satellite/terrestrial link design, especially for tropical and equatorial regions which experience heavy rainfall (Narayana,2007). Therefore, this paper is aimed at the evaluation of the propagation losses during a rainy period.

Electromagnetic wave propagation is described by Maxwell's equations which form the basis of electromagnetic wave propagation. The Maxwell's equation shows that a time-varying electric field produces a magnetic field and a time-varying magnetic field produces an electric field. A time-varying magnetic field can be generated by an accelerated charge.The relationship between the time-varying electric and magnetic fields is expressed mathematically for uniform plane waves as (Abdollah*et al.*, 2012)

$$\nabla \; x \; \bar{E} = -\mu \frac{\partial \hat{H}}{\partial t}$$

$$\nabla \; x \; \overline{H} = \bar{J} + \varepsilon \frac{\delta \bar{E}}{\delta t}$$

(where J=σE = 0 as σ = 0 in air)

The differential form of Maxwell's equations are used to derive the wave equation which is expressed in one dimension as (Abdollah*et al.*, 2012)

$$\frac{\partial^2 E_x}{\partial t^2} = \mu\varepsilon \frac{\partial E_x}{\partial Z^2} \quad (1)$$

This partial differential equation is the fundamental relationship that governs the propagation of electromagnetic waves. The velocity of propagation for the electromagnetic wave is determined from the wave equation and is a function of the permittivity and permeability of the medium (Abdollah*et al.*, 2012)

$$V = \frac{1}{\sqrt{\mu\varepsilon}} \quad (2)$$

When expressed in terms of the relative permittivity and permeability, the equation for the velocity of propagation becomes (Abdollah*et al.*, 2012)

$$V = \frac{1}{\sqrt{\mu_r\varepsilon_r}\sqrt{\mu_0\varepsilon_0}} \quad (3)$$

Using the values of μ_o and ε_o in this expression yields

$$V = \frac{1}{\sqrt{\mu_r\varepsilon_r}} C$$

Where C =3.0 x 10^8m/s

Thus the velocity of propagation is equal to the velocity of light in free space divided by the square root of the product of the relative permittivity and permeability

2. Materials and Methods

Data were retrieved from the National Space Research and Development Agency (NASRDA) Abuja, Nigeria. The data collected was rainfall rate (mm/h) for the period of three year (2015–2017) over Jos. These data include average monthly rainfall rate for the 3-years 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 were processed using statistical means to find the probability of exceeded of some of the months within the study period and ITU-R P.839 recommendation was used to determine the propagation losses due to rain.

The following procedures were used in estimating the long-term statistics of the propagation losses at Jos for frequencies up to 55 GHz. The parameters used were:

$R_{0.01}$: point rainfall rate for the location for 0.01% of an average year (mm/h)

h_s: height above mean sea level of the earth station (km)

θ: elevation angle (degrees)

φ: latitude of the earth station (degrees)

f: frequency (GHz)

R_e: effective radius of the Earth (8 500 km)

Step 1: Determination of the rain height, h_R, as given in Recommendation ITU-R P.839.

Step 2: For $\theta \geq 5°$ the slant-path length, L_S, below the rain height was computed using:

$$L_S = \frac{(h_R - h_s)}{\sin\theta} \quad \text{km}$$

For $\theta < 5°$, the following formula was used:

$$L_S = \frac{2(h_R - h_s)}{\left(\sin^2\theta + \frac{2(h_R - h_s)}{R_e}\right)^{1/2} + \sin\theta} \quad \text{km}$$

Step 3: Calculation of the horizontal projection, L_G, of the slant-path length from:

$$L_G = L_S \cos\theta \quad \text{km}$$

Step 4: The rainfall rate, $R_{0.01}$, exceeded for 0.01% of an average year (with an integration time of 1 min) was obtained.

Step 5: The specific attenuation, γ_R was obtained using the frequency-dependent coefficients given in Recommendation ITU-R P.838 and the rainfall rate, $R_{0.01}$, determined from Step 4, by using:

$$\gamma_R = k\,(R_{0.01})^{\alpha} \quad \text{dB/km}$$

Step 6: Calculate the horizontal reduction factor, $r_{0.01}$, for 0.01% of the time:

$$r_{0.01} = \frac{1}{1 + 0.78\sqrt{\frac{L_G\,\gamma_R}{f}} - 0.38\left(1 - e^{-2L_G}\right)}$$

Step 7: The vertical adjustment factor, $v_{0.01}$, for 0.01% of the time was calculated:

$$\zeta = \tan^{-1}\left(\frac{h_R - h_s}{L_G\ r_{0.01}}\right) \qquad \text{degrees}$$

For $\zeta > \theta$, $\qquad L_R = \frac{L_G\ r_{0.01}}{\cos\theta}$ km

Else, $\qquad L_R = \frac{(h_R - h_s)}{\sin\theta}$ km

If $|\varphi| < 36°$, $\qquad \chi = 36 - |\varphi|$ degrees

Else, $\qquad \chi = 0$ degrees

$$\nu_{0.01} = \frac{1}{1 + \sqrt{\sin\theta}\left(31\left(1 - e^{-(\theta/(1+\chi))}\right)\frac{\sqrt{L_R\ \gamma_R}}{f^2} - 0.45\right)}$$

Step 8: The effective path length is:

$$L_E = L_R\ \nu_{0.01} \qquad \text{km}$$

Step 9: The predicted attenuation (propagation losses) exceeded for 0.01% of an average year is obtained from:

$$A_{0.01} = \boldsymbol{\gamma}_R\ L_E \qquad \text{dB}$$

Step 10: The estimated attenuation to be exceeded for other percentages of an average year, in the range 0.001% to 5%, is determined from the attenuation to be exceeded for 0.01% for an average year:

If $p \geq 1\%$ or $|\varphi| \geq 36°$: $\qquad \beta = 0$

If $p < 1\%$ and $|\varphi| < 36°$ and $\theta \geq 25°$: $\qquad \beta = -0.005(|\varphi| - 36)$

Otherwise: $\qquad \beta = -0.005(|\varphi| - 36) + 1.8 - 4.25\sin\theta$

$$A_p = A_{0.01}\left(\frac{p}{0.01}\right)^{-(0.655+0.033\ln(p)-0.045\ln(A_{0.01})-\beta(1-p)\sin\theta)} \quad \text{dB}$$

3. Results

Using the ITU-R P.839 recommendation, the effective rain height (h_R) was determined as

$h_R = 5.0$ for $0^0 \leq \phi < 25^0$

$h_R = 5.0 - 0.075(\phi - 23^0)$ for $\phi < 23^0$

where $\phi = 9.956^0$N (Latitude of the earth station-Jos)

$h_R = 5.0 - 0.075(9.956^0 - 23^0)$

$h_R = 5.978$ km

using equation (7), the slant-path length $L_S = 8.02$ km

Table 1: Rain rate frequency, cumulative frequency and commutative distribution function (CDF) in Jos (Sept. 2015)

Rain Rate (mm/hr)	Frequency	Cumulative Frequency	Exceedance Distribution Freq. of Percentage time = $\frac{N\times 100\%}{30\times 24\times 60}$
1	663	2223	5.145
2	719	1560	3.611
5	537	841	1.946
10	148	304	0.703
15	53	156	0.361
20	24	103	0.238
30	29	79	0.182
40	13	50	0.115

50	18	37	0.085
60	5	19	0.043
80	3	14	0.032
100	2	11	0.025
120	5	9	0.020
140	1	4	0.009
160	1	3	0.006
180	2	2	0.004

Table 2: Rain rate frequency, cumulative frequency and commutative distribution function (CDF) in Jos (Oct. 2015)

Rain Rate (mm/hr)	Frequency	Cumulative Frequency	Exceedance Distribution Freq. of Percentage time = $\frac{\boldsymbol{N}\times\mathbf{100\%}}{\mathbf{31\times24\times60}}$
1	277	1088	2.437
2	202	811	1.816
5	230	609	1.364
10	119	379	0.849
15	46	260	0.582
20	43	214	0.479
30	45	171	0.383
40	40	126	0.282
50	26	86	0.192
60	12	60	0.134
80	15	48	0.107
100	11	33	0.073
120	9	22	0.049
140	7	13	0.029
160	2	6	0.013

180	1	4	0.008
240	1	3	0.006
300	1	2	0.004
500	1	1	0.002

Table 3: Rain rate frequency, cumulative frequency and commutative distribution function (CDF) in Jos (July 2016)

Rain Rate (mm/hr)	Frequency	Cumulative Frequency	Exceedance Distribution Freq. of Percentage time = $\frac{N\times 100\%}{31\times 24\times 60}$
1	424	2079	4.657
2	505	1655	3.707
5	717	1150	2.587
10	208	433	0.969
15	62	225	0.504
20	31	162	0.362
30	49	132	0.295
40	30	83	0.192
50	72	53	0.118
60	15	29	0.064
80	11	14	0.031
100	3	3	0.006

Table 4: Rain rate frequency, cumulative frequency and commutative distribution function (CDF) in Jos (Sept 2016)

Rain Rate (mm/hr)	Frequency	Cumulative Frequency	Exceedance Distribution Freq. of Percentage time = $\frac{N\times 100\%}{30\times 24\times 60}$
1	663	2218	5.134
2	719	1555	3.599
5	537	836	1.935
10	148	299	0.692
15	53	151	0.342
20	24	98	0.226
30	29	74	0.171
40	13	45	0.104
50	18	32	0.074
60	5	14	0.032
80	3	9	0.020
100	4	6	0.013
120	2	2	0.004

Table 5: Rain rate frequency, cumulative frequency and commutative distribution function (CDF) in Jos (July 2017)

Rain Rate (mm/hr)	Frequency	Cumulative Frequency	Exceedance Distribution Freq. of Percentage time = $\frac{N\times 100\%}{31\times 24\times 60}$
1	334	1156	2.589
2	358	822	1.841
5	192	464	1.039
10	132	272	0.601
15	54	140	0.313

20	24	86	0.192
30	18	62	0.138
40	18	44	0.098
50	7	26	0.058
60	4	19	0.042
80	6	15	0.033
100	5	9	0.020
120	3	4	0.008
140	1	1	0.002

Table 6: Rain rate frequency, cumulative frequency and commutative distribution function (CDF) in Jos (Aug 2017)

Rain Rate (mm/hr)	Frequency	Cumulative Frequency	Exceedance Distribution Freq. of Percentage time = $\frac{\boldsymbol{N}\times\mathbf{100}\%}{\mathbf{31}\times\mathbf{24}\times\mathbf{60}}$
1	286	1104	2.473
2	280	818	1.832
5	246	538	1.205
10	99	292	0.654
15	42	193	0.432
20	25	151	0.338
30	27	126	0.282
40	24	99	0.221
50	23	75	0.168
60	17	52	0.116
80	9	35	0.078
100	10	26	0.058
120	9	16	0.035
140	7	7	0.015

4. Discussion

Table 1 and 2 presents the computation of rainfall rate, frequency, cumulative frequency and commutative distribution function (CDF) in the month of September and October 2015 respectively. The month of September 2015 had 5.145% time of exceedance at 1mm/hr and 0.004% time of exceedance at 180mm/hr, October 2015 recorded 2.437% at 1mm/hr and 0.002% at 500 mm/hr. Table 3 and 4 present theExceedance Distribution Frequency of Percentage time at Various Rain Ratefor the month of July and September 2016 respectively. The month of July 2016 recorded 4.657% time of exceedance at 1mm/hr and 0.006% at 100 mm/hr, the month of September 2016 has 5.134% at 1mm/hr and 0.004% at 120mm/hr. Tables 5 and 6 presents the computation of rainfall rate, frequency, cumulative frequency and commutative distribution function (CDF) in the month of July and August 2017 respectively. The month of July 2017 experienced 2.589% time of exceedance at 1mm/hr and 0.002% at 140mm/hr, the month of August 2017 experienced 2.473% at 1mm/hr and 0.015 at 140mm/hr.

The results obtained from 2015 to 2017 clearly revealed that higher rainfall rate (above 100 mm/hr) account for about 0.01 and 0.001% time of exceedance and it is during such times that maximum propagation losses due to rainfall is significant and can be best estimated.

5. Conclusion

The estimation of the long-term propagation losses due to rain on microwave satellite links was determined based on theexceedance distribution frequency of percentage time (%) and cumulative distribution of one- minute rain rate over Jos. Only the months with significant and higher rainfall rate were presentedand used. Theresults obtained revealed that low and high intensities of rainfall over short period of time have less effect on the transmitted signals whereas low and high intensities of rain over long period of time have a significant effect on the transmitted signals. This is because the amount of water particles in the atmosphere becomes more concentrated when the rainfall prevailed for a longer period thereby increasing the rate of signal degradation.

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