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Mitigation of Rain Fading Effect on Satellite Signal Reception Using Uplink Power Control System

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Abstract— **Signal transmission through wireless communication channels over long distance at frequencies above 10 GHz heightens the probability of link unavailability. This is further compounded in the tropical region with characteristic extended rainfall periods. For relatively mild and not-too-severe weather impairments occasioned by short durations of rain event, this paper aimed to maintain the integrity of NigComSat-1R received signal strength during rain event. This was accomplished through Simulink implementation of open-loop and closed-loop uplink power control algorithms. The input to these algorithms was gotten from the computed rain rate value that aided the assessment of the level of attenuation of signal encountered at 20 GHz and 30 GHz, respectively which simplified the determination of link margins and fade event durations with computed attenuation factor. Furthermore, the value of attenuation obtained was utilized in the calculation of uplink power adjustment parameters such as attenuation gain factor, attenuation correction factor, hub uplink power, optimal power and offset power. Plots obtained from the Simulink implementation showed 97% and 99.5% performance in terms of offset of established uplink power.**

Keywords— Signal transmission, wireless communication channel, NigComSat-1R, uplink power control, attenuation.

I. INTRODUCTION

Link availability in satellite communication systems all-year-round especially for Direct-To-Home (DTH) broadcast/multicast setup is of paramount importance with a recommended outage probability of less than or equal to 0.5% which in cumulative term is approximately 44 hours per year [1]. Given the extensive usage of satellites in diverse sectors, [2] stated that link unavailability as a result of weather impairment and natural disaster has direct effect on the wellbeing of humans in general in that as operating frequency increases, the attenuation and scintillation effects of atmospheric gas, clouds, and rain become more severe. Strong propagation impairments have made it necessary to incorporate various fade mitigation techniques (FMTs) which aim to reduce the effects of propagation losses such as rain attenuation in the design of telecommunication systems operating at Ku, Ka, Q and V band frequencies. The extent and type of signal impairment (attenuation, distortion and noise) varies from one region of the world to another; however, the predominant fade encountered in the tropics and most other regions of the world as established by [3] is rain attenuation.

According to [4], FMTs refers to methods employed to cushion the effect of signal transmission impairment. Examples of FMTs are uplink power control (UPC), transmission rate control, diversity techniques and adaptive modulation as stated by [5], some of these FMTs allow systems with rather small static margin to be designed, while overcoming in real time cloud attenuation, significant fraction of rain attenuation, scintillation and depolarization events. Adaptive modulation/coding has been of peculiar interest as it allows for the performance of individual links to be optimized, and the transmission characteristics to be adapted to the propagation channel conditions and to the service requirements for the given link [6].

In this paper, uplink power control on NigComSat-1R received signal at University of Uyo (UniUyo) will be studied with the aim of determining power control parameters suitable for automated power control as an FMT at the transmission station against signal attenuation.

II. REVIEW OF RELATED LITERATURES

Over the years, the need to have sustainable signal transmission and reception elicited the desire by communications experts that culminated in several innovations which preceded the introduction of diverse FMTs. However, due to the sensitive nature of UPC technique, there has been limited number of published works when compared with other FMTs.

Li in [7] proposed a new method of FMT based on uplink power compensation for rain attenuation. According to the author, the ground station emission power could be adjusted to achieve the maximum compensation for rain attenuation using computed data from mathematical equations based on downlink rain fading. As stated by the author, the new method overcame the shortcomings of the traditional diversity reception and had high practical value for base-band digital signals. Nevertheless, point rainfall data was not used for predicting attenuation by the author as ideal scenario was assumed to derive mathematical expression that was used for uplink power control.

Bourdillon and Johnfrancis in [5] worked on mitigation of rain attenuation in fixed wireless microwave link using an adaptive transmit power control (ATPC) with rainfall data collected at Nigerian meteorological station (NiMet) for a period of five years (2012 to 2016). They modelled rain attenuation using ITU-R model and implemented modelled ATPC algorithm on MATLAB Simulink. Despite closeness of the authors study location to the one chosen in this study; they were unable to produce suitable results for rain fade duration that was used alongside the computed transmission gain factor.

Pan *et al.* [1] presented the performances of annual, and seasonal site-diversity and time-diversity measurements. According the authors, the variations in the received clear-sky level of the satellite beacon showed evidence of a diurnal variation that has a period of a solar day due to the atmospheric thermal tide. They reported that they found evidence of annual periodicity in absorption levels through the atmosphere on top of the diurnal tidal effect suspected to be due to longer period of atmospheric tide. The study locations chosen by the authors is of different rain characteristics from the one proposed in this study and as such, findings from the research will produce inaccurate power control if adopted for the proposed location.

III. Research Methodology

Uplink power control performance was carried out taking into consideration the non-uniformity of rainfall in the study area. A long-term rainfall measurement data was obtained from University of Uyo Meteorological station for the study location. This was used to describe the behaviour and variation of rainfall intensity. For a viable prediction of rain attenuation, the cumulative distribution (CD) of rainfall intensity obtained from long-term measurements (5 years in this case) was used. Data processing was done using semi-empirical (empirical/analytical) method. A statistical method was employed to determine the probability of exceedance of each rainfall rate value. The value at 0.01 % time of an average year was determined, which was inputted into ITU-R rain attenuation model to determine its corresponding rain attenuation value. The results obtained from ITU-R rain attenuation model is used to determine the transmission gain factor which is the core parameter used for power adjustment during fade event. First the incremental power step is determined to know the appropriate steps for increasing or decreasing power during fade. These parameters were computed with the aid of MATLAB program. Fig. 1 shows the flowchart of the research methodology highlighting the steps taken - ranging from selection of study site to the determination of power control parameters for the study area as well as the automation of the power control process through the use of threshold.

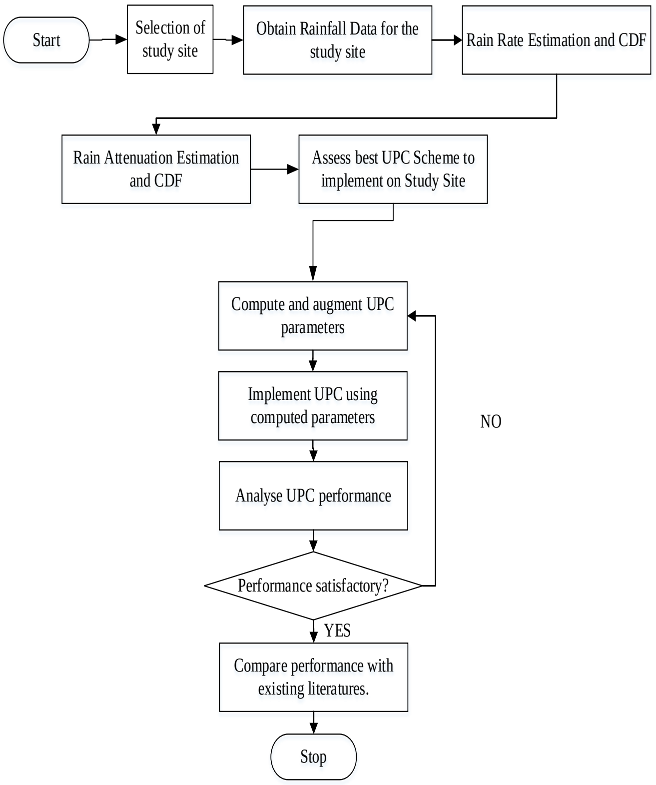

Fig. 1 Flowchart of the research procedure

A. *Rainfall Data Description*

Rainfall data for UNIUYO was obtained from the University's meteorological station for a period of five years (2016 – 2020). The rainfall data retrieved show daily rainfall volume (measured in mm), obtained using tipping bucket rain gauges.

B. *Surface Point Rain Rate Distribution*

Point rainfall rate was obtained for the study site using the Chebil's rain rate model; the Moupfouma model which approximates a log-normal distribution at low rates and a gamma distribution at high rates was used to derive the rain rate cumulative distribution for 0.01 % of time exceedance.

C. *Power Adjustment Parameters*

In this research, an attempt is made to develop algorithms for both open-loop and close-loop uplink power control with the latter being far more complex and resource-demanding than the former. Generally, power control in signal transmission is done with great degree of caution as excessive increment of transmission power at the ground station will overload the satellite receiver system leading to signal interference with adjourning service providers [8]. The major parameter that determines the level of power adjustment during fade event is the transmission gain factor, G_{Tx} which is initially set to 1 (corresponding to 0 dB) and adjusted periodically according to the received power level that is determined from the attenuation intensity experienced along the path of transmission. The rain attenuation value, (A) obtained based on ITU P.618-13 was used to compute the rain attenuation factor, G as given in (1).

$$G = 10^{-A} \quad (1)$$

In order to have effective power control, it is paramount to determine the incremental power step (ΔP) which is a function of the average received power, $P_r[n]$ as given in (2).

$$\Delta P = g(1 - P_r[n]^{-1}) \quad (2)$$

where $g(\quad)$ is a non-linear function that is comprised of two-level quantizer and a dead zone.

These constituents of $g(\quad)$ depends on the initializing values of ΔP that is either used for decreasing or increasing the power level at the transmitting end. The new power level, $P_r[n+1]$ at the transmitter is computed from (3) as follows.

$$P_r[n+1] = (1 + \Delta P)P_r[n] \quad (3)$$

Hence, G_{Tx} is computed by taking the square root of the new power level using (4).

$$G_{Tx} = \sqrt{(P_r[n+1])} \quad (4)$$

The determination of optimal transmission power level (P_{opt}) as a function of signal attenuation encountered is the goal of power control in signal transmission. This is done so that the optimal carrier-to-noise (C/N_{opt}) ratio of the satellite reaches 90% saturation level (C/N_{BH}) as evaluated from (5) [9].

$$(C/N_{BH}) = \Phi_{sat} - G_{RX} + (G/L)_{SL} - 10\log K \quad (5)$$

where Φ_{sat} is the saturation power density on the satellite $(-90\,dBW/m^2)$; G_{RX} is the receiver antenna gain (45 dB); $(G/L)_{SL}$ is the satellite receiver antenna quality $(206\ dB/K)$ and K is Boltzmann constant $(-228.6\,dBW/K/Hz)$. Thus;

$$C/N_{BH} = -90 - 45 + 206 - 10\log(-228.6)$$
$$= 95\ dB$$

The effective power current density (Φ_{hd}) on the satellite in rainy condition is evaluated from (6) [10].

$$\Phi_{hd} = EIRP - L_u - L_{rain} + G_{RX} = P_{TX} + \cdots$$
$$\ldots + G_{TX} + G_{RX} - L_u - L_{rain} \quad (6)$$

where P_{TX} is the uplink antenna power, G_{TX} is the transmit antenna gain, L_{rain} is a parameter that accounts for rain losses, Lu is the uplink miscellaneous losses with a value of 206.8 dB at 14.5 GHz and above. Substituting some parameter values into (6), Φ_{hd} becomes:

$$\Phi_{hd} = -206.8 + 45 + P_{TX} + G_{TX} - L_{rain}$$
$$= P_{TX} + G_{TX} - L_{rain} - 161.8$$

Hence the uplink carrier to noise ratio at the satellite receiver (C/N_{HD}) is calculated using (7) which further gives the control expression in (8).

$$C/N_{HD} = \Phi_{hd} - G_{RX} + (G/L)_{SL} - 10\ log\ K \quad (7)$$

Substituting for the values of G_{RX}, $(G/L)_{SL}$, and K; Equation 3.20 becomes;

$$C/N_{HD} = 206 - 45 + 10\log(228.6) + P_{TX} + \cdots$$
$$\ldots + G_{TX} - L_{rain} - 161.8$$
$$= 184.59 + P_{TX} + G_{TX} - L_{rain} - 161.8$$

The hub station uplink antenna gain (G_{TX}) is 60.31 dB. Hence;

$$C/N_{HD} = 22.79 + 60.31 + P_{TX} - L_{rain}$$
$$= 83.10 + P_{TX} - L_{rain} \quad (8)$$

P_{TX} and L_{rain} vary according to the weather condition at each time instant.

The control model aims to determine the near-optimal transmission power level (P_{opt}) under random effects of various factors on the transmission line while maintaining optimal carrier to noise ratio at the satellite receiver $(C/N_{HD} = C/N_{OPT} = 0.9 \times C/N_{BH})$.

D. Open-Loop Power Control

Open-loop control relies on independent schemes for estimating uplink fade such as satellite-borne beacon signal or radiometry monitoring. The control method is done such that the uplink power correction applied does not affect the measured Downlink Signal Strength (DSS) [11]. The DSS measurements are averaged and reported once in every Sample Time (ST) period.

The carrier signal strength feedback from the satellite to the hub station does not determine the extent of transmission power correction, pre-set beacon signal at NigComSat-1R satellite control centre is the foremost power correction constituent. The measurements obtained from beacon signal strength are averaged and reported once per sampling interval. This is achieved at the control centre by setting the first state of attenuation $(A0)$ to be equivalent to the threshold value (ACS_n). The measured attenuation level in form of radio frequency (RF) from the beacon at the hub station is converted to different voltage intensities (input voltage, DC_{in}) depending on the weather condition, is further regulated by the control model containing the RF/DC conversion block. The loss change factor, A for channel n of the instantaneous transmission line in clear air for the beacon signal is calculated according to [11] as expressed in (9).

$$A_n = ACS_n\left(1 - \frac{DC_{in}}{10}\right) \quad (9)$$

According to [12], attenuation factor for channel n is calculated using (10).

$$ATT_n = A_n + \Delta FSL \quad (10)$$

where ΔFSL is the free space attenuation difference factor between uplink (UL) carrier and the beacon signal.

The computed ATT_n is compared with the initialization value $A0$, the difference is consequently used to either increase or decrease the value of the loss change factor, A_n. Fig. 2 gives the flowchart of the open-loop algorithm implemented in stages.

E. Closed-Loop Power Control

The closed-loop control algorithm is based on the principle of measuring the signal-noise-interference ratio by using the UL carrier signal feedback from the satellite to the receiver. Even though the carrier signals are transmitted simultaneously on the same transmission line, the losses on UL and DL paths are not comparable, hence, the measured downlink signal-noise ratio (C/N_{DL}) is also different [13]. At the end of each adjustment, an idle period is established. For the algorithm to attain high efficiency, the idle period must be greater than or equal to the total period of time that the carrier transmitted feedback is received. Another waiting period is initiated to enable the algorithm to check the carrier parameters on the return path. Due to the long transmission distance between NigComSat-1R and the earth station, approximately 0.225 seconds (225 ms) delay is encountered and also accounted for as the idle period is set between 225 ms and 250 ms, which is sufficient for the receiver to check the C/N_{DL} ratio and compare it to the optimal level $\left(C/N_{opt}\right)$. Thus, the received signal power on the feedback line is evaluated using (11) [14].

$$P_{RX} = EIRP - L_t + G_{RX} - L_{cable} - L_{rain} \qquad (11)$$

where EIRP = 55 dBW; miscellaneous transmission loss, $L_t = L_u = 206.8\ dB$; cable losses, $L_{cable} = 3.5\ dB$ and $G_{RX} = 44.20\ dB$.

Hence (11) becomes:

$$\begin{aligned} P_{RX} &= 55 - 206.8 + 44.2 - 3.5 - L_{rain} \\ &= -111.1 - L_{rain}\ (dBW) \qquad (12) \end{aligned}$$

The maximum heat noise (T_{max}) is experienced in rain and thus, the noise power (P_N) is evaluated using the expression in (13) [9], [15].

$$P_N = kTB \qquad (13)$$

where k is Boltzmann constant, T is noise temperature and B is the noise bandwidth. $P_N = 1.38 \times 10^{-23} \times 500 \times 6.67 \times 10^5 = 4.60 \times 10^{-15} W$

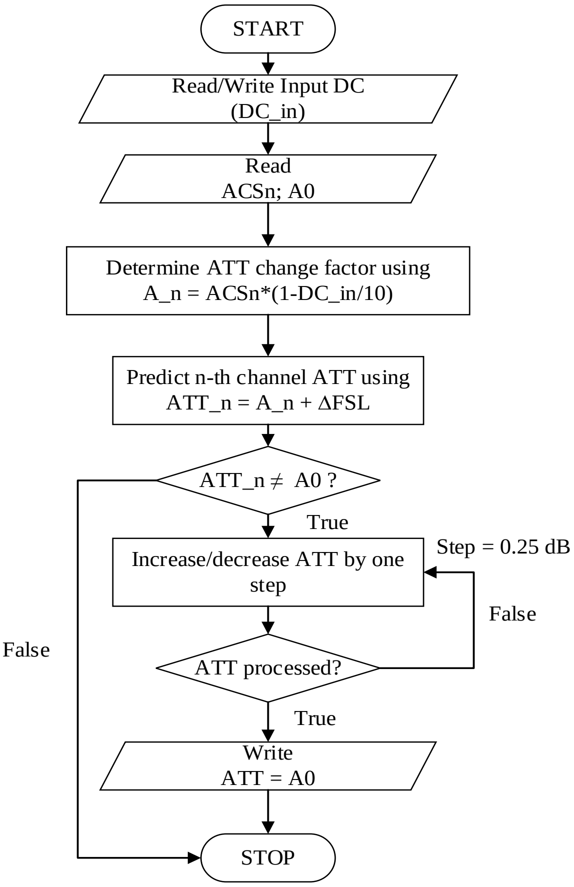

Fig. 2 Open-loop power uplink control flowchart

$$\begin{aligned} P_N &= 10\log(4.60 \times 10^{-15}) \\ &= -143.37\ dBW \end{aligned}$$

Therefore, the downlink signal-to-noise ratio $\left(C/N_D\right)$ in rain is the difference between the received signal power and the noise power as calculated using (14).

$$\begin{aligned} C/N_D &= P_{RX} - P_N \\ &= -111.1 - L_{rain} - (-144.49) \\ &= 33.39 - L_{rain} \qquad (14) \end{aligned}$$

Attenuation correction coefficient (A_n) is evaluated using the expression in (15) as follows.

$$A_n = ACS_n - \left(\left(C/N_{OPT}\right)_D - C/N_D\right) \qquad (15)$$

Optimum downlink signal-to-noise ratio $\left(C/N_{OPT}\right)_D$ is equivalent to the clear air downlink carrier to noise ratio is 28.95 dB, (15) becomes (16).

$$\begin{aligned} A_n &= ACS_n + 28.95 - 33.39 - L_{rain} \\ &= ACS_n - 4.44 - L_{rain} \qquad (16) \end{aligned}$$

where $ACS_n - 4.44 = Rain\ Loss$.

Worthy of note is that loss change factor in open-loop control is synonymous with attenuation variation coefficient in closed-loop control; they are however evaluated differently with different parameters. The optimal transmit power was determined using (17).

$$\begin{aligned} P_{OPT} &= 90\% \times C/N_{BH} - 83.10 + L_{rain} \qquad (17) \\ &= 90\% \times 95 - 83.10 + L_{rain} \\ &= 2.4 + L_{rain}(dBW) \\ &= 32.4 + L_{rain}(dBm) \qquad (18) \end{aligned}$$

According to[16], L_{rain} can be approximated from the expression in (19) as follows.

$$L_{rain} = 0.0996 \times R^{1.232} \qquad (19)$$

where R is the instantaneous rain rate at the point of measurement.

Cumulatively, for the five (5) year duration of measurement utilized for this study, the L_{rain} was computed as follows.

$$L_{rain} = 0.0996 \times 132.17^{1.232} \approx 41\ dB$$

$$P_{OPT} = 32.4 + 41 = 73.4\ dBm$$

However, the L_{rain} changes with the amount of rainfall and can be computed in real time to ensure accurate power adjustment at the ground station (GS). Thus, the uplink hub power is calculated using (20) while the optimal power is evaluated using (21).

$$P_{HUB\_out} = P_{HUB\_in} + 72.8 - A_n(dBm) \qquad (20)$$

$$\Delta P(\%) = 100\% \times \frac{(P_{OPT} - P_{HUB\_out})}{P_{OPT}} \qquad (21)$$

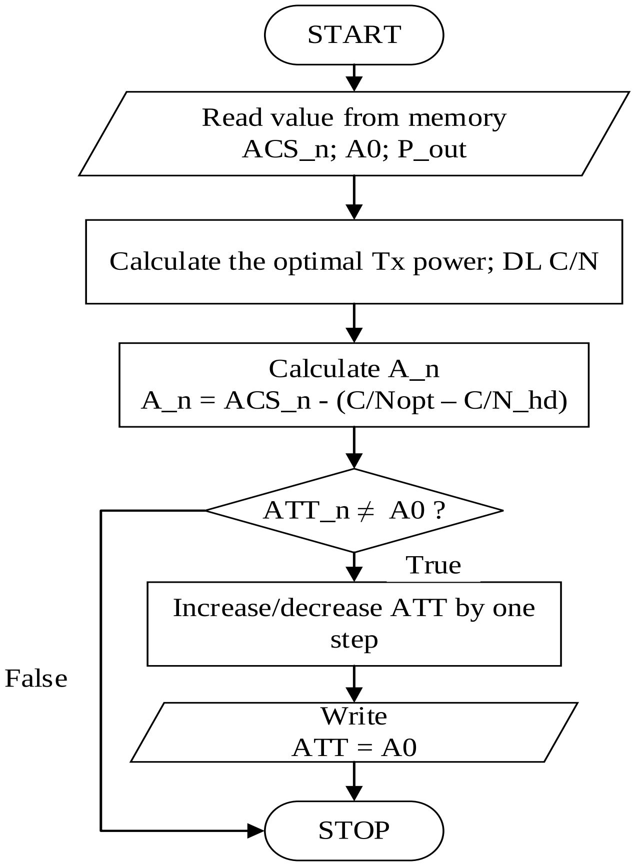

Fig. 3 Closed-loop power uplink control flowchart

By way of evaluation, for an effective power control, estimated channel attenuation (dB) is computed via (22) and (23).

$$\text{uplink channel power ratio} = \frac{\text{uplink power correction (dB)}}{\text{downlink signal strength (dB)}} \quad (22)$$

$$\text{Channel attenuation (dB)} = \text{Clear sky attenuation (dB)} + \text{uplink power correction (dB)} \quad (23)$$

Flowchart of close-loop algorithm is presented in Fig. 3. To compute the anticipated receive antenna pointing error at Half Power Beamwidth (3 dB), (24) was used.

$$\phi_{3dB} = \frac{70\lambda}{d} \quad (24)$$

$$= \frac{70 \times 0.01}{4} = 0.175$$

IV. SIMULATION OF UPC

Simulink implementation of uplink power control was achieved by modifying the RF Satellite Link module available in MATAB. The modification process included a mask UPC algorithm loop (MATLAB function block) with programs that activates either open-loop or closed-loop power control depending on the requirement

V. RESULTS

A. Rain Rate and Attenuation Cumulative Distribution

The cumulative distribution of rain rate for UNIUYO is presented in Fig 4. Rain rate was plotted for other percentages of time ranging from 0.001 % to 10 % 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. It can be seen from Fig 4 that UNIUYO had a rain rate distribution at 0.01 % of outage time with 132.17 mm/hr. Also, the cumulative distribution of rain attenuation for UNIUYO at 20 GHz and 30 GHz frequency respectively are presented in Fig 5 (a) and (b). 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 UNIUYO was 47.94 dB; at 30 GHz, long-term rain attenuation was 93.44 dB. These values were computed at 0.01 % of time exceedance (unavailability).

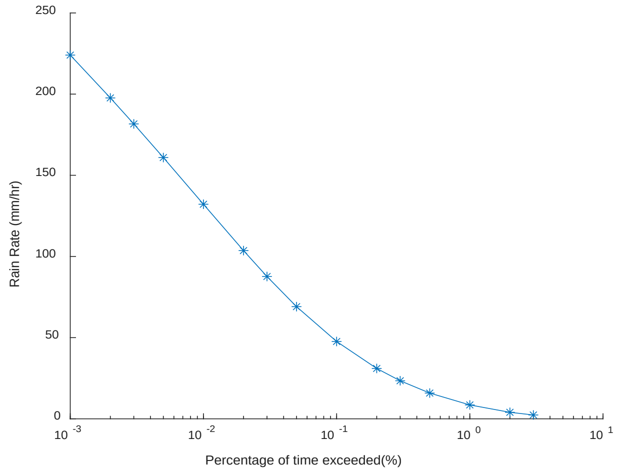

Fig. 4 Cumulative distribution of rainfall rate for UNIUYO

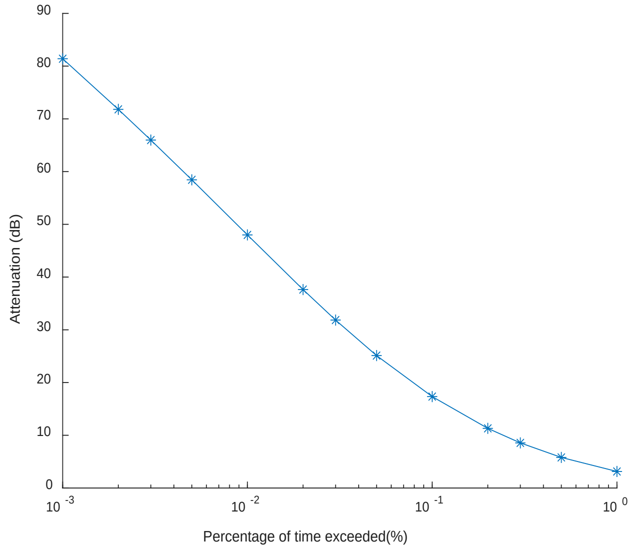

Fig. 5 (a) Rain attenuation CDF at 20 GHz

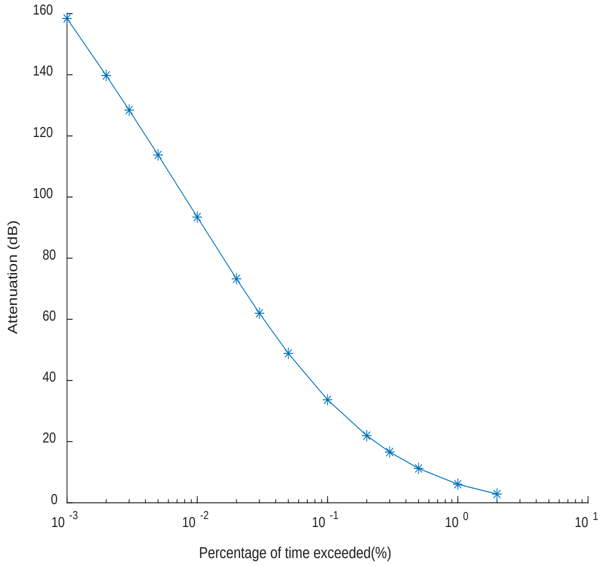

Fig. 5 (b) Rain attenuation CDF at 30 GHz

B. Open Loop UPC

Several computed parameters were simulated alongside other variables in MATLAB with function blocks; it was discovered that the predominant factor that influence wave transmission in the region under study was rain rate. For ease of analysis, rain path length of 6 km was assumed. The simulated results presented in Fig 6 to 8 show heightened bias that is consistent between established hub transmission power $\left(P_{HUB\_out}\right)$ and optimal transmission power (P_{OPT}) under varying rain rate as it is observed to be high in each simulation scenario implemented. Also, increased rain loss is experienced by transmitted signal with increased rainfall as is seen in Fig 6 and this is similar to the case of hub transmission power requirement as well as optimal transmission power requirement in rain to effectively reduce attenuation as illustrated in Fig 7 and 8.

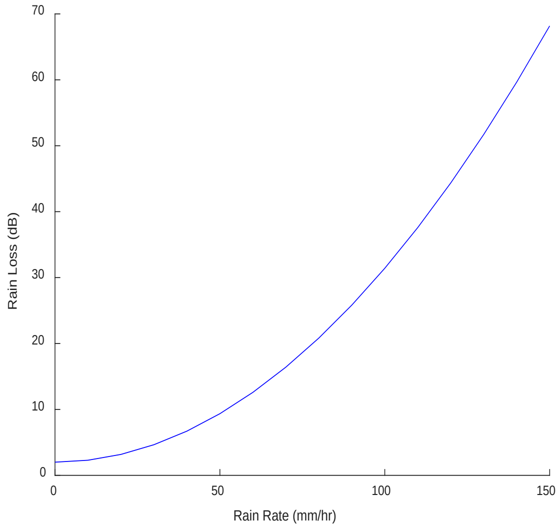

Fig. 6 Rain Loss versus rain rate

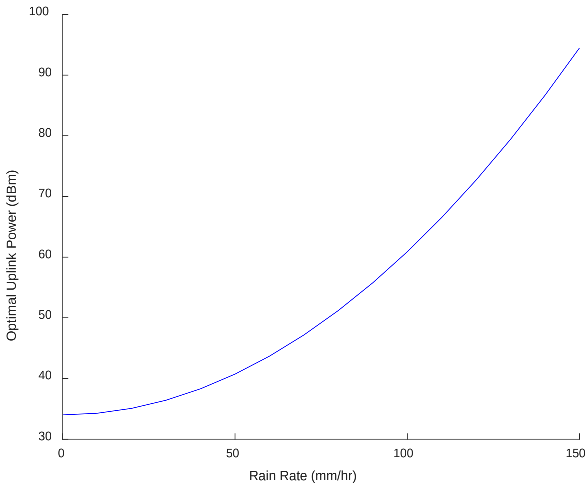

Fig. 7 Optimal uplink power versus rain rate

Therefore, incremental change on attenuation offset in free space (ΔFSL) at the uplink frequency (30 GHz) (FSL_U) in comparison to the satellite beacon frequency (20 GHz) (FSL_{Beacon}) at the computed rain rate is determined by taking the difference between the free space pathloss of the uplink satellite frequency and that of the satellite beacon (downlink) frequency as given in (25):

$$\Delta FSL = FSL_U - FSL_{Beacon} \tag{25}$$

$$= 20\log(30) - 20\,log(20)$$

$$= 3.35\,dB$$

Thus, combining (16) and (19) from Chapter three, the attenuation correction factor, A_n is approximated using (26).

$$A_n = ACS_n - 0.0996 \times R^{1.232} \tag{26}$$

According to [5], the stipulated attenuation threshold value is pegged at 30 dB corresponding to 1000 W and the Losses due to rain for the study duration of five (5) years was calculated to be approximately 41 dB, the attenuation correction factor, A_n becomes:

$$A_n = 30 - 41 = -11\,dB$$

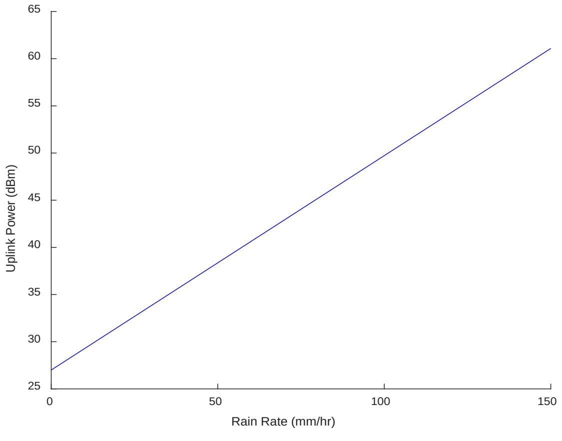

Fig. 8 Hub transmission power versus rain rate

Attenuation factor, ATT_n for the five (5) years under study is therefore calculated according to (10) to be:

$$ATT_n = A_n - \Delta FSL$$
$$= -11 + 3.35$$
$$= -7.65\ dB$$

The ATT_n value computed indicates that the transmission power needs to be augmented by 7.65 dB below the threshold during rain to effectively overcome attenuation barrier. As obtained from [5], the input power to the hub is usually set to -12 dBm at the attenuation threshold. Substituting these deduced values into (20) and (21), the uplink power and the offset of the established uplink power at the hub becomes;

$$P_{HUB\_out} = -12 + 72.8 + 11 = 71.8\ dBm$$

$$P_{OPT} = 73.4\ dBm$$

$$\Delta P(\%) = 100\% \times \frac{(P_{OPT} - P_{HUB\_out})}{P_{OPT}}$$
$$= \frac{73.4 - 71.8}{73.4} \times 100 \approx 2.2\%$$

This means that for UniUyo with a cumulative rate of 132.17 mm/hr over a period of five (5) years, ΔP is above 2.2% which indicates that the accuracy of the open-loop power control model is above 97% as highlighted in Fig. 9.

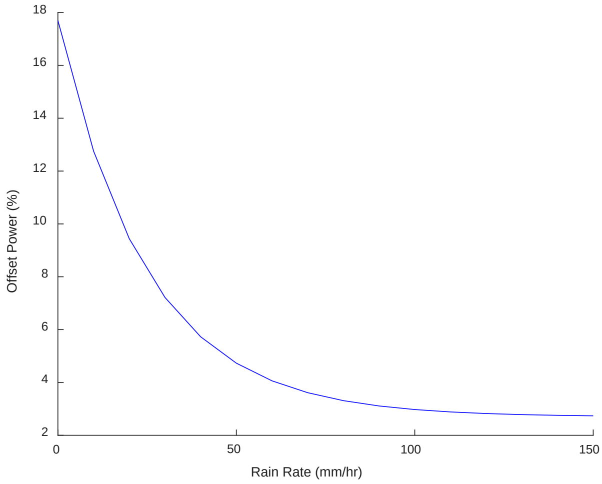

Fig. 9 Percentage uplink offset power versus rain rate

C. *Closed-Loop Power Control*

The implementation of the closed-loop scheme is based on the building blocks of the open-loop algorithm with the inclusion of signal feedback path (included receiver in the transmitter direction) as contained in (14). This enables the evaluation of loss level on transmission link by the control unit in addition to the noise temperature level emanating from the satellite link with the consequent effect of easy adjustment of transmission power [14], [18]. The included receiver in the transmitting direction has a meter for determining downlink carrier to noise ratio (C/N_D) which serves as reference parameter for calculating attenuation correction coefficient (A_n) by the Arithmetic and Logic Unit (ALU) based on which the Control Unit (CU) makes adjustment decisions for increasing or decreasing the transmission power depending on the corresponding attenuation factor (ATT_n) value of the transmission channel. For closed-loop power control, A_n is calculated as follows.

$$A_n = 30 - 4.44 - 41 = -15.44\ dB$$

The hub transmit and incremental power are calculated as follows.

$$P_{HUB\_out} = -14.5 + 72.8 + 15.44 = 73.74\ dBm$$
$$\Delta P(\%) = \frac{73.74 - 73.4}{73.4} \times 100 \approx 0.5\%$$

From the values computed above, it is observed that the uplink power and the optimal transmission power (presented in Fig 10 and Fig 11) have very low bias $\left(P_{OPT} \approx P_{HUB\_out}\right)$. The closed-loop power control shows that for UniUyo with a cumulative rate rate of 132.17 mm/hr over a period of five (5) years, ΔP is above 0.5% which indicates that the accuracy of the closed-loop power control model is above 99.5% as highlighted in Fig. 11.

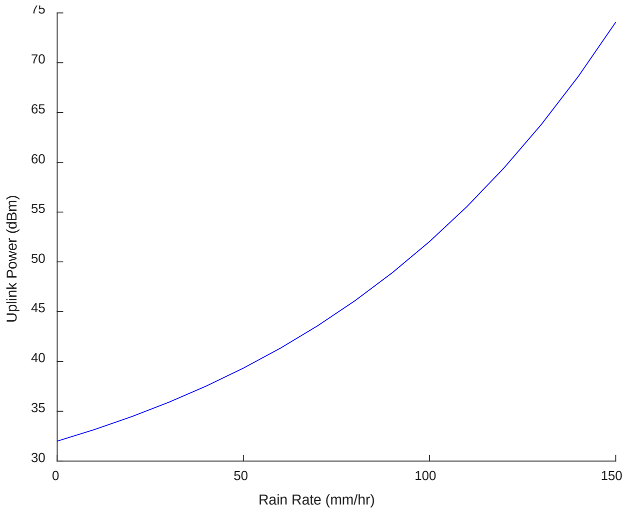

Fig. 10 Hub transmission power versus rain rate

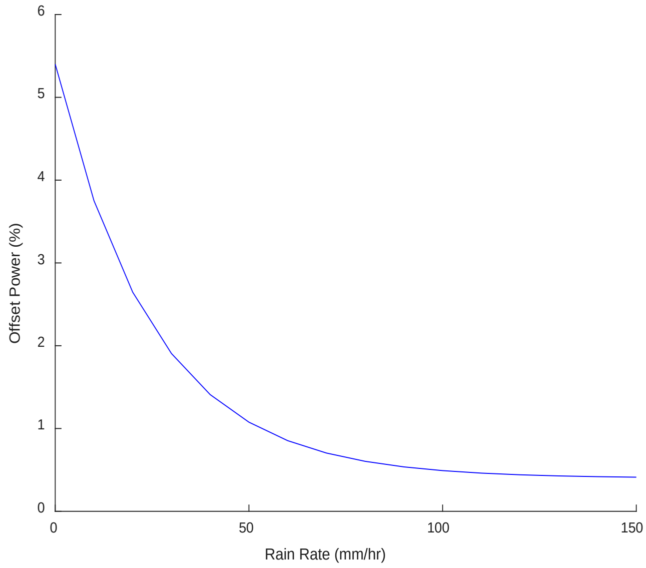

Fig. 11 Percentage uplink offset power versus rain rate

VI. CONCLUSION

This paper x-rayed the use of power control as rain fade mitigation technique in respect of NigComSAT-1R signal. Specifically, reduction of attenuation with aid of automatic uplink power adjustment using measured rain data was the technique applied. Rain rate value of 132.17 mm/hr was first computed and its CDF plotted for percentages of time ranging from 0.001 % to 1 % of an average year alongside rain attenuation values of 47.94 dB and 93.44 dB at frequencies of 20 GHz and 30 GHz, respectively. The attenuation value computed at 30 GHz was utilized in determining the power control parameters such as attenuation gain factor, attenuation correction factor, power output at the hub, optimal and offset power, respectively. Plots obtained from Simulink implementation of both open-loop and closed-loop algorithms showed 97% and 99.5% respective performance in terms of offset of established uplink power.

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