Characterization of rain specific attenuation and frequency scaling technique for satellite communication systems in a tropical location

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Abstract. Increased demand for satellite system applications and congestion of the lower frequency bands has mandated the foray into higher frequency spectrum which is more susceptible to rain-induced attenuation. This research explores the characterization of rain specific attenuation and frequency scaling technique for satellite communication system in Akure (7.17°N, 5.18°E, 358 m), Nigeria. Two-year archived rain-attenuation data on Ku-Band satellite link over the earth-space path of Akure was used for the study. Concurrent measurement of rainfall parameters and Eutelsat W4/W7 satellite radio beacons was carried out at the Department of Physics, Federal University of Technology Akure, between January 2017 and December 2018 using Tektronix Y400 NetTek spectrum analyzer. Estimated and measured rain attenuation statistics were compared, and exact determination of the power law coefficients which support the computation of explicit attenuation from measured rain rate was carried out. Recommended frequency scaling technique was also employed to investigate the magnitude of rain-induced attenuation at higher frequency bands. Results show that, at 0.01 percentage exceedance window, combined estimated and measured rain attenuation have respective magnitudes of about 13.09 dB and 21.43 dB. Also, estimated and scaled attenuation at 16 GHz, 20 GHz, 30 GHz and 40 GHz are about 21.97 dB, 31.78 dB, 56.64 dB, 77.23 dB and 28.36 dB, 33.95 dB, 42.17 dB, 46.07 dB respectively.

Keywords: Specific attenuation, frequency scaling, satellite communication, rainfall parameters, exceedance.

1. Introduction

Rapid growth in satellite services such as internet access, multimedia application, Local Area Network (LAN) interconnection, Supervisory Control And Data Acquisition (SCADA) among others, have led to serious congestion at lower communication frequency bands such as the L-band (1-2 GHz) and C-band (4-8 GHz), therefore compelling the use of higher frequencies bands such as Ku-band (12-18 GHz), K-band (18-27 GHz), Ka-band (27-40 GHz) and so on [1]. Propagation at frequencies above 10 GHz suffers serious attenuation due to hydrometeors such as atmospheric gases, cloud, fog, snow, hail, glaze and rain. The influence of attenuation due to hydrometeors increases with increasing operating frequency. For a
tropical location, rain attenuation is perhaps the most dominant propagation impairment at such frequencies [1, 2].

Electromagnetic wave passing through rain drops at high frequency bands gets absorbed, scattered or transmitted through the medium. The scattering and absorption often lead to reduction in signal quality and strength termed rain attenuation. Rain also changes the polarization of the electromagnetic waves as it propagates through it, which also causes reduction in the quality of the received signal [3]. The magnitude of rain attenuation depends on rain parameters such as raindrops size, rain temperature, drop velocity, polarization, raindrop orientation, as well as transmitting frequency of the communication systems [2, 3].

In the tropical region where rainfall is characterized by high rain rate and the presence of large raindrops sizes, the propagation of radio signals at frequencies approaching 10 GHz is susceptible to rain attenuation effects while at higher frequencies above 10 GHz, these rain attenuation effects become of greater magnitude and concern [1-3].

The frequency scaling technique includes the prediction of attenuation at the desired frequency from estimated attenuation values at a reference frequency. It is a helpful and integral tool for assessing rain attenuation at the desired frequency when the estimated data are available at a specific frequency [4]. Over the years, estimation of rain attenuation for terrestrial and satellite communication applications have always been based on prediction using measured rain rate as one of the major input parameters. Recently however, few measurement of rain-induced attenuation indicates that predicted rain attenuation often overestimate or underestimate the actual value which usually leads to inaccurate link budgeting. Moreover, when measured attenuation data are even available, it is usually restricted to a particular frequency [2, 4]. The method of frequency scaling comes handy in order to deduce measured rain attenuation at the other frequencies. Consequently, this work attempts to characterize rain specific attenuation at different frequencies using frequency scaling technique, and deduce the level of signal loss to be compensated for during terrestrial and satellite radio propagation.

2. Site and instrumentation

The experimental site is located at the Department of Physics, the Federal University of Technology, Akure, Nigeria. Measurement of radio beacons on EUTELSAT-W4 (geostationary at 36°E) at 12.245 GHz frequency (Ku-Band), with 90cm parabolic antenna using Tektronix Y400 NetTek spectrum analyzer was employed. The received signal level is collected for 24 months (Jan 2017 to Dec 2018) is utilized in this paper. In addition, rainfall rate is concurrently measured using a Vantage Vue automatic weather station at 1- minute interval [7].
3. Theory of Rain Attenuation and Frequency Scaling Technique

Total attenuation, $A$ is determined from the product of specific attenuation, $\gamma_R$ and the effective path length, $L_{eff}$, while the specific attenuation, $\gamma_R$, is acquired from the rain rate, $R$, exceeded at a certain percentage of time, $p$, using power law relationship follows: as :

$$A(dB) = \gamma_R(dB/km) \times L_{eff}(km)$$  \hspace{1cm} (1)

$$\gamma_R(dB/km) = kR^\alpha$$  \hspace{1cm} (2)

where $k$ and $\alpha$ depend on the frequency and polarization of the propagating radio wave [5,6]. It is a common practice to determine attenuation at other time percentage exceedance ranging between 0.001% to 5% via interpolation, using:

$$A_p = A_{0.01} \left( \frac{p}{0.01} \right)^{-(0.655+0.033 \ln(p)-0.045 \ln(A_{1.1})-\beta(1-p) \sin \theta)}$$  \hspace{1cm} (3)

where $\theta$ equals elevation angle, and $\beta$ is a parameter that depends on the location of propagation[5,6].

Similarly, using the Boithias frequency scaling model [6], which provides an empirical expression for a scaling factor that yields attenuation ratio directly as a function of frequency and measured attenuation, given as:

$$A_2 = A_1 \left( \frac{f}{f_0} \right)^{-H(\varphi_1, \varphi_2, \ldots, A)}$$  \hspace{1cm} (4)

$$\varphi(f) = \frac{f^2}{1+10^{-4} f^2}$$  \hspace{1cm} (5)

$$H(\varphi_1, \varphi_2, A) = 1.12 \times 10^{-3} (\varphi_2 / \varphi_1)(\varphi_1, A)^{0.55}$$  \hspace{1cm} (6)

where $\varphi$ is a frequency dependent parameter, $H$ is the frequency and base attenuation dependent parameter. $A_1$ is the measured attenuation and $A_2$ is the predicted attenuation.

Lastly, the path attenuation ($A$, dB) along the propagation column is obtained by calculating the difference between the Received Signal Strength (RSS) during clear sky and rainy conditions for the Ku-band communication links [6], i.e:
\[ A(dB) = RSS_{clear\ sky} - RSS_{rainy} \] (7)

4. Results and discussion
Typical time series analysis of cumulative rain rate measured using Davis Vantage Vue weather station at one minute integration time over the location are presented in Figure 2 (a) and (b) for the years 2017, and combined two-year 2017 and 2018 respectively. The plots also show the time series of the corresponding RSS measured using Tektronix Y400 NetTek spectrum Analyzer, and the computed attenuation obtained from the difference between RSS during clear sky and rainy periods. Appreciable alignment can be observed in the distribution profile of each set of parameters as increase in one reflects increase in the others and vice versa. The same pattern is true for the entire period of the experiment, as well as for diurnal, monthly and seasonal trends. The rain rate values for 2017 (and the combined period) range between 0 mm/hr and 172 mm/hr, (185 mm/hr). Likewise, the RSS values range between about -85 dB and -62 dB for both durations. Consequently, the estimated rain attenuation (path attenuation) range between 0 and 23 dB.

Sub-annual values reflect this pattern, an indication of consistency in the measurement prowess of both instrument and obtained data. This also reflects on the severity of the impact of rain attenuation on signal propagation and the need to develop effective fade mitigation architecture to manage these unavoidable natural phenomena.

Also, Figures 3(a) and (b) show typical complimentary cumulative distribution curves of measured rain rate for year 2017, and the combined years 2017 and 2018 respectively. The curves show the percentage of time exceedance for each value of rain rate for the duration under consideration. It can be deduced for year 2017 that rain rate values of 0.8 mm/hr, 33.8 mm/hr, 110.3 mm/hr and 145.1 mm/hr were exceeded for 1%, 0.1%, 0.01% and 0.001% of the year respectively. While the combined curve returns rain rate values of 2.5 mm/hr, 39.65 mm/hr, 111.8 and 165.4 for the respective exceedance windows. The curves also provide information on the coefficients k and α required for computation of rain specific attenuation (equation 2). It implies that coefficient k is analogous to 26.17 and 33.01, while α is analogous to -1.79 and -1.78 for year 2017 and combined 2017-2018 respectively.
Similarly, a complimentary cumulative distribution analysis was performed on the measured rain attenuation as shown in Figures 4 (a) and (b) which show that attenuation values of 1.47 dB, 5.01 dB, 13.12 dB, and 19.89 dB were exceeded by 1%, 0.1%, 0.01% and 0.001% of year 2017, as against 1.49 dB, 5.03 dB, 13.49 dB, and 19.48 dB for the respective exceedance windows for the combined years.
The percentage exceedance curve for the scaled attenuation from 12.245 GHz to 16 GHz, 20 GHz, 30 GHz and 40 GHz for the two distinct durations is shown in Figure 5, while Figure 6 shows the estimated attenuation for the same frequency bands. Of particular interest is the 0.001% exceedance window in which scaled attenuation values of about 30, 44, 76 and 98 dB were projected for the respective frequency bands; whereas estimated rain attenuation for this exceedance window are about 300, 375, 480 and 516 dB for each of 16, 20, 30 and 40 GHz respectively. While the measured attenuation projects about 20 dB for the 0.001% window, the estimated projects about 218 dB. Such wide margin makes frequency scaling a worthy method that could be adopted.

5. Conclusion
This work has undertaken the characterization of rain specific attenuation and frequency scaling technique for satellite communication over Akure, Nigeria. Time series analysis showed appreciable alignment among measured rain rate, received signal strength, and attenuation, establishing the severe impact of rain on radio communication. Percentage exceedance analysis of measured rain rate and attenuation suggest that a rain
fade allowance of about 13.5 dB is required to ensure that service outage does not exceed 0.01% according to the recommendation of the international telecommunications union (ITU). Lastly, wide margins between attenuation projections of frequency scaling and ITU estimation, establishes the suitability of frequency scaling technique to provide adaptive fade countermeasures, and address inaccurate radio link budgeting.

References
[1] Ojo, J. S., Ajewole, M. O. and Emiliani, L. D., (2009), One-minute rain rate contour maps for microwave-communication-system planning in a tropical country: Nigeria, IEEE Antennas and Propagation, 51 (5), 82–89
[2] Ojo, J. S. and Falodun, S. E., (2012), NECOP propagation experiment: rain rate distributions observations and prediction model comparisons. International Journal of Antenna and Propagation, 12 (12).
[3] Ippolito Jr. L. J., Satellite Communications Systems Engineering: Atmospheric Effects, Satellite Link Design and System Performance, vol.6, John Wiley &Sons, 2008.
[4] Shrestha, S., and Choi, D. Y. (2017). Characterization of rain specific attenuation and frequency scaling method for satellite communication in South Korea. International Journal of Antennas and Propagation, 2017.
[5] ITU-R P.618-13 (2017), Propagation data and prediction methods required for the design of Earth-space telecommunications systems, Recommendation, P Series ITU-R, Int. Telecomm. Union, Geneva.
[6] ITU-R, Specific Attenuation Model for Rain for Use in Prediction Methods, Recommendation P.838-3, ITU-R Recommendations, P Series, International Telecommunications Union, Geneva, Switzerland, 2005.
[7] Ashidi, A., Ojo, J., Adediwi, A., & Ajewole, O. (2021). Development and performance evaluation of tropospheric scintillation model on Ku-band satellite link over Akure, Nigeria. Advances in Space Research, 67(5), 1612-1622.