Evaluation of Concurrent Variation in Rain Specific Attenuation and Tropospheric Amplitude Scintillation Over Akure, Southwest Nigeria

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Received: 1 February 2021 / Revised: 10 May 2021 / Accepted: 11 May 2021 / Published online: 8 June 2021
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Abstract

Rain constitutes a major limitation to the performance and use of terrestrial and satellite communication systems with operational frequencies greater than 10 GHz. The situation gets further complicated by fast fluctuations in the received signal amplitude due to inhomogeneities in atmospheric weather conditions; a phenomenon known as amplitude scintillation. The concurrent evaluation of the two phenomena guarantees a better fade margin determination for the planning of radio communication over any location. This work employs 3 years of in-situ measurement of temperature, humidity, rainfall rate and rainfall amount for the estimation of tropospheric amplitude scintillation and rain specific attenuation over Akure (7.17° N, 5.18° E, 358 m) South West Nigeria. Davis vantage pro weather station at 1-min integration time was used for the measurement and the ITU models for rain specific attenuation (ITU-R P.838-3) and amplitude scintillation (ITU-R 618-13) were employed for the estimation. Time series and statistical analyses of the phenomena show that rain attenuation is the more prominent cause of signal degradation at Ku-band frequencies. Nevertheless, the need to make an extra fade margin allowance of about 0.25 dB due to amplitude scintillation fade subsists to forestall any loss of synchronization on the link. Also, a 3-parameter power-law expression developed for estimating amplitude scintillation fade from rain attenuation performed excellently well, as indicated by average root mean square error (RMSE) and coefficient of determination (R^2) values of 0.002151 and 0.8747, respectively.

Keywords Rain attenuation · Signal scintillation · Fast fluctuations · Signal amplitude · Weather parameters · Tropospheric variables

1 Introduction

The propagation impairments of radio wave signals whose frequencies exceed 10 GHz are predominantly caused by the tropospheric constituents that spread between the Earth's surface and an altitude of about 10–20 km, the vertical extent being lowest at the temperate and highest in the tropical regions (Matricciani et al. 1996; Adediji and Ajewole

2010; Fuwape et al. 2016). Degradations induced in the ionosphere (50–100 km) generally affect frequencies well below 10 GHz, implying that the ionosphere is transparent to radio waves that nears or exceeds 10 GHz in frequency. The major factors affecting earth–space paths in the frequencies above 10 GHz thus include impairment by atmospheric gases, cloud, rain and tropospheric scintillations (Karasawa et al. 1988; Karasawa and Matsudo 1991; Akinwumi et al. 2018). Knowledge of attenuation due to rainfall is crucial when designing satellite links above the stated frequency threshold. Given the current proliferation of satellite communication systems worldwide, continuous study of microwave attenuation by precipitation and other tropospheric constituents in various climatic regions remains necessary.

Studies on propagation impairments in Nigeria have skewed favorably in the direction of rain attenuation, since it is the predominant cause of signal degradation at ultra-high frequencies (UHF) and above in this region. However,

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scintillation becomes important when dealing with low-availability systems, and systems operating at low elevation angles as well as “very small aperture terminals (VSATs)” according to Otung, and Van de Kamp et al. (Otung 1996; Van de Kamp et al. 1999). The cause of tropospheric scintillation can be adduced to small-scale refractive index inhomogeneity, induced by turbulence along the channel of propagation, which results in the received signal amplitude and phase experiencing rapid fluctuations (Haddon and Vilar 1986; Karasawa and Matsudo 1991; Hossain and Samad 2017). Above 10 GHz, intensity of scintillation within the troposphere is reputed to vary directly with carrier frequency and inversely with elevation angle and antenna diameter (Omosho et al. 2016; Ashidi et al. 2021). Fading due to scintillation also poses major challenge to the performance of low-margin communication systems, whose availability over a long period of time is sometimes more predominantly governed by scintillation mechanism than rain attenuation. Moreover, scintillation dynamics may trigger channel interference in tracking and fade-mitigation systems (Otung 1996; Van de Kamp et al. 1999; Ojo et al. 2018).

Tropospheric scintillation is observed under different unique conditions. Turbulence in the lower troposphere can cause random mixing between air masses, resulting in dry scintillation or clear-air scintillation i.e., when the air is not saturated with water vapor. But when the air does get saturated with water vapor, it leads to cloud formation. As these clouds move within the propagation channel it results in scintillation at the boundaries of the cloud and the clear atmosphere. Since this type of scintillation involves air already saturated with water vapor, it is referred to as wet/moist air scintillation (Cox et al. 1981). Also, the condensation of cloud droplets gives rise to rainfall within the propagation channel, and variation in rainfall within the channel leads to signal fluctuations which results in another source of scintillation (Otung and Mahmoud 1996). All variations in signal due to scintillation usually last for a period of few seconds irrespective of the underlying cause. This forms the basis for differentiating scintillation from slow-fading rain attenuation events which are known to last for periods of several minutes (Ashidi 2020). Furthermore, unlike rain fading, scintillation is not a lossy process. In scintillation, the propagating signal fluctuates above (enhancement) and below (fading) the mean signal level, but the average signal level over time remains unchanged. Although scintillation phenomenon is experienced simultaneously with rain attenuation during rain events, yet both phenomena are caused by different mechanisms (Karasawa and Matsudo 1991). While scintillation is the product of turbulence in the mixing of different air masses and randomly distributed scatterers within the troposphere, rain attenuation can be

attributed to absorption and scattering of electromagnetic energy by liquid raindrops (Karasawa et al. 1988; Semire et al. 2012; Ojo et al. 2018). Concurrent evaluation of rain specific attenuation and amplitude scintillation for satellite link design is the crux of this study. Many studies have been carried out on each of rain attenuation and amplitude scintillation in isolation; as well as the simultaneous occurrence of both phenomena. Some of such works in this region include Ajewole et al. (1999a, b, c); which conducted theoretical calculations of attenuation and depolarization parameters for frequencies between 1 and 100 GHz using the four tropical rainfall regimes. Other works which understudied the characterization of rain and its effects on the propagation of radio waves include Ojo et al. (2008) as well as Ojo and Falodun (2012). Omosho and Oluwafemi (2009a, b) and Semire et al. (2011) also converted archived daily and hourly data into one-minute data and derived useful attenuation parameters for NIG-COMSAT-1R. Ojo et al. (2009) also produced the cumulative distribution of rainfall exceedance and rain rate contour maps for Nigeria. Several studies on tropospheric amplitude scintillation on satellite link have been done such as Haddon and Vilar (1986); Otung (1996); Singh and Hassan (2003); Van de Kamp et al. (1997); Van de Kamp (1998); Van de Kamp et al. (1999); Yu et al. (2006); Banjo and Vilar (1986); Mousley and Vilar (1982); Vilar and Haddon (1984); and Karasawa et al. (1988). These and other studies have led to many proposed prediction models. The dependence of scintillation on local climatology and link factors—frequency, elevation angle and antenna diameter, have also been reported by Mousley and Vilar (1982), Otung (1996), Van de Kamp et al. (1999), Singh and Hassan (2003), Hossain and Samad (2017) and so on. With regards to the concurrent study of rain attenuation and scintillation, Otung and Mahmoud (1996) examined rain-induced scintillation on satellite downlinks using the experimental setup at Sparsholt, UK. The result showed that heavy rain produces both large attenuation and large amplitude scintillation. Matriciani et al. (1996) equally investigated the relationship between averaged rain attenuation (A) and standard deviation of tropospheric scintillation in 1 s intervals. The data were derived from high-resolution experimental setup at 19.77 GHz in Spino d’Adda (45.4°N), at 30.6° slant path to the Olympus for an observation time of approximately 1 year. The authors reported that a relationship between scintillation and rain attenuation, suitably separated, can be fitted by the power law: $\sigma = 0.0391A^{5/12}$; a formula derivable from a turbulent-thin layer model.

However, only few works on tropospheric amplitude scintillation have been reported from Nigeria due to dearth of data, these include but not limited to—characterization of Ku-band amplitude scintillation on Earth-space path over

Akure, SW Nigeria (Ashidi 2020; Ashidi et al. 2017, 2020, 2021), experimental analysis and comparison of tropospheric scintillation prediction models in tropical Nigeria (Ojo et al. 2018), analysis and comparison of tropospheric scintillation prediction models at Covenant University (Akinwumi et al. 2018), and prediction of tropospheric scintillation over some selected locations in Nigeria (Adebo and Akindugbagbe 2019). Locally, no study has been reported on the concurrent evaluation of rain attenuation with amplitude scintillation. Consequently, this study employed measured meteorological parameters, including rainfall rate, surface temperature and relative humidity, to investigate the distribution and severity of simultaneously occurring rain specific attenuation and amplitude scintillation.

2 Methodology

2.1 Scope of Data and Study Location

The measurement site is located within the Federal University of Technology, Akure (7.17° N, 5.18° E, 358 m), Nigeria. It can be categorized as a tropical climate which

is characterized by dry and rainy seasons occurring yearly between November and March; and April and October, respectively. The dry season is synonymous with high temperature and humidity while the rainy period experiences all categories of rain in abundant proportions. The average annual rainfall in Akure is about 1455 mm. This climate varies significantly from those of temperate regions where the annual average temperature is moderate, though temperature can vary rapidly within the year. The climatic uniqueness of individual location must be accorded due consideration for high precision (low percentage signal outage) communication link to be achieved. It is against this background that the concurrent evaluation of rain specific attenuation and amplitude scintillation for this location is being undertaken. The geographical map of Akure located within Ondo State, Nigeria is indicated in Fig. 1.

Measurement of meteorological/radio-climatic variables that include rainfall amount, rainfall rate, temperature, relative humidity, dew point, wind speed, heat index, pressure, solar radiation, ultraviolet index and evapo-transpiration (ET) among others—was carried out every day from January 2013 to December 2015 at one minute integration time. The data were archived

Fig. 1 Geolocation of the study location showing maps of **a** Nigeria; **b** Ondo State; and **c** Akure

in the repository of the Communications Research Group, Department of Physics, Federal University of Technology, Akure. The equipment used for the measurement is the Davis Vantage Vue wireless weather station equipped with an integrated sensor suite (ISS). The ISS consists of various weather instruments integrated into one. A PN junction diode serves as the temperature sensor while relative humidity is captured by a film capacitor element. The precipitation measuring device is a tipping spoon type, unstably balanced spool-like assembly seated at the base of a conical funnel with a collection area of 116 cm² rain collector (Adediji and Ajewole 2008, 2010; Adediji et al. 2015; Ashidi et al. 2019 and Kayode et al. 2019). Contemporaneous data of rain rate, temperature and humidity were extracted for the computation of rain specific attenuation and scintillation fade using ITU-R models.

2.2 Computation of Attenuation and Scintillation

2.2.1 Rain Specific Attenuation

Estimation of rain specific attenuation and scintillation fade was made following ITU recommendations as stipulated in ITU-R P.838-3 and ITU-R 618-13, respectively. A synopsis of some important terms and expressions for the estimation of the rain specific attenuation are presented as follows:

Recommendation of the radio unit of the international telecommunication union (ITU-R) allows the 0.01 percentage exceedance rain attenuation ($A_{0.01}$) to be computed using equivalent rain specific attenuation, $\gamma_{R(0.01)}$, which is determined from corresponding rainfall rate, $R_{0.01}$, according to ITU-R (2003, 2015, 2017):

$$A_{0.01} = \gamma_{R(0.01)} L_E \text{ (dB)}, \quad (1)$$

Fig. 2 Mutual occurrence of estimated rain specific attenuation and scintillation intensity events for **a** 2013; **b** 2014; and **c** 2015

Table 1 Descriptive statistics of scintillation fade and rain specific attenuation

Descriptive statistics	Scintillation fade (dB)			Rain specific attenuation (dB)		
	2013	2014	2015	2013	2014	2015
Average	0.244	0.246	0.245	0.343	0.297	0.392
Standard error	$1.5e^{-4}$	$5.0e^{-5}$	$6.8e^{-5}$	0.021	0.007	0.011
Median value	0.246	0.248	0.247	0.054	0.054	0.060
Modal value	0.251	0.250	0.249	0.019	0.019	0.019
Standard deviation	0.007	0.006	0.006	0.947	0.809	0.941
Variance	0.000	0.000	0.000	0.897	0.654	0.885
Range of values	0.036	0.046	0.046	9.866	9.903	9.217
Minimum value	0.216	0.207	0.206	0.019	0.019	0.019
Maximum value	0.252	0.252	0.253	9.885	9.921	9.236
Summation	493.674	3076.256	1942.332	692.573	3712.756	3108.273
Sample count	4021.000	12,493.000	7927.000	2021.000	12,493.000	7927.000

where L_E represents the effective path length, and $\gamma_{R(0.01)}$ is given as:

$$\gamma_{R(0.01)} = k(R_{0.01})^\alpha \text{ (dB/km)}, \quad (2)$$

where k and α represent frequency- and polarization-dependent coefficients for calculating rain specific attenuation (ITU-R, 2017). It is then possible to estimate attenuation exceedance for other time percentages in the range 0.001%–5%, of a duration, from the determined 0.01% window using:

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

θ represents the angle of elevation (53°), while β is a location-dependent parameter. Details of the stepwise determination of parameters L_E and β are given in (ITU-R 2017).

However, it is possible to evaluate the concurrent variation in rain attenuation and amplitude scintillation from the computed time series values of rain specific attenuation (γ_R), determined from rainfall rate, R , as ($\gamma_R = kR^\alpha$) and scintillation amplitude standard deviation (otherwise known as scintillation intensity, σ_χ) according to ITU-R (2003, 2015).

2.2.2 Scintillation Fade

Similarly, the stepwise determination of amplitude scintillation is articulated in ITU-R 618-13; while a synopsis of key terms and expressions are stated as follows:

$$\sigma_{pre} = \frac{\sigma_{ref} \cdot f^{7/12} \cdot g(x)}{(\sin \theta)^{1.2}}, \quad (4)$$

where

$$\sigma_{ref} = 3.6 \times 10^{-3} + N_{wet} \times 10^{-4}, \quad (5)$$

$$g(x) = \sqrt{3.86(x^2 + 1)^{11/12} \times \sin \left[\frac{11}{6} \arctan \left(\frac{1}{x} \right) \right] - 7.08x^{5/6}}, \quad (6)$$

$$a(p) = \sigma_{pre}(-0.06(\log p)^3 + 0.072(\log p)^2 - 1.71 \log p + 3.0), \quad (7)$$

$$As(p) = a(p) \cdot \sigma_{pre}, \quad (8)$$

for $0.01 \leq p \leq 50$

$$N_{wet} = \frac{3.732H \cdot e_s}{(273 + T)^2}, \quad (9)$$

and

$$e_s = 6.1121 \cdot \exp \left(\frac{17.502T}{(T + 240.97)} \right), \quad (10)$$

where σ_{pre} and σ_{ref} represent the predicted scintillation intensity and its weather dependent component respectively. Parameters f , N_{wet} , $g(x)$, and $a(p)$ represent the operating frequency (12.245 GHz), wet term of radio refractivity, antenna gain factor and percentage of time (p) exceedance factor respectively. T , H and e_s represent temperature, humidity and saturated water vapour pressure respectively.

Fig. 3 pdf of estimated rain specific attenuation fitted to lognormal model for **a** 2013; **b** 2014; and **c** 2015

2.2.3 Combined Effects of Tropospheric Scintillation and Rain Attenuations

To evaluate the concurrent effect of tropospheric scintillation and rain specific attenuation on signal degradation at a Ku-band frequency using ITU-R P.618-12 2015 we follow the step below:

$$A_T(p) = \sqrt{A_R^2(p) + A_S^2(p)}, \quad (11)$$

where $A_T(p)$, $A_R(p)$, and $A_S(p)$ represent combined attenuation effect; rain specific attenuation effect, and attenuation due to scintillation fade.

3 Result and Discussion

3.1 Time Series Analysis and Statistics of Attenuation and Scintillation

The time series plots of mutually occurring of rain specific attenuation and signal scintillation are shown in Fig. 2a–c for the years 2013–2015 respectively. It can be seen from the plots that strong rain specific attenuation events occurred simultaneously with “strong” scintillation fade events just as periods of weak attenuation regimes coincide with periods of quiet scintillation fade regimes. This implies that the propagating radio signal will simultaneously experience significant reduction in quality due to rain attenuation, and loss of synchronization at the receiving

Fig. 4 pdf of estimated scintillation fade fitted to Weibull model for **a** 2013; **b** 2014; and **c** 2015

point due to scintillation. Hence system designs and fade mitigation techniques (FMTs) must make additional provision to counter the effect of signal scintillation during raining events. Another important deduction from the time series analysis and summary of descriptive statistics table (Table 1) is the difference in magnitude of rain specific attenuation statistics and that of scintillation fades. For instance, while maximum values of rain specific attenuation recorded are as high as 9.8 dB, 9.9 dB and 9.2 dB for 2013, 2014 and 2015, respectively; those of scintillation fades are 0.2516 dB, 0.2524 dB and 0.2527 dB for the same period of observation. Similarly, the range for rain specific attenuation is 9.8, 9.9 and 9.2 for the respective years as against 0.036, 0.046 and 0.046 for scintillation fade. A similar pattern is observed for the standard error, standard

deviation and sample variance of the two parameters. However, while the statistics of the scintillation fade appear to be comparatively of little or no arithmetic significance, fast fluctuations of such magnitude are very much sufficient to cause severe loss of synchronization on communication systems particularly for low margin, high accuracy and precision digital systems. Especially since the signal quality must have been severely degraded by rain impairments. It is also noteworthy that the modal occurrence of rain specific attenuation for the respective years averaged 0.19 while that of scintillation fade averaged 0.25. This shows that scintillation fade phenomenon observed during occurrence of modal raining events is of higher magnitude than rain attenuation; an observation that is consistent throughout the period of the study.

Fig. 5 pdf of combined attenuation fitted to lognormal model for **a** 2013; **b** 2014; and **c** 2015

3.2 Probability Density Function of Rain Specific Attenuation and Scintillation Fade

Atmospheric variables that affect radio propagation are usually random spatial–temporal functions. It is therefore standard practice to quantify and analyze the propagation phenomena arising from such variables, like rain specific attenuation and scintillation fade, using statistical models. One method of specifying these statistical models is usually through a probability density function (pdf), $p(x)$. It presents the probability of determining variable x between $x - \frac{1}{2}dx$ and $x + \frac{1}{2}dx$ as a function that can be expressed as $p(x)dx$

(Otung 1996). Figures 3, 4 and 5 show the histogram plots of estimated rain specific attenuation, scintillation fade and combined rain attenuation and scintillation fade, for years 2013–2015. As indicated, the scintillation fade histogram was best fitted to a Weibull distribution model, while the estimated rain specific attenuation as well as the combined rain attenuation and scintillation fade plots, were best fitted to lognormal distribution pdfs.

This implies that while scintillation fade phenomenon during raining events can be characterized individually and suitably by a Weibull pdf; and rain attenuation by lognormal pdf; the combined effects can best be characterized

Fig. 6 Estimated rain specific attenuation and scintillation fade for **a** 2013; **b** 2014; and **c** 2015

by Lognormal model. This is most likely an affirmation of the fact that rain-induced scintillation phenomenon is often suppressed under rain attenuation (Karasawa et al. 1991; Otung and Mahmoud 1996). The distribution parameters and fit statistics for the different models are shown in Table 2. The scale and shape parameters of the models (μ and σ for lognormal; and A and B for the Weibull) are indicators of the goodness of the different fits. The low values of their respective standard errors indicate

the suitability of the propagation phenomenon to be characterized by these models with minimal error margins (Van de Kamp et al. 1997; Singh and Hassan 2003). Also, the fact that the distribution parameters for the estimated rain specific attenuation were marginally higher than those of the combined phenomenon, despite the former having comparatively lower values; suggests that the combined attenuation–scintillation phenomenon can be best characterized by the lognormal pdf.

Fig. 7 Power law model development for estimation of scintillation fade from rain specific attenuation in **a** 2013; **b** 2014; and **c** 2015

3.3 Modeling of Scintillation Fade from Rain Specific Attenuation

Adequate allowance for mitigating simultaneously occurring rain specific attenuation and rain-induced scintillation fade requires a model that describes the magnitude of the latter in terms of the former. Such factors can thereafter be inculcated into any of the desired/appropriate fade mitigation techniques (FMTs) to ensure improved system performance. As mentioned earlier, the atmospheric variables which affect radio propagation, and their respective impairments, are usually observed as random functions in space and time. This observation is depicted in Fig. 6a–c being the plots of the relative occurrence of estimated rain specific attenuation and scintillation fade for the years 2013–2015 respectively. Although it can be established that occurrence of high rain attenuation values coincide with high scintillation fade values significantly (Matricciani et al. 1996; Otung and Mahmoud 1996), yet instances abound where the converse is true. There are

many instances as well where no definite pattern can be identified. This observation is valid for both year 2013, in which relatively lower amount of rainy events was captured, and the other two years with comparatively higher rainfall amounts. This implies uniformity in the annual distribution pattern of simultaneously occurring rain specific attenuation and scintillation fade. To develop the requisite model for rain attenuation/scintillation fade characterization, each of the estimated rain specific attenuation and scintillation fade dataset was subjected to smoothing technique; and an empirical model was developed to characterize rain specific attenuation in terms of scintillation fade. A power law model of the form ($A_s = aA_R^b + c$) was developed as shown in Fig. 7; where A_s and A_R represent attenuation due to scintillation and rain respectively; while a , b and c are constants. The model parameters for this function are as indicated in Table 3. From the Table, the sum of square error (SSE) as well as root mean square error (RMSE) values are significantly low, while the coefficient of determination (R-square) and adjusted R-square values are significantly high;

Table 2 Distribution parameters and fit statistics for the pdf models

Year/parameters	2013	2014	2015
Lognormal–rain attenuation (dB)			
Mean	0.251032	0.198701	0.293411
Variance	0.665762	0.217368	0.726321
Mu	− 2.32511	− 2.55228	− 2.34849
Sigma	1.47702	1.36845	1.49821
StdErr (mu)	0.0183145	0.0122432	0.0168274
StdErr (sigma)	0.0129518	0.0086578	0.0118999
Weibull–scintillation intensity (dB)			
Mean	0.244551	0.24654	0.245335
Variance	3.33e-05	1.86e-05	2.15e-05
A (scale)	0.247125	0.248469	0.247409
B (shape)	53.6716	72.626	67.1244
StdErr (A)	0.0001069	3.18e-05	4.30e-05
StdErr (B)	1.00782	0.560123	0.645614
Lognormal–combined rain and scintillation effect (dB)			
Mean	0.41999	0.3968	0.46289
Variance	0.09955	0.07396	0.1438
mu	− 1.09129	− 1.11686	− 1.0276
Sigma	0.66896	0.62055	0.71659
StdErr (mu)	0.01488	0.00555	0.00804
StdErr (sigma)	0.01052	0.00392	0.00569

Table 3 Model parameters for the power law expression

Year/parameters	2013	2014	2015
Model coefficients			
a	-2.008×10^{-5}	-1.662×10^{-6}	-3.461×10^{-6}
b	− 1.722	− 2.29	− 2.134
c	0.251	0.25	0.2493
Goodness of fit			
SSE	0.08082	0.06136	0.03963
R-square	0.9131	0.8474	0.8636
Adj R-square	0.9131	0.8474	0.8635
RMSE:	0.002001	0.002216	0.002236

proving the suitability and dependability of the model. Upon averaging, the suitable expression for this location becomes:

$$A_s = -8.40 \times 10^{-6} A_R^{-2.0487} + 0.2501. \quad (12)$$

4 Conclusion

The magnitude and distribution of the cumulative effect, in which simultaneous occurrence of rain specific attenuation and amplitude scintillation pose to the quality of signal in the Ku-band frequency range have been examined in this

study. The recommendations of ITU-R P.618-13 and P.838-3, were adopted for estimating rain specific attenuation from measured rain rate data, and scintillation fade from measured temperature and relative humidity. Time series analysis of each phenomenon revealed significant alignment in the occurrence of strong rain specific attenuation and amplitude scintillation as well as the occurrence of their weak regimes. Also probability density function (pdf) analyses revealed that while rain specific attenuation and scintillation fade can be suitably modeled individually by lognormal and Weibull pdfs respectively; the combined effect can best be described by a lognormal pdf. This observation established the fact that scintillation events are often suppressed under rain attenuation when both occur simultaneously; notwithstanding the fact that rain attenuation is by far more severe radio propagation impairment mechanism. Finally, a 3-parameter power law model was found suitable for determining the magnitude of scintillation fade from rain specific attenuation through low root mean square error (RMSE) and sum of square error (SSE) values, and high coefficient of determination (R^2) values. In all, the magnitude of scintillation fade may appear numerically negligible relative to rain specific attenuation, it nonetheless must be factored into any operational fade mitigation techniques (FMTs) to eliminate frequent loss of synchronization of signals due to amplitude scintillation during satellite and/or terrestrial radio propagation.

Acknowledgements The authors are grateful to the Communications Research Group, Department of Physics, Federal University of Technology, Akure, for the enabling environment to conduct this research.

Funding The authors did not receive support from any organization for the submitted work.

Availability of data and materials Data that support the findings in this study are available upon reasonable request from the authors.

Code availability Codes that support the findings in this study are available upon reasonable request from the authors.

Declarations

Conflict of interests The authors have no conflicts of interest to declare that are relevant to the content of this article.

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