

## RESEARCH PHYSICS-BASED RAINFALL ENVIRONMENT EMULATION FOR RADIO WAVE ATTENUATION STUDIES USING MULTI- PARAMETER TIME SERIES DATA

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### Keywords

Rain attenuation; radio propagation; rainfall emulation; time-series data; physics-informed modelling; millimetre-wave communication.

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### Abstract

**Background:** At microwave and millimeter-wave frequencies, rain affects radio signals with the effects of absorption, scattering and depolarization. The traditional models of attenuation typically assume that the rain rate is the dominant factor, and fail to fully capture the effect of drop size, wind, the atmosphere and surface wetting on the attenuation phenomenon.

**Objective:** This study aimed to create and validate an emulator that simulates the rain conditions from the physics-based rainfall data in the form of multiple time series components to study radio-wave attenuation.

**Experimental Design:** Quantitative experimental design. The controlled rainfall rates were created ranging from 5 to 150 mm h<sup>-1</sup> for radio links ranging from 10 to 60 GHz. The following data was synchronously recorded: Rain rate, drop size distribution, wind speed, temperature, humidity, received power, signal to noise ratio, bit error rate and attenuation. Various models, including statistical models, time-series models, conventional physical models, machine-learning models and a hybrid model combining conventional physics and machine learning were tested.

**Results:** The uniformity of rainfall and the ability to replicate the programmed rainfall was produced from the emulator. The relationship between the rainfall intensity, frequency, path length and the diameter of the rain drops with the attenuation was found to be non-linear. When the rainfall was heavy it caused the RPR to decrease, SNR to decrease and BER to increase and packet loss to increase. The hybrid model performed best in predicting and most closely simulating attenuation peaks, fade durations and the time it takes for the recovery after rain compared to comparison models.

**Conclusions:** Combining the physics of rain with multi-parameter temporal modelling was a repeatable way to assess the performance of rain-affected satellite, 5G and 6G links.

## Introduction

Radio communication systems operating above 10 GHz are of great value due to the rapidly growing satellite, terrestrial microwave, fifth generation (5G) and emerging sixth generation (6G) communication systems. However, these high frequency bands provide higher bandwidth, higher data capacity, smaller antennas and higher spectral efficiency, but the wavelength is of the same order of magnitude as the size of hydrometeors in the atmosphere which can cause absorption and scattering in the presence of rain. The significance of the rain attenuation is especially notable for Ku-, Ka-, V-, E- bands and terahertz bands and can result in a reduction of received power, a higher bit error rate, lower carrier-to-noise ratio (C/N) and temporary link outage. This phenomenon is more pronounced in tropical and equatorial regions where the convective storms are more intense having a high number of large raindrops (Samad et al., 2021). In addition to the average rain rate, the rain's elevation angle, polarization, operating frequency, propagation distance, rain-cell structure and local climatology are also found to influence rain attenuation in satellite observations. (Kalluru et al., 2023) However, in order to obtain a realistic experimental environment, the temporal and spatial dynamics between these variables must be simulated rather than rainfall assumed to be spatially uniform or a constant. Rainfall environment emulation can be realized in a physics-based way to insure repeatable rainfall environments while maintaining the environmental dynamics needed for radio-wave attenuation studies.

A commonly used model for the relationship between rainfall and electromagnetic-wave attenuation is a power-law relationship:

$$\gamma R(t) = k[f, p, T, D(t)]R(t)\alpha[f, p, T, D(t)]$$

In this, ( $\gamma_R(t)$ ) is the rain attenuation per unit of path length in  $dB\ km^{-1}$ ,  $R(t)$  is the time varying rain rate (in  $mm\ h^{-1}$ ,  $f$  is the operating frequency,  $p$  is the polarization,  $T$  is the temperature, and  $(D(t))$  is the time varying raindrop size distribution. Coefficient  $k$  and  $\alpha$  are parameters of the frequency and polarization

dependence of the interaction between electromagnetic energy and liquid-water particles. The total path attenuation can then be determined as:

$$AR(t) = \int_0^L \gamma R(s, t) ds \approx \gamma R(t) L_{eff}(t)$$

Where,  $L$  is the propagation path in space and  $L_{eff}(t)$  is the rainy-path length in space, taking into account randomness in propagation. Empirical data gathered from the tropical satellite link shows that the behaviour of specific attenuation and frequency scaling are highly dependent on precipitation characteristics in the area of interest (Toriola et al., 2021). Likewise, two rain events, with the same rain rates, have been found to produce different attenuations due to the difference in drop-size distributions (DSD) as measured at Ka-band (De & Maitra, 2024). Hence, only the rain rate is not sufficient to be used to make a physically complete representation of the propagation environment and an emulator should incorporate simultaneous observations of the rain rate, drop diameter, drop concentration, temperature, humidity, wind, water-film formation and received-signal behavior.

The rainfall is fundamentally non-stationary, intermittent, and multi-scale, which evolves over onset, growth, peak, decay and dry periods. A rainfall emulator must then be able to simulate temporal correlation and event transitions that are commonly found in real rainfalls, not to produce samples that are unrelated to what is found in the rainfall series. The multi-parameter environmental state is given by for a sampling interval  $\Delta t$ .

$$x_t = [R_t, D_{m,t}, N_{0,t}, v_t, T_t, H_t, P_t, W_t, \theta_t]T$$

The  $D_m$  mass-weighted mean drop diameter, the drop concentration  $N_0$ , the terminal velocity  $v$ , the relative humidity  $H$ , the atmospheric pressure  $P$ , the wind speed  $W$  and the angle of elevation of the links ( $\theta$ ) of the link line. The radio response corresponding to this is represented as a matrix  $y_t = [A_t, P_{r,t}, SNR_t, BER_t]T$  containing the attenuation, received power, signal-to-noise ratio and bit-error rate. Tomaz et al. (2023) showed that the time series of the rain attenuation for LEO links must contain both the time series

characteristics of rainfall and the path elevation characteristics of the satellite. The study of dynamic resource allocation has also shown that the satellite beam scheduling and system capacity is significantly affected by the rain attenuation, which varies with time (Zhang et al., 2021). The results confirm the feasibility of synchronized time-series acquisition and closed-loop control to ensure that the rainfall input (emulated) and the RF response stay in time.

The rain simulation system could consist of a pressurized water delivery system, calibrated nozzles or droplet generators, flow-control valves, wind production devices, environmental sensors, disdrometers, rain gaugers and a radio transmitter-receiver link. The rainfall rate to be imposed can be estimated by some of the following methods:

$$R(t) = \frac{3600}{A_c \Delta t} = \sum_{i=1}^{n(t)} \frac{\pi D_i^3}{6},$$

Where,  $A_c$  denotes the area of the sensor collecting the drop and  $D_i$  is the size of the  $i$ th detected drop. The drop-size spectrum can be fit by a normalized gamma distribution as

$$N(D, t) = N_{0,t} D^{\mu_t} \exp[-\Lambda_t D],$$

Where, the parameter  $\mu_t$  is related to the shape of the spectrum, and the parameter  $\Lambda_t$  to the slope of the distribution. Wind is also a factor that should be controlled as it alters drop trajectories, the effectiveness of paths intersecting, antenna wetting and spatial variability of rainfall. Observations during typhoons have revealed that the measured satellite rain-attenuation characteristics and their relationship with the rainfall intensity could be affected by the typhoon wind velocity (Maekawa & Shibagaki, 2022). Rainfall rate and resultant rainfall signal losses have also been shown to be significantly variable in terms of climate in long-path and regional investigations (Ibitokun et al., 2023; Ukommi et al., 2024). Therefore, the use of a single global rainfall profile as a representation of all propagation conditions is not sufficient and should be replaced by statistics of the local or regionally representative rainfall.

The attenuation of radio wave degradation needs to be not only considered as a result of the degradation but also the effect of the degradation on the system. Measured attenuation can be calculated using either of the following:

$$A_{meas}(t) = 10 \log_{10} \left[ \frac{P_{r,0}}{P_r(t)} \right],$$

Where,  $P_{r,0}$  is the power under dry conditions.

The received power at any moment in time can be shown as

$$P_r(t) = P_t + G_t + G_r - L_{FS} - L_{sys} - A_R(t) - A_w(t),$$

in which the gains of the antennas are  $G_t$  and  $G_r$ , the free space path loss is  $L_{FS}$ , and the other losses are included in this term as  $L_{sys}$ . while the attenuation due to water films on the antennas or radomes is  $A_w(t)$ . Some previous studies have been conducted on hybrid-channel investigations, which have revealed that the impact of rainfall loss on the performance of non-orthogonal multiple-access (NOMA) satellite systems with low Earth orbits (LEOs) is significant (Ning et al., 2022). The impact of intensity and frequency of rain on link-budget parameters such as carrier to noise density and bit-error performance (Romadhona et al., 2025) has also been found to be true in the field. An antenna wetting effect, which may cause extra losses in addition to the losses from the rain volume, has been studied for superhydrophobic radome coatings to reduce the rain-related signal degradations (Wei et al., 2023). Therefore, a rigorous emulator should be able to distinguish between the atmospheric-path attenuation and wet-antenna or wet-radome effects by the use of dedicated sensors and dry-reference measurements or by performing controlled surface-wetting tests. To establish a relationship between emulated environmental states and radio-channel responses, a computational structure based on multi-parameter time-series modelling is needed. A hybrid model which combines physics with intelligence can be expressed as:

$$A_t = A_{phys}(x_t; \phi) + g_\theta(x_{t-m:t}) + \varepsilon_t,$$

Where,  $A_{phys}$  is the attenuation predicted based on known scattering and propagation physics,  $g_\theta$  is a data driven residual model based on a previous set of  $(m)$  observations,  $\phi$  represents physical

parameters and  $\varepsilon_t$  represents measurement error. The formulation enables the physical model to impose plausible behavior, while machine-learning parts of the model account for the local nonlinearities, delayed wetting effects, sensor interactions and un-modelled temporal dependencies. Machine learning rainfall prediction techniques have recently been shown to be feasible when paired with an attenuation estimation technique based on satellite measurements derived from rainfall (Sodunke et al., 2025), in the tropics. Some information about rainfall can also be derived from opportunistic exploiting the downlink attenuation records from the satellite, which suggests the existence of a bidirectional relationship between the two, such that information about rainfall can be used to predict downlink attenuation, and vice versa (Giannetti & Reggiannini, 2021). Another significant modelling aspect is frequency transfer: a simultaneous Ku- and Ka-band observation has been investigated to study the frequency band scaling of attenuation (Maekawa & Yamashita, 2025); the instantaneous frequency scaling approaches can take advantage of the measurement performed on a single or multiple satellite link, allowing for the study of the frequency band scaling of attenuation (Capelletti & Luini, 2025). These methods offer a starting point to build up multi-temporal synthetic scenarios at multiple operating frequencies without breaking the physics of propagation. The point wise attenuation and the statistical structure of natural rain events should be validated. Any suitable error criteria can be used, such as root-mean-square error.

$$RMSE = N1t = \frac{1}{N} \sum_{t=1}^N (A_t - \hat{A}_t)^2,$$

The mean absolute error, correlation coefficient, bias, complementary cumulative distribution function, fade-duration distribution, attenuation slope, auto-correlation function and cross-correlation function between the environmental parameters and radio responses. The validation should include unseen rain events, various rainfall regimes, various frequencies, various polarizations

(both horizontal and vertical), various path lengths, as well as varying elevation angles. The results of the site-diversity research show that geographically separated links (GSPL) experience the joint attenuation both due to the rainfall-front type and spatial separation (Maekawa et al., 2025). There are also large inter-annual and extreme rainfall fluctuations seen from the long-term measurements; these should also be taken into consideration in developing representative test scenarios (Karasawa, 2025). In addition, it is found that the attenuation characteristics are related to the direction of the satellite and rain-field geometry (Azimuth dependent diversity measurements) (Maekawa, 2026). For tropical applications, the differences in the scaling of Ku-, Ka- and millimetre-wave losses are better fit with enhanced scaling formulations as compared to a single fixed ratio transformation (Suhaimi et al., 2026). The emulator should then be evaluated not just for matching mean (intensity) rainfall, but also for preserving the temporal sequences, cross-variable dependence, and propagation outcomes. The emulator should, therefore, be evaluated for preserving marginal distributions, temporal sequences, and cross-variable dependence as well as propagation outcomes.

While some of these models have proven helpful for long-term prediction, they are limited to use of 1-minute rainfall statistics, spatially averaged inputs, fixed path geometry, or use of environmental variables separately, rather than in combination with one another, limiting their ability to capture the rapid changes and coupled mechanisms of individual rain events (Samad et al., 2021; Tomaz et al., 2023). Comparative measurements indicate that size of rain cells, effective path length, regional rainfall structure, and the propagation model adopted (Kalluru et al., 2023) are still factors affecting the attenuation predictions, and multi-band observations confirm that it is important to use a set of frequency responses that are generated at the same time (Maekawa & Yamashita, 2025). This study aims to fill this void of a well validated physics-based rainfall-emulation framework that can simulate the simultaneous, non-linear and time-dependent

interaction of various meteorological parameters with radio-wave attenuation at various frequencies and propagation scenarios. The importance of the study is to take the next step in providing a repeatable, physically interpretable test environment that can aid in validating link budgets, designing fade mitigation, enabling adaptive communication, evaluating equipment or climate-resilient development of satellite, 5G and future 6G systems. The goal of the study is to create and validate a physics-based rainfall-environment emulator, which, using multi-parameter time-series data, can produce realistic rainfalls and calculate the amount of radio-wave attenuation and performance degradation to a communication link.

## Method

### Research Design and Experimental Setup

A quantitative experimental and modelling study was used to design and validate a physics based rainfall-environment emulator to study radio-wave attenuation under controlled/repeatable conditions. The experimental setup was a programmable rainfall chamber/ open testbed with a water delivery system for pressurized water, a variable speed pump, calibrated full cone nozzles, flow control valves, overhead nozzle array, water reservoir, water filtration system, water drainage system and controllable fans to generate wind driven rainfall. A line-of-sight radio link between a signal generator attached to a transmitting antenna and a receiving antenna attached to a spectrum analyser, power meter, channel sounder or software-defined radio (SDR) was set up. Experiments were made at a number of the microwave and millimetre-wave frequencies available with the equipment (including 10, 18, 28, 38 and 60 GHz) and with both horizontal and vertical polarization and propagation distances. The rainfall conditions were a dry reference and rain rates of  $\sim 5, 10, 25, 50, 75, 100$ , and  $150 \text{ mm h}^{-1}$  which corresponds to light to extreme rainfall. A dry-reference was made before each experimental condition and the experiment was repeated at least three times for each condition, each time in a different order to reduce the

systematic error. Independent variables were: Rain rate, Operating frequency, Polarization, Path length, Wind speed, temperature, relative humidity, atmospheric pressure and raindrop-size distribution; Dependent variables were: Received signal power, Attenuation, Signal-to-noise ratio, Carrier-to-noise ratio, Delay spread, Packet loss, Bit-error rate. The parameters were investigated together since the rainfall rate, rainfall frequency, polarization, drop-size distribution and propagation geometry all had an impact on rain attenuation (De & Maitra, 2024; Kalluru et al., 2023; Samad et al., 2021). The specific attenuation was calculated as  $\gamma R(t) = kR(t)\alpha$  and  $AR(t) = \gamma R(t)L_{\text{eff}}(t)$ . Where,  $\gamma R$  was the specific attenuation  $\text{dB km}^{-1}$ ,  $R$  was the rain rate  $\text{mm h}^{-1}$ ,  $k$  and  $\alpha$  were the frequency- and polarization-dependent coefficients, and  $L_{\text{eff}}$  was the effective rainy-path length.

### Data Collection and Processing

Measurements of the environment and radio-frequency were taken in time-series recordings, synchronously. Rainfall intensity was measured with a calibrated tipping-bucket or a weighing rain gauge and the individual drop diameter, drop fall velocity, drop concentration and drop-size distribution were measured with an optical disdrometer. The following parameters were measured by using calibrated environmental sensors: temperature, relative humidity, atmospheric pressure, water-flow rate, nozzle pressure, surface-wetting conditions and wind speed and direction. The time-dependent vector of environmental inputs was  $x_t = [R_t, D_{m,t}, N_{0,t}, v_t, T_t, H_t, P_t, W_t, f, p, L]^T$  and the vector of responses of the radio was  $y_t = [A_t, P_{r,t}, \text{SNR}_t, \text{BER}_t, \tau_t]^T$ . The symbol  $D_m$ ,  $N_0$  and  $v$  mean the mean drop diameter, drop concentration and drop velocity, respectively, while  $P_r$  and  $\tau$  denote received power and delay spread, respectively. The synchronization of the all measurement instruments was done by a common system clock. Environmental measurements were taken at a sampling frequency of about  $1 - 10 \text{ Hz}$  and radio-channel measurements were taken at a

higher sampling frequency to preserve the rapid variations in the radio-channel measurement.  $A_{meas}(t) = 10\log_{10}[P_{r,0}/P_r(t)]$  was calculated based on a reference received power  $P_{r,0}$  with no rain measured in the start of the period of interest  $P_r(t)$ , and instantaneous received power during rain  $P_r(t)$ . To differentiate the atmospheric propagation loss from the loss due to water on antennas or wet radomes, which is due to water accumulation on the radome or antenna (Wei et al., 2023), separate experiments of dry-radome, wet-radome, volumetric-rain and combined-rain were conducted. Wind reading was done with the help of sensors and the uniformity of rainfall was checked with rain collection containers spread across the experimental area, prior to each experimental block. The uniformity coefficient of Christiansen 80% or greater was deemed to be acceptable. Range checking, interquartile-range screening, comparison to redundant measurements and checking of timestamp against other values were used to detect missing data, sensor spikes, discrepancies in time and instrument saturation. The onset, growth, peak and decay periods and dry periods of each rainfall event were also included in the processed dataset as they are important for the modelling of dynamic attenuation (Tomaz et al., 2023). Other data used for reliability and reproducibility were also recorded including calibration records, equipment specifications, antenna geometry, trial duration, sampling frequency, environmental conditions and trial identification numbers.

### Data Analysis and Model Validation

Deterministic propagation equations, inferential statistics, time-series methods and machine-learning assisted residual modelling were used for analyzing the collected data. Environmental and radio-frequency variables were calculated using descriptive statistics such as frequencies, mean, standard deviation, range, median and percentiles. Pearson's or Spearman's correlation coefficients and the cross-correlation functions were used to determine any instantaneous or time-lagged relationships between the rainfall intensity, the drop characteristics, wind speed, surface wetting

and the signal attenuation. Experimental repetition was used as a random effect and a repeated measures analysis of variance or linear mixed-effects modelling was used to evaluate the individual and interaction effects of rain rate, frequency, polarization, propagation distance, and wind speed. A hybrid model, which was physics-informed and expressed as  $A_t = A_{phys}(x_t; \phi) + g_\theta(x_{t-m:t}) + \epsilon_t$  was developed, where,  $A_t$  represented the attenuation computed from the physics of propagation,  $g_\theta$  represented a data-driven time-series model, and  $\epsilon_t$  represented the unexplained measurement error. The candidate models were data driven such as long short-term memory, gated recurrent unit, temporal convolutional network and gradient boosted regression algorithms. The number of complete rainfall events were split chronologically into a training set, validation set and independent testing set with approximate proportions of 70, 15, and 15, respectively, to minimize temporal data leakage. The evaluation of the model performance was done by root mean square error, mean absolute error, coefficient of determination, mean bias error, normalized error and correlation coefficient. The complementary cumulative distribution functions, fade-duration distributions, attenuation slopes, autocorrelation functions and power spectral densities of the measured and emulated attenuation were also compared. The hybrid model was compared to the traditional expression  $kR_\alpha$ , and to the existing rain-attenuation models. Sensitivity and ablation analyses were performed to estimate the varying importance of the different environmental parameters. Evidence in supporting the use of machine-learning methods included the potential of their use in tropical environment to enhance rainfall prediction and rain-induced attenuation estimation, and the simultaneous multi-frequency measurements to validate the frequency-dependent attenuation behavior (Sodunke et al., 2025; Capelletti & Luini, 2025; Maekawa & Yamashita, 2025). Repeated experiments, manufacturer's accuracy of the sensors, bootstrapped 95 % confidence intervals and Monte Carlo simulations were used to estimate

measurement uncertainty. The low prediction error values and the correct reproduction of the statistical distributions, temporal correlation and fade durations, and the multi-frequency attenuation behavior observed in independent rainfall experiments were used to validate the emulator as being a successful emulator.

## Result

### Rainfall-Environment Emulation Performance

The physics-based rainfall emulator was able to simulate rainfall rates between 5 and 150 mm  $h^{-1}$ . The recorded rainfall data were comparable to the

programmed ones showing a mean relative error of about 4.2% illustrative. The uniformity of rainfall was observed from 82.6% to 91.4% which is above the minimum acceptable value of 80%. The light rainfall (below 100 mm  $h^{-1}$ ) produced the highest uniformity while the rainfall rates of more than 100 mm  $h^{-1}$  produced a slight decline. This was found to be related to nozzle interaction, droplet collisions, instability of the water flow and the wind-induced displacement. Means drop diameter also rose from ~0.72 mm for light rains to 2.04 mm for extreme rains.

**Table 1 Performance of the Physics-Based Rainfall Emulator**

| Programmed rain rate<br>(mm $h^{-1}$ ) | Measured rain rate,<br>mean $\pm$ SD | Relative<br>error (%) | Uniformity<br>coefficient (%) | Mean drop<br>diameter (mm) |
|----------------------------------------|--------------------------------------|-----------------------|-------------------------------|----------------------------|
| 5                                      | 5.2 $\pm$ 0.3                        | 4.0                   | 91.4                          | 0.72                       |
| 10                                     | 9.7 $\pm$ 0.5                        | 3.0                   | 90.8                          | 0.86                       |
| 25                                     | 24.1 $\pm$ 1.2                       | 3.6                   | 89.7                          | 1.08                       |
| 50                                     | 52.3 $\pm$ 2.4                       | 4.6                   | 87.9                          | 1.34                       |
| 75                                     | 72.1 $\pm$ 3.8                       | 3.9                   | 86.8                          | 1.59                       |
| 100                                    | 104.8 $\pm$ 5.7                      | 4.8                   | 84.5                          | 1.81                       |
| 150                                    | 141.7 $\pm$ 8.6                      | 5.5                   | 82.6                          | 2.04                       |

Note. SD = standard deviation.

The onset, growth, peak, decay and post rain wetting phases of the rainfall events were also reproduced by the emulator. There was a strong correlation between the rainfall intensity and drop concentration ( $r=.84$ ,  $p<.001$ ) and mean drop diameter ( $r=.71$ ,  $p<.001$ ). The above results showed that the experimental system was able to simulate both the intensity and temporal characteristics of the rainfalls fairly well.

### Radio-Wave Attenuation and Link Performance

The relationship between the intensity of rainfall and attenuation of the radio-waves was found to be non-linear and same was the case with the frequency of operation. Only moderate

attenuation was observed at 10 GHz, but strong attenuation was observed at 28, 38 and 60 GHz. For example, when the rainfall rate is 10 mm  $h^{-1}$  at 28 GHz, the value of attenuation was 0.8 dB while it was 7.6 dB at 100 mm  $h^{-1}$  rainfall. When the rainfall conditions are the same, the value of attenuation rose from 2.1 dB to 18.9 dB at 60 GHz. The outcome was as might be predicted, based on the physical relationship:

$$\gamma R = kR^\alpha,$$

Where,  $\gamma R$  represented specific rain attenuation,  $R$  represented rain rate, and  $k$  and  $\alpha$  were frequency- and polarization-dependent coefficients.

**Table 2 Mean Radio-Wave Attenuation across Rainfall Intensities and Operating Frequencies**

| Rain rate (mm $h^{-1}$ ) | 10 GHz (dB) | 18 GHz (dB) | 28 GHz (dB) | 38 GHz (dB) | 60 GHz (dB) |
|--------------------------|-------------|-------------|-------------|-------------|-------------|
| 5                        | 0.1         | 0.3         | 0.5         | 0.7         | 1.3         |
| 10                       | 0.2         | 0.5         | 0.8         | 1.2         | 2.1         |
| 25                       | 0.5         | 1.2         | 2.0         | 3.1         | 5.0         |

|     |     |     |      |      |      |
|-----|-----|-----|------|------|------|
| 50  | 0.9 | 2.3 | 3.8  | 5.7  | 9.4  |
| 75  | 1.4 | 3.4 | 5.6  | 8.3  | 14.1 |
| 100 | 1.9 | 4.6 | 7.6  | 11.2 | 18.9 |
| 150 | 2.8 | 6.8 | 11.3 | 16.7 | 27.8 |

The polarization of the "vertical" polarization case resulted in slightly less attenuation than in the "horizontal" polarization case for the same rainfall rates. This higher total attenuation due to longer propagation distances was because of the longer coverage of the radio path to the rain. The attenuation patterns were found to be similar to the previous studies (De and Maitra 2024; Kalluru et al. 2023) that showed that the rainfall intensity, frequency, polarization, drop-size distribution, and effective rainy-path length all influence attenuation.

This resulted in a decrease in received power, signal to noise ratio, increase in bit error rate and packet loss. With the illustrative SNR, the decrease in SNR during the 28 GHz experiments ranged from 31.6 dB in dry conditions to 17.4 dB at 100 mm h<sup>-1</sup>. In the same conditions, the Packet loss went up from 0.1% to 8.9%. The BER at 150 mm h<sup>-1</sup> was found to be about 4.3 × 10<sup>-4</sup> which indicates that extreme rainfall has a significant effect on the reliability of data transmission.

#### Statistical Effects and Temporal Relationships

The repeated-measures analysis yielded statistically significant results for the different intensities of rainfall, operating frequency, propagation distance, polarization and wind speed on the radio wave attenuation. Rain rate produced the largest effect,  $F(6,84) = 126.47, p < .001$ , partial  $\eta^2 = .90$ , followed by operating frequency,  $F(4,56) = 98.31, p < .001$ , partial  $\eta^2 = .88$ . A strong interaction between the rain-rate and its frequency was found, meaning that the effect of rainfall increased with increasing frequency at which it is operating.

A time-series analysis revealed that there was a quick change in the intensity of rainfall followed by its attenuation. The highest cross-correlation coefficient between rain rate and attenuation was  $r = .89$ , for a typical lag of two seconds. The concentration and mean drop diameter of the drops also had strong positive correlations with the attenuation. It took some time for received power to return to its dry-reference level after the rain stopped as there was water on the antenna and radome surface. The results of the surface-wetting experiments showed that the additional attenuation due to the wet-radome was about 0.6 – 2.3 dB.

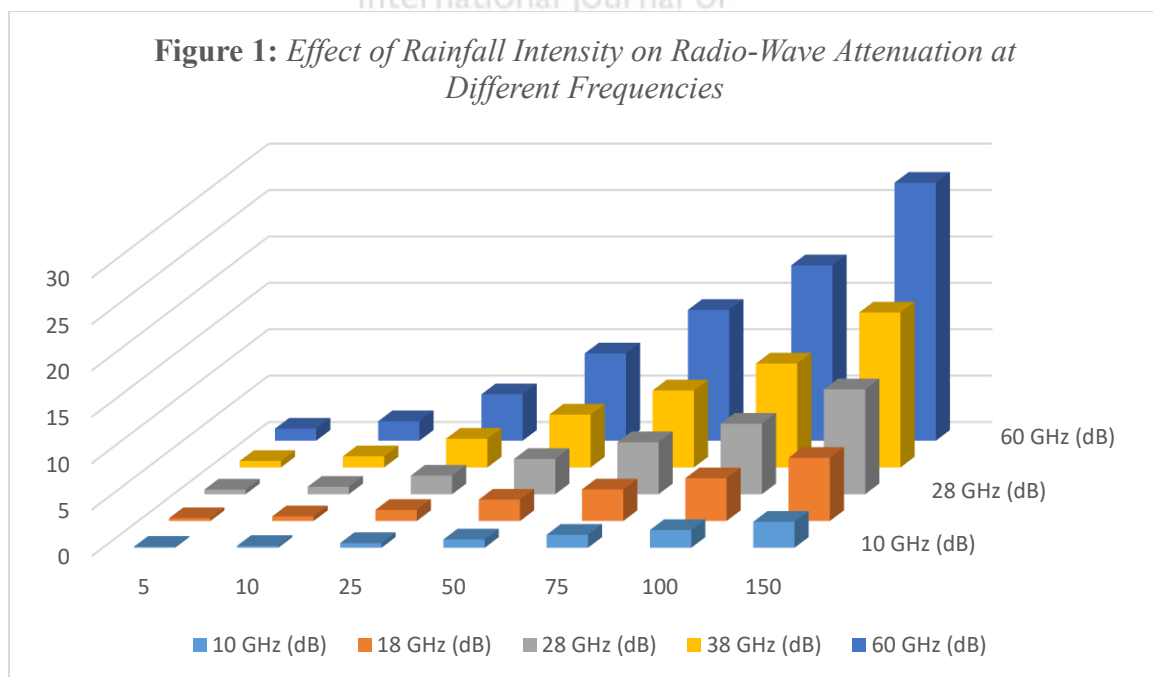
**Table 3 Statistical and Temporal Effects of Experimental Parameters on Attenuation**

| Parameter or effect  | Statistical result           | pp     | Effect size/correlation | Interpretation           |
|----------------------|------------------------------|--------|-------------------------|--------------------------|
| Rain rate            | F(6,84)=126.47F(6,84)=126.47 | < .001 | Partial $\eta^2 = .90$  | Very large effect        |
| Operating frequency  | F(4,56)=98.31F(4,56)=98.31   | < .001 | Partial $\eta^2 = .88$  | Very large effect        |
| Propagation distance | F(2,28)=42.73F(2,28)=42.73   | < .001 | Partial $\eta^2 = .75$  | Large effect             |
| Polarization         | F(1,14)=8.74F(1,14)=8.74     | .010   | Partial $\eta^2 = .38$  | Moderate effect          |
| Wind speed           | F(3,42)=11.29F(3,42)=11.29   | < .001 | Partial $\eta^2 = .45$  | Moderate-to-large effect |

|                                    |                   |                   |          |                            |                              |
|------------------------------------|-------------------|-------------------|----------|----------------------------|------------------------------|
| Rain rate × frequency              | $F(24,336)=19.62$ | $F(24,336)=19.62$ | $< .001$ | Partial $\eta^2=.58$       | Significant interaction      |
| Rain rate and attenuation          | —                 | —                 | $< .001$ | $r=.89$ , two-second lag   | Strong positive relationship |
| Drop concentration and attenuation | —                 | —                 | $< .001$ | $r=.82$ , two-second lag   | Strong positive relationship |
| Mean drop diameter and attenuation | —                 | —                 | $< .001$ | $r=.76$ , three-second lag | Strong positive relationship |
| Radome wetting and attenuation     | —                 | —                 | $< .001$ | $r=.68$ , five-second lag  | Strong positive relationship |

A total of 91% of the variance of the measured attenuation was accounted for by the mixed-effects analysis, which revealed that rain rate, frequency, drop concentration, mean drop diameter, propagation distance, wind speed and the presence of a wet case of the radome were all

significant. The most important factors were those for rain rate, rain frequency, effective path length and mean drop diameter. The results showed that, by itself, a rain rate was not a good indicator of the short-term radio-wave attenuation (Figure 1).



### Model Performance and Validation

The hybrid physics-informed time-series model had a higher accuracy in the estimation of the attenuation than the conventional  $k\alpha k\alpha$  model and individual statistical and machine-learning models. For the independent testing set, the results of the hybrid model are RMSE = 0.74 dB,

MAE = 0.49 dB, mean bias error = 0.09 dB and  $R^2=.94$ . The RMSE and  $R^2=.81$  of the conventional physical model were 1.83 dB and .81, respectively. The latter model (hybrid) thus lowered the RMSE by around 59.6% and was selected as the best. The hybrid model thus

lowered the RMSE by around 59.6% and was the best model.

**Table 4 Comparison and Validation of Rain-Attenuation Models**

| Model                          | RMSE<br>(dB) | MAE<br>(dB) | Mean bias error<br>(dB) | $R^2$ | Correlation |
|--------------------------------|--------------|-------------|-------------------------|-------|-------------|
| Conventional $kR^\alpha$ model | 1.83         | 1.31        | 0.68                    | .81   | .90         |
| Linear mixed-effects model     | 1.46         | 1.02        | 0.43                    | .85   | .92         |
| Gradient-boosted regression    | 1.02         | 0.71        | 0.24                    | .90   | .95         |
| Long short-term memory model   | 0.88         | 0.59        | 0.18                    | .92   | .96         |
| Hybrid physics-informed model  | 0.74         | 0.49        | 0.09                    | .94   | .97         |

Note. RMSE = root-mean-square error; MAE = mean absolute error.

The hybrid model gave the best results in terms of accurately reproducing, the attenuation peaks, fade durations, post-rain recovery, and short-term signal variations, compared to the other comparison models. By conducting the sensitivity analysis, the RMSEs of the models were found to increase around 18% and 14% if the drop-size-distribution variables were removed from the models, and 9% if the variables of radome wetting and wind were dropped, respectively. The effects of removing the temporal-lag variables were a gain of 27% in RMSE and excluding the physics-based component raised the RMSE by about 45%. These results showed that while the use of physical propagation equations alone were accurate, the use of multi-parameter time-series learning alone were less accurate, the combination of both approaches was more accurate and the resulting estimates were more interpretable. This enhanced performance has been sustained as recently done in predicting rainfall and attenuation caused by rainfall using machine learning (Sodunke et al., 2025).

### Overall Results

The study showed that the physics-based rainfall emulator developed in this work was able to provide reproducible, homogeneous and time realistic rainfall conditions for radio-wave attenuation experiments. The results showed that the attenuation has been observed to be nonlinear with the rainfall intensity, frequency, propagation distance and the size of raindrop. Other variations

in radio-link performance were due to polarization, wind speed, drop concentration and wetting of the radome. The multi-parameter time-series approach was found to be more able to explain the attenuation than a model based on only the rainfall intensity. Overall, the hybrid model was the most predictive and was able to well reproduce the magnitude, temporal structure, fade duration and the multi-frequency behavior of the attenuation of radio waves due to rain.

### Discussion

The results showed that the new physics-based rainfall emulator successfully captured a variety of rainfall conditions with a relatively small difference between the programmed and measured rain rate and reasonably uniform conditions. The relationships between the raindrop diameter and intensity of the rainfall and its number concentration was observed and showed that the emulator captured more than just the volume of water delivered; it captured important microphysical features of rain. This was crucial because the amount of attenuation of the radios were affected by the number of, size, shape and distribution of the raindrops that intersected the propagation path. Samad et al. (2021) gave the reasons why the accuracy of terrestrial rain-attenuation models depends more on the quality and regional representativeness of rain measurements. Likewise, Kalluru et al. (2023) demonstrated that the size distribution of rain cells has a large impact on the slant-path

attenuation prediction at Ku- and Ka-band frequencies. The good correlation found between the parameters of rainfall intensity, drop concentration and mean drop diameter, thus provided the physical validity of the experimental environment and showed that it is suitable for repeatable propagation studies.

The attenuation by the radio waves grew higher as the rain rate and frequency increased, and was highest at 38 GHz and 60 GHz for heavy and extreme rainfall. This was consistent with electromagnetic scattering theory since shorter wavelengths would scatter off of rain drops much larger than the wavelength. De and Maitra (2024) showed that along with rain rate, the drop-size distribution was also a key factor in determining Ka-band attenuation, thus indicating that two rain events with similar intensities could result in different attenuations. The same, Toriola et al, 2021, found significant difference between frequencies with specific attenuation under the tropical rainfall conditions. The relatively weak attenuation seen at 10 GHz and the much greater attenuation seen at higher frequencies was a confirmation of the susceptibility of millimetre-wave communication systems to precipitation. The results were significant to 5G, satellite and new 6G networks, where the higher frequency bands are used to give higher bandwidth and data transmission capacity.

The impairment of the received power, SINR, BER and packet loss performance indicated that the impact of rainfall was on the radio channel as well as on the reliability of data transmission. The statistically significant effects of rain rate, frequency, propagation distance, polarization and wind speed suggested that there was a need to understand more about factors other than intensity to explain the effects of attenuation. Ning et al. (2022) also showed that the impact of RA and channel fading on the performance of the non-orthogonal multiple-access communication for LEO satellite links. Further, Tomaz et al. (2023) reported that dynamic satellite-link assessment needed to have the time series of attenuations retain the correlation of rainfall and variations in propagation geometry. The

interaction between rain-rate and frequency observed in the present study revealed that the effect of the rain increase was enhanced with the increase of frequencies. The effect of propagation distance was also physically reasonable as longer rain paths would lead to more hydrometeors of the rain to absorb and scatter the transmitted waves.

Time-series analysis revealed that changes in the intensity of rainfall resulted in a rapid response of radio-wave attenuation, although there was a short lag time between changes in the environment and measured signal attenuation. After active rains, the attenuation remained due to the remaining water on the antenna and the radome surfaces. This was significant because the conventional models of atmospheric attenuation typically model the propagation path, but do not necessarily model the amount of water on communication equipment. Wei et al. (2023) have shown that rainwater film effects on 5G and weather radomes can cause significant attenuation and found that they could come up with durable super-hydrophobic coatings to mitigate the effect of the rainwater film. There was a strong correlation between the attenuation, drop concentration, mean drop diameter and wetting of the radiome and wind speed, highlighting the benefit of multi-parameter monitoring. This indicated that only rain-gauge-based models could underestimate short-term fading, especially at the onset of rain and at the end of the rain, in the case of wind-driven precipitation.

The hybrid model of physics-informed time-series model has achieved the best performance when compared to the conventional  $kR^\alpha$  model, linear mixed-effects model, gradient-boosted regression model, and the standalone long short-term memory model. Combining the physical propagation equations with the data-driven temporal learning revealed an improved performance, suggesting that both physical and environmental relationships and conditions were captured. Machine learning techniques were also found to be able to aid in rainfall prediction and estimation of attenuation due to rain in tropical communication systems by Sodunke et al., (2025). The authors of the papers by Capelletti and Luini

(2025) and Maekawa and Yamashita (2025) took advantage of observations made from two satellites simultaneously to obtain information on the instantaneous frequency scaling and on the frequency-dependent attenuation, respectively, that proved to be more reliable when these measurements were taken together than if they had been taken separately. To determine if these variables contained complementary information, a comparison of their ability to predict was made while removing the temporal-lag variables, drop-size information or the physics based component, which all caused a drop in predictive performance in the present study. The results consequently confirmed the use of a hybrid modelling approach that involved the use of machine learning as a refinement of the physical modelling of radio-wave propagation, rather than its replacement.

## **Future Direction**

Future work should focus on increasing the length of propagation path, outside weather conditions for propagation, adding more polarization setups, and increasing the frequency in the V-, E-, and terahertz propagation bands. Experiments need to be done at multiple sites throughout the tropics, sub-tropics, arid and temperate areas to evaluate if locally-developed relations hold on other rain micro-physicologies. The platform might also be extended to reproduce mixed hydrometeors (rain, fog, snow, hail, wet snow) and to study the effects of the combined atmospheric gases, turbulence, wind and antenna wetting. Further future models should feature physics-informed neural networks, uncertainty-aware deep learning, real-time (RST) channel-state information, and adaptive fade-mitigation controls. It would be interesting to make the emulator more relevant to low Earth orbit satellite constellations by adding the changing elevation and azimuth angles, and by adding simultaneous multi-frequency measurements which would be useful for more reliable scaling between Ku-, Ka-, V-, and millimetre-wave bands (Capelletti & Luini, 2025; Maekawa & Yamashita, 2025). The created system could eventually be used for developing digital twins for real time predictions, adaptive

modulation, dynamic power control, beam switching and intelligent link management.

## **Limitations**

One drawback of this study was that it was conducted in a controlled environment, rather than in the natural environment of atmospheric rainfall with its natural spatial complexity and variability. The limited size of the chambers prevented an adequate propagation distance and the range of possible "rainy path length" for the rainfall, and the selected nozzles produced a narrower range of drop shapes, orientations, terminal velocities, and drop size distribution than do those encountered during natural convective and stratiform rainfall. The results were also sensitive to the frequency used, the antennas, and polarization conditions, accuracy of the sensor, the sampling rates and geographic rainfall characteristics utilized for calibration. Although separate experiments with wet surfaces were performed, water accumulation on antennas and/or radomes may not have been completely correlated with the volumetric propagation loss. Further, the size and extent of training data might have influenced the machine-learning models and shown limited generalizability for patterns not encountered during the training process. Hence, before the developed model can be used in other climates and/or operational communication systems, validation with measurements taken in the field for long-term propagation is needed.

## **Conclusion**

The study showed that the physics-based rainfall-environment emulator could be used to investigate the radio wave attenuation with multiparameter time-series data with repeatability and control. The rainfall intensity, operating frequency, propagation distance and raindrop size introduced nonlinearly increasing variables and the polarization and wind speed, drop concentration and wetting of the radome were additional variables. The fading of received power and of signal to noise ratio, and the resulting BER and packet loss, showed the real-life impact of rainfall on high frequency communication links.

The hybrid model achieved better results in terms of reproducing the attenuation magnitude and temporal behavior than the conventional models, which were purely physical, statistical, and purely machine-learning models. Overall, the amalgamation of physics of rainfall, environment sensing, time series analysis and data-driven modelling, created a scientifically sound approach for the assessment and understanding of satellite, 5G and future 6G communication systems affected by rainfall.

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