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Rain Fade Analysis on High Frequency Signal: A Review

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ABSTRACT

A reliable transmission of high-frequency signal of more than 10 GHz is crucial for various communication systems, especially in the era of advanced technologies and wireless communications. Rain-induced signal fades pose a significant challenge to signal integrity, making accurate rain rate measurement methods essential for system optimization. This review critically examines the existing techniques for measuring rain rate and the applicability in analysing high-frequency signal fades. Several case studies and practical examples are presented to illustrate the significance of accurate rain rate measurements in predicting and mitigating signal degradation. Researchers are working to enhance existing models to better fit local environmental variables based on all the case studies. Having an accurate estimation of the level of rain attenuation in the signal is one of the components to ensuring the quality of service of a communication signal. Signal availability can be ensured with suitable rain attenuation modelling, assuming that all other communication elements are functioning as planned.

Keywords:

Rain rate; Rain attenuation; 5G communication; Climate change prediction; Signal fade mitigation

1. Introduction

The traditional wireless communication frequency bands, i.e., those below 6 GHz, are experiencing a spectrum crunch due to the fast-growing demands for increased mobile data speeds and ubiquitous internet access [1]. The fifth generation (5G) of communication standards is being actively researched, as it is anticipated that the current technology would not be able to meet the demand. The 5G technology is expected to be the main enabler for high-speed wireless communication in the next several years. As reported by Statista.com, the number of mobile device and gadget users reached 8.8 billion in 2018. With the advent of the Internet of Things (IoT), billions of connected devices are also being deployed. Both evolutions have a major impact on Information and Communications Technology (ICT) usage and consequently to the economy. By 2023, the number of worldwide mobile devices will increase to 13.1 billion, with 4G and 5G generating 46% and 11% of

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global connections, respectively [2-4]. With the increase of smartphones, Machine-to-Machine (M2M) connections, connected televisions and tablets, the number of devices will reach 3.6 per capita. International Telecommunication Union (ITU) estimates that approximately 5.4 billion people or 67% of the world's population using the Internet in 2023 [5]. This represents an increase of 17% since 2019, with 782 million people estimated to be connected online during that period [6].

A secure communication link is necessary for good signal reception. Nevertheless, many factors influence the signal's quality at the receiver as it passes across the communication channel. Rain is the primary factor causing connection damage in Ku band digital satellite transmission as mentioned by Abdus Samad *et al.,* [7]. High-frequency signal fades caused by rain attenuation is a persistent issue in communication systems. Rain attenuates the propagating wave of terrestrial and slant link communication in the temperate area at 10 GHz [8]. These attenuation effects may begin at 5-7 GHz, according to research by [9-11]. Ka-band signals, which travel through the earth's atmosphere at frequencies higher than 20 GHz, are twice as vulnerable to propagation impairment, particularly from rain, as Ku-band signals [12-14].

A case study by Trilochan Patra *et al*., [15] presented a prediction model for 5G communication design to minimize signal attenuation due to heavy rainfall using a frequency diversity technique. The proposed model is designed for a wide frequency range and is intended to enhance the reliability of microwave communication links in tropical regions. The paper also highlighted the importance of developing systems i.e. site diversity, uplink power control, variable rate encoding to overcome rain attenuation, especially at high frequencies and the implementation of the proposed frequency diversity model in designing reliable microwave communication links in tropical regions.

Trilochan Patra *et al*., [16] discussed the application of the MIMO system in improving communication in tropical regions affected by heavy rainfall through a proposed link budget and comparison of assumption values with practical data. The study focused on minimizing signal attenuation through diversity techniques, emphasizes the importance of link budget in assessing communication links and highlights the significance of SNR values.

Therefore, it is essential to estimate rain attenuation to propagate electromagnetic waves and accomplish the required operation transfer of data. Hence, this paper will provide an overview of the importance of rain rate measurement in mitigating the impact of rain-induced signal fades on communication links operating at high frequencies.

1.1 Fundamentals of Rain Attenuation

Rain-induced signal fades primarily occur due to two fundamental physical mechanisms which are absorption and scattering. For absorption, raindrops absorb a portion of the electromagnetic energy carried by the signal as it passes through the raindrops. This absorption is more significant at higher frequencies, such as in the millimetre-wave bands. The absorbed energy is converted into heat, leading to a reduction in the signal strength. While for scattering, raindrops act as scattering centres for the incident electromagnetic waves. The electromagnetic waves are scattered in various directions as they interact with raindrops. Scattering causes the signal to deviate from its original path, leading to a decrease in the received signal strength at the intended destination according to Ashidi *et al.,* [17].

Basahel *et al.,* [18] emphasized that both absorption and scattering effects are influenced by factors such as the size and concentration of raindrops, the frequency of the signal and the distance travelled through the rain. Higher frequency signals are more susceptible to these rain-induced fades due to increased absorption and scattering.

In summary, rain-induced signal fades result from the combined impact of absorption and scattering mechanisms, leading to a reduction in signal strength and potential disruptions in communication systems during adverse weather conditions [40].

1.2 The Correlation Between Rain Rate and Rain Attenuation

The correlation between rain rate and signal attenuation is a critical aspect of understanding the impact of precipitation on communication systems. Rain rate, which quantifies the amount of rainfall over a specific area and time, is directly linked to the degree of signal attenuation experienced by electromagnetic waves passing through the rain.

Christofilakis *et al.,* [19] paper stated that rainfall is a significant obstacle to millimetre-wave (30-300 GHz frequency) propagation between the transmitter and receiver. Wave propagation may be restricted by the interaction between incident electromagnetic radio waves and rain. As the rate of rain rises, the attenuation increases dramatically. This attenuation increases because there is a greater chance of a raindrop forming a barrier to radio wave propagation with a higher mean rain rate [20].

Higher rain rates typically correspond to more intense rainfall. As the rain rate increases, the number and size of raindrops in the path of the signal also increase. The intensity of rainfall is a crucial factor influencing the absorption and scattering of electromagnetic waves, resulting in more significant signal attenuation [21].

The correlation between rain rate and signal attenuation is also frequency-dependent. At higher frequencies, such as millimetre waves, the absorption by raindrops becomes more pronounced. As the rain rate increases, the attenuation of higher-frequency signals is more severe compared to lower-frequency signals, making it essential to consider the frequency characteristics of the communication system [22-24]. The Recommendation ITU-R P.838-3 [25] explained on the specific attenuation model for rain and shows further understanding of the relationship between rain rate, frequency and rain attenuation. The specific attenuation γ_R (dB/km) is obtained from the rain rate *R* (mm/h) using the power-law relationship:

$$\gamma_R = KR^{\alpha} \tag{1}$$

Values for the coefficients k and α are determined as functions of frequency, f (GHz), in the range from 1 to 1 000 GHz, from the following equations, which have been developed from curve-fitting to power-law coefficients derived from scattering calculations:

$$log_{10}k = \sum_{j=1}^{4} a_j \exp\left[-\left(\frac{log_{10}f - b_j}{c_j}\right)^2\right] + m_k log_{10}f + c_k \tag{2}$$

$$\alpha = \sum_{j=1}^{5} a_j exp\left[-\left(\frac{log_{10}f - b_j}{c_j}\right)^2\right] + m_a log_{10}f + c_a \tag{3}$$

where

f: frequency (GHZ)
k: either k_H or k_V
α : either α_H or α_V

Values for the constants for the coefficient k_H and α_H (horizontal polarization) and coefficient k_V and α_V (vertical polarization) are given in tables in [25].

The cumulative effect of rain-induced signal attenuation is directly proportional to the distance the signal travels through the rain. Higher rain rates over a more extended path result in a more substantial overall signal attenuation, impacting the reliability and performance of communication links. The ITU-R P.530-17 Model [26] provides an easy approach for forecasting long-term rain attenuation data. In this model, Figure 1 simplified steps are provided for approximating the long-term rainfall attenuation data.

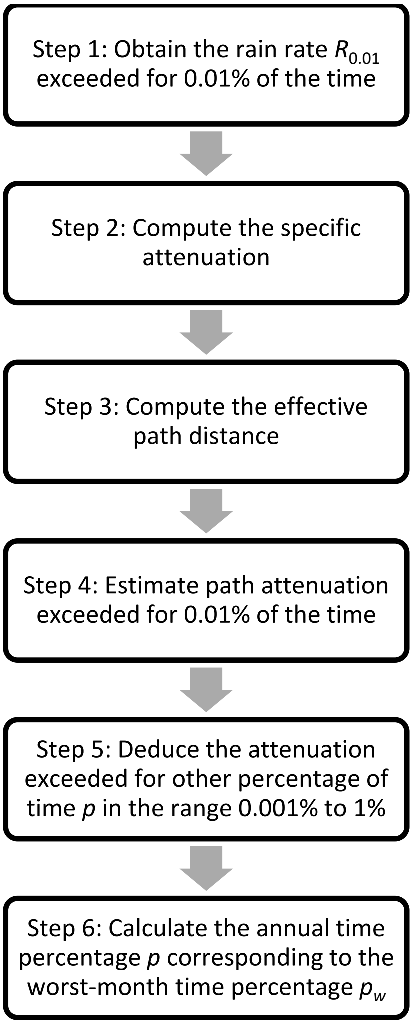

Fig. 1. Flow of the steps to determine the long-term statistics of rain attenuation

In step 1, rain rate R 0.01 exceeded for 0.01% of the time (with an integration time of 1 min) is calculated. Then, the specific rain attenuation (γ_R) specified in Eq. (1), (dB/km) is computed for the desired frequency, polarization and rain rate based on Recommendation ITU-R P.838-3 [25]. In step 3, the effective path distance, d_{eff}, of the link is calculated by multiplying the actual path distance d by a link path reduction factor r. The value of r is approximated by:

$$r = \frac{1}{0.477 d^{0.633} R_{0.01}^{0.073\alpha} f^{0.123} - 10.579\left(1 - e^{-0.024d}\right)} \tag{4}$$

It is recommended that the highest value of r is 2.5. Subsequently, in case the denominator of Eq. (4) is below 0.4, it is advised to use this highest value for r. Next, the approximate total link attenuation due to rain surpassed 0.01% of the time is computed in step 4 as in Eq. (5).

$$A_{0.01} = \gamma R d_{eff} = \gamma R \times d \times r \tag{5}$$

In step 5, the attenuation exceeded for other percentages of time p in the range of 0.001% to 1% may be deduced from the following power law:

$$\frac{A_p}{A_{0.01}} = C_1 P^{-(C_2 + C_3 log_{10} P)} \tag{6}$$

$$C_1 = (0.007^{C_0})[0.12^{1-C_0}] \tag{7}$$

$$C_2 = 0.855C_0 + 0.546(1 - C_0) \tag{8}$$

$$C_3 = 0.139C_0 + 0.043(1 - C_0) \tag{9}$$

$$C_0 = \begin{cases} 0.012 + 0.4 \left[log_{10}\left(\frac{f}{10}\right)^{0.8}\right], f > 10\ GHz \\ 0.12, \qquad\qquad\qquad\qquad f < 10 gHz \end{cases} \tag{10}$$

Finally, in step 6 the worst-month data are determined by computing the annual time percentages p corresponding to the worst-month time percentages p_w using climate information stated in ITU-R P.841-5 [27]. The magnitude of A surpassed for percentages of the time p on an annual basis will be exceeded for the corresponding percentages of time p_w on a worst-month basis.

Values of coefficient *k* and α in Eq. (2) are frequency, f (GHz), dependent on the spectrum 1 to 1000-GHz. Table 1 depicts a selected frequency of operation with their associated coefficients *k* and α for vertical polarization. These frequencies are selected from rain-induced attenuation-affected microwave frequency range (frequency higher than 10 GHz) and millimetre-wave (mm-Wave) bands, which is the spectrum roughly from 30 to 300 GHz. Of the selected frequencies 28, 38and 60-GHz, are considered leading candidates for 5G systems [28].

Table 1
Coefficient for indicated frequency of operation [25]

Frequency (GHz)	K_v	α_v
11	0.01731	1.1617
15	0.05008	1.0440
28	0.1964	0.9277
38	0.3844	0.8552
45	0.5375	0.8123
60	0.8515	0.7486
72	1.0561	0.7171

Understanding and quantifying the correlation between rain rate and signal attenuation is crucial for the development of accurate models, prediction algorithms and mitigation strategies in communication systems. By considering this correlation, engineers and researchers can better design and optimize systems to handle the challenges posed by rain-induced fades, ensuring robust and reliable communication even in adverse weather conditions.

2. Literature Review

High-frequency signal fade analysis involves studying the attenuation or degradation of communication signals, particularly at higher frequencies (more than 5GHz), due to various atmospheric factors. This phenomenon, often influenced by weather conditions like rain, can impact the reliability and performance of communication systems. Electromagnetic wave propagation is greatly affected by rain [29]. This force draws the interest of numerous researchers, organizations and businesses, leading to an abundance of research conducted globally to formulate the rain and its impact on rain attenuation with radio wave propagation.

2.1 Rain Rate Measurement Method

Rain rate measurement techniques are essential for understanding the impact of precipitation on communication systems, particularly in wireless and satellite communication. Accurate measurement of rain rate aids in predicting signal attenuation caused by rain, allowing for the design and optimization of communication links [30]. Table 2 lists some common rain rate measurement techniques

Table 2
Comparison of rain rate measurement method

Method	Coverage Area	Sampling Time
Rain Gauge	Hundreds of meters to few kilometres	1 minute to 1 hour
Weather Radar	Hundreds of kilometres	5 to 15 minutes
Weather Satellites	Globally	1 hour

Most of these methods include data on rain rate in millimetres per hour (mm/hr), with varying integration or sampling times (some as long as one hour). Nevertheless, these can be adjusted to 1-minute integration or sample periods by employing an ITU-Recommendation regression technique to modify different integration times to one-minute integration times for rain rate and, as a result, rain fade prediction [31]. The International Telecommunication Union (ITU) P. 837 and 530 recommendations state that a minute integration time of the yearly rain rate distribution is usually necessary for plotting annual rain attenuation or rain fade distribution for statistical analysis [32,33]. Rainfall rate estimation in mm/hr is provided by rain gauges, radars and satellites. This data can be translated to rain attenuation or fade in dB using the standard ITU-R 838 model.

2.2 Recent Case Studies

Table 3 listed case studies and practical examples to illustrate the significance of accurate rain rate measurements in predicting and mitigating signal degradation.

Table 3
Comparison of the recent case studies

Case Study	Meteorological measurement method	Sampling area	Integration Time	Sampling time
Budalal *et al.,*	Rain Gauge	~300 meter	1 minute	15 months (Jan 19999-Mar 2000)
M.N. Ahuna *et al.,*	JWD, RD-80 impact type disdrometer	University of Kwazulu-Natal, Durban,	30 seconds	4 years (2013-2016)
Thabiti *et al*.,	ITU-R P.837-7 recommendation	Comoros	1 hour	Not stated
Woldamanuel *et al.,*	Rain Gauge	Ethiopia	1 minute	2 years (Oct 2016-Sept 2018)
Basarudin *et al.,*	Hydro-estimator	Peninsular Malaysia, Sabah and Sarawak	1 hour	10 years (2011-2020)
Alam *et al.,*	Rain Gauge	IIUM, Malaysia	10 seconds	1 year (Jan 2014- Dec 2014)
This Work	Hydro-estimator	Peninsular, Sabah &Sarawak, Malaysia	1 hour	17 years (2006-2023)

A case study by Budalal *et al.,* [34] investigated the time-varying and multipath channel behaviour of point-to-point millimetre-wave short-terrestrial radio links. With a K factor, the effect of rain attenuation on mm-wave channel parameters such as the RMS delay spread, path loss received power strength and Rician distribution is emphasized. Based on the simultaneous observation of the one-minute rain rate and its effects on a short experimental link of 38 GHz, a quick analysis of rain fade was presented. This research investigates the effects on mm-wave bands in outdoor activities for 5G systems in tropical regions, rain rate and rain fade based on real measurement data implemented in Malaysia at 38 GHz with 300 m TX to RX separation distance in a LOS environment. During rainy occurrences, the data logger was used to measure the received signal strength and rain rate every minute for fifteen months. The data logger was monitored and recorded every minute of the 24 hours. To determine the average annual rainfall attenuation and rain rate, the gathered data was analysed using MATLAB software code modification. Path reduction factors techniques are the foundation of current rain fade prediction models. Rain fade levels have been compared between predicted and measured using the ITU-R 530-17 prediction model.

In M. N. Ahuna *et al.,* [35] case study, the backpropagation neural network (BPNN) is designed to forecast the likelihood of attenuation on a link based on rainfall rates. The subtropical region around Durban, South Africa (29.8587°S, 31.0218°E), is the focus of this study. Rainfall data from 2013 to 2016 is used to train the backpropagation neural network, which predicts rainfall rates by leveraging the non-linear mapping capability between inputs and outputs. When long-term rain attenuation statistics derived from predicted rain rates are compared to the actual and ITU-R models, the findings indicate that the predicted rain attenuation surpassed 0.01 percent of average years, with a comparatively narrow margin of error. Additionally, a study of the actual and expected attenuation of rain inside specific rain events from various rainfall regimes was conducted. The findings indicate that the suggested model is capable of predicting the link's state. This is shown by testing the trained BPNN using unseen data gathered between January 2017 and May 2018, which covers all four different climate seasons (summer, autumn, winter and spring).

Next, study by Thabiti *et al.,* [36] analyses rain fade in the tropical nation of Comoros, taking into consideration ITU-R recommendations for rain intensity. The rain fades for earth-to-satellite links operating in this country in L, C, Ka, Kuand V bands in horizontal, vertical and circular directions for 0.001% to 1% of exceeded each year was calculated using this rain intensity. According to the investigation, the link can operate between 99.999% and 99% of the time with minimal impact in all frequency bands at vertical polarization, except the V-band. It indicates that B-PSK is the optimal modulation method at 99% availability to increase the proposed link's dependability. The antenna's gain, receiver, diameter and figure of merit were raised while maximizing its footprint to achieve a 10dB fade margin, which enables the antenna to achieve a specific quality of service. The results of this study will provide Comoros with valuable resources to improve the reliability and accessibility of the earth-to-satellite microwave link.

In Woldamanuel *et al.,* [37] research paper, an improved adaptive code modulation (ACM) for reducing rainfall fade in Ethiopia is presented. The rain attenuation in this study is calculated using locally gathered one-minute rain rate data. The neuro-fuzzy inference system is then used to improve the mitigation plan in light of this outcome. In addition, the performance of this suggested scheme is compared to that of the non-adaptive technique as well as the fuzzy-based adaptive modulation and coding technique. The results of a MATLAB simulation indicated that in bad weather, a lower-order quadrature amplitude modulation (QAM) scheme with a lower convolutional coding rate performs better in maintaining link availability. On the other hand, when rain does not affect the channel, spectral efficiency can be increased by using a bigger constellation size of quadrature amplitude modulation (QAM) scheme with a greater convolutional coding rate.

Basarudin *et al.,* [38] focused on the effect of climate change on Malaysia's rainfall rate distribution. Ten years of Hydro-Estimator data, covering the years 2011 to 2020, are gathered and analysed. The data shows the rainfall rate in millimetres per hour over the Peninsular Malaysia, Sabah and Sarawak regions. A little increase in the rain rate distribution at 0.01% yearly probability is found using the linear regression approach for Peninsular Malaysia as well as Sabah and Sarawak regions, suggesting that the rain rate distribution in Malaysia is affected by climate change. The rate in Sabah and Sarawak is 0.4046 mm/hr annually, compared to 0.2356 mm/hr in the Peninsular region. Rain fade would rise with an increase in rain rate distribution, which would result in signal distortion and losses for high-frequency wireless communication signals. In the end, assessing the impact of climate change on the distribution and rain rate can help create long-term predictions of the signal performance in 5G systems and high-frequency radio links due to hydrometeor.

Alam *et al.,* [39] stated that the earth-to-satellite communications operating at frequencies higher than 18 GHz are severely impacted by the propagation impairments caused by rain, primarily because of the severe degradation in performance of the satellite communication system. Rain fade can be effectively mitigated by using the time diversity technique with a suitable time delay between successive transmissions. To build future high-frequency links, time diversity analysis requires measurable rain attenuation data, which is not accessible in most regions. It has been discovered that the time diversity gain prediction model is reliable for improving time diversity.

Here, taking into account the three variables of rain rate, time delay and frequency, the researcher proposes a new model for the rain rate with and without the time delay. First, the constants were derived by regression from the rain rate and rain rate gain using the rain rate and time delay functions. Next, using the analytically identified ITU-R and gain equations, the constant for the frequency function was retrieved from the cumulative distribution function of the attenuation. The proposed model can be reliably used for future earth-to-satellite link designs by using measured rain rates at any higher frequencies. It was validated using one-year rain rate and attenuation data measured at two different locations in Malaysia, showing a 7% prediction inaccuracy when compared to the existing models.

However, this work proposed hydro-estimator as the meteorological measurement method. Leveraging the strengths of high-frequency networks, which offer extensive coverage and real-time data transmission capabilities, hydro-estimator integrates ground-based observations with satellite-derived data to provide high-resolution rainfall estimates over large geographical areas. The hydro-estimator utilizes a combination of precipitation radar data, satellite imagery and ground-based measurements to enhance the accuracy and reliability of rainfall estimation. Through advanced data fusion techniques and machine learning algorithms, hydro-estimator method delivers real-time precipitation estimates with improved spatial and temporal resolution, overcoming the limitations of traditional rain measurement methods. Given the attributes of hydro-estimator, including its global coverage scale and 1-hour sampling time, the data could revolutionize rain measurement practices within high-frequency network applications.

2.3 Comparisons of Method Implementation in Previous Case Study

Budalal *et al.,* [34] utilised a rain gauge and SSCM simulation software to analyse 5G channels, generating power delay profiles and calculating path attenuation due to rain while Basarudin *et al.,* [38] method involved collecting ten years of Hydro-Estimator data, analysing it using the linear regression method, utilizing MATLAB for data processing, assessing the impact of climate change on rain rate distributions, following the ITU-R 837 standard and plotting rain rate data at 0.01 percent exceedance probability yearly.

Next, a case study by Thabiti *et al.,* [36] involved in analysing the availability and outage time of the microwave link in Comoros at different frequency bands and polarizations under the effects of rain, based on ITU-R Recommendations and simulations compared to Woldamanuel *et al.,* [37] using 2 years of rain gauge data and neuro-fuzzy system to calculate rain attenuation with adaptive coding and modulation schemes based on locally recorded rain data. The system is trained using manually generated data from BER performance simulations of different modulation-code pairs to achieve the desired BER performance and channel data rate.

Alam *et al.,* [39] proposed a new model using the rain gauge method for rain rate with and without time delay, validating it using one-year data from IIUM, Malaysia and emphasizing the use of time diversity for mitigating rain fade in Earth-to-satellite connections. Finally, Alhuna *et al.,* [35] utilised a backpropagation neural network (BPNN) using rainfall data (JWD, RD-80 impact type disdrometer) collected from 2013 to 2016 in Durban, South Africa, with specific training functions and performance metrics.

From all of the previous methods, the most accurate way to measure rain rate is with a rain gauge, which is also frequently used for calibration and validation by other measurement sources. Furthermore, the price per rain gauge is far lower than that of other providers. However, a rain gauge's greatest spatial coverage is usually only a few hundred meters; hence, it would need an absurdly large number of rain gauges to cover the entire country, which would present logistical challenges. The Hydro-Estimator tool shows a global map of the distribution of rain rates. To improve accuracy, the product uses worldwide measurement sources such as rain gauges, rain radars and other weather satellites. The product requires one hour of sample time for global coverage; however, this can be resolved by utilizing the ITU's regression technique, which converts one hour to one minute of integration time for rain rate and, rain fade prediction. Thus, it can be concluded that the Hydro-Estimator tool is the best and most reliable method for rain rate data collection due to its spatial coverage, sampling time and cost.

2.4 Findings in The Previous Case Studies

Budalal *et al.,* [34] highlighted the significant impact of rain attenuation on millimetre-wave communication systems, utilizing real measurements to simulate these effects and observing an average attenuation of 16 dB over a 300 m path. Figure 2 shows a plot of the two worst rainy episodes in February, separately, together with measured receive signal level and rain rate data for the same period. The data shows that during the intense rainstorm event on February 16, 2000, the received signal strength dropped dramatically by about 22 dB or 6.6 dB/m.

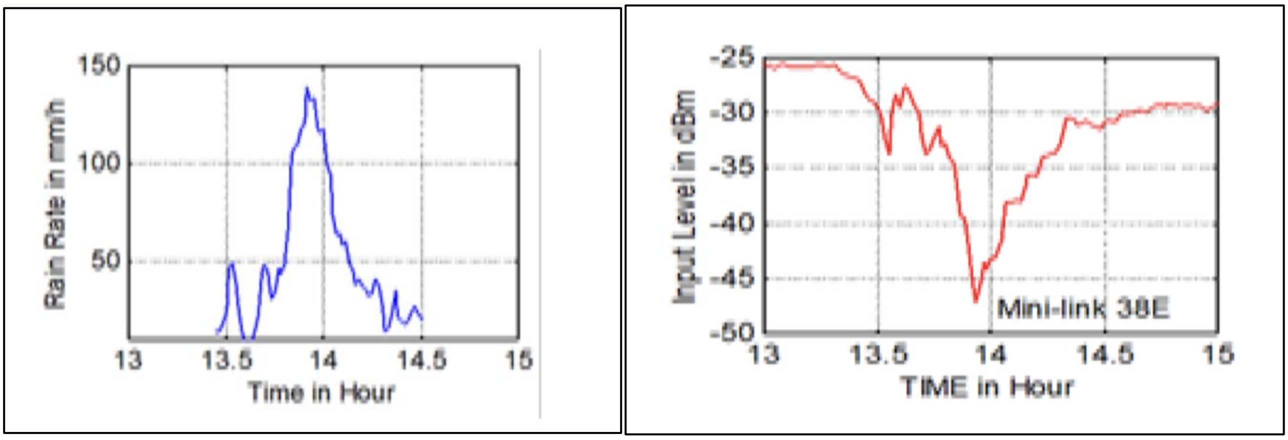

Fig. 2. Measured rain rate and the corresponding received signal strength on experimental Mini-links at 38 GHz operating in Malaysia [34]

Table 5 shows absolute path loss and rain attenuation values at 38 GHz for horizontal polarization by link, measurement date and weather condition. The total path signal attenuation experienced by the propagating millimetre wave is rather minor at lower rain rates. The receiving signal strength (RSS) decreasing level grows linearly with increasing rain rate. Rainy events are reported to cause a rapid increase in the received signal fluctuations.

Table 5
Absolute path loss and rain attenuation values at 38 GHz [34]

Rain rate mm/h	Path loss in dB	Rain attenuation in dB
30	104.08	6.72
30	105.42	8.06
30	104.90	7.545
30	105.88	8.52
60	107.15	9.79
60	108.63	11.27
60	108.87	11.51
60	110.21	12.85
90	111.55	14.20
120	108.33	10.97
90	112.90	15.54
120	112.18	14.71
120	115.59	18.23
150	114.05	16.68
90	108.17	10.81

Table 5 compares the rain attenuation values for a horizontal polarization configuration with the corresponding values predicted by the ITU-R 530-2017 attenuation model for various rain rates, for a given short path between the transmitting and receiving antennas. The expected and measured attenuation at 0.1%, 0.01%and 0.001% of the time are compared here. The average measured value for rain fade is 4.71 dB, 10.84 dB and 16.25 dB, whereas the ITU-R projected values are 3.8 dB, 8.5

dB and 11.6 dB, respectively. Hence it can be concluded that the ITU-R model in tropical climates underestimates the rain attenuation.

Ahuna *et al.,* [35] presented the result of a backpropagation neural network that effectively predicted rainfall rates using collected data. As shown in Figure 3, the actual and expected outputs of rainfall are 177 mm/h and 178 mm/h, respectively and exceed 0.01 percent of the time in an average year.

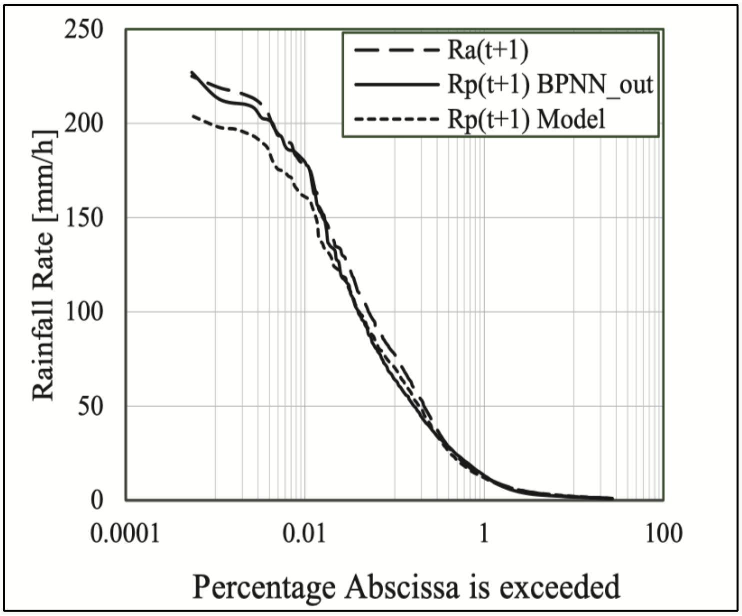

Fig. 3. Rain rate complementary cumulative distribution functions (2017-2018) [35]

This value for the model is 160 mm/h. Figure 4 and Table 6 show the resulting long-term rain attenuation statistics for both actual and anticipated rainfall rates. The attenuation exceeds the average annual rainfall by 0.01 percent at 53 dB for real rain rates, 50 dB for ANN anticipated rain rates, 48 dB for the suggested model and 53 dB for the ITU-R model.

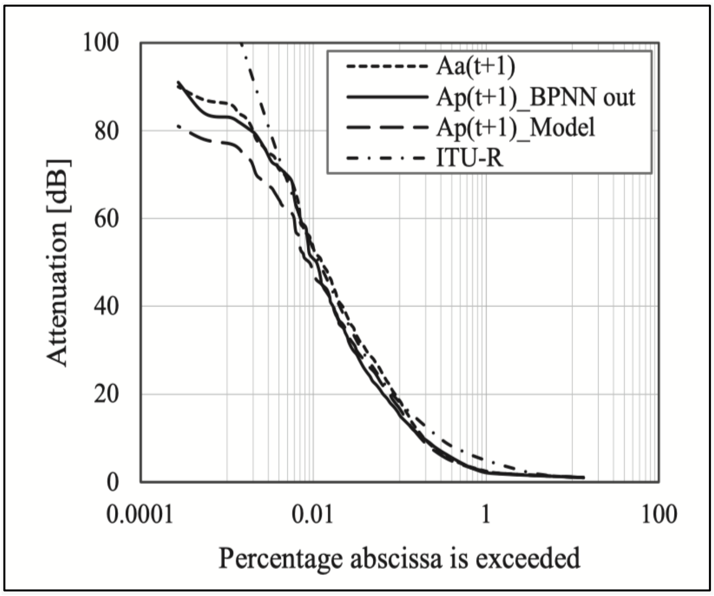

Fig. 4. Rain fades complementary cumulative distribution functions (2017-2018) [35]

Table 5
Rain attenuation exceeded [35]

%	dB	BPNN out (dB)	Model(dB)	ITU-R(dB)
1	2	2	2	5
0.1	18	15	16	18
0.01	53	50	48	53
0.001	86	83	77	106

Besides, with a reasonable agreement between the simulated rain rates and the ITU-R 837 model, the study by Basarudin *et al.,* [38] found a slight increase in the distribution of rain rates as a result of climate change, indicating an increasing tendency in the rain rate distribution over time in Malaysia. Figure 5 illustrates the minor agreement between the Hydro-Estimator rain rate distribution result and the ITU-R 837 model for both the Peninsular Malaysia and Sabah Sarawak regions. Sabah and Sarawak regions appear to be in more agreement with the model, whereas the Peninsular result appears to underestimate the ITU-R model, especially at lower exceedance probability.

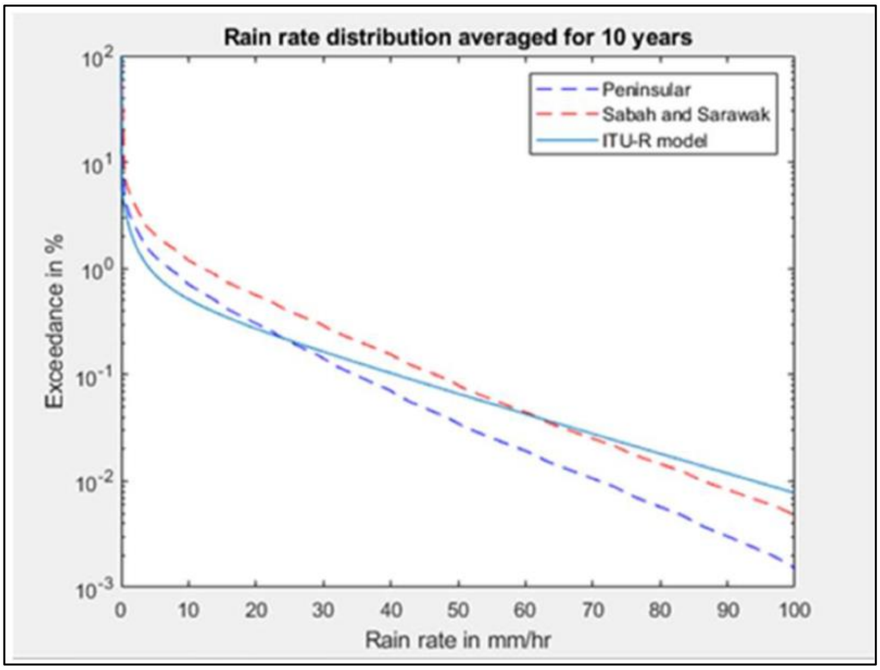

Fig. 5. Comparison of the ITU-R model with the average of rain rate for ten years from Hydro-Estimator data [38]

Figure 6 shows the rain attenuation gains are obtained similarly from 10 to 60 GHz with time delays from 1 to 60.

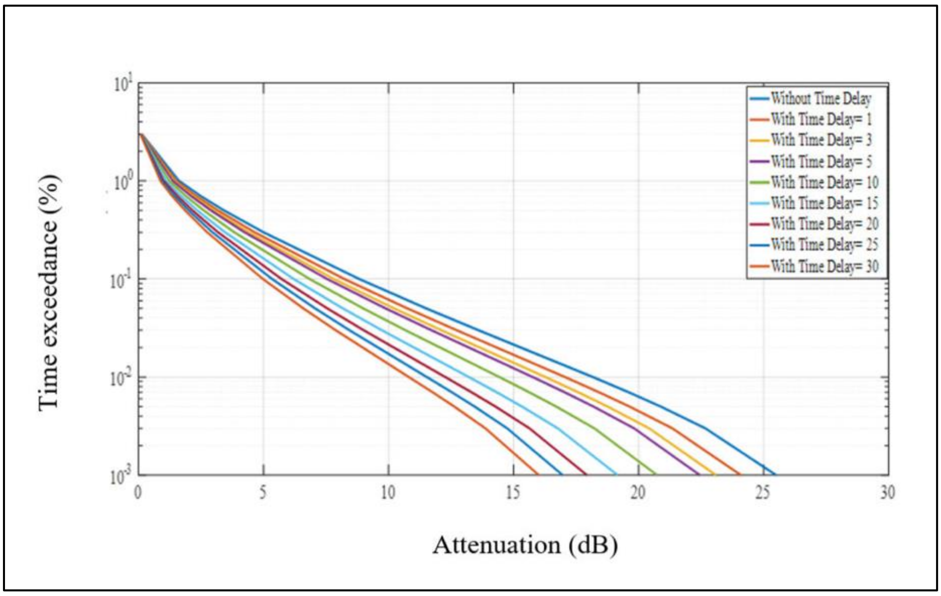

Fig. 6. Complementary cumulative distribution function of predicted rain attenuation using ITU-R P.618-13 formula and measured R 0 .01% with delays [39]

The rain attenuation increases exponentially with frequency as shown in Figure 7. The approach of using the rain rate gain analysis for time diversity gain at any desired frequency, using the 1-minute rain rate, is assessed in this study, for the same period and location, rain rate gain with delay can be equivalent to rain attenuation gain with delay. To calculate rain rate gain, the measured 1-year rain rate distribution with and without delay was used. Rain attenuation distributions are predicted using the ITU-R technique based on the rain rate. Similar properties to those found by measurements are found in this distribution with and without delay. A comparison is made between the measured attenuation gain for various frequencies and the predicted attenuation distribution to estimate the attenuation gain. The observed attenuation gain is found to be roughly equal to the predicted one. The measured temporal diversity gains at Ku-bands with time delays of 1, 3, 5, 10, 15, 20, 25and 30 minutes are compared with the derived model. With a maximum difference of 7%, the gains predicted by the suggested model are very close to the actual gains at 12.0 and 12.225 GHz for Kuala Lumpur and Penang, respectively.

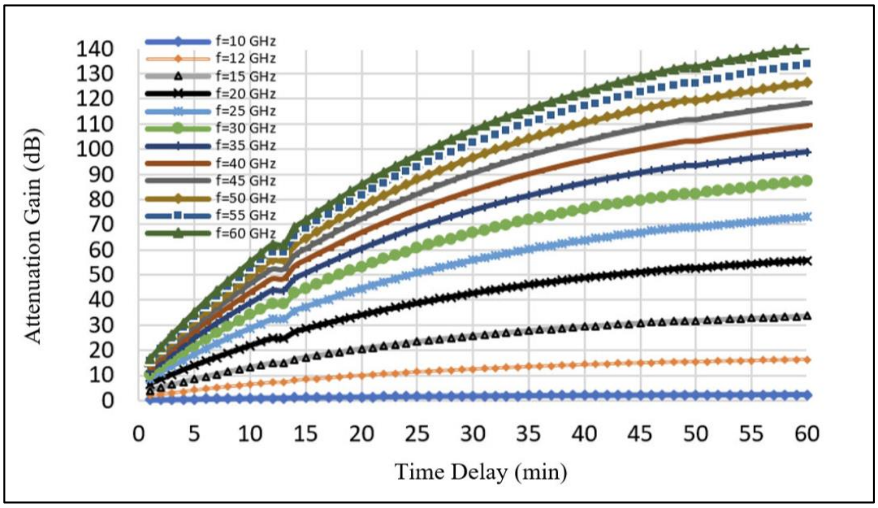

Fig. 7. Attenuation gain obtained by marginal rain attenuation from 0 to 150 dB, at 10 to 60 GHz as the function of Time delay [39]

Woldamanuel *et al.,* [37] researched on the rain rate vs percentage of time surpassed 0.01% (R0.01). Figure 8 shows the correlation between the amount of rain and the percentage of time exceeded by 0.01%. The ITU-R rain-induced attenuation model was used to compute the R 0.01, which comes out to be 113 mm/h at an operating frequency of 11 GHz and a path distance of 13.4 km (the distance between Jimma and Mujja).

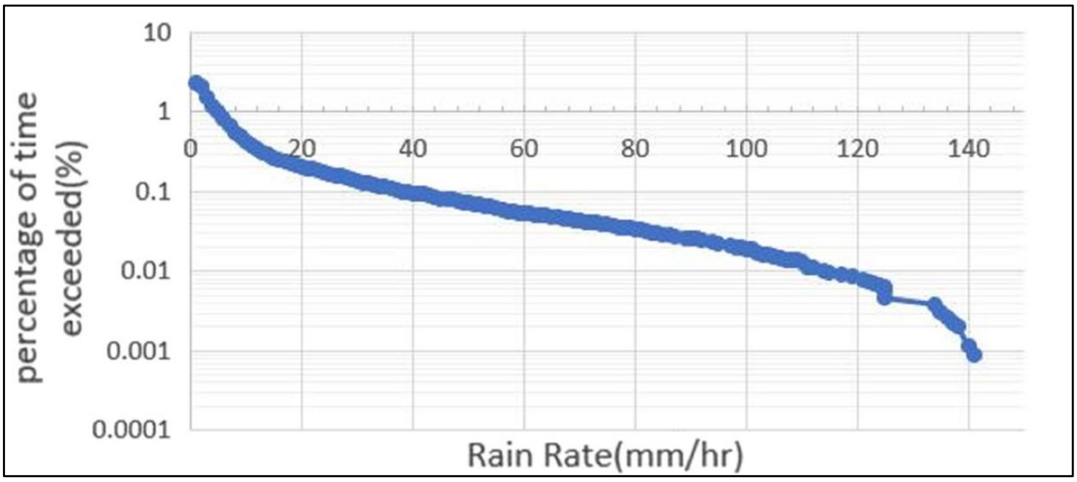

Fig. 8. Rain rate versus percentage of time exceeded for 0.01% [37]

3. Challenges and Future Directions

Table 6 shows the challenges by the researchers in analysing the rain rate distribution and potential avenues for future research.

Table 6
The challenges and recommendations

Challenges	Recommendations
Improving accuracy and calibration	Standardized calibration procedures and reference standards
Enhancing spatial and temporal resolution	Deploy more instruments
Integrating multiple data sources	Understand and quantify the uncertainties associated with each dataset

Improving accuracy and calibration in rain rate measurement poses several challenges due to the complex nature of precipitation and the limitations of existing measurement techniques. Over time, instruments may experience calibration drift, leading to inaccuracies in measurements [41]. Environmental factors, wear and tear and aging components can contribute to drift, requiring regular maintenance and calibration checks [42]. Besides, different precipitation types such as rain, snow and sleet, have varying physical properties [43]. Designing instruments that can accurately measure the intensity of each type is challenging, especially during mixed precipitation events. Raindrops come in various sizes and their size distribution can affect the accuracy of measurements. Instruments may be sensitive to certain raindrop sizes and less sensitive to others, leading to discrepancies in measured rain rates. Precipitation intensity also can vary widely over short distances and time scales. Achieving accurate measurements that capture this variability requires high-resolution instruments and networks, which can be technically challenging and costly to implement [44-46]. Establishing and maintaining a robust calibration infrastructure for rain rate measurement instruments is crucial. The lack of standardized calibration procedures and reference standards can hinder efforts to ensure consistent and accurate measurements [47]. Addressing these challenges requires a multidisciplinary approach involving meteorologists, engineers, physicists and data scientists. Ongoing research and advancements in sensor technologies, calibration methods and data assimilation techniques are essential to improve the accuracy and calibration of rain rate measurements.

Next, enhancing the spatial and temporal resolution of rain rate measurements is also a challenging task because existing rain rate measurement instruments, such as traditional rain gauges and radar systems, may have inherent limitations in their design that prevent them from achieving higher spatial and temporal resolutions [48]. Developing new instruments with improved capabilities can be technically challenging. Traditional rain gauges are often sparsely distributed across an area, leading to a lack of spatial resolution. The limited number of gauges may not adequately capture the variability in rainfall across different locations. While radar systems may face challenges in achieving high spatial resolution due to the need for a minimum beam width, the spacing of radar beams may result in data gaps. Increasing spatial and temporal resolution often involves deploying more instruments, which may require additional power sources, financial investment and allocation of resources. In remote or inaccessible areas, providing a reliable power supply for instruments with uniform coverage across large geographical areas can be challenging [49]. Wind can affect the accuracy of rain gauge measurements by causing undercatch or splashing of raindrops. This impact becomes more significant in windy conditions, leading to inaccuracies in the recorded rainfall. Then, radars may experience beam broadening and attenuation effects due to heavy rain and strong winds, affecting the accuracy of rainfall estimates [50]. Precipitation patterns can change rapidly over short intervals, making it challenging to accurately capture the temporal evolution of rainfall events. This dynamic nature requires instruments with rapid response times and continuous monitoring capabilities.

The last challenge, the integration of multiple data sources in rain rate measurement is difficult due to various technical, logistical and methodological factors [51]. Different instruments and technologies used for rain rate measurement (e.g., rain gauges, radar, satellites) often employ distinct measurement techniques. Some instruments may have limited spatial coverage, while others cover larger areas. Integrating data from instruments with different spatial footprints requires careful consideration to avoid introducing biases [52]. Variability in data quality and uncertainty levels among different sources can also complicate integration efforts. Processing large volumes of data from multiple sources and developing algorithms that can effectively merge and assimilate diverse datasets is a complex task. Understanding and quantifying the uncertainties associated with each dataset is essential for producing reliable integrated results.

Despite these challenges, ongoing research aims to develop improved methodologies and frameworks for the integration of multiple data sources in rain rate measurement. Advances in data assimilation techniques, standardization efforts and collaborative initiatives can contribute to more effective and accurate integration in the future [53-56].

4. Conclusions

This comprehensive review provides valuable insights into the current state of rain rate measurement methods and their application to high-frequency signal fade analysis. It serves as a valuable resource for researchers, engineers and practitioners working on optimizing communication systems in regions prone to rain-induced signal fades. Accurate rain rate measurements are crucial in addressing high-frequency signal fades, especially in the context of communication systems, particularly satellite communication and terrestrial microwave links. Accurate rain rate measurements also aid in designing and implementing techniques like antenna diversity and site diversity. Both methods rely on accurate rain rate information to switch between antennas or sites to maintain signal quality during rain fade events. Communication network planners use accurate rain rate data to design and optimize networks, ensuring that links are resilient to rain fade. This is particularly important for critical applications such as emergency services, where reliable communication is essential during adverse weather conditions.

In summary, accurate rain rate measurements play a pivotal role in addressing high-frequency signal fades by providing essential data for system design, link budget calculations, diversity techniques, adaptive modulation, coding strategies and the development of effective fading prediction models. This ensures the reliability and performance of communication systems under varying weather conditions, particularly during rain events. Accurate rain rate measurements could also support any study of Beamforming's Power Allocation for (5G) Networks such as by Khalaf *et al.,* [57] by providing accurate information of real time rain fade.

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