

Rain Fade Models

Subjects: Computer Science, Artificial Intelligence

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Developing a rain fade model involves mathematical analysis of rain attenuation phenomena by reasoning and cause-based interaction.

Earth-space link

attenuation measurement

microwave propagation

rain fading

rain attenuation

1. Introduction

Satellite communication is playing major role in the back-haul data network. In addition, satellite communication links can be used to enhance the existing telecommunication infrastructure in 5G and beyond networks [1][2][3], and satellite communication also has enormous applications for unmanned aerial vehicles (UAVs) and the Internet of Things (IoT) [4]. Because of radio congestion and broader bandwidth requirements, satellites switch to higher-frequency (33–75 GHz and 75–110 GHz) bands. However, atmospheric disturbances wreak havoc on these frequencies, causing attenuation, scintillation, and depolarization, lowering service efficiency [5]. Rain is one of the significant factors that creates attenuation on the propagation of electromagnetic waves. This effect has directed the interest of researchers in reducing the effect of rain on radio waves by controlling the transmitted power. Thus, multiple studies have been conducted on this globally. The research on rain attenuation is used to predict rain attenuation in various geographical areas over a wide range of frequency bands, especially for frequency bands over 10 GHz, and determine a suitable model that can predict attenuation. To develop such a model, the factors that impact attenuation first need to be determined. Some of the factors are related to the infrastructure setup (latitude, longitude, antenna size, antenna height, elevation angle, operating frequency) and some of them are related to the rain events such as wind flow, humidity, wind direction, and temperature.

It may be possible to evaluate the attenuation of atmospheric elements such as wind flow and the effect of the direction of wind flow on propagated signal attenuation separately, but it is conventional to consider attenuation due to other factors such as temperature, wind flow, and wind direction, along with rain attenuation. Even though rain attenuation issues were noticed in the middle of the last century, the problem has not yet been efficiently addressed. Besides the necessity to transfer a massive volume of data due to the fourth industrialization, the lower frequency bands are getting exhausted. This has led researchers to develop rain attenuation models that can work with higher frequency bands such as Q/V, W, and E-bands. For example, the application of a rain attenuation model for slant link, where the operating frequency is at 75 GHz, was assessed in [6][7]. Several models of rain

attenuation have been proposed in the literature, and scientists are aiming to refine existing models for local climate conditions [\[8\]](#)[\[9\]](#)[\[10\]](#)[\[11\]](#)[\[12\]](#)[\[13\]](#).

Precise rain attenuation determinations are critical for preparing the link budget, maintaining communication efficiency, and the architecture of the system. In addition, following probable rain attenuation determined by the rain attenuation model, the over- or underestimation of the power of the transmitter can be avoided. Radio-frequency engineers must comply with the permissible power transmission specifications in compliance with spectrum management rules for each frequency band. If the engineers do not follow such power regulations, the transmitted signal power may interfere with another frequency band, e.g., neighbor channel, which may disturb the neighboring telecommunication equipment. Thus, by deploying a rain attenuation model in Earth–space telecommunication, such disturbance can also be avoided. In the literature, there is currently a lack of survey papers addressing the issues and algorithms of slant link fade prediction models, which inspired us to write this survey paper. In [Table 1](#), some of the existing survey papers are presented, which are not adequate for covering the slant link fade prediction models.

Table 1. Rain attenuation survey papers.

Ref. Survey Concentrations

- [\[14\]](#) The results show that rain attenuation in horizontal polarization is slightly larger than that in vertical polarization. A differential coupling-based compensation was recommended to reduce the rain attenuation effects on polarization in the depolarization processes.
- [\[15\]](#) In this survey, the artificial-neural-network-based models were classified based on input parameters. In addition, the accuracy of the artificial-neural-network-based models was accessed through a comparative study.
- [\[16\]](#) Rain attenuation in a satellite system is more severe than in a terrestrial system, and for a good model, it should be implemented into the model through local climatic elements.

2. Comparative Study of Slant Link Rain Fade Models

In the previous sections, we discussed the rain fade model prediction process. However, we may be interested in finding out some of the qualitative and quantitative characteristics of these models. Rain attenuation models for telecommunication links that support a wide variety of frequency spectra are a positive force. However, it is recommended to use a maximum 40 GHz frequency, as the next higher frequency band (above 40 GHz) may be used for astronomical and space communication purposes [\[17\]](#). A 3–40 GHz frequency range is recommended for use in the telecommunication purposed Earth–space link to avoid possible interference with the deep-space communication link [\[18\]](#). [Table 2](#) presents the properties of slant link rain fade models such as whether they support terrestrial links; whether they consider rain structure including cloud, rainfall rate, frequency, elevation angle, rain layer height; and whether the models take into account the melting layer length within the effective path length. [Table 3](#) shows the frequency spectrum supporting capabilities, the polarization used to evaluate the model,

whether the model has a regional climatic parameter, whether the model considers rainfall rate distribution in a non-homogeneous means, and the recorded geographic area that suits the model properties. [Table 4](#) shows whether these models were validated and the sources of rain attenuation related to measured databanks, constraints, and the complexity levels of the models in terms of low, medium, and high levels are classified. To validate the models, different validation tools such as the error figure and goodness-of-fit function, which is also known as relative error probability function, were mostly used [\[19\]](#)[\[20\]](#)[\[21\]](#). [Figure 2](#) shows the frequency range supporting capacity of the studied models. As we can see, the maximum frequency range supporting model is the unified model [\[22\]](#), the second highest is the Crane TC model [\[23\]](#), and the third top model is the GSST model [\[24\]](#). The lowest frequency band supporting models from lowest to highest bands are Singapore [\[25\]](#), the Breakpoint model [\[26\]](#), the LU model [\[20\]](#), and the Karasawa model [\[27\]](#).

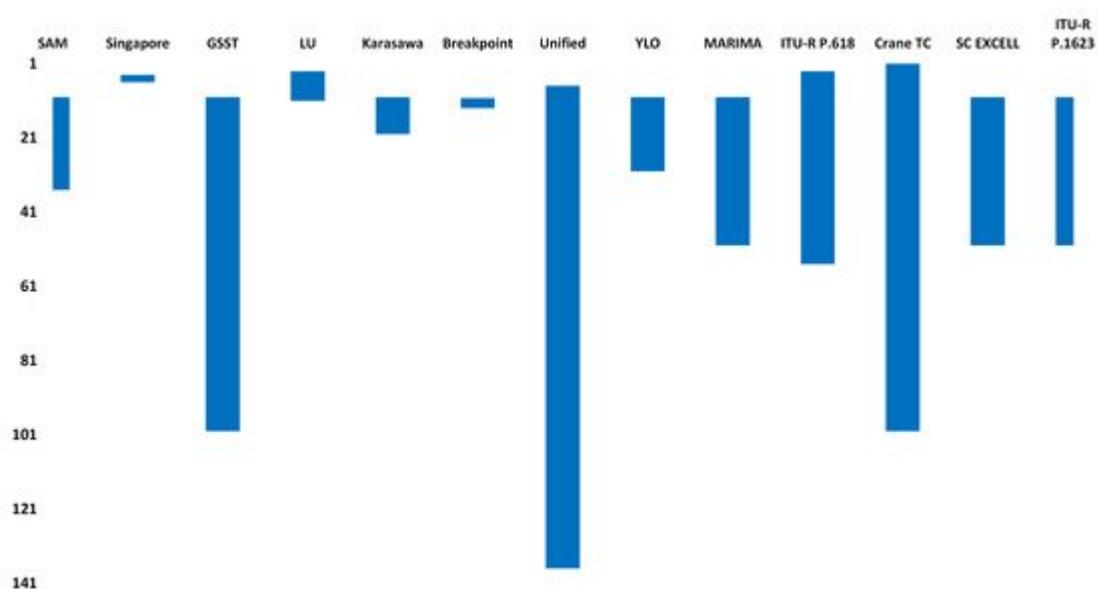


Figure 2. Each “vertical bar” represents the supported frequency range of the studied models. The vertical axis represents frequency in GHz and the horizontal axis represents the models.

Table 2. Characteristics table.

Type	Ref.	Slant or Both	Rain Structure	Rainfall Rate	Frequency	Angle(Earth Station)	Rain Height	Melting Layer Height	Time Series
EMPI	[28]	Slant	✓	✓	✓	✓	✗	✓	✓
	[25]	Slant	✗	✓	✓ ‡	✓ ↗	✓	✗	✗
	[29]	Slant	✓	✓	✓	✓	✓	✗	✗
	[24]	Slant	✓	✓	✓	✓ ↗	✓	✓	✓
	[20]	Slant	✓ ↳	✗	✗	✗	✓	✓	✗

Type	Ref.	Slant or Both	Rain Structure	Rainfall Rate	Frequency	Angle(Earth Station)	Rain Height	Melting Layer Height	Time Series
	[27]	Slant	✓	✓	✗	✓	✓ ▷	✗	✗
	[26]	Slant	✗	✓	✓ ‡	✓	✓	✗	✗
	[22]	Both	✗ ✕	✓	✓	✓ ✕	✗	✗	✗
	[12]	Slant	✗	✓	✓ ‡	✓ ‡	✓	✗ ✕	✗
	[30]	Slant	✗	✓	✓ T	✗	✗	✗	✗
	[31]	Slant	✗	✓	✓	✓	✓	✗	✓
STAT	[32]	Slant	✗	✓	✓	✓	✓	✗	✗
	[33]	Slant	✗	✓	✓ △	✓ △	✗	✗	✗
	[34]	Slant	✗	✗ u	✗	✗	✗	✗	✓
	[35]	Slant	✓	✓	✓	✓	✓	✗	✗
PHY	[23]	Both	— ▷	✓	— □	✓	✓	✗	✗
	[36]	Both	✓ △	✓	✗	✓	✓	✓	✓
	[37]	Slant	✓	✓	✓	✓	✓	✓	✗
	[38]	Slant	✗	✗	✓	✓	✗	✗	✗
	[39]	Slant	✗	✗	✗	✗	✗	✗	✓
FADE	[40]	Slant	✗	✗	✓ □	✓	✗	✗	✗
	[41]	Slant	✗	✗	— ⊕	✓ ⊖	✗	✗	✗
LB	[42]	Slant	✓	✓	✓	✓	✓	✓	✓

Begassat, Y.; Brunel, A.P.; et al. An integrated satellite-terrestrial 5G network and its use to demonstrate 5G use cases. *Int. J. Satell. Commun. Netw.* 2021.

2 Goratti, I.; Herle, S.; Petz, T.; Carriga, F.; Khalili, H.; Khodashenas, P.S.; Brunel, A.P.; Chau, 20–60 D. K.; Ravuri, S.; Vasudevan, S.; et al. Satellite integration into 5G: A focus on testbed as implementation and demonstration results for 5G Aero platform backhauling use case. *Int. J. Satell. Commun. Netw.* 2020.

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Table 3. Characteristics table.

4. Marchese, M.; Moheddine, A.; Patrone, F. IoT and UAV Integration in 5G Hybrid Terrestrial-Satellite Networks. *Sensors* 2019, 19, 3704.

Type	Ref.	Frequency Range	Polarization	Regional Climatic Parameter	Spatial Friendly	Reported Region that Suits	dt, M. J. Satell.
	[28]	10–35 GHz	✓	✓	✓	The USA, Europe, and Japan	satellite
	[25]	4–6 GHz	NM ‡	Rainfall rate	✗	Singapore	erniakov,
	[29]	NM	✓	4 coefficient constants called a,b,c and d depend on geographic area	NM	Best suited areas are in Europe, the USA, Japan, and Australia	
	[24]	10–100 GHz	✓ Circular, horizontal and vertical	Rainfall rate	✗	Temperate region	through
EMPI	[20]	Above 11 GHz	✗	Local rainfall rate	No information available	No practical information; test information is limited within DBSG3 databank	ni, J.; m
1							TU-R
1	[27]	10–20 GHz	NM	Rainfall rate, the probabilities of occurrence and mean rainfalls, for cell and debris	The model considers a single volume rainfalls area and does not consider convective (cell) and stratified rain (debris)	CCIR rain zone	, 24–26
1	[26]	10.7–13 GHz (Ku band)	✓	Rainfall rate	NM	Fiji	ions in
1	[22]	Terrestrial: 7–137 GHz	✓ k and α	Rainfall rate	✓	Worldwide (ITU-R databank)	odel for EEE
1	[12]	10–30 GHz	Both	Rainfall rate	✗	Tropical	–11
STAT	[30]	NM	✓	Rainfall rate	✗	Temperate region	s. Proc.
1	[31]	10–50 GHz	✓	Climate characteristics, link elevation angle	Has spatial dynamics of rainfall rate parameter due to Van de Kamp [43]	Xi'an, China	2020,

1 , K.S.; Kim, J.H.; Ahn, D.S.; Jeong, N.H.; Pack, J.K. Trends in Rain Attenuation Model in Satellite System. In Proceedings of the 13th International Conference on Advanced Communication Technology (ICACT2011), Gangwon, Korea, 13–16 February 2011; pp. 1530–1533.

Type	Ref.	Frequency Range	Polarization	Regional Climatic Parameter	Spatial Friendly	Reported Region that Suits	20
1	[32]	Up to 55 GHz	✓	Rainfall rate	✗	Worldwide	arch
1	[33]	NM (only 20 GHz is mentioned)	NM	NM	Information	NM	France
1	[34]	NM	✓ Horizontal	Measured rain attenuation	NM	Kolkata, India	restrial
2	[35]	Reported frequencies are 15, 30, 39.6 GHz	NM	✓	Rainfall rate is not a function of distance	Temperate and tropical	18, 66,
2	[36]	1–100 GHz	✗	Cell and debris parameter	No spatial correlation function is included	Temperate region	ation;
2	[37]	11.6 GHz (Range NM)	✓ Circular, Linear	Rainfall rate, wind velocity	✓ (1-year rainfall rate PDF was used)	Italy	enuation
2	[38]	10–50 GHz	✓	Rainfall rate; rain height; melting layer height, etc.	✓ Vertical and horizontal	Worldwide	Sci.
2	[39]	Ku-band	RHCP, Linear polarization	✗	✗	Japan (low-elevation Earth-space path)	uation
2	[40]	NM	Horizontal	✓	✗	Tropical area	inth
2	[41]	10–50 GHz	NM	✓ ✗	✗	Designed for global perspective	ands, 4–7
2	[42]	10.982 GHz (Ku-band)	Vertical	s-parameter	✗	Malaysia	band
LB		NM	NM	Local rainfall data: it needs to train the BPNN networks	NM	Butare, Rwanda	method 22,

28. Stutzman, W.L.; Yon, K.M. A simple rain attenuation model for earth-space radio links operating at 10–35 GHz. *Radio Sci.* 1986, 21, 65–72.

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30. Maseng, T.; Bakken, P. A Stochastic Dynamic Model of Rain Attenuation. *IEEE Trans. Commun.* 1981, 29, 660–669.

Table 4. Characteristics table.

Type	Ref.	Used/Validation Databank	Remarks about Validation	Complexity Level	Constraints
	[28]	62 experiments in the USA, Japan and Europe	Shows better prediction with minimum 2 years rainfall datasets	low	The operating frequency range is limited to 10–35 GHz
	[25]	INTELSAT POR experiment (Singapore)	The results have been validated with CCIR model and measured attenuation	low	The recommended frequency is limited to 4–6 GHz
	[29]	77 satellite links placed in Europe, the USA, Japan, and Australia (CCIR data bank)	Validated by the author	low	The model is suitable for prediction with an elevation angle ranging from 10° to 40°
	[24]	ITU-R databank	ITU-R databank is used to examine the behavior of m parameter at different frequencies as well as different sites	low	Not spatial friendly
EMPI	[20]	DBSG3 databank	The RMS value show that the new model provides the smallest rms and STD in all percentages of time except at 0.001%	high	Application area is limited by low latitudes (between 36° South and 36° North) and low elevation angles ($25^{\circ} <$)
	[27]	CCIR rain zone with different elevation angle	Validated by the author	medium +	10–20 GHz
	[26]	Used 6 tropical city's rain databanks from ITU-R	The experimental result agreed about correction factor induced attenuation especially at elevation angle less than 60° compared to ITU-R model	medium	In this model it is assumed that rain is uniformly distributed inside a rain cell
	[22]	ITU-R databank	The model gives decent results with the correctness of its terrestrial and slant direction	medium	The model was not checked with actual data for attenuation
	[12]	x	Verified with the beacon signals from WINDS and GE23 satellites (2009 to 2012)	low	Up to 30 GHz frequency is examined
STAT	[30]	x	Not validated with heavy rainfall or with rainfall data	low	The model is applicable only during the rain periods because no

36, 416–426.

Type	Ref.	Used/Validation Databank	Remarks about Validation	Complexity Level	Constraints	space
			around the world for different sites		transition is included in the model to switch from rainy to clear sky conditions	
	[31]	Validated based on the measured rain attenuation data at Xi'an, China	The validation is a good agreement between measured and predicted attenuation using this model, but has not been compared with other important rain attenuation models	high	The size of the area is not defined for a specific set of parameters	
	[33]	X	Not validated	—	The probabilistic weather forecasts could be beneficial to maximize the economic value accounting the transmitted data for higher frequencies (say 50 GHz).	
	[34]	X: used measured attenuation data	The validation shows a good agreement between measured and predicted attenuation using this model, but has not been compared with other important rain attenuation models	medium	It needs to derive mean and standard deviation of the Gaussian distribution for a different geographic area and find the coefficients of second-order polynomials from real measured attenuation	
PHY	[35]	✓	Validated at Lae, Papua New Guinea	low	—	
	[23]	Satellite: validated through CCIR procedure. Terrestrial: 35 terrestrial paths around the world	Both satellite and terrestrial links have been verified	high †	The probabilities of incidence and mean precipitation for cells and debris are difficult to determine	
	[36]	Experimental dataset	The experimental results show that the method show less error probability.	medium	Needs 1 min rainfall rate	
	[37]	DBSG3 databank	Although the model does not outperform the existing ITU-R model	high	The correctness is limited by the local values of input parameters like the	

Type	Ref.	Used/Validation Databank	Remarks about Validation	Complexity Level	Constraints
FADE			(approximately 2.4% error), it supports a few additional facilities (e.g., site diversity) and takes account of the interference due to hydrometer scattering		melting layer and the rain plateau value, which might not be available everywhere
	[38]	Experimental dataset	Validated with	low	—
	[39]	x	Validated in Kolkata, India, with experimental set-up	low	To use fade margin data it needs to remove tropospheric scintillation
	[41]	Only experimental dataset	The resulted output agrees with the measured standard deviation of attenuation	low	The method was tested only at 10.982 GHz
	[40]	NM	Validated in [44][45]	low	Applicable for limited elevation angle 5–60°
LB	[42]	Durban, South Africa	The model was not validated with standard DSDB3 or CCIR rain databanks	—	The model was not tested with established well-known rain databanks like DBSG3 or CCIR

EMPI: empirical, STAT: statistical, + it needs to solve at least seven equations. PHY: physical, FADE: fade slope, LB: learning-based rain attenuation model, † it needs to solve ten equations.