

**FREQUENCY SCALING IN MILLIMETRE-WAVE RAIN
ATTENUATION ESTIMATION FOR SATELLITE LINK
IN TROPICAL REGIONS**

BY

NUR HANIS SABRINA BINTI SUHAIMI

**A thesis submitted in fulfilment of the requirement for the
degree of Doctor of Philosophy in Engineering**

**Kulliyyah of Engineering
International Islamic University Malaysia**

APRIL 2023

ABSTRACT

The congestion at the lower frequency bands is pushing the demands for the usage and operation in the higher bands. The bands above 10 GHz are now required to satisfy the tremendously increasing needs in satellite communication (SatCom) systems. The biggest problem in deploying frequencies above 10 GHz in tropical-equatorial regions is that such areas will experience acute degradation of signal quality due to heavy rainfall throughout the year. A reliable estimation of rain attenuation is required. Dependable fade margins are required in mitigating the harsh signal losses. It is found that data validation for rain attenuation estimation using the frequency scaling technique is not available in any previous studies conducted in tropical regions. It has been suggested that instead of using the conventional method of predicting rain attenuation using the point rainfall rate information, an applicable non-meteorological technique should also be established. A frequency scaling technique can be the alternatives mean to predict rain attenuation when rainfall data is not available. The objectives of the research entail rain-induced attenuation studies for SatCom in tropical regions. They comprise identifying the best fade margin for rain attenuation at various links, formulating a new frequency scaling model with improved accuracy, and validating the proposed model. The methodologies involved in the study encompass the processing of the beacon signals into first-order statistics of rain attenuation. This, later, leads to the generation of monthly and annual rain attenuation Cumulative Distribution Functions (CDFs). The worst month analysis for rain intensity and rain attenuation was also carried out. The signal loss is expected to be appalling in the worst month because of the high occurrence of rain events. The required fade margin was determined from an exceedance at a specific point from the annual CDF. In brief, the frequency scaling model was derived based on the correlation between the attenuation ratio of a higher and lower frequency against the attenuation at a lower frequency. The newly developed formulation was utilized to generate new CDFs of attenuation at different frequencies. The proposed model offers a lower RMSE value and percentage error of 2.8 and 11.3% respectively. In contrast, the generic method suggested by the ITU-R only managed to perform prediction with RMSE value and percentage errors of 28.3 and 28% accordingly. The new model was validated using data set from alternative years and alternate locations. In conclusion, the results from the research demonstrate a model that can be used in the tropical-equatorial region in a way denoting the achievement of fulfilling the stated objectives. The satellite signal performance can be improved by applying developed mitigation techniques with an economically viable cost where dependable fade margins can be attained. The newly developed frequency scaling technique can offer the right margin to achieve the required quality of service (QoS) for future SatCom in supporting near-future 5G communication. Consistent connectivity for high-speed broadband communication demand in delivering digital and internet applications during heavy precipitation can be attained.

خلاصة البحث

يؤدي الازدحام في نطاقات التردد المنخفضة إلى زيادة الطلب على استخدام وتشغيل نطاقات التردد الأعلى. لذلك، فإنّ النطاقات فوق 10 جيجاهرتز مطلوبة الآن لتلبية الاحتياجات المتزايدة بشكل كبير في أنظمة اتصالات الأقمار الاصطناعية (SatCom). ولكنّ أكبر مشكلة في نشر الترددات فوق 10 جيجاهرتز في المناطق الاستوائية المدارية هي أن هذه المناطق ستشهد تدهوراً حاداً في جودة الإشارة بسبب هطل الأمطار الغزيرة على مدار العام. فمن المطلوب تقدير موثوق للتوهين الناجم عن المطر. وكذلك، هناك حاجة لهوامش تلاشي موثوقة للتخفيف من الخسائر الحادة في الإشارة. لقد وجد أن التحقق من صحة البيانات لتقدير التوهين الناجم عن المطر باستخدام تقنية تعديل التردد (Frequency Scaling) لم يرد في أي دراسات سابقة أجريت في المناطق المدارية. لذا يقترح هذا البحث أنه بدلاً من استخدام الطريقة التقليدية للتنبؤ بالتوهين الناجم عن المطر باستخدام معلومات معدل هطل المطر النقطي، ينبغي أيضاً إنشاء تقنية قابلة للتطبيق غير متعلقة بالأرصاد الجوية. ويمكن أن تكون تقنية تعديل التردد هي الوسيلة البديلة للتنبؤ بالتوهين الناجم عن المطر عندما لا تتوفر بيانات هطل الأمطار. تتضمن أهداف البحث دراسات التوهين الناجم عن المطر لاتصالات الأقمار الاصطناعية (SatCom) في المناطق المدارية. وتشمل تحديد أفضل هامش تلاشي للتوهين الناجم عن المطر في وصلات مختلفة، وصياغة نموذج جديد لتعديل التردد بدقة محسنة، والتحقق من صحة النموذج المقترح. كما تشمل المنهجيات المتضمنة في الدراسة معالجة الإشارات المرسله للحصول على إحصائيات أولية للتوهين الناجم عن المطر. ويؤدي هذا لاحقاً إلى توليد دوال توزيع تراكمي (CDFs) للتوهين الناجم عن المطر شهرية وسنوية. كما تم إجراء تحليل الشهر الأسوأ لكثافة المطر والتوهين الناجم عن المطر. حيث من المتوقع أن تكون خسارة الإشارة مروعة في أسوأ شهر بسبب ارتفاع معدل هطل المطر. وقد تم تحديد هامش التلاشي المطلوب من خلال تجاوز الحد الأقصى عند نقطة معينة من (CDF) السنوي. باختصار، تم اشتقاق نموذج تعديل التردد بناءً على الارتباط بين نسبة التوهين لتردد أعلى وتردد أدنى مقابل التوهين عند تردد أدنى. كما تم استخدام الصيغة المطورة حديثاً لتوليد (CDFs) جديدة للتوهين عند ترددات مختلفة. يقدم النموذج المقترح قيمة (RMSE) ونسبة خطأ بمقدار 2.8 و 11.3% على التوالي. وعلى النقيض من ذلك، فإن الطريقة العامة التي اقترحها قطاع الاتصالات الراديوية (ITU-R) لم تتمكن إلا من التنبؤ بقيمة (RMSE) ونسبة خطأ بمقدار 28.3 و 28% على التوالي. تم التحقق من صحة النموذج الجديد باستخدام مجموعة بيانات من سنوات مختلفة ومواقع مختلفة. وفي الختام، تظهر نتائج البحث نموذجاً يمكن استخدامه في المنطقة الاستوائية المدارية بطريقة

تدل على تحقيق الأهداف المذكورة. يمكن تحسين أداء إشارة القمر الاصطناعي من خلال تطبيق تقنيات تخفيف مطورة بتكلفة مجدية اقتصادياً، حيث يمكن تحقيق هوامش تلاشي موثوقة. ويمكن أن توفر تقنية تعديل التردد المطورة حديثاً الهامش الصحيح لتحقيق جودة الخدمة (QoS) المطلوبة لاتصالات الأقمار الاصطناعية (SatCom) المستقبلية في دعم اتصالات الجيل الخامس (5G) في المستقبل القريب. كما يمكن تحقيق اتصال ثابت لتلبية حاجة اتصالات النطاق العريض عالي السرعة في تقديم التطبيقات الرقمية وتطبيقات الإنترنت أثناء هطل الأمطار الغزيرة.



APPROVAL PAGE

The thesis of Nur Hanis Sabrina Binti Suhaimi has been approved by the following:

Ahmad Fadzil bin Ismail
Supervisor

Khairayu bt Badron
Co-Supervisor

Md Rafiqul Islam
Co-Supervisor

Yasser Asrul bin Ahmad
Co-Supervisor

Mashkuri Yaacob
Internal Examiner

Jafri Bin Din
External Examiner

Asadullah Shah
Chairman

DECLARATION

I hereby declare that this dissertation is the result of my investigations, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at IIUM or other institutions.

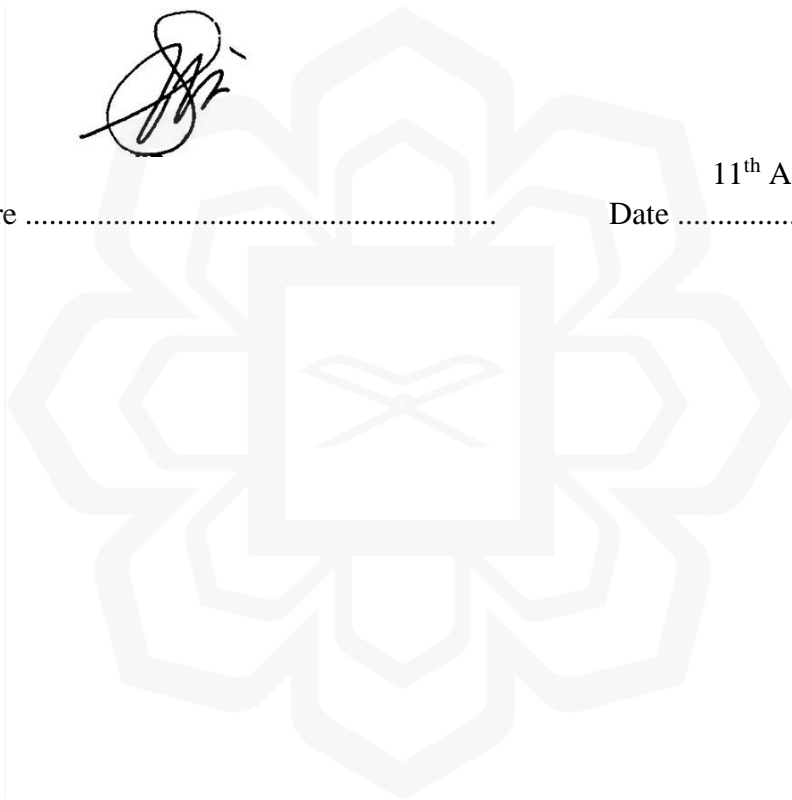
Nur Hanis Sabrina Binti Suhaimi



Signature

11th April 2023

Date



INTERNATIONAL ISLAMIC UNIVERSITY MALAYSIA
DECLARATION OF COPYRIGHT AND AFFIRMATION OF
FAIR USE OF UNPUBLISHED RESEARCH

FREQUENCY SCALING IN MILLIMETRE-WAVE RAIN
ATTENUATION ESTIMATION FOR SATELLITE LINK IN
TROPICAL REGIONS

I declare that the copyright holder of this thesis/dissertation are jointly owned by the student and IIUM.

Copyright © 2023 Nur Hanis Sabrina binti Suhaimi and International Islamic University Malaysia. All rights reserved.

No part of this unpublished research may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise without prior written permission of the copyright holder except as provided below.

1. Any material contained in or derived from this unpublished research may only be used by others in their writing with due acknowledgement.
2. IIUM or its library will have the right to make and transmit copies (print or electronic) for institutional and academic purpose.
3. The IIUM library will have the right to make, store in a retrieval system and supply copies of this unpublished research if requested by other universities and research libraries.

By signing this form, I acknowledged that I have read and understand the IIUM Intellectual Property Right and Commercialization policy.

Affirmed by Nur Hanis Sabrina Binti Suhaimi.



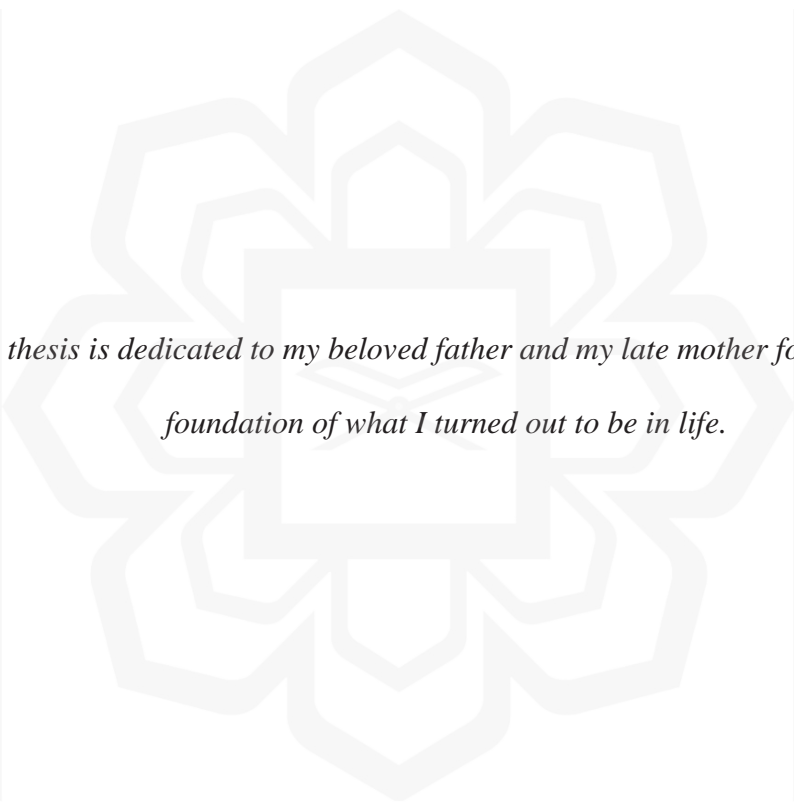
.....

Signature

11th April 2023

.....

Date



*This thesis is dedicated to my beloved father and my late mother for laying the
foundation of what I turned out to be in life.*

ACKNOWLEDGEMENTS

Praise to Allah SWT, The Most Gracious and Most Merciful, for granting me opportunities to complete this dissertation, and for blessing me throughout the years upon seeking knowledge in this PhD journey. Without the grace, mercy and blessings from Allah SWT, this achievement would be impossible. His Mercies and Blessings on me ease the difficulty of completing this journey.

I would like to express my sincerest gratitude to my supervisor Prof. Ir. Dr Ahmad Fadzil Ismail for his continuous courage and guidance for me in completing the research. I am most indebted to him for his highly committed characteristics, kindness, and thoroughness attitude have led to the successful completion of my work. His detailed comments and suggestions have improved this thesis and made this thesis well-written. His vast knowledge, patience and wisdom have been thorough and of great assistance to me in completing my study. Despite his very busy commitments, he always makes time to attend to me whenever requested. His moral support and high cooperation are the boosters that helped me in writing this research work.

I would also like to extend this act of gratitude to my co-supervisors Dr Khairayu bt Badron, Prof. Md Rafiqul Islam and Dr Yasser Asrul bin Ahmad throughout this journey of knowledge-seeking, for their guidance, assistance, fruitful discussions and their never-ending encouragement, have had motivated me to accelerate on the completion of this study. Besides that, I want to deliver my acknowledgement towards MEASAT Satellite System Sdn. Bhd. (MEASAT), MEASAT Broadcast Network System Sdn Bhd (ASTRO) and the Department of Irrigation and Drainage, Malaysia for the collaboration in providing the data for this research. Special thanks to Mr Mohd Akmal Yahaya and Mr Ahmad Faiz Yahaya as well, for their assistance in supplying the massive raw data on rain attenuation for this research.

It is with great pleasure to dedicate this achievement to my beloved dad, Suhaimi bin Abas, the vital backbone that has been continuously supporting and guiding me with his knowledge and experience in the field throughout my research completion journey. To my lovely family; my husband Alang, and my dearest children; Amni, Ali, and Aleesa whose unwavering faith in my capability and effort to accomplish the research made me work even harder and perform my best in completing my study, I owe each and every achievement to all of them. Their endurance and understanding when I am struggling in completing this study is the most valuable gift.

Last but not least, I would also like to extend my appreciation and gratitude to families and friends who have contributed their effort and supported this work, directly or indirectly, be it financial, time, as well as moral support, they have been the source of my strength and motivation to complete this research, and that they are truly cherished for a lifetime.

Table of Contents

Abstract	ii
Abstract in Arabic	iii
Approval Page.....	v
Declaration	vi
Copyright Page.....	vii
Acknowledgements	ix
Table of Contents	x
List of Tables	xiii
List of Figures	xv
CHAPTER ONE: INTRODUCTION	1
1.1 Background of the Study	1
1.2 Problem Statement	5
1.3 Purpose of the Study	10
1.4 Research Objectives.....	11
1.5 Research Questions.....	11
1.6 Theoretical Framework.....	12
1.7 Research Scope	13
1.8 Research Philosophy.....	14
1.9 Research Hypotheses	15
1.10 Significance of the Study.....	15
1.11 Limitations of the Study	16
1.12 Definition of Terms	17
1.13 Organization of the Thesis	18
1.14 Chapter Summary	19
CHAPTER TWO: LITERATURE REVIEW	21
2.1 Introduction.....	21
2.1.1 Satellite Communication System.....	22
2.1.2 Terrestrial Communication System	23
2.2 Importance of Satellite Communication System	24
2.3 Distribution of Frequencies Spectrum	27
2.3.1 Microwave Bands (C, X and Ku-bands).....	29
2.3.2 Millimetre Wave (Ka, Q and V-bands).....	30
2.4 Classification of Tropical Climate.....	31
2.4.1 Distribution of Equatorial Climate	32
2.4.2 Malaysia’s Climate	32
2.4.3 Precipitation Type in Tropical Regions	36
2.5 Propagation Impairment in Satellite-Earth Link at Higher Frequencies	37
2.6 Fade Margin Requirement for Good Quality of Services (QOS)	39
2.7 Rain Attenuation Prediction for Earth-Space Telecommunication System.....	42

2.7.1 Approaches for the Prediction of Rain Attenuation	44
2.7.2 ITU-R Prediction Method of Determining Rain Attenuation.....	44
2.7.3 Meteorological Technique.....	46
2.7.4 Non-meteorological Technique.....	48
2.7.4.1 Frequency Scaling.....	49
2.7.4.2 Elevation Scaling	49
2.7.4.3 Path Length Scaling	50
2.7.4.4 Polarization Scaling	51
2.8 Frequency Scaling Technique	52
2.8.1 Statistical Frequency Scaling	54
2.8.2 Instantaneous Frequency Scaling	56
2.8.3 Previous Model of Frequency Scaling	58
2.8.3.1 ITU-R 618-13 Model (2017)	59
2.8.3.2 Hodge’s Model (1977).....	59
2.8.3.3 Battesti’s Model (1982)	60
2.8.3.4 Kheirallah’s Model (1980).....	61
2.8.3.5 CCIR (1980).....	62
2.8.3.6 Simple Power Law (SPL) Model (1974-1995).....	62
2.8.3.7 Boithias’s Model (1989)	63
2.8.3.8 Zhou’s Model (1999)	64
2.8.4 Previous Related Research	64
2.8.5 Research Gap.....	69
2.9 Worst Month Analysis	70
2.10 Chapter Summary.....	73
CHAPTER THREE: METHODOLOGY.....	74
3.1 Introduction.....	74
3.2 Measurement Setup.....	77
3.2.1 C-band Beacon Measurement Setup.....	82
3.2.2 Ku-band Beacon Measurement Setup.....	85
3.2.3 Ka-band Beacon Measurement Setup.....	87
3.2.4 Rain Gauge Measurement Setup.....	90
3.3 Collection of Data.....	92
3.4 Data Processing.....	92
3.4.1 Extraction & Conversion of Raw Data into Rain Attenuation Data	93
3.4.2 Generation of Probability Density Function (PDF)	94
3.4.3 Generation of Cumulative Density Function (CDF).....	95
3.4.4 Generation of Time Exceedance	95
3.4.4.1 Monthly.....	96
3.4.4.2 Annual.....	96
3.5 Data Analysis.....	97
3.5.1 Time Exceedance Analysis for C, Ku & Ka-band	98
3.5.2 Technique to Extrapolate the Ka-band Attenuation Data	102
3.5.3 Selection of The Best Extrapolation Technique to Determine Ka-band.....	104
3.5.4 Comparison with ITU-R.....	105
3.5.5 Determination of Worst Month	105

3.6 Determination of Frequency Scaling Technique	106
3.6.1 Proposed Frequency Scaling Model	106
3.7 Validation of the Model	107
3.8 Summary	107
CHAPTER FOUR: RESULT	109
4.1 Introduction.....	109
4.2 Diurnal Time-Series Analysis.....	110
4.2.1 Monthly Analysis.....	117
4.2.1.1 Rainfall Rate	117
4.2.1.2 Rain Attenuation	120
4.2.2 Annual Analysis.....	130
4.2.2.1 Rainfall Rate	130
4.2.2.2 Rain Attenuation at the C-band.....	132
4.2.2.3 Rain Attenuation at the Ku-band	134
4.2.2.4 Rain Attenuation at the Ka-band.....	137
4.2.2.5 Extrapolation of Rain Attenuation at the Ka-band	139
4.3 Determination of Fade Margin	144
4.4 Comparison With ITU-R	148
4.5 Worst Month Analysis	151
4.6 Frequency Scaling.....	158
4.6.1 ITU-R 618-13 Frequency Scaling.....	158
4.6.2 Hodge.....	159
4.6.3 Battesti	161
4.6.4 Kheirallah.....	162
4.6.5 CCIR	163
4.6.6 Simple Power Law	164
4.6.7 Boithias	167
4.6.8 Zhou	168
4.7 Proposed Frequency Scaling Technique.....	170
4.8 Implementation of Frequency Scaling Technique for Q-band and V-band	179
4.9 Validation of Proposed Frequency Scaling Technique.....	182
4.10 Summary	190
CHAPTER FIVE: DISCUSSION AND CONCLUSION.....	192
5.1 Discussion	192
5.2 Conclusion and Future Works	195
REFERENCES.....	197
APPENDIX I: SAMPLE PDF OF KA-BAND RAIN ATTENUATION	213
APPENDIX II: SAMPLE CDF OF KA-BAND RAIN ATTENUATION	214
APPENDIX III: EXTRAPOLATIONS FORMULA FOR THE KA-BAND LINK	215

LIST OF TABLES

Table 2.1	Comparison of Frequency Scaling Technique in Predicting Rain Attenuation for the Satellite Communication Link	65
Table 2.2	Limitation of Frequency Scaling Technique in Predicting Rain Attenuation for the Satellite Communication Link	68
Table 2.3	Q_l and β for Various Propagation Effects and Areas in Tropical Regions	72
Table 3.1	C-band Beacon Signals Receiving Setup	83
Table 3.2	Ku-band Beacon Signals Receiving Setup	86
Table 3.3	Ka-band Beacon Signals Receiving Setup	88
Table 3.4	Vaisala Weather Transmitter WXT520 Specifications	91
Table 3.5	Rain Detected at Different Rain Gauge Locations in January 2016	101
Table 4.1	Total Precipitations in Cyberjaya for the Year 2016	120
Table 4.2	Rainfall Rate at 0.01% of Time Exceedance for C-band Rain Attenuation at 0.1%, 0.3%, 0.01% and 0.03% of Time Exceedance	122
Table 4.3	Rainfall Rate at 0.01% of Time Exceedance with Ku-band Rain Attenuation at 0.1%, 0.3%, 0.01% and 0.03% of Time Exceedance	124
Table 4.4	Rainfall Rate at 0.01% of Time Exceedance with Ka-band Rain Attenuation at 0.1%, 0.3%, 0.01% and 0.03% of Time Exceedance	128
Table 4.5	Annual Rainfall Rate and Annual Rain Attenuation of the C-band at 0.1%, 0.3%, 0.01% and 0.03% of Time Exceedance	134
Table 4.6	Annual Rainfall Rate and Annual Rain Attenuation of the Ku-band at 0.1%, 0.3%, 0.01% and 0.03% of Time Exceedance	135
Table 4.7	Annual Rainfall Rate and Annual Rain Attenuation of Ka-band at 0.1%, 0.3%, 0.01% and 0.03% of Time Exceedance	138
Table 4.8	Summary of Techniques Used to Determine the Best Extrapolation Graph for Extended Ka-band	142
Table 4.9	Comparison of Measured Rain Attenuation at 0.1%, 0.01% and 0.001% of Time Exceedance with Ahmad's (2019) Model and ITU-R 618-13 (2017)	143

Table 4.10	Fade Margins for C, Ku And Ka-band Links Operating at 99.70%, 99.90%, 99.97% and 99.99% in 2016	147
Table 4.11	Measured Values and Proposed Values for Q_1 and β in Tropical Regions for Slant Path and Rain Rate Propagation	156
Table 4.12	RMSE and Percentage Error of Available Model over the Interval [0.001% to 1%]	169
Table 4.13	RMSE and Percentage Error Obtained after Testing the Proposed Model over the Intervals [0.001% to 1%]	177
Table 4.14	Comparison of Statistical Parameters between the Proposed Frequency Scaling Model and the ITU-R Frequency Scaling Method	179
Table 4.15	Tabulated Values of Scaled Attenuation at Ka, Q and V-band links	181
Table 4.16	Comparison Values of V-band Rain Attenuation at 99.9% and 99.99% of Link Availability Between the Existing Model and the New Model.	182
Table 4.17	RMSE and Percentage Error Value of Rain Attenuation Predicted at Cyberjaya in the year 2015 using the Proposed Model	184
Table 4.18	RMSE and Percentage Error Value of Rain Attenuation using the Proposed Model Predicted at Rawang in the year 2016	186
Table 4.19	RMSE and Average Percentage Error Value of Rain Attenuation at the V-band (40 GHz) Predicted in Nigeria using the Proposed Model	188
Table 4.20	RMSE Percentage Improvement for the Ka-band using the Proposed Model as compared to the ITU-R Frequency Scaling Technique	189
Table 4.21	RMSE Percentage Improvement for Estimating V-band Rain Attenuation using the Proposed Model as compared to the ITU-R Rain Attenuation Prediction Model	190

LIST OF FIGURES

Figure 1.1	Map of Tropical Regions (IEEI, 2014)	4
Figure 1.2	Overview of System Setup for the C & Ku-bands	8
Figure 1.3	Miniature Model of Measat-3 Satellite	8
Figure 1.4	Overview of System Setup for the Ka-band	9
Figure 1.5	Miniature Model of Measat-5 Satellite	9
Figure 1.6	Theoretical Framework of Statistical Frequency Scaling Study	13
Figure 2.1	Satellite Communication (SatCom) System (Walter, 2018)	23
Figure 2.2	Terrestrial Communication System (Yee et al., 2007)	24
Figure 2.3	Wavelength Designation for Frequency Band	28
Figure 2.4	Climate Region (Mustafa et al., 2017)	31
Figure 2.5	Total Rainfall in Malaysia in 2016 (MMD, 2016)	35
Figure 2.6	Schematic Diagram of an Earth-Space Input Parameter Needed in the Attenuation Prediction Process (ITU-R P.618-13, 2017)	45
Figure 2.7	The Research Gap Identified in the Study	70
Figure 3.1	Overview of the Research	75
Figure 3.2	Research Flow Chart	76
Figure 3.3	Earth Stations at the MEASAT Teleport and Broadcast Centre	77
Figure 3.4	Receiver Station at the ASTRO Broadcast Centre	78
Figure 3.5	MEASAT-3 Specifications and Footprints (MEASAT, 2022)	79
Figure 3.6	MEASAT-5 Specifications and Footprints (MEASAT, 2022)	79
Figure 3.7	MEASAT-3 and MEASAT-5 in reference to their Earth Stations	80
Figure 3.8	Earth-Space Link Design	81
Figure 3.9	C/Ku-band Configuration	84
Figure 3.10	C-band Antenna (General Dynamics SATCOM Technologies)	84

Figure 3.11	Ku-band Antenna (General Dynamics SATCOM Technologies)	86
Figure 3.12	Digital Tracking Receiver for Ku and C-band	87
Figure 3.13	Ka-band Configuration	88
Figure 3.14	Ka-band Antenna	89
Figure 3.15	Digital Tracking Receiver for Ka-band	89
Figure 3.16	ASTRO Rain Sensor	91
Figure 3.17	Flow Chart of Processing Data	93
Figure 3.18	Steps in Generating Time Exceedance for C, Ku and Ka-band Beacon Signals, and Rainfall Rate Data.	97
Figure 3.19	Time-Series for Rain Event on 6th February 2016	98
Figure 3.20	Attenuation Time-Series of Ka-band for One Day on 6th February 2016	99
Figure 3.21	Location of Rain Gauge at Paya Indah, Puncak Niaga, and Earth Station at Cyberjaya	100
Figure 3.22	Time-Series of Rain Attenuation of Ka-band on 4th January 2016	102
Figure 3.23	Plot of Annual Rain Attenuation of Ka-band versus Annual Rainfall Rate	103
Figure 4.1	Time-Series Plots of Rainfall Intensity and Attenuation During Rainfall on 20 th May 2016	111
Figure 4.2	Time-Series for Rain Events on 6 th February 2016	112
Figure 4.3	Time-Series of C-band Attenuation for the Entire Day of 6 th February 2016	113
Figure 4.4	Time-Series of C-band Attenuation during Rainfall on 6th February 2016	113
Figure 4.5	Time-Series of Ku-band Attenuation for One Day (6 th February 2016)	114
Figure 4.6	Time-Series of Ku-band Attenuation during Rainfall on 6 th February 2016	115
Figure 4.7	Rain Attenuation Time-Series of Ka-band on 6 th February 2016	116
Figure 4.8	Time-Series of Rainfall on 4 th January 2016	117
Figure 4.9	Monthly Rain Intensity of Time Exceedance in 2016	119

Figure 4.10	Monthly Distribution of the C-band Rain Attenuation at Cyberjaya in 2016	121
Figure 4.11	Monthly Distribution of the Ku-band Rain Attenuation at Cyberjaya in 2016	123
Figure 4.12	Histogram of Certain Attenuation Thresholds and Monthly Time Exceedance	125
Figure 4.13	The Probability of Specific Rain Attenuation Thresholds at the Ku-band Link	126
Figure 4.14	Monthly Distribution of Rain Attenuation of Ka-band at Cyberjaya in 2016	127
Figure 4.15	Histogram of a Specific Threshold of Attenuation is Exceeded Monthly at the Ka-band Link	129
Figure 4.16	Probability of Specific Thresholds of Rain Attenuation Exceedance at the Ka-band Link	130
Figure 4.17	Annual CDF of Rain Intensity for 2016 in Cyberjaya	131
Figure 4.18	Annual CDF of C-band Rain Attenuation for 2016 in Cyberjaya	132
Figure 4.19	C-band Rain Attenuation Correlated to Rainfall Rate in Cyberjaya's Rain Gauge	133
Figure 4.20	Annual CDF of Ku-band Rain Attenuation for 2016 in Cyberjaya	135
Figure 4.21	Ku-band Rain Attenuation Correlated to Rainfall Rate in Cyberjaya's Rain Gauge	136
Figure 4.22	Annual CDF of Ka-band Rain Attenuation for 2016 in Cyberjaya	137
Figure 4.23	Ka-band Rain Attenuation Correlated to Rainfall Rate in Cyberjaya's Rain Gauge	138
Figure 4.24	Measured Plotted Values with Linear Extrapolation Model	139
Figure 4.25	Measured Plotted Values with First-Order Power Law Extrapolation Model	140
Figure 4.26	Measured Plotted Values with Second-Order Power Law Extrapolation	140
Figure 4.27	Measured Plotted Values with Second-Degree Polynomial Extrapolation Model	141
Figure 4.28	Measured Plotted Values with Ahmad's (2019) Extrapolation Model	141

Figure 4.29	Extrapolated Ka-band Rain Attenuation Correlated to Rainfall Rate in Cyberjaya's Rain Gauge	144
Figure 4.30	Annual CDF of C-band Rain Attenuation	145
Figure 4.31	Annual CDF of Ku-band Rain Attenuation	145
Figure 4.32	Annual CDF of Measured Ka-band Rain Attenuation	146
Figure 4.33	Annual CDF of Extrapolated Ka-band Rain Attenuation	146
Figure 4.34	Annual CDF of the Measured Rain Rate Value in 2016 compared to ITU-R 837-7 Rainfall Prediction	149
Figure 4.35	Annual CDF of Measured Values compared to ITU-R Prediction Values of Rain Attenuation for C, Ku and Ka-band Links	150
Figure 4.36	The Probability of a Specific Threshold of Rainfall Rate Exceeded for the year 2016 at Cyberjaya	151
Figure 4.37	Annual and Worst Month Rain Rate Exceedance Curve	152
Figure 4.38	Q as a Function of Annual Rainfall Rate Exceedance Percentage	153
Figure 4.39	Q as a Function of Annual Rain Attenuation at Ku-band Exceedance Percentage	154
Figure 4.40	Worst Month Model Comparison of Ku-band Rain Attenuation	155
Figure 4.41	Q as a Function of Annual Rain Attenuation at Ka-band Exceedance Percentage	157
Figure 4.42	Worst Month Model Comparison of Ku-band Rain Attenuation	158
Figure 4.43	ITU-R 618-13 Frequency Scaling	159
Figure 4.44	Hodge Frequency Scaling Model	160
Figure 4.45	Battesti Frequency Scaling Model	161
Figure 4.46	Kheirallah Frequency Scaling Model	162
Figure 4.47	CCIR Frequency Scaling Model	163
Figure 4.48	Simple Power Law Frequency Scaling for Pairs Ku-band/C-band and Ka-band/C-band	164
Figure 4.49	Simple Power Law Frequency Scaling for Pairs Ka-band/Ku-band	165
Figure 4.50	Drufuca Frequency Scaling Model	166
Figure 4.51	Boithias Frequency Scaling Model	167

Figure 4.52	Zhou Frequency Scaling Model	168
Figure 4.53	Time Percentage Exceedance Curve of Measured Rain Rate and Rain Attenuation of C, Ku and Ka-band Links for 2016	170
Figure 4.54	RAS for the Year 2016 as a Function of Lower Frequency Attenuation for the Frequency Pairs of 20/12 GHz	171
Figure 4.55	Graph of Attenuation at the Ku-band versus Attenuation at the Ka-band	172
Figure 4.56	Graph of Attenuation at the Ku-band versus Attenuation at the C-band	173
Figure 4.57	Graph of Attenuation at the Ka-band versus Attenuation at the C-band	174
Figure 4.58	Comparison of Scaled-up Ka-band Rain Attenuation Using the Proposed Frequency Scaling Model with Measured Rain Attenuation at the Ka-band in 2016	175
Figure 4.59	Comparison of the Derived Frequency Scaling Technique and Available Frequency Scaling Models, including ITU-R at Frequency Pair of Ka/Ku-band	176
Figure 4.60	Scale-up of Ka, Q and V-band links using the Proposed Frequency Scaling Model	180
Figure 4.61	Comparison of Measured Rain Attenuation of the Proposed Model at Cyberjaya in 2015	183
Figure 4.62	Comparison of Measured Rain Attenuation of the Proposed Model at Rawang in 2016	185
Figure 4.63	Comparison of the Proposed Model with the Measured Rain Attenuation at the V-band Link in Nigeria	187
Figure 4.64	RMSE Comparison between the New Model and ITU-R model	189

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND OF THE STUDY

The Covid-19 global pandemic has caused serious problems for the world's leading satellite industries. They faced several challenges in delivering reliable link availability of satellite-Earth signals. Since the start of the pandemic, broadband connectivity provided by satellite operators had drastically increased from 15% to 70% in network usage. Satellites can instantly connect isolated communities and offer connectivity to unreachable and remote areas. However, the main challenge experienced by satellite industries is providing consistent internet connection in places that experience frequent heavy precipitation where severe impairment of satellite signal reception occurs. Precipitation like rain prominently degrades the quality of satellite signals. When signals travel from satellites to the Earth's receivers, they pass over unpredictable rain along their propagation paths. The signal power may weaken before reaching its destination, especially when longer slant paths and lower elevation angles are involved (Igwe et al., 2019; Nazrul et al., 2013). These factors affect link availability, leading to negatively impacting consumer satisfaction which further damages and causes a tumble in the reputation of satellite providers.

The International Telecommunication Union's (ITU) Radio Regulations (RR) defined satellite links as radio links transmitting between Earth stations to satellite receivers and vice versa. An "uplink" refers to an Earth-to-satellite propagation, and a "downlink" implies transmission from the satellite to a receiving Earth station. Radio frequencies that have wavelengths (λ) ranging between 1 mm to 10 mm in satellite-Earth links are referred to as millimetre-wave frequencies. Communication satellites facilitate human connection regardless of location (Badron et al., 2015). Satellite communication (SatCom) is then considered the best option for addressing user demands for areas not economically reachable by terrestrial links, such as for

developing countries with vast lands or in the middle of the ocean. Numerous requirements in the telecommunication and broadcasting industries have prompted an increase in demand for high-speed broadband communication, especially for multimedia services. These have subsequently led to the growing demands for greater bandwidth (Yussuff et al., 2019). Although the rollout of fibre in South Africa significantly enhanced the speed of home broadband in the year 2014, satellite infrastructures continue to fulfil a crucial role in providing communication access to rural, remote and inland areas throughout the continent and across the globe as well. The fast growth in telecommunications, increasing bandwidth demands, congestion in lower frequency bands, and miniaturisation of communication equipment have forced designers to employ higher frequency bands such as the Ku (12 to 18 GHz), Ka (26.5 to 40 GHz) and V (40 to 75 GHz) (Kamruzzaman & Islam, 2014). Unfortunately, higher operating frequency bands are very susceptible and vulnerable to tropospheric conditions that impair and reduce signal quality (Sujimol et al., 2015).

The proposed satellite television broadcast for home reception is called Direct Broadcast Satellite (DBS) or Direct-to-Home (DTH). It enables the easy access to live television channels from other countries. Various multimedia applications are offered by satellite communication which all require extremely high data rate transmissions, including videoconferencing, broadcasts, data broadcasts that include High Definition (HD) television broadcasts, bandwidth on demand, intranet works and telemedicine. Such applications lead to spectrum congestion in lower frequency bands. Shifting to higher frequency bands is one option for achieving better services in satellite communication applications since these bands support high data-rate broadcasts and internet applications. SatCom systems are now moving towards the use of Ka-bands (20/30 GHz). In future, the shift to higher frequency bands, such as the Q/V (40/50 GHz), will undoubtedly occur to accommodate larger bandwidth requirements. High radio frequency offers several advantages such as larger spectrum availability, smaller equipment size requirements and less interference for SatCom (Samat & Singh, 2020).

High Throughput Satellites (HTS) are communication satellites with higher throughput than traditional Fixed Satellite Services (FSS) which give advantages in frequency reuse and multiple spot beams. High throughput is important because of its high-speed information delivery (bits/sec). It can be influenced by frequency reuse and

channel efficiency. The first commercial HTS in Asia is the IPSTAR (Thaicom-4) operating in the Ku-band and is now developing to operate in the Ka-band (ITU-R P.618-13, 2017). The main purpose of these satellites is fast internet connectivity. The commercial HTS, IPSTAR, was launched by Thaicom in 2005. This satellite was designed for FSS, which is a two-way communication over an Internet Protocol (IP) platform with a maximum capacity throughput of 45 Gbps, a user download speed of up to 5 Mbps and an upload speed of 4 Mbps.

Today, the IPSTAR is licensed to operate in 14 countries in the Asia Pacific areas, which directly allows service providers and operators to deliver real-time broadband internet access via satellite. In May 2011, Thaicom began selling some parts of its satellite capacity to Malaysia. Malaysia's satellite operator, MEASAT, signed a contract for a specific capacity on the IPSTAR. MEASAT Satellite Systems Sdn. Bhd. purchased access to seven IPSTAR spot beams under a decade contract for delivering a total of 3.3 Gbps, representing 7% of the satellite's total capacity. The bandwidth was known and marketed in Malaysia as MEASAT-5 (Christensen, 2012).

The idea of deploying a new satellite system in the Ka-band frequency started to evolve and gain attention in countries with tropical environments. The areas between the Earth's latitudes of 23°27' North and 23°27' South are identified as tropical regions, as shown in Figure 1.1. The propagation impairments are quite critical in locations with tropical weather. This is due to the occurrence of frequent heavy rain which severely affects high-frequency radio wave signals. The rain can cause severe signal fading as well as interference (Yeo et al., 2009a). The dominant factor for signal impairment of satellite links at higher frequencies is rain, and this depends on the rain rate, the raindrop size and raindrop density (Kamruzzaman & Islam, 2014; Islam et al., 2018). Raindrops absorb and scatter radio waves with shorter wavelengths, hence resulting in signal attenuation as well as reducing system availability and reliability (Mom et al., 2021). The attenuation due to rain on any path depends on several parameters, such as the specific attenuation in dB/km, frequency, polarization, temperature, path length and latitude. As it is known rain attenuation causes a reduction of the received signal level, therefore, upon designing dependable Ka-band satellite communication systems, rain attenuation must be considered as an important propagation element to ensure signal quality. The conventional quality of service (QoS) criterion in Malaysia for broadcasts

is 99.99% availability (MCMC, 2022). The QoS requirement recommended by the ITU-R Telecommunication Standardisation is 99.9% link availability for communication services (ITU-T G.1028, 2016).

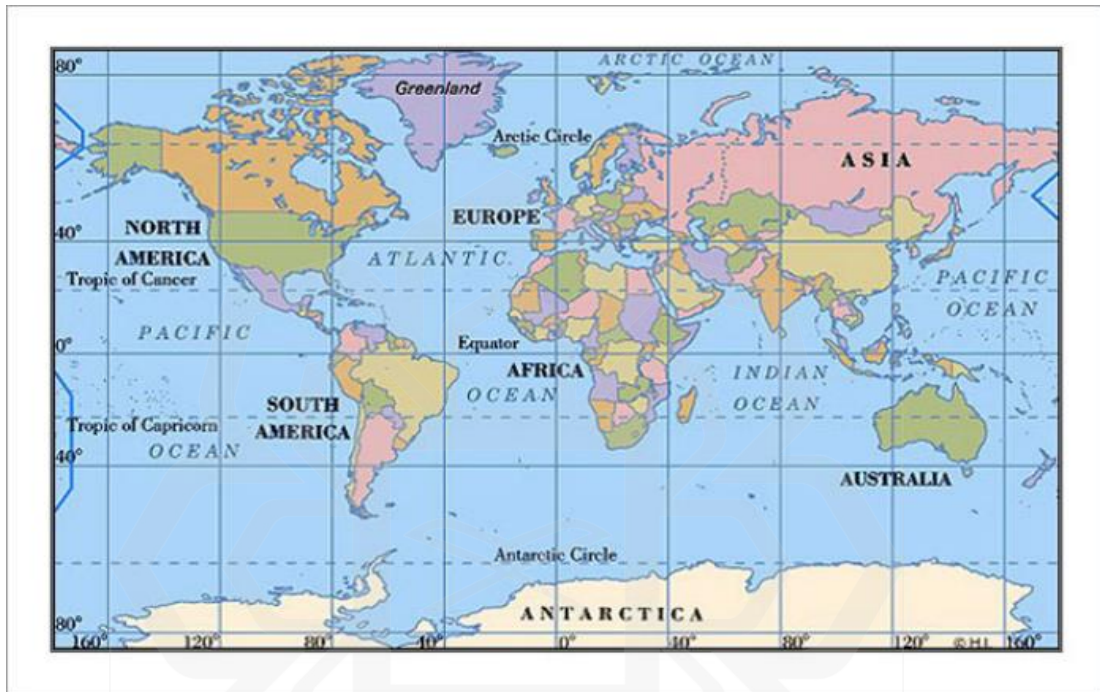


Figure 1.1 Map of Tropical Regions (IEEI, 2014)

Rain attenuation is typically assumed as a product of specific attenuation (dB/km) and the effective propagation path length (km). The effective path length is the product of the path reduction factor and the physical path length of a microwave link (Islam et al., 2012). Rain is the most destructive source of signal propagation on these bands. The consequence of rain attenuation on band signal quality, especially in tropical countries such as Malaysia, requires comprehensive research. The appropriate fade margins must be identified to ensure successful implementation in all provinces throughout Malaysia.

Several methods can be used for identifying and estimating rain attenuation. The frequency scaling technique is one suggested approach (Ulaganathan et al., 2013). Frequency scaling of attenuation is the prediction of rain attenuation at the desired frequency derived from attenuation values at another frequency (Laster & Stutzman, 1995; Ramana, 2015; Ulaganathan et al., 2013). The method can be used to obtain an estimation of the attenuation statistics at the desired frequency from attenuation values measured at a lower frequency. This is very much applicable where and when reliable long-term rain attenuation statistics are available. Numerous scaling models have been developed either from theory, from empirical data of various propagation experiments or from both (Islam et al., 1999).

Generally, statistical models (such as ITU-R) are suitable for establishing fade margins to mitigate the impairment of transmitted signals. However, it has been highlighted by various research that the proposed margin cannot cater to large attenuations and acute impairments in tropical regions (Ismail et al., 2013; Sujimol et al., 2015; Yaccop et al., 2016). The design and deployment of satellite systems in tropical regions for higher frequencies require an accurate and precise prediction of impairment statistics. The statistics must have the smallest error margin to employ several adaptive techniques at the receiver system. This applies to Malaysia, a country with a tropical climate with persistent heavy rainfall every year. The research outcomes will help in solving the relevant problems and setting an appropriate link budget when designing new satellite networks. Appropriate allocation of higher power transmission can be deployed to overcome rain fade endured by higher frequency satellite-Earth links.

1.2 PROBLEM STATEMENT

The terrestrial network has a serious limitation in terms of offering mass coverage for rural areas and isolated locations. This can be complemented by satellite-Earth