DETERMINATION OF SPECIFIC ATTENUATION FOR SATELLITE LINKS IN EQUATORIAL-TROPICAL REGION

BY

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ABSTRACT

Satellite technology is coping with the advancement in bandwidth and technology in terrestrial communication by incorporating new technology for Fixed Satellite Services (FSS) and Broadcast Satellite Services (BSS) for communication satellite located in the geostationary orbit recognised as High Throughput Satellite (HTS). Compare to conventional communication satellite, HTS provides larger bandwidth and operates at higher frequency bands mainly in the Ku and Ka-band. However, Ku-band and frequencies above 10 GHz are well known to be susceptible to rain hence require larger rain fade margin. On top of that, the equatorial region has a heavier rainfall rate than the temperate climate hence worsening the rain attenuation. The widely used rain attenuation model such as the ITU-R and other rain models have not been successful to accurately predict the rain attenuation in equatorial region particularly with tropical condition. The specific attenuation is the major component in determining the rain attenuation prediction. This research aims to evaluate and analyse specific attenuation in the equatorial region for satellite link exposed to heavy rainfall. This research also aims to produce a simplified specific attenuation model to be used in the prediction of satellite communication links in the tropical-equatorial region to improve the rain attenuation prediction. Three frequencies, each from C, Ku and Ka-band are measured using commercial earth station systems belongs to MEASAT and ASTRO. At the same time, the point rainfall rate is measured. The rain attenuations from each frequency bands are then correlated with the rainfall rate to produce specific attenuation. The regression analysis is used to produce the measured specific attenuation coefficients at each frequency and further analysed into models for k and α coefficients. At the same time, the areal rainfall rate is measured from five rain gauges using the Department of Irrigation and Drainage rainfall stations. The rainfall rate distribution from the five stations is modelled into a local rainfall rate model. Together, the rainfall rate model and specific attenuation coefficients produce a specific attenuation model based on the power law form. The proposed specific attenuation produces, specific attenuation for frequencies ranging from 4 GHz to 21 GHz suitable for satellite communication links in the equatorial region. Out of the ten rain attenuation models evaluated, two rain attenuation models which are Crane Global and SAM showed the best agreement for the equatorial region. The modified specific attenuation model implemented with Crane Global and SAM model made a 68% and 59% improvement for Ku-band and 21% and 24% improvement for Ka-band in term of root mean square error (RMSE), respectively. Implementing the modified specific attenuation model into various rain attenuation models has shown improvement to the prediction of rain attenuation in the tropical-equatorial region.

خلاصة البحث

تتكيف تكنولوجيا الأقمار الصناعية مع التقدم في عرض النطاق الترددي والتكنولوجيا في الاتصالات الأرضية من خلال دمج تقنية جديدة لأجل خدمات القمر الصناعي الثابت (FSS) وخدمات البث الفضائي (BSS) لأجل الاتصالات الموجود في المدار الثابت بالنسبة للأرض والمعترف به كقمر صناعي عالي الإنتاجية (HTS). مقارنة بقمر الاتصالات التقليدي ، توفر HTS عرض نطاق أكبر وتعمل في نطاقات تردد أعلى بشكل رئيسي في النطاق Kuو Ka. مع ذلك ، فإن النطاق الترددي Ku والترددات التي تفوق 10 GHz معروف جيداً أنها عرضة للأمطار ، وبالتالي فهي تتطلب هامش أكبر من المطر. علاوة على ذلك ، تتمتع المنطقة الاستوائية بمعدلات هطول أمطار غزيرة مقارنة بالمناخ المعتدل ، مما يؤدي إلى تفاقم التخفيف الناجم عن المطر. نموذج التخفيف الناجم عن المطر المستخدم على نطاق واسع مثل قطاع الاتصالات الراديوية والأمطار الأخرى لم تنجح النماذج في التنبؤ بدقة بالتخفيف الناجم عن المطر في المنطقة الاستوائية خاصةً مع الظروف الاستوائية. التخفيف المحدد هو المكون الرئيسي في تحديد التنبؤ بتخفيف المطر. يهدف هذا البحث إلى تقييم وتحليل الضعف النوعي في المنطقة الاستوائية للوصلة الساتلية المعرضة لهطول الأمطار الغزيرة. يهدف هذا البحث أيضًا إلى إنتاج نموذج تخفيف محدد مبسط لاستخدامه في التنبؤ بوصلات الاتصالات الساتلية في المنطقة المدارية الاستوائية لتحسين التنبؤ بتخفيف المطر. يتم قياس ثلاثة ترددات ، كل من C و Ku و Ka-band باستخدام أنظمة المحطة الأرضية التجارية التابعة لـ MEASAT و ASTRO. في نفس الوقت، يتم قياس معدل سقوط المطر. ثم يتم ربط الضعف الناجم عن المطر من كل نطاقات تردد بمعدل هطول الأمطار لإنتاج تخفيف محدد. يستخدم تحليل الانحدار لإنتاج معاملات الضعف المحددة المقاسة في كل تردد ويتم تحليله في نماذج لمعاملات k و α. في الوقت نفسه ، يتم قياس معدل هطول الأمطار في المناطق من خمسة أجهزة قياس المطر باستخدام محطات الري والري والصرف. يتم توزيع معدل هطول الأمطار من المحطات الخمس على نموذج معدل هطول الأمطار المحلي. معًا ، ينتج نموذج معدل هطول الأمطار ومعاملات الضعف المحددة نموذجًا محددًا للضعف استنادًا إلى نموذج قانون الطاقة. التخفيف المحدد المقترح ينتج تخفيفا محددًا للترددات التي تتراوح من 4 GHz إلى 21 GHz ومناسبة لوصلات الاتصالات الساتلية في المنطقة الاستوائية. من بين عشرة نماذج للتخفيف من المطر تم تقييمها ، أظهر نموذجان للتوهين بالمطر وهما Crane Global و SAM أفضل اتفاق للمنطقة الاستوائية. حقق نموذج التوهين المحدد المعدل الذي تم تنفيذه باستخدام Crane Global و SAM نموذجًا بنسبة 68٪ و 59٪ لتحسين Ku-band و 21٪ و 24٪ لتحسين Ka-band في فترة الخطأ التربيعي لمتوسط الجذر (RMSE) ، على التوالي. أظهر تنفيذ نموذج التخفيف المحدد المعدل في نماذج التخفيف بالمطر المختلفة تحسنا في التنبؤ بالتخفيف بالمطر في المنطقة الاستوائية .

APPROVAL PAGE

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DECLARATION

I hereby declare that this thesis is the result of my own 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.

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LIST OF ABBREVIATIONS

ASTRO	MEASAT Broadcast Network Systems Sdn Bhd
BSS	Broadcast Satellite Services
CDF	cumulative distribution function
dB	decibel
dBm	decibel-miliwatts
DDS	Direct Digital Synthesizer
DID	Department of Irrigation and Drainage
DSP	Digital Signal Processing
FSS	Fixed Satellite Services
G/T	Gain over Temperature
GB	Gigabytes
GHz	GigaHertz
GPM	Global Precipitation Measurement
GPS	Global Positioning System
HTS	High-throughput satellite
HydroNET	Malaysia Hydrology Network
ITU	International Telecommunication Union
ITU-R	ITU- Radiocommunication Sector
Ka	K above
kHz	kiloHertz
km	kilometres
Ku	K under
LEO	low earth orbiting
LNA	Low Noise Amplifier
MEASAT	Malaysia East Asia Satellite Sdn Bhd
MSS	Mobile Satellite Services
NA	Not Available
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization
NWP	Numerical Weather Prediction
PC	Personal Computer
PDF	probability density function
RMSE	root mean square error
SAM	Simplified Attenuation Model
TRMM	Tropical Rainfall Measuring Mission

LIST OF SYMBOLS

A	Attenuation due to Rain
A(p%)	Predicted Rain Attenuation
D	Drop Size
f	Frequency of Operation
H_e	Effective Rain Height
Hi	Zero Isotherm Height
H_o	Earth Station Altitude above Sea Level
h_R	Mean Annual Rain Height
h_s	Altitude of Earth Station above Seal Level for ITU-R model
k	Power-law Coefficients for Specific Attenuation
L	Slant Path Length
L_E	Effective Path Length
L_G	Horizontal Projection
L_S	Slant Path Length for ITU-R
L_{eff}	Effective Path Length
l_{es}	Earth Station Longitude
l_{st}	Satellite Longitude
$N(D)$	Drop Size Distribution
Q_t	Total Extinction Cross Section
R	Rainfall Rate
$r_{0.01}$	Horizontal Reduction Factor
$R_{0.01}$	Rainfall Rate at 0.01%

$R_{0.1}$	Rainfall Rate at 0.1%
R_p	Rainfall Rate Distribution at p%
$v_{0.01}$	Vertical Adjustment Factor
Z	Radar Reflectivity
α	Power-law Coefficients of Specific Attenuation
γ	Specific Attenuation
γ_R	Specific Attenuation in Power Law
$\gamma_{Tropics}$	Specific Attenuation for Equatorial-Tropical Region
θ	Elevation Angle of Earth Station
τ	Polarization Tilt Angle Relative to Horizontal
φ	Earth Station Longitude

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND OF THE STUDY

The specific rain attenuation is defined as the attenuation per unit distance during rains; the attenuation is in decibel (dB) and the distance is in kilometres (km). It is a function of the rainfall rate and frequency based on a power law relationship where specific attenuation increases with the increase of rainfall rate and frequency (Kestwal, Joshi & Garia, 2014). The specific attenuation is a crucial and fundamental parameter for determining the rain fade of earth to space links (Ojo, Ajewole & Sarkar, 2008). During a precipitation event, a signal propagating from the satellite to the earth station (or vice versa) undergoes a slant path distance where it interacts with rain. The distance of the slant path from the earth station antenna along the rain is defined as the effective path length (M. R. Islam, Ali Hussein Budalal, Habaebi, Badron & Ismail, 2017). The specific attenuation, multiplied by the effective path length, determines the attenuation due to precipitation or rain attenuation.

Rain attenuation or rain fade refers to the signal amplitude depletion due to rainfall in the event where the satellite signal is prevented from reaching its destination, resulting in slow, inconsistent or distorted transmissions (Ismail & Watson, 2002). The rainfall scatters and absorbs the radio wave. Scattering of signals depends the incident of the signal wavelength. The absorption of signal energy by rain droplets is the primary factor for rain fade at lower frequencies (Vivekanandan, Zhang & Politovich, 2000). Higher frequency radio waves will have a shorter wavelength, and shorter wavelengths are more severely affected by absorption and scattering by raindrops (U. Kesavan, Islam, Abdullah & Tharek, 2015). Thus, the rain fade margin is an important parameter that must be emphasised to overcome signal degradation due to heavy rainfall, such as in tropical regions (Nuroddin, Ismail & Badron et al., 2013).

Satellite communication uses various frequency bands for different types of applications. The range of frequencies employed by the satellite is usually referred to a specific letter code. Frequencies such as C-band, X-band, Ku-band and Ka-band are primarily utilised for satellite communications. Conventional satellites typically operate using C-and Ku-band (Gokten et al., 2012). The demands for bandwidth are ever increasing as technology improves. Satellite industries are moving from the conventional satellite system that uses a single satellite beam technology to a high-throughput satellite (HTS). HTS employs higher microwave frequencies in the Ku and Ka-band because such frequencies are able to support broader bandwidth with the use of multiple smaller spot beams (Mignolo, Ginesi & Michael, 2013). Ku and Ka-band have the ability to carry a wider bandwidth and enable smaller terminals, but they are subjected to impairment due to rain (Berretta et al., 2017). This becomes a significant limitation for higher frequency bands (> 10 GHz) to operate in tropical regions (Rafiqul, Alam, Lwas & Mohamad, 2018).

In order to mitigate rain attenuation, the ITU-R has developed a method for predicting attenuation due to rain along a slanted path (ITU-R P.618-13, 2017). The study has shown that the ITU-R model works well in temperate climates (F Cuervo et al., 2017; Vilhar, Kelmendi & Hrovat, 2017); but numerous studies also claimed that the ITU-R model has not been able to accurately predict rain fade for tropical regions (Félix Cuervo et al., 2016; Sujimol, Acharya, Singh & Gupta, 2015; J. X. Yeo, Lee & Ong, 2009). Several models were developed to provide an alternative for better rain fade prediction in tropical regions. Based on experiments in Malaysia, some of these models (Ramachandran, Bryant, Matricciani & EXCELL) were shown to provide good agreement in contrast to the measured rain attenuation in tropical regions at 12.255 GHz (Ku-band) with a ground antenna elevation of 40.1^0 (Mandeep, 2009). From another study in Singapore, Ramachandran Model, Karasawa Model and the DAH model presented a relatively good prediction capability (but could be improved) against the measured value at 18.9 GHz and 12.75 GHz, and at 45^0 and 13.2^0 antenna elevation angles, respectively (Jun Xiang Yeo, Lee & Ong, 2014). In a more recent study at Lagos Nigeria, the ITU-R P618-11 outperformed the Simple Attenuation Model (SAM), the Synthesized Storm Technique (SST) and the Bryant Model at the frequency of 12.437 GHz with antenna elevation of 51.66^0 (Yussuff, 2016). The measurements indicate that the performance of rain attenuation models varies depending on location. This demonstrates that many rain attenuation models for tropical regions have been established with reasonable estimation, but they could be further enhanced. These models require specific attenuation knowledge to predict attenuation due to precipitation. Most models use specific attenuation information adopted from the ITU-R model, except for classical models such as Crane Global (Crane, 1980) which rely on the statistical model of instantaneous rainfall rate profile along a slanted path based on radar measurement derivation (Leitao & Watson, 1986; Matricciani, 1991). However, the ITU-R models usually rely on atmospheric data produced by Numerical Weather Prediction (NWP) models (Nebuloni, Capsoni, Luccini & Luini, 2015). ITU-R models were developed based on temperate climates; hence, difficulty exists in providing an accurate prediction for tropical regions. Several specific attenuation measurements were reported, but they are still inadequate to provide a reliable model suited for tropical regions (Alhilali, Lam & Din, 2018). Thus, in order to appropriately predict rain fade or improve the rain attenuation model for tropical areas, the fundamental quantity of specific attenuation should be determined based on the tropical condition.

1.2 PROBLEM STATEMENT

Numerous studies have shown that rain fade based on the ITU-R prediction is less accurate in tropical regions, perhaps due to the fact that the model was developed in temperate regions (Yaccop, Yao, Ismail & Badron, 2013; Jun Xiang Yeo et al., 2014). Studies have also shown that rain attenuation prediction models vary when tested in different countries with tropical weather (Mandeep, 2009; Jun Xiang Yeo et al., 2014; Yussuff, 2016). The equatorial region has heavy rainfall with a well-distributed rainfall rate throughout the year. The tropical zone, on the other hand, has two seasons; a dry season with very low rainfall and a wet season with very high rainfall (Chang et al., 2005). Malaysia is unique as it experiences an equatorial climate with tropical monsoons (Tang, 2019). The rainfall rate in equatorial regions greatly varies according to different geographical areas (Alhilali et al., 2018). Therefore, understanding the characteristics of rainfall rate is imperative and should be based on local areas and climatic conditions.

The rainfall rate model is the major parameter in determining specific attenuation based on the power law relationship (ITU-R P.838-3, 2005). The ITU-R (ITU-R P.837-7, 2017) provides a rainfall rate model for exhibiting the propagation of electromagnetic wave under the condition of precipitation. However, the ITU-R rainfall rate model developed in temperate regions tends to underestimate the rainfall rate in other areas with heavier rainfall (Singh & Acharya, 2018). The ITU-R P.837-7 and the Singh & Acharya model focus on predicting the rainfall rate at $R_{0.01\%}$ to be suitable with the ITU-R 618 rainfall rate prediction model. However, rainfall rate distribution <1% is more critical due to the variation in rainfall rate in the equatorial climate (H.Y. Lam, Luini, Din, Capsoni & Panagopoulos, 2012). Intriguingly, there is a developed model based on local area; the Moupfouma model for Southern India (Chandrika, Vijaya Bhaskara Rao, Kirankumar & Narayana Rao, 2015).

Other important parameters in specific rain attenuation include power-law coefficients. Obtaining power-law coefficients require complex analysis. The required knowledge includes empirically measured rain attenuation alongside the rainfall rate (Shrestha & Choi, 2017). Rain attenuation measurements are conducted in the torrid zone, but the numbers are too scarce and limited to produce accurate rain attenuation and specific attenuation models (S. Das, 2010). Instantaneous measurement of attenuation is difficult to obtain; nevertheless, when a set of rain attenuation measurement and a set of rainfall rate from the same location are available, it will provide accurate values of power-law coefficients for specific attenuation determination (Ostrometzky, Raich, Eshel & Messer, 2016). This is due to the fact that empirical procedures require multiple sets of instruments for measuring rain attenuation at different frequencies and the rainfall rate. Obtaining the instruments are generally difficult and expensive.

To determine specific attenuation, the simplest method is to use the model from ITU-R P.838 recommendation (ITU-R P.838-3, 2005). However, with regards to specific attenuation in satellite communication links, previous studies conducted in tropical regions show that the specific attenuation is different from the ITU-R model prediction due to higher rainfall rate (Alhilali et al., 2018; Hong Yin Lam, Din, & Jong, 2015; Maitra, 2004; S. Das, 2010; Zabidi, Rafiqul & Wajdi, 2013). The power law parameters from P.838 are useful for calculating rain attenuation in temperate climates at rainfall rates between 0 to 150 mm/hr (W. Zhang & Moayeri, 1999). The specific attenuation model by ITU-R P.838 is not exclusive for satellite communication links, where it is used for both terrestrial and earth-space setups. Efforts are being made to