RAIN FADE DYNAMICS FOR KA-BAND SATELLITE COMMUNICATION MITIGATION TECHNIQUE IN EQUATORIAL MALAYSIA

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DEDICATIONS

So verily, with every difficulty, there is relief. With every difficulty, there is relief
(Al-Insyirah, 94:5-6)

In loving memory of my father, *Abah* who passed away in December 9, 2015 while I'm struggling on my intricate PhD journey.

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ABSTRACT

Modern satellite communication system in higher frequency (Ka-band and above) is very much impaired by rain attenuation particularly in tropical and equatorial region. The desired Quality of Service (QoS) and system availability can be guaranteed only by resorting to smart strategies, named Propagation Impairment Mitigation Techniques (PIMTs) such as power control, adaptive modulation schemes and link diversity. These requires knowledge of the first- and second-order statistics of rain attenuation. Hence, this work concentrates on those aspects in equatorial Johor Bahru, Malaysia, based on one year Ka-band propagation measurement campaign, utilizing the equipment of Beacon Receiver and 2D-Video-Disdrometer (2DVD). Study begins by investigation the rain fade behaviour such as rain attenuation, fade duration, inter-fade duration and fade slope as well as their seasonal and diurnal variations. It is observed that rain attenuation experienced by the Ka-band link requires fade margin of 26.8 dB for 99.9% link availability with the convective events mostly like to occur during the afternoon hour (12:00 pm to 6:00 pm) at high intensity, shorter duration and relatively high rate of change of attenuation particularly during Northeast Moonsoon. Then, the Stratiform Convective-Synthetic Storm Technique (SC-SST) is proposed to estimate the dynamic characteristics of rain attenuation in equatorial region. The SC-SST is found 11% better than SST and 51% better than ITU-R P.1623-1 model in average value of fade dynamics prediction. Finally, a time diversity technique is recommended to mitigate strong signal fades in equatorial region. The results depicted that 10-minute outage tolerance will significantly lower the fade margin requirement to 15 dB for 99.9% of link availability. Afterwards, the generation of time diversity statistics is modelled which can be best represents by gamma-law in this area. The results can provide system engineers with critical information in the design and implementation of PIMTs, and it is expected that the probability of system outages will be greatly reduced.

ABSTRAK

Sistem komunikasi satelit moden dalam frekuensi yang lebih tinggi (jalur-Ka dan ke atas) sangat terjejas oleh pelemahan hujan terutamanya di kawasan tropika dan khatulistiwa. Kualiti perkhidmatan (QoS) yang dikehendaki dan ketersediaan sistem boleh dijamin hanya dengan menggunakan strategi pintar, bernama Teknik Mitigasi Rosotan Perambatan (PIMT) seperti kawalan kuasa, skim modulasi adaptif dan kepelbagaian pautan. Ini memerlukan pengetahuan mengenai statistik tertib pertama dan kedua gangguan hujan. Oleh itu, kajian ini menumpukan kepada aspek-aspek tersebut di khatulistiwa Johor Bahru, Malaysia, berdasarkan kempen pengukuran perambatan jalur-Ka selama setahun, menggunakan peralatan Penerima Bikon dan 2D-Video-*Disdrometer* (2DVD). Kajian ini bermula dengan penyiasatan ciri-ciri pemudaran hujan seperti gangguan hujan, tempoh pudar, tempoh antara pudar dan cerun pudar serta variasi bermusim dan diurnal. Didapati bahawa pengurangan hujan yang dialami oleh pautan jalur-Ka memerlukan margin pudar sebanyak 26.8 dB untuk ketersediaan pautan 99.9% dengan hujan perolahakn yang kebanyakannya berlaku pada waktu petang (12:00 hingga 6:00 petang) pada intensiti tinggi, tempoh masa yang pendek dan kadar perubahan perlahan yang agak tinggi terutamanya pada musim Timur Laut. Kemudian, Teknik Ribut Sintetik-Perolakan *Stratiform* (SC-SST) dicadangkan untuk mengganggarkan ciri-ciri dinamik pengurangan hujan di rantau khatulistiwa. SC-SST didapati 11% lebih baik daripada SST dan 51% lebih baik daripada model ITU-R P.1623-1 dalam purata nilai ramalan dinamik pudar. Akhirnya, teknik kepelbagaian masa adalah disyorkan untuk mengurangkan kesan pudar yang tinggi di kawasan khatulistiwa. Hasilnya didapati bahawa toleransi pemadaman selama 10 minit akan menurunkan keperluan margin kepada 15 dB untuk 99.9% ketersediaan pautan. Selepas itu, penjanaan statistik kepelbagaian masa dimodelkan yang mana digambarkan terbaik oleh aturan gamma di kawasan ini. Hasilnya dapat memberikan jurutera sistem dengan maklumat penting dalam perancangan dan pelaksanaan PIMTs, dan dijangka kebarangkalian kesan pudar dapat dikurangkan.

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LIST OF ABBREVIATIONS

ATS	-	Application Technology Satellite
ACTS	-	Advanced Communication Technology Satellite
BER	-	Bit Error Rate
CCDF	-	Complementary Cumulative Distribution Function
COMSTAR	-	Commercial Communication Satellite
COST	-	Cooperation in Science and Technology
CRC	-	Communications Research Centre Canada
DAH	-	Dissanayake, Allnut and Haidara
DLPC	-	Downlink Power Control
ECMWF	-	European Centre for Medium-Range Weather Forecasts
ENSO	-	El Niño- Southern Oscillation
ESA	-	European Space Agency
EU	-	European Union
EXCELL	-	Exponential Cell
IF	-	Intermediate Frequency
FFT	-	Fast Fourier Transform
ITALSAT	-	Italian Satellite
ITU-R	-	International Telecommunication Union, Radio Communication Sector
JR	-	Joanneum Research
KLIA	-	Kuala Lumpur International Airport
LNB	-	Low Noise Block Down Converter
MMD	-	Malaysia Meteorological Department
PDF	-	Probability Density Function
PIMT	-	Propagation Impairment Mitigation Technique
PSU	-	Power Supply Unit
QoS	-	Quality of Service
RAL	-	Rutherford Appleton Laboratory
RF	-	Radio Frequency
RHCP	-	Right Hand Circular Polarization

RHI	-	Range Height Indicator
RMS	-	Root Mean Square
SatCom	-	Satellite Communication
SatNex	-	Network of Experts for satellite communications
SC	-	Stratiform-Convective
SIRIO	-	Satellite Italiano di Recerca In dustriale e Operative
SST	-	Synthetic Storm Technique
SYRACUSE	-	Systeme de Radio Communication Utilisant Un Satellite
ULPC	-	Uplink Power Control
UPS	-	Uninterrupted Power Supply
USRP	-	Universal Software Radio Peripheral
UTC	-	Universal Time Coordinated
UTM	-	Universiti Teknologi Malaysia
WINDS	-	Wideband Internetworking Engineering Test and Demonstration Satellite
2DVD	-	2 Dimension Video Disdrometer

LIST OF SYMBOLS

A	-	Attenuation
d, D	-	Duration of fades
f_C	-	Cut-off frequency
P	-	Probability
Q	-	Standard cumulative distribution function
$R_{0.01}$	-	Rain intensity exceeded for 0.01%
Δt	-	Time daly
ξ	-	Fade slope
α	-	Power law exponential coefficient
k	-	Power law multiplier coefficient
x_o	-	Location of ground station
Δx	-	Shift that account the path enters layer A
γ	-	Specific attenuation
L	-	Effective path length
h_r	-	Rain height
h_s	-	Height above mean sea level
μ	-	Mean
σ	-	Standard deviation
f	-	Frequency
θ	-	Elevation angle
φ	-	Latitude and longitude of the Earth station
τ	-	Wave polarization
v	-	Storm translation speed
$g(p)$	-	Relative diversity gain

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CHAPTER 1

INTRODUCTION

1.1 Research Background

The evolution of satellite communication (SatCom) systems using Ka-band frequency is an emerging trend to meet the growing demand of high broadband services. Ka-band feature narrow spot beams (0.5° to 1.5° at 3dB beam width) which allows an extensive frequency reuse with wider spectrum availability than at the Ku-band. These new mode of high throughput satellites enable larger amount of bandwidth to support higher transmission rates thus opening the door to faster, cheaper and efficient communication for the user.

However, the major drawback of this Ka-band is their strong attenuation phenomena due to atmospheric propagation to the ground such as ice depolarization, gaseous attenuation, cloud and fog attenuation, rain attenuation and amplitude scintillation. Among these, rain is the certainly dominant impairment that limits the reliability and high availability of the system. This situation is more intense in the tropical/equatorial regions including Malaysia and this is mostly attributable to the high rainfall intensity and large raindrop size characterizing rainfall events in the tropics (Ismail and Watson, 2000). Thus, large rain attenuation at the Ka-band may not fully compensated by static power margins, instead application of advanced Propagation Impairment Mitigation Techniques (PIMTs) are necessary (Castanet. *et al.*, 2007).

In order to properly design and implement the PIMTs, it is necessary to have precise knowledge of the first- and second-order statistics of rain attenuation (Cheffena and Amaya, 2008). First-order statistics refers to the cumulative distribution of rain-induced attenuation, while second-order statistics describes the fade dynamic characteristics, including fade duration, fade slope, and inter-fade duration. System designers use the information on these distributions when choosing error-correction codes, especially to specify the best modulation schemes, range of uplink power control (ULPC), and the tracking speed of PIMTs (Cheffena and Amaya, 2008). These are the great concern in the capacity planning and designing robust satellite links to meet the availability requirements to the user.

To that aim, numerous propagation measurement campaigns have been actively carried out to characterize the dynamic behavior of rain attenuation experienced by satellite radio links. Unfortunately, most of the studies have been concentrated in temperate regions that exhibit lower rainfall rates compared with tropical and equatorial region (Matriacianni, 1997; Van de Kamp, 2003; Franklin *et al.*, 2006; Garcia-del-Pino *et al.*, 2010; Gracia-Rubia *et al.*, 2011). A reliable measurement data of Ka-band signals in these regions are very limited and only concentrated on first-order statistic of rain attenuation (Yeo *et al.*, 2014). Adding to that, a study on fade dynamics statistics in tropical/equatorial regions particularly in Malaysia have been carried out in the past but only focuses on Ku-band frequencies (Dao *et al.*, 2013; Mandeep, 2013; Jong *et al.*, 2014).

As consequences, the crucial statistics of fade dynamics at Ka-band frequencies in the tropical/equatorial region remain an interesting topic of investigation. Therefore, this study is to explore those crucial statistics in an equatorial site by exploiting the propagation measurement campaign carried out at Universiti Teknologi Malaysia (UTM) in Johor Bahru, Malaysia. In addition, a mitigation technique namely Time Diversity is explored to mitigate the increased rain fades at Ka-band and improves overall link availability. This work demonstrates that is feasible to use the Ka-band to support SatCom mission operation in tropical/equatorial region.

1.2 Problem Statement

As briefly mentioned above, dynamic characteristics of fading due to atmospheric propagation are of great concern in optimizing system capacity. In this respect, several problem statements that need to be addressed and resolved in this thesis work are summarized as below:

A study of atmospheric impairments involving the experimental measurement of received signal strength under various weather conditions is needed to develop a better understanding of channel characteristics and improve the design of modern SatCom systems. However, reliable measurement data on Ka-band signals in tropical/equatorial region are still in scarce (Jong *et al.*, 2016). Therefore, this work presents a statistical analysis of rain attenuation based on measurement data of Ka-band propagation measurement campaign that was carried out in Malaysia. The information from rain attenuations statistics will help system designers to determine reliable fade margin required in setting up the best quality of service (QoS) of the link to end users. Recommendation ITU-R S.1557 (2006) was used to calculate propagation attenuation in this study. Ka-band frequency usually provides link availability of 99.7% to 99.9% of the year. The uplink availability is assumed to be 99.95% of the year and the downlink availability is assumed to be 99.8% of the year; this results in an overall system availability of 99.75% of the year (ITU-R, 2006).

Although the statistics distribution of rain attenuation gives important information for the design of link margin, this information should be completed with parameters that allow the characterization of fade dynamics; including fade duration, inter-fade duration and fade slope statistics. The information of fade dynamics is important for system designers to appropriately implement PIMTs in a way to increase system availability and reliability of the system. For example, an assessment of link availability solely based on rain attenuation statistics can leads to very high power margin (Vilar *et al.*, 1988). This misuse of system resources unnecessarily escalates the cost of service. Thus, the knowledge from fade duration statistics that described when and how frequent the service is available could help system designers to decide whether to go for mitigation of fading or wait for the signal recovery. Up to date, only few researchers have performed the analysis of fade dynamics in tropical and equatorial regions (Dao *et al.*, 2013; Mandeep, 2013; Jong *et al.*, 2014) and all of these studies were only focuses on Ku-band frequencies. Higher frequency bands are more susceptible to weather effects than lower frequency bands which consequently leads to much serious communication link outage during heavy rain events. Hence, precise information on fade dynamics at Ka-band is needed as they will provide different characteristics than in Ku-band.

Besides statistical analysis of fade dynamics from experimental database, it is essential to have an alternative method to predict fade dynamic characteristics as the measured data is not always available. Moreover, many existing fade dynamics prediction model such as ITU-R P.1623-1 (2005) might not satisfies tropical/equatorial statistics, as they were developed mainly based on measurements done in temperate climate. Therefore, the Stratiform-Convective Synthetic Storm Technique (SC-SST) (Lam *et al.*, 2012) is proposed to estimate rain fade dynamics in tropical/equatorial region taking advantage of local weather features from rainfall rate measured data. SC-SST is an adaptation from the conventional dual-layer SST model which has match pretty well not only for long-term first order statistics but as well as fade dynamics statistics particularly in temperate climates (Matricianni, 1997). On the other hand, SC-SST separately considering the types of rain events (i.e. stratiform and convective events) is very much likely to be used in the tropics as it is more suited to the local peculiarities. Adding to that, the use of synthetic models in the present study to characterise fade dynamics particularly for tropical/equatorial climate is not yet very well documented in the literature.

The application of time diversity in SatCom systems to reduce the effect of severe rain attenuation is getting more attention as it can provide high level of gain by an accurate retransmission with low-costs system (Fukuchi, 1992). There are numerous kind of method has been studied in the past to evaluate the performances of time diversity, such as analysis from direct measurement data (Fabbro *et al.*, 2009), through simulation weather radar maps (Luini *et al.*, 2011), and modelling approaches. However, up to now there are no model extensively validated has been proposed in the literature to estimate the performance of time diversity. As the statistical performance is related to local climatology, thus a global database of time diversity is needed. Therefore, it is worthwhile to further investigate and estimate the natural characteristics of time diversity distribution in tropical/equatorial region with respect to the experimental database.

1.3 Research Objectives

The objectives of this research study are listed as:

(a) To determine rain fade and fade dynamic characteristics for Ka-Band Earth-space propagation link in Johor Bahru, Malaysia.

(b) To evaluate and validate the performances of SC-SST model in predicting fade dynamic characteristics in equatorial region.

(c) To provide applicable parameters of time diversity technique of PIMTs based on measured rain attenuation statistics.

1.4 Scopes of Work

The research scopes and limitation of this work are:

(a) The work focuses on received signal data of Ka-band with frequency of 20.245 GHz (Syracuse-3A satellite) measured in UTM-Johor Bahru, Malaysia for one-year duration (July 2015 – June 2016).

(b) The beacon receiver has approximate dynamic range of 30 dB and minimum required C/N_o shall be 28 dB.

(c) The SC-SST prediction model is performed based on one-minute rainfall rate datasets obtained from 2DVD measurement at the same site with same duration.

(d) Rain rate threshold of 10 mm/h has been selected in the discrimination of stratiform and convective events to generate SC-SST rain attenuation statistics. The selection is based on rain profile model that use an exponential-shaped of rain spatial distribution for convective events (Stutzman and Dishman, 1982). Later it was proven to be an effective technique to be used in the tropics owing to its simple discrimination threshold yet effectively maintain the prediction accuracy of the stratiform-convection separation (Capsoni *et al.*, 2009; Lam *et al.*, 2013).

(e) Wind velocity which is one of the input parameters for SC-SST prediction model is extracted from one-year radiosonde data measured at Kuala Lumpur International Airport (KLIA), Sepang at a pressure level of 700 mbar.

(f) The performance of fade dynamics estimated from SC-SST model with respect to measured data is evaluated by means of figure of merit.

1.5 Research Contributions

Satcom systems operating at higher frequency bands (Ka-band and above) in tropical/equatorial climates are severely degrades by many fade occurrences due to heavy rain. An appropriate PIMTs is needed by the service providers to be use during severe rain fade periods to compensate link impairment thus provide high QoS to end users. In order to establish reliable Earth-space communication services in these heavy rain regions, comprehensive study of the effect of rain attenuation on the satellite propagation path needs to be quantified. To this aim, this work mainly focused on the knowledge of propagation channel characteristics at Ka-band based on local peculiarities, which is important in the implementation of PIMTs. The main contributions have been identified as follows:

(a) The first contribution focuses on the analysis of rain intensity, rain attenuation, and fade dynamics (i.e fade duration, fade slope and inter-fade duration) in equatorial site. Statistical analyses are presented on annual, seasonal, monthly and diurnal basis. The information obtained will be useful to system engineers for link budget analysis in order to obtain the required fade margin for optimal system performances in tropical/equatorial region as well as in the design and implementation of PIMTs.

(b) In second contribution, the SC-SST model is proposed for the prediction of fade dynamics in the absence of measured rain attenuation time series, starting with local rainfall rate time series. SC-SST model seems to be in reasonable agreement with the actual measurement carried out in this particular area. These characteristics provide essential information on expected evolution of fade dynamics which is particularly important in choosing economical link margin and a suitable adaptive power control subsystem.

(c) The last contribution of this work is the characterization and modeling of time diversity technique based on time correlation of attenuation time series. This approach considers that the conditional statistics follows a gamma law which is extracted during the rain attenuation event. The results can provide system engineers with critical information in the design and implementation of PIMTs, and it is expected that the probability of system outages will be greatly reduced.

1.6 Thesis Organization

This thesis is presented in five chapters. This chapter provides an overview of the research background on the topic of interest and identifies problem statements that need to be resolved. This section outlines the research objectives, scope of work and highlights the contributions of this work. The remaining chapters of the thesis are organized as follows.

Chapter 2 begins by discussed the main features of climatology characteristics in tropical and equatorial region, particularly in equatorial Malaysia. These characteristics include type of precipitation, seasonal and diurnal variations of rain attenuation. Then, a review of fade dynamics characteristics with respect to measured study carried out in temperate and tropical/equatorial region at Ka-band are given. Next followed by the slant path rain attenuation channel model as well as fade dynamic prediction models that have been developed and proposed in the literature, are briefly discussed. Afterward, time diversity technique as one of the PIMTs is also presented. Finally, some brief introduction to Syracuse satellite communication system.

Chapter 3 focuses on the methodology and concept used in this work. It begins by providing an overview of the methodology of this work including the flow chart for ease of understanding. Two sets of equipment are described, Satellite Beacon Receiver and 2D-Video-Disdrometer, which are used to collect time series of received signal and rainfall rate, respectively. Detailed discussions on rain attenuation data processing as well as scintillation filtering and clear sky reference level description are also presented. Afterwards, a specific calculation is provided for the distribution of fade dynamics, especially fade slope which aims to characterize the dynamic characteristics of rain attenuation. In addition, this chapter also provides a brief discussion on the key concept and necessary input parameters for SC-SST rain attenuation prediction model. Finally, specific information on time diversity assessment and modeling which relies on the time correlation of rain attenuation time series are provided.

Chapter 4, which presents the results of this work, is divided into three parts. First, discussion on the statistical analysis of rain intensity, and fade dynamics which includes parameters such as fade duration, inter-fade duration and fade slope. The analysis includes discussion on seasonal, monthly and diurnal variations and its impact on overall system performances. Then, comparison analysis of fade dynamic prediction models from several established literatures together with performances of SC-SST in estimating fade dynamics are also given. Lastly, evaluation on the performances and modeling of time diversity that aims to mitigate rain attenuation on Earth-space path link are presented.

Chapter 5 presents the conclusion and future works. The major works in this thesis are concluded and summarized, followed by some constructive recommendations for future work.

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