RAIN FADE DYNAMIC CHARACTERISTICS FOR KU-BAND SATELLITE COMMUNICATION SYSTEMS IN MALAYSIA

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A thesis submitted in fulfilment of the requirements for the award of the degree of Doctor of Philosophy (Electrical Engineering)

Faculty of Electrical Engineering
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MARCH 2015
ABSTRACT

Satellite communication systems operating at frequencies above 10 GHz are always subjected to signal fade occurrences due to heavy precipitation, particularly in equatorial regions. In order to reduce the impact of these fades, there are several Propagation Impairment Mitigation Techniques (PIMTs) exist to cope with deep fades, such as implementation of power control, link diversity, and adaptive modulation schemes. However, the proper design and implementation of PIMTs require 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 a one year Ku-band propagation measurement campaign that includes the equipment of Direct Broadcast Receiver (DBR) and Automatic Weather Station (AWS). The investigation of precipitation characteristics begins by processing the rain tip data collected from AWS. A new processing method is proposed to improve the estimation of precipitation statistics, specifically for lower rain rates than 12 mm/h. Then, rain fade behaviour such as rain attenuation, fade duration and fade slope as well as seasonal and diurnal variations of rain attenuation are also investigated. It was found that convective rain are likely to occur during the afternoon hour from 3 to 5 pm with high intensity, shorter duration and relatively high rate of change of attenuation during the inter-monsoon season. Besides, the Synthetic Storm Technique (SST) and Stratiform Convective-Synthetic Storm Technique (SC-SST) are proposed to estimate the dynamic characteristics of rain attenuation directly from rain rate time series, especially in the absence of measured attenuation data. The SC-SST was found 10% better than the SST and 57% better than ITU-R models in predicting fade duration, while SST was comparable with ITU-R P.1623-1 model in estimating fade slope statistics. Finally, by taking advantage of local rain attenuation characteristics, a time diversity technique is recommended to compensate for deep fades, particularly in heavy rain regions.
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LIST OF ABBREVIATIONS

ACTS - Advanced Communications Technology Satellite
ASCII - American Standard Code for Information Interchange
Astro - All-Asian Satellite Television and Radio Operator
AWS - Automatic Weather Station
CAPPI - Constant Altitude Plane Position Indicator
CCDF - Complementary Cumulative Distribution Function
COST - Cooperation in Science and Technology
DBR - Direct Broadcast Receiver
DID - Department of Irrigation and Drainage
ECMWF - European Centre for Medium-Range Weather Forecasts
EIRP - Effective Isotropically Radiated Power
ESA - European Space Agency
FIR - Finite Impulse Response
IF - Intermediate Frequency
ITALSAT - Italian Satellite
ITU-R - International Telecommunication Union, Radio communication sector
KL - Kuala Lumpur
KLIA - Kuala Lumpur International Airport
LNB - Low Noise Block down Converter
LOS - Line of Sight
LPF - Low Pass Filter
MATLAB - Matrix Laboratory
MEASAT - Malaysia East Asia Satellite
MMD - Malaysia Meteorological Department
NE - Northeast
OTS - Orbital Test Satellite
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<tr>
<td>PDF</td>
<td>Probability Density Function</td>
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<tr>
<td>PIMT</td>
<td>Propagation Impairment Mitigation Technique</td>
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<td>PNG</td>
<td>Papua New Guinea</td>
</tr>
<tr>
<td>QoS</td>
<td>Quality of Service</td>
</tr>
<tr>
<td>QPSK</td>
<td>Quadrature Phase Shift Keying</td>
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<td>RMS</td>
<td>Root Mean Square</td>
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<td>SAM</td>
<td>Simple Attenuation Model</td>
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<tr>
<td>SatCom</td>
<td>Satellite Communication</td>
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<tr>
<td>SC</td>
<td>Stratiform-Convective</td>
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<tr>
<td>SIRIO</td>
<td>Satellite Italiano di Recerca Industriale e Operative</td>
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<td>SST</td>
<td>Synthetic Storm Technique</td>
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<td>SW</td>
<td>Southwest</td>
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<td>ULPC</td>
<td>Uplink Power Control</td>
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<td>UPS</td>
<td>Uninterrupted Power Supply</td>
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<tr>
<td>UTC</td>
<td>Universal Time Coordinated</td>
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<tr>
<td>UTHM</td>
<td>Universiti Tun Hussein Onn Malaysia</td>
</tr>
<tr>
<td>UTM</td>
<td>Universiti Teknologi Malaysia</td>
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<tr>
<td>WINDS</td>
<td>Wideband InterNetworking engineering test and Demonstration Satellite</td>
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<td>$A$</td>
<td>Attenuation</td>
</tr>
<tr>
<td>$C$</td>
<td>Capacity</td>
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<td>$d, D$</td>
<td>Duration of fades</td>
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<tr>
<td>$F$</td>
<td>Fresnel zone radius</td>
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<td>$f_B$</td>
<td>Cut-off frequency</td>
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<td>$P$</td>
<td>Probability</td>
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<td>$Q$</td>
<td>Standard cumulative distribution function</td>
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<tr>
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<td>Rain intensity exceeded for 0.01%</td>
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<td>$T_d$</td>
<td>Time delay</td>
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<tr>
<td>$\lambda$</td>
<td>Wavelength of transmitted signal</td>
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<td>$\zeta$</td>
<td>Distance measured along satellite path</td>
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<td>$\Delta t$</td>
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<td>$\zeta$</td>
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<td>$\Delta x$</td>
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<td>$h_R$</td>
<td>Rain height</td>
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CHAPTER 1

INTRODUCTION

1.1 Research Background

Rain attenuation is the dominant impairment in satellite communication links, especially at frequencies above 10 GHz, and particularly in tropical and equatorial regions like Malaysia, where Malaysia is considered as high rainfall rate region. In fact, precipitation causes attenuation due to scattering and absorption of the electromagnetic energy and leads to significant performance degradation. Consequently, Ku-band broadcasting services are affected by link outages, especially during time-critical transmissions such as real-time news and sports events. The probable duration of rain fade, the time of day when it is likely to occur, and how frequently it happens are all important aspects to consider in the design of satellite services (Allnutt and Haidara, 2000).

In order to make satellite systems operations feasible at frequencies above 10 GHz, appropriate Propagation Impairment Mitigation Techniques (PIMTs) are required, such as power control, link diversity, and adaptive modulation scheme (Pan et al., 2008; Panagopoulos et al., 2004). In general, the proper design and implementation of PIMTs requires knowledge of first- and second-order statistics of rain attenuation (Cheffena and Amaya, 2008). First-order statistics refers to the cumulative distribution of rain attenuation and rainfall rate, while second-order statistics describes the dynamic characteristics of rain attenuation, such as fade duration, fade slope, and inter-fade interval. In fact, knowledge of second-order statistics for rain attenuation in a given environment is essential for helping service
providers specify type of modulation and error correction schemes, range of uplink power control, and the tracking speed of PIMTs that need to be used during severe rain periods to reduce the probability of link outages (Cheffena and Amaya, 2008).

To that aim, numerous propagation measurement campaigns have been actively carried out to characterise the dynamic behaviour of rain attenuation experienced by satellite radio links. Unfortunately, most of the studies have been concentrated in temperate regions (Matricciani, 1981; Van de Kamp Max, 2003; Franklin et al., 2006; Garcia-del-Pino et al., 2010; Gracia-Rubia et al., 2011) that exhibit lower rainfall rates compared with tropical and equatorial regions. Therefore, the rainfall rates and dynamic characteristics of rain attenuation in temperate regions might not represent the dynamic characteristics of tropical and equatorial regions (ITU-R Study Group 3, 2012). Furthermore, a very limited number of investigations carried out in heavy rain regions particularly focus on fade dynamics of rain attenuation statistics (Ismail and Watson, 2000; Dao et al., 2013; Singh, 2013).

As a consequence, the crucial statistics of fade dynamics in the equatorial zone remains an interesting topic of investigation. Therefore, this study is to explore those crucial statistics in an equatorial site by exploiting the propagation measurements carried out at Universiti Teknologi Malaysia (UTM) in Johor Bahru, Malaysia. Such details information are particular importance to appropriately parameterise the PIMTs, especially in this heavy rain regions. As rain attenuation data obtained from measurement campaigns is time-consuming and costly, this work also provides a solution for characterising the dynamic behaviour of rain attenuation, especially in the absence of measured rain attenuation data, by introducing the Synthetic Storm Technique (SST) and Stratiform Convective-Synthetic Storm Technique (SC-SST).
1.2 Problem Statement

As stated previously, knowledge of the dynamic characteristics of fading due to atmospheric propagation is necessary in order to design PIMTs appropriately. Therefore, the characteristics of rain attenuation should be intensively investigated.

It is well known that rain intensity is one of the important parameters to consider when designing microwave propagation links, as it directly influences the cumulative statistics of rain attenuation in the prediction of attenuation statistics. In order to predict system outages due to rain attenuation at millimetre wavelengths, rain rate averaged over one minute is required by most of the propagation prediction models. Unfortunately, most of the recently-manufactured tipping bucket rain gauges do not measure rain rate. Rather, these rain gauges provide only a rough estimate of the quantity of water accumulated in one minute by counting the number of tips. It is interesting to note that rain rate distribution is strongly dependent on the methodology of rain rate data processing used. Therefore, it is worthwhile to investigate a new solution to extract rain rate from data gathered with modern rain gauges in order to improve the prediction of rain attenuation statistics.

In addition to rain gauge data processing, the dynamics of rain attenuation, such as fade duration and fade slope, play an important role in the design of fade countermeasures. Seasonal and diurnal variations also provide good insight in the design and implementation of fade margin. Unfortunately, only few researchers perform the analysis of fade dynamics in tropical and equatorial regions. For instance, Singh (2013) presented only one year of measured fade duration statistics collected in North of Peninsular Malaysia, Penang; Dao et al. (2013) focused only on fade slope statistics in Kuala Lumpur, Malaysia and an improvement factor was proposed to improve the ITU-R P.1623-1 model by fitting the measured fade slope statistic. Even though both of the local researchers have been investigated on fade duration and fade slope respectively, they not provide detailed analysis on rain fade characteristics. In addition, Pan and Allnutt (2004) performed analysis on the characteristics of diurnal fade duration and fade interval in Lae, Papua New Guinea. It is found that strong convective events frequently occurs from 9 pm to 4 pm in Lae,
this might not be similar to the climate in equatorial Johor Bahru. Therefore, the aim of this study is to investigate and provide details analysis of those crucial statistics such as fade duration, fade slope and as well as seasonal and diurnal variations of rain attenuation in an equatorial site. However, rain attenuation time series that can be used to produce fade dynamics are still in scarce, particularly in equatorial regions. Thus, it is important to set up the experimental site carefully and to process the raw data wisely.

Instead of using real attenuation data collected from expensive and lengthy experiments, the alternative is to generate synthetic rain attenuation from available rain rate time series. Although there is a prediction model available to predict fade dynamics, such as ITU-R P.1623-1 (2005), the results obtained from the ITU-R model might not be comparable to measured statistics, as it does not include any locally measured data (which, in turn, depends on elevation angle and frequency). Therefore, it is recommended that SST and SC-SST be used to predict dynamic fading characteristics from available local rain rate time series. Most studies have reported that SST is able to generate reliable time series of rain attenuation (Matricciani and Riva, 2005), duration of fade (Matricciani, 1997a) and diurnal slant path rain attenuation statistics (Kanellopoulos et al. 2006), on a yearly Cumulative Distribution Function (CDF) basis and even on event-by-event basis (Sanchez-Lago et al., 2007). However, those investigations were conducted in temperate regions. Although the SST was tested on the small tropical island of Guam (a territory of United States, approximately 550 km²) (Acosta et al., 2013) for CDF of rain attenuation only, it might not be able to represent completely the rain attenuation characteristics in equatorial Johor Bahru, Malaysia. In addition, the characteristics of rain fade in temperate regions are completely different from those in tropical/equatorial regions (Lam et al., 2012). To the best of the knowledge of the author, the use of SST and SC-SST in the present study to characterise fade dynamics, particularly in equatorial regions is the first of its kind.
1.3 Research Objectives

The objectives of this research are:

i. To analyse rain and rain fade characteristics for the Ku-band earth-space propagation link in equatorial Malaysia.

ii. To evaluate the performances of the SST and SC-SST models in estimating the dynamic characteristics of rain attenuation in equatorial Johor Bahru.

1.4 Scope of Work

The scope of this research work is as follow:

i. Investigate the data processing method in estimating rain rate based on eight years of database collected in Spino d’Adda.

ii. Receive the satellite signal from MEASAT-3 satellite and at a frequency of 12.2 GHz.

iii. Analyse the rain and rain fade characteristics based on one year of measurements in UTM.

iv. Investigate seasonal and diurnal variations of rain attenuation based on one year of attenuation data collected in 2013 at UTM.

v. Obtain wind velocity at a pressure level of 700 mbar based on one year of radiosonde data measured at KLIA as one of the input parameters to the SST and SC-SST models.

vi. Evaluate the performance of fade dynamics estimated from SST and SC-SST with respect to measured data and the ITU-R prediction model by means of figure of merit.

1.5 Research Contributions

Future operational frequencies of satellite communication systems are moving towards Ka-band (20 GHz) and above, driven by the increasing demand of
users for multimedia services. However, precipitation attenuation appears to be the most dominant impairment to the satellite signal at those frequency bands, and even at Ku-band, in the tropical and equatorial climate where Malaysia is located. In fact, rainfall and rain attenuation statistics alone are not enough to characterise completely the precipitation phenomena due to atmospheric propagation. Furthermore, the methodology of rain intensity data processing plays an important role in producing an accurate rain rate distribution. To this end, the present work focused mainly on rain rate data processing and specific knowledge of the dynamic characteristics of rain attenuation based on local peculiarities, which is useful for designing and implementing appropriate PIMTs. The main contributions are as follows:

i. The first contribution is the development of a newly proposed processing method to estimate rain rate statistics collected from a tipping bucket rain gauge that only provides number of tips per minute. This method is capable of inferring the missing values of a lower rain rate (less than 12 mm/h).

ii. The second contribution focuses on the statistical analysis of rain fade characteristics, particularly fade dynamics in equatorial Johor Bahru. These characteristics provide essential information on expected evolution of fade dynamics, which is particularly important for the design and operation of adaptive PIMTs.

iii. In the third contribution, the SST and SC-SST models were proposed for the prediction of fade dynamics (i.e. fade duration and fade slope) in the absence of measured rain attenuation time series, starting with local rain rate time series. Both models are capable to perform significantly better than the ITU-R model in predicting fade duration. In addition, the fade slope prediction seems to be in reasonable agreement with the actual measurements carried out in this particular area.

1.6 Thesis Outline

This thesis contains five chapters. Chapter 1 provides an overview of the research background to the topic of interest and identifies the problem statements
that need to be resolved. This section clearly outlines the research objectives, scope of work and highlights the contributions of this work.

Chapter 2 begins by providing the climatology characteristics of the equatorial region, particularly equatorial Malaysia. These characteristics include type of precipitation, and seasonal and diurnal variations of rain attenuation in this heavy rain region. Next, the rain gauge data processing method collected by a former tipping bucket rain gauge (i.e. provides tipping time) is reviewed. Afterward, the specifications of a low pass filter to remove the tropospheric scintillation effect are also carefully reviewed and an introduction of MEASAT-3 satellite is briefly explained. Then, the development of prediction model for fade duration and fade slope in estimating dynamics statistics of attenuation is carefully reviewed. A review of measured dynamic characteristics of rain attenuation carried out in temperate and tropical/equatorial regions is also included. Afterward, slant path rain attenuation channel model such as the ITU-R rain attenuation, and SST models which are available in the open literature, are discussed. Finally, an introduction to time diversity technique as one of the PIMTs is given at the end of the chapter.

Chapter 3 focuses on the methodology and concept used in this work. It begins by providing an overview of the methodology of this work; flow chart is included for ease of understanding. Two sets of equipment are described, Direct Broadcast Receiver (DBR) and Automatic Weather Station (AWS) which are used to collect time series of received signal and number of tips, respectively. The criteria of experimental setup as well as maintenance and calibration of the equipment are also provided. Next, a new rain gauge data processing technique is described, followed by a detailed rain attenuation data processing description. In addition, necessary input parameters for the SST/SC•SST rain attenuation model are provided, and some key concepts of SC•SST are briefly discussed. Finally, a specific calculation is provided for the distribution of fade dynamics, especially fade slope which aims to characterise the dynamic characteristics of rain attenuation.

Chapter 4, which provides the results, is divided into three parts. First, the performance of a current rain gauge data processing method is evaluated; the data
used to test the method was collected in Spino d’Adda satellite station and provided by Politecnico di Milano (POLIMI) in Italy. Second, rain intensity, rain attenuation and characteristics of fade dynamics for a heavy rainfall region are statistically analysed. Such statistics were obtained from the measurement campaign carried out at UTM, Johor Bahru, Malaysia. Furthermore, seasonal and diurnal variations are also included. Lastly, the performances of the SST and SC-SST models in estimating rain fades, especially in the absence of measured data, are evaluated. The performance of the time diversity technique is also presented. The former includes a quantitative evaluation of the models’ performances in predicting fade dynamics, specifically in the equatorial region, whereas the latter compares the performances of the measured and predicted time diversity.

Chapter 5 summarises the conclusions obtained from the studies and followed by some recommendations for future work.
CHAPTER 2

LITERATURE REVIEW

The new multimedia services provided by satellite communication systems require large bandwidth and hence stimulate the use of higher frequency bands, such as Ku, Ka, Q/V and W-bands. Even though at such frequency bands all tropospheric effects (atmospheric gases, clouds, precipitation and tropospheric turbulence) must be considered, precipitation remains as one of the dominant impairment in earth-space communication link. Therefore, appropriate PIMTs is necessary to guaranty the link availability and Quality of Service (QoS) perceived by the end users.

This chapter is dedicated to review several topics related to precipitation effect and prediction models. Firstly, the characteristics of local climatology in tropical/equatorial region are identified and processing methods for former and current tipping bucket rain gauge are briefly discussed. Next, specifications of the LPF to remove scintillation effect are presented, followed by reviewing the dynamic characteristics of rain attenuation and its prediction models. Lastly, several PIMTs available to overcome severe rain attenuation are briefly summarised.

2.1 Characteristics of Climate in Equatorial Malaysia

The increasing demand for higher capacity and higher speeds of data transmission has led to the usage of higher frequencies such as Ku-band (12/14 GHz), Ka-band (20/30 GHz) and Q/V-band (40/50 GHz). Unfortunately, frequencies higher than 10 GHz are susceptible to severe attenuation and this causes link outages to
satellite services. The percentage of link outages is particularly severe in tropical and equatorial regions. For instance, there are more than 200 fade events exceeding 10 dB in equatorial Malaysia at 12 GHz of frequency over a 12 month period (Ismail and Watson, 2000). It is reported that these regions always experience convective rain with a high precipitation rate and the system performances degrade due to rain induced fades (Green, 2004). Moreover, Figure 2.1 clearly evidenced extremely heavy rainfall occurs in tropical and equatorial regions from 40 years of mean annual rainfall map obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) database (ITU-R, 2012). This is further supported by the Complementary Cumulative Distribution Functions (CCDFs) of precipitation rate for different climatic conditions, shown in Figure 2.2. Kuala Lumpur (Lam et al., 2012) and Johor Bahru, Malaysia as well as Singapore (Ong and Zhu, 1997) are characterised by the tropical/equatorial climate, whereas Spino d’Adda, Italy (Riva, 2004), represents temperate regions. The nearly good agreement between the Kuala Lumpur, Johor Bahru and Singapore curves gives a clear indication of local climatic peculiarities within an equatorial area. Even though the distance between Kuala Lumpur and Johor Bahru is about 300 km and the statistics for Johor Bahru only consist of one year of data (compared to the three years of disdrometer measurement in Kuala Lumpur), it is clear that the CCDF is stable enough to correctly represent the precipitation characteristics of this region, which are remarkably different from those in Spino d’Adda.
Figure 2.1 Mean annual rainfall map of the world for 40 years obtained from ECMWF databases (ITU-R Study Group 3, 2012).

2.1.1 Type of Precipitation in Malaysia

In general, precipitation can be categorised into two main types, namely stratiform and convective rains, which have different space-time evolutions (Capsoni et al., 2006) respectively. Stratiform precipitation results from warm air masses shifting horizontally below cold air masses and this causes huge cloud formations (some hundreds of km) at a low altitude (Capsoni et al., 2006). The cloud formation forms small ice particles in the upper tropospheric layers. When the ice particles are sufficiently large, they slowly fall and join the other ice particles to form snowflakes; they fall more quickly as the size increases. The snow falls and passes through the melting layer, in which the temperature varies at about 500 m to 1 km including below 0°C. Subsequently, the snow turns into raindrops when it is falling through the air at temperatures of more than 0°C. Generally, stratiform rain is characterised as low intensity, of long duration and extending over wide areas (Timothy et al., 2003; Green, 2004).

On the other hand, convective rain is produced by cumulus clouds that are formed by warm air shifting towards higher layers, becoming cold immediately and condensing into clouds. The associated rain generated by vertical air currents is often characterised as very powerful, with a high precipitation rate, large vertical rainfall but of short duration. As reported by Green (2004), tropical rainfall is predominantly convective. This statement is further supported by Lam et al. (2013) who found that 64% of rain in equatorial Kuala Lumpur is convective.

Since both stratiform and convective types of rain are governed by different characteristics, they may contribute to different impacts on radio waves propagating through the earth-space path (Capsoni et al., 2006), especially on the model of rain attenuation (Das et al., 2009). Capsoni et al. (2009) recommend considering stratiform and convective rain separately in order to considerably improve the accuracy of rain attenuation prediction. This is further confirmed by Lam et al. (2012) who finds that the classification of rain enhances the accuracy of prediction in the first order statistic of rain attenuation. Therefore, stratiform and convective rain should be differentiated in studies. One such approach is to discriminate by a rain rate peak threshold of 10
mm/h (Stutzman and Dishman, 1982; Capsoni et al., 2009). A rain event that contains more than 10 mm/h of rain rate is considered as convective rain.

2.1.2 Seasonal Variation

Precipitation characteristics in Southeast Asia are very much dependent on the monsoon season which is caused by a seasonal shift in wind direction. In Malaysia, wind flow patterns can be classified into four yearly seasons, namely pre-Northeast (pre-NE), Northeast (NE), pre-Southwest (pre-SW) and Southwest (SW). These correspond to October-November, December-March, April-May and June-September (Kozu et al., 2006). The dominant influences on the climate are the northeast and southwest Asian Monsoon winds as shown in Figure 2.3, which bring a wetter and drier season to Malaysia respectively. The NE monsoon originates from Siberia and it brings stronger precipitation events, especially to the east coast of peninsular Malaysia; whereas the SW monsoon is relatively drier as the warm air originates from the Australian deserts. This is further evidenced by Figure 2.4 which shows the monthly statistics of diurnal variation based on the four monsoon seasons. During the NE monsoon, rain frequently occurs in the late afternoon with the peak hours from 14 to 16. December appears as the rainiest (percentage occurrence more than 15%) month in a year whereas February and March exhibit relatively low percentage of rain in the early morning and mid night hours. In the pre-SW monsoon, the diurnal cycle of the month is more variable, as it is a transition period from NE to SW monsoon season. During the SW monsoon, the frequency of occurrence shows a consistent of diurnal cycle and rain frequently occurs in the early afternoon hour at around 14th hours; whereas two different diurnal cycles are observed in pre-NE monsoon. Dominant rainfall in this season falls in the early morning and afternoon hours, however, frequent rainfall occurs on November than on October particularly in the early afternoon.
Figure 2.3 Seasonal wind direction: a). Northeast monsoon season, b). Southwest monsoon season (Abdullah et al., 2011).

Figure 2.4 Seasonal and monthly statistics of diurnal variations (Adapted from Zhou et al., 2010).
2.1.3 Diurnal Variation

Apart from seasonal variation, diurnal variation also plays an important role in designing mechanisms to ensure the high performance of satellite systems. It provides statistics of hourly rain fade variation and therefore it is a key element in determining the link margin and providing a suitable compensation scheme during the service period in an economic and efficient way (Lekkla and Prapinmongkolkarn, 1998). For instance, extra power transmission is only provided during a severe rain period. It is reported that the diurnal variation strongly depends on the seasonal variation (Zhou et al., 2010) as can be observed in Figure 2.5, which depicts results based on the Singapore region. It is evident that frequent rainfalls tend to occur in the afternoon, approximately between 3 pm and 4 pm. However, the diurnal variation pattern not only depends on local convective events but may also be influenced by geographical topographies (Lekkla and Prapinmongkolkarn, 1998) as well as the location of interest. For example, in Lae, Papua New Guinea (PNG), Figure 2.6 depicts rain attenuation usually occur between 9.00 pm and 4.00 am and it is very rare to record rain attenuation between 12 pm and 4 pm (Pan and Allnutt, 2004). Hence, it is worth highlighting that the diurnal variation of rain attenuation in tropical PNG cannot completely represent the diurnal behaviour in equatorial Malaysia.

![Figure 2.5](image-url)  
*Figure 2.5* Seasonal distribution of diurnal variation (Zhou et al., 2010).
2.2 Review of Processing Methods for Tipping Bucket Rain Gauge

It is well known that the most common instrument to measure rainfall is the tipping bucket rain gauge. The tipping bucket rain gauge is a meteorological device that measures the amount of precipitation that has fallen on the ground. It consists of a funnel, with a typical aperture of 200-1000 cm², which conveys the precipitation into a small bucket mounted on a lever. After an amount of rain equal to the bucket capacity has fallen (typically 0.1 or 0.2 mm), the lever tips dumping the collected water and sending a pulse to a data logger.

The accuracy of rain rate distribution strongly depends on data processing (Kvíčera, 2005). It is widely recognised that rain rate distribution at 0.01% of time is particularly important to the estimation of rain attenuation statistics such as the ITU-R P.618-11 model (2013). For propagation of purposes, the best accuracy is obtained when the data logger records the tip instant (with a resolution of at least one second) by dividing the bucket capacity $C$ (mm) by the time separation $T$ (s) between two consecutive tips; it is possible to get an estimate of the ‘instantaneous’ rain rate $R$ (mm/h) through the relation:
\[ R = 3600 \frac{C}{T} \quad (2.1) \]

This value can then be averaged over one minute to obtain the 1-min integrated rain rate. As mentioned earlier, this represents the high resolution or reference data and the data set has been processed according to the following procedure named the ‘original method’ (Kvicera, 2005):

i. If the time interval between 2 tips is shorter than 2 seconds and the rain intensity is greater than 360 mm/h, the second tip is cancelled as it is likely due to bucket bounce;

ii. If the rain event is starting with 2 tips separated by a time interval shorter than 1 hour, the first of the two tips is not considered;

iii. Considering 2 tips in the same event, constant rain intensity is assigned to the period between 2 tips (e.g. by using Equation 2.1, \( C \) equal to 0.2 mm and \( T \) equal to the separation in seconds between the 2 tips);

iv. Daily files with 1440 samples from 00:00 to 23:59 Universal Time Coordinated (UTC) are saved. The rain intensity at each minute is equal to the average rain intensity.

Unfortunately, the data processing method mentioned above is not applicable to the current tipping bucket as it does not provide a tipping time but only counts the number of tips in each minute; Figure 2.7 shows when the number of tips is multiplied by \( C \), it gives an estimate of the ‘total amount of water’ in that minute, termed as ‘method I’. In fact, this is not correct, since the water corresponding to the first tip of the minute could have been accumulating in the bucket over a much longer period of time. Furthermore, by applying such a calculation step, the minimum readable rain rate is 12 mm/h, where the lower rain rate value is missing. The comparison of rain rate distribution derived from the ‘original method’ for conventional and modern tipping bucket rain gauge is shown in Figure 2.8 and Figure 2.9 respectively.
Figure 2.7 Data processing procedure for ‘method 1’.

Figure 2.8 Comparison of a rain event derived from the ‘original method’.

Figure 2.9 Comparison of a rain event derived from ‘method 1’.
2.3 Review of MEASAT-3 Satellite System

The Malaysia East Asia Satellite system (MEASAT) is a Malaysian communication satellite owned by MEASAT Satellite System Sdn. Bhd. that aims to provide satellite services such as Direct-to-Home (DTH) satellite television called “Astro” and reliable telephone and data transmission services over Malaysia as well as providing a telecom operator service for Asia, the Middle East, Africa, Europe and Australia. Several geostationary satellites have been active since 1996, namely MEASAT-1 (AFRICASAT-1), MEASAT-2, MEAST-3, MEASAT-3a and MEASAT-3b. MEASAT-1 was launched in 1996, initially located at 91° East but afterward relocated to 46° East in 2009 to provide service to the African continent, and later it was renamed AFRICASAT-1. MEASAT-2 was launched in 1996 and located at 148° East while MEASAT-3 was launched in 2006 to replace MEASAT-1 at 91.5° East. Besides, MEASAT-3a and MEASAT-3b were launched in 2009 and 2014 respectively to extend the capacity of C and Ku-band (MEASAT, 2014).

In this work, MEASAT-3 is used to collect the Ku-band satellite signal through a measurement campaign carried out in Johor Bahru. Figure 2.9 and Figure 2.10 show the location of satellite and the coverage area of MEASAT-3 satellite for the Malaysia beam as well as its (Effective Isotropically Radiated Power) EIRP of the location. In addition, the specification of the MEASAT-3 Ku-band transponder is listed in Table 2.1.

![Figure 2.10 Location of MEASAT-3 satellite (Satbeam, 2014).](image)
Figure 2.11 The coverage of MEASAT-3 beam (MEASAT, 2014).

Table 2.1: MEASAT-3 Ku-band transponder and performance specification (MEASAT, 2014).

<table>
<thead>
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<tbody>
<tr>
<td>Bandwidth</td>
<td>36 MHz</td>
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<tr>
<td>Channel Polarization</td>
<td>Linear</td>
</tr>
<tr>
<td>EIRP (dBW)</td>
<td>58</td>
</tr>
<tr>
<td>G/T (dB/°K)</td>
<td>16.5</td>
</tr>
</tbody>
</table>

2.4 Scintillation

The time series of received signals are always contaminated by rapid fluctuations attributed to tropospheric scintillation (signal fluctuations due to air turbulence). Tropospheric scintillation increases with temperature, humidity and the liquid content of heavy clouds. It is caused by air turbulence and normally happens during hot and wet days, as well as in humid areas. It should be noted that scintillation effects cannot be compensated by PIMTs due to their low autocorrelation (Pooe-Baptista and Davies, 1994; Gracia-del-Pino et al., 2010) and they may have an impact on the performance of low-margin communication systems (Castanet, 2007). Therefore, tropospheric scintillation needs to be removed. In order to distinguish between rain attenuation (signal fluctuations due to scattering and absorption of hydrometeors) and scintillation, the two effects must be separated as much as possible
by filtering the time series of signal (Tatarski, 1961; Karasawa and Matsudo, 1991; Matricciani et al., 1996b; Matricciani and Riva, 2008).

Rain attenuation and scintillation are usually distinguished by observing a change of spectrum slope in power spectral density of signal variation (Karasawa and Matsudo, 1991; Matricciani et al., 1996b). In general, the effect of rain attenuation only exists at a much lower frequency while scintillation tends to appear toward higher frequencies (Karasawa and Matsudo, 1991). Such scenarios are depicted in Figure 2.12 to 2.14 with respect to three types of power spectra analysed from experimental data collected at Spino d’Adda, Italy for frequency 19.77 GHz. Figure 2.12 demonstrates rain attenuation has a -20 dB/decade slope up to 0.02-0.03 Hz, followed by typical tropospheric scintillation first at 0 dB/decade then a -80/3 dB/decade slope. However, it is slightly different in Figure 2.13, the power spectra only illustrates the effect of rain up to 0.1 Hz and beyond this is the scintillation effect at 0 dB/decade. The third type shows the huge rain attenuation effect extends the power spectral density up to Nyquist frequency as shown in Figure 2.14.

![Power Spectral Density](image)

**Figure 2.12** Sample of power spectral density on 21 September 1992 (Matricciani et al., 1996b).
Figure 2.13 Sample of power spectral density on 5 October 1992 (Matricciani et al., 1996b).

Figure 2.14 Sample power spectral density in 10 August 1992 (Matricciani et al., 1996b).

According to several studies, few types of low-pass filter are used to extract the scintillation effect. Initially, Karasawa and Matsudo (1991) suggested filtering out the scintillation effect by applying the 2 minute moving average technique. Later, Smith (1997) reported that although the moving average is a remarkably good smoothing filter, it is an exceptionally bad low-pass filter especially in the action of
frequency domain; this is because the filter’s rolloff is very slow and ripples exist at the stopband attenuation. Hence the moving average filter is unable to separate one band of frequencies from another. Subsequently, Matricciani et al. (1997b) and Matricciani (2008) employed the fifth-order Butterworth low-pass filter to eliminate the majority of the scintillation power. It is reported that 0.025 of cutoff frequency is used in low-pass filtering in which the tropospheric scintillation appears. A comparison of a few types of low-pass filter is provided in Appendix B.

2.5 Review of Fade Dynamics

Satellite communication systems operating at frequencies above 10 GHz are often subject to deep fades owing to atmospheric propagation, notably caused by rain. Hence, fade countermeasures need to be introduced to counteract rain attenuation, which is generally based on the first order statistic of rain attenuation such as the cumulative distribution function of attenuation. However, rain attenuation statistics alone are not sufficient for the proper design of adaptive PIMTs. Therefore, the knowledge of a second order statistic which describes the dynamic characteristics of rain-induced fades is of great importance to the system designers as far as fade countermeasures are concerned to optimise system capacity and reduce the probability of system outages. In fact, the second order statistics are not derivable from the first order rain fade statistics and must be extracted from the time series of signal attenuation (Nelson and Stutzman, 1996). Such fade dynamics include fade duration, fade slope, interfade interval and inter-event interval. The features that characterise the dynamic of fade events are presented in Figure 2.15. Among these fade dynamics, only fade duration and fade slope characteristics are of interest in the design and implementation of PIMTs and are highlighted in the following subsection.
2.5.1 Fade Duration

As can be observed in Figure 2.15, fade duration is defined as the duration between two consecutive crossings of an attenuation signal above the same attenuation threshold. Knowledge of this parameter is essential in the planning and designing of satellite system services for several reasons (COST 280, 2002; ITU-R P.1623-1, 2005) as below:

- **System outage**: fade duration statistics provide information on the number and duration of outages and system unavailability due to propagation conditions;
- **Sharing of system resources**: it is crucial for system operators to re-assign the resource to the other users based on the statistical behaviour of fade duration;
- **PIMTs**: fade duration statistics are essential for the system to decide how long it should stay in a compensation configuration before returning to nominal mode;
- **System coding and modulation**: the duration of rain fade is a key element in the process of choosing forward error correction codes and the best modulation schemes.

In the past two decades, much effort has been devoted to extensively studying the fade duration along the earth-space propagation path. Various prediction models are available in the literature. Initially, European action COST 205 (1985) used Ku-
REFERENCES


