UNIVERSITI PUTRA MALAYSIA

CHANNEL CHARACTERIZATION AND MODELING FOR GEO SATELLITE-TO-LAND TERMINALS AT KU-BAND WITH TROPICAL WEATHER AWARENESS

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By

ALI MOHAMMED ALI AL-SAEGH

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

March 2015

DEDICATION

My beloved parents,

My two sisters, Maysam and Noora

For their endless encouragement, patience, and support

And for being a great source of motivation and inspiration

My missing brother, Muthanna

Please come back soon

All my friends

And to my homeland, Iraq

Abstract of thesis presented to the Senate of Universiti Putra Malaysia
in fulfilment of the requirement for the degree of Doctor of Philosophy

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March 2015

Chair: Associate Professor Aduwati Sali, PhD

Faculty: Engineering

Severe tropical weather dynamic impairments on the earth-sky signal quality at Ku-band compared to temperate weather have increased the demand for channel characterization and modeling for satellite-to-land terminals in tropical regions. Consequently, this will achieve improvement in identifying the type and the performance of the Fade Mitigation Technique (FMT), managing the available communication resources, and enhancing the reliability and efficiency of the communication link. The variation in weather dynamics decreases the accuracy of the existing Land Mobile Satellite (LMS) channel models when applied in tropical regions which may negatively impact the performance of the satellite networks in the tropical regions. This may also attributed to the lack of reliable investigations and studies on channel performance characterization, experiments, and analysis of the LMS channel in tropical regions under atmospheric impairments. Moreover, the existing LMS channel models do not consider several other essential issues in channel modeling. Therefore, it is necessary to design a comprehensive, reliable, and more accurate LMS channel model that considers these issues.

To overcome such drawbacks: Firstly, we developed a signal attenuation prediction method for extracting the atmospheric impairments out of other impairments affecting signal quality for multi-regions in tropics, update the world's database with the first measured data of some regions in the tropics, design and validate a new satellite-to-land mobile channel model at Ku-band with features that enhance accuracy, comprehensiveness, and reliability. Finally, the

study proposed a tropical weather-aware LMS channel model that can be applied under different atmospheric (rain, clouds, and tropospheric scintillation) and mobility impairments. Furthermore, the resultant signal quality was evaluated for different modulation and coding schemes using an improved Quality Indicator Module (QIM) that is included in the proposed channel model.

The results obtained show that the proposed method provides reliable multi-region channel performance analysis in the tropical regions. The method enables the system designer to accurately predict the atmospheric impairments on satellite link and signal quality performance with error rates during dynamic weather conditions in various tropical regions. Moreover, the proposed extended LMS channel (ELMSC) model during non-rainy and -cloudy environments, and the comprehensive satellite to tropical LMS channel (STROC) model that incorporates atmospheric dynamics, were proven to have lower Root Mean Square Error (RMSE), and higher reliability than the conventional models. The measured data were provided, and a significant agreement was observed between the proposed model and the measured data. The comparison of the performances of the proposed model with the measured channel performances confirms the reliability and the accuracy of the proposed ELMSC model with lower RMSE (reaches 0.0543 dB) than the conventional model (0.187 dB).

Moreover, the proposed STROC model is shown to have lower RMSE (reaches 0.0072 dB) than the existing model with 0.0297 dB RMSE. The proposed channel models are suitable for analytical and numerical performance prediction and evaluation of various realistic atmospheric conditions and channel states, for narrow- and wide-band LMS systems, at various modulation and uncoded/coded schemes, and different satellite terminal speeds. The model and its associated modules can be used to study the signal performance, availability, and error rates of different services, including communications, broadcast, and navigation, as well as to develop a FMT for channel-aware strategies.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia Sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PERINCIAN SALURAN DAN PEMODELAN UNTUK TERMINAL GEO SATELIT-KE-TANAH PADA KU-BAND DENGAN KESEDARAN TERHADAP CUACA TROPIKA

Oleh

ALI MOHAMMED ALI AL-SAEGH

Mac 2015

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Kecacatan dinamik cuaca yang teruk terhadap kualiti isyarat Ku di langit dalam kawasan tropika berbanding kawasan sederhana menjadikan penilaian saluran dan permodelan bagi terminal satelit-ke-tanah sebagai satu keperluan penting. Oleh hal yang demikian, kemajuan dapat dicapai dari segi mengenal pasti jenis dan prestasi Teknik Pudar Tebatan (FMT), menguruskan sumber komunikasi yang ada, dan meningkatkan kebolehpercayaan dan kecekapan komunikasi. Kepelbagaian dalam dinamik cuaca ini mengurangkan ketepatan model saluran Satelit Bergerak Tanah (LMS) yang sedia ada jika digunakan di kawasan tropika yang mungkin memberi kesan negatif kepada prestasi rangkaian satelit di kawasan tropika. Ini mungkin disebabkan kekurangan penyiasatan yang meyakinkan dan kajian mengenai penilaian prestasi yang tepat, eksperimen, dan analisis pada pautan komunikasi satelit dalam kawasan tropika di bawah kecacatan atmosfera. Tambahan pula, model saluran LMS yang sedia ada tidak mempertimbangkan beberapa isu penting dalam pemodelan saluran. Oleh itu, reka bentuk model saluran LMS yang komprehensif, boleh dipercayai, dan tepat yang mengambil kira titik penting tersebut adalah diperlukan.

Untuk mengatasi masalah tersebut: Pertama, kita menghasilkan satu kaedah ramalan isyarat pengecilan untuk mengekstrak kecacatan atmosfera daripada kecacatan lain yang mempengaruhi kualiti isyarat bagi pelbagai wilayah di kawasan tropika mengemaskini pangkalan data dunia bagi data pertama yang diukur di sebahagian rantau dalam kawasan tropika, mereka bentuk dan

mengesahkan model saluran mudah alih satelit-ke-tanah yang baru pada Ku-band dengan ciri-ciri yang meningkatkan ketepatan, komprehensif, dan kebolehpercayaan. Akhir sekali, kajian mencadangkan satu model saluran satelit-ke-tanah mudah alih tropika yang boleh digunakan pada kecacatan atmosfera yang berbeza (hujan, awan, sintilasi troposfera), dan kemerosotan mobiliti. Tambahan pula, kualiti isyarat yang dihasilkan dinilai pada modulasi yang berbeza dan skim pengekodan menggunakan modul penunjuk kualiti yang lebih baik disertakan dalam model saluran yang dicadangkan.

Keputusan yang diperolehi menunjukkan bahawa kaedah yang dicadangkan menyediakan analisis prestasi isyarat bagi pelbagai tapak di kawasan tropika. Kaedah ini berguna bagi pereka sistem untuk meramal dengan tepat kecacatan atmosfera pada pautan satelit dan prestasi kualiti isyarat dengan kadar kesilapan semasa keadaan cuaca dinamik di pelbagai kawasan tropika. Selain itu, model saluran lanjutan LMS (ELMS) yang dicadangkan dalam persekitaran tanpa hujan dan cerah, dan juga model komprehensif satelit ke tropika saluran LMS (STROC) yang menggabungkan dinamik atmosfera, telah terbukti kurang Ralat Root Mean Square (RMSE), dan lebih dipercayai daripada model konvensional. Data pengukuran disediakan, dan persamaan yang agak baik telah diperhatikan di antara model yang dicadangkan dan data pengukuran. Perbandingan prestasi antara model cadangan dengan prestasi saluran yang diukur menunjukkan kebolehpercayaan dan ketepatan model ELMSC yang dicadangkan dengan nilai RMSE yang rendah (mencapai 0.0543 dB) daripada model konvensional (0.187 dB).

Tambahan pula, model cadangan STROC menunjukkan nilai RMSE yang rendah (mencapai 0.0072 dB) daripada model sedia ada dengan nilai RMSE, 0.0297 dB. Model saluran yang dicadangkan adalah sesuai untuk ramalan prestasi dan analisis berangka dan penilaian pelbagai keadaan atmosfera realistik dan negara saluran, sistem LMS yang berjalur sempit dan luas, untuk pelbagai modulasi dan skim dinyahkod/dikodkan, dan kelajuan terminal satelit yang berbeza. Model dan modul yang berkaitan dengannya boleh digunakan untuk mengkaji prestasi isyarat, ketersediaan, dan kadar ralat perkhidmatan yang berbeza, termasuk komunikasi, penyiaran, dan pelayaran, dan juga untuk membangunkan FMT untuk strategi saluran-sedar.

ACKNOWLEDGEMENTS

This work would not be accomplished without the help of so many people. In the following lines is a brief account of some but not all who deserve my thanks.

I would like to extend my gratitude to Associate Professor Dr. Aduwati Sali, for her valuable supervision, advice, and guidance from the very early stage of this research as well as giving me experiences throughout the work. Above all and the most needed, she provided me unflinching encouragement and support in various ways.

I am also delighted to convey my appreciations to Dr. J. S. Mandeep and Dr. Alyani Ismail, for their professional reviews, comments, and suggestions which have been indispensable during the research.

My warmest gratitude goes to my parents who always believed in me, gave me all the possible support, and being patient with me for years, providing me with everything, just to make me focus on my goals.

I would like to thank my two sisters, Maysam and Noora, for their endless support in so many aspects, and sharing my happiness and sorrow.

I would like also to express my gratitude to the University Putra Malaysia and especially the academic and the technical staff of the Faculty of Engineering for their help and support throughout my study period.

I am deeply thankful to all my friends I met in this country; I am thankful for every word of information, advice, and support. I am grateful for every moment of laugh and sadness we shared together. I am so grateful to have such helpful friends around who always showed concern for my work, and I hope they will accept my apology for not mentioning their names to not forget anyone of them. Nonetheless, my gratitude to the Malaysian people in general for their perfect hospitability in their green land during my study period.

I certify that a Thesis Examination Committee has met on 9 April 2015 to conduct the final examination of Ali Mohammed Ali Al-Saegh on his thesis entitled "Channel Characterization and Modeling for GEO Satellite-to-Land Terminals at Ku-band with Tropical Weather Awareness" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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- the research conducted and the writing of this thesis was under our supervision;
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Signature: ____________________________
Name of Member of Supervisory Committee: Associate Professor Dr. Mandeep Jit Singh

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LIST OF ABBREVIATIONS

ACM	Adaptive Coding and Modulation
AI-MS	Atmospheric Impairments on Multi-Site
AI-SS	Atmospheric Impairments on Single Site
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BPF	Band Pass Filter
CDF	Cumulative Distribution Function
DAH	Dissanayake, Allnutt, and Haidara
DAQ	Data Acquisition
DTH	Direct–To-Home
DVB-S	Digital Video Broadcasting via Satellite
DVB-S2	Digital Video Broadcasting via Satellite – Second generation
EAI-MS	Extracted Atmospheric Impairments on Multi-Site
EHF	Extremely High Frequency
EIRP	Effective Isotropic Radiated Power
ELMSC	Extended Land Mobile Satellite Channel
EM	Electromagnetic
erfc	complementary error function
ESA	European Space Agency
FMT	Fade Mitigation Technique
FSL	Free Space Loss
GEO	Geostationary Earth Orbit
GPS	Global Positioning System
hPa	hectoPascal
ITU	International Telecommunication Union
LBM	Link Budget Module
LEO	Low Earth Orbit
LMS	Land Mobile Satellite
LMT	Land Mobile Terrestrial

LNA	Low Noise Amplifier
LNB	Low-Noise Block
LOS	Line-Of-Sight
LPF	Low-Pass Filter
LWC	Liquid Water Content
mbar	millibar
MEO	Medium Earth Orbit
MMD	Malaysian Meteorological Department
MODCOD	Modulation and Coding
M-QAM	M-*ary* - Quadrature Amplitude Modulation
PER	Packet Error Rate
PNG	Papua New Guinea
PSD	Power Spectral Density
PSK	Phase-Shift Keying
QAM	Quadrature Amplitude Modulation
QIM	Quality Indicator Module
QoS	Quality of Service
QPSK	Quadrature Phase-Shift Keying
SAM	Simple Attenuation Model
SER	Symbol Error Rate
SNR	Signal to Noise Ratio
STROC	Satellite-To-Tropics Channel
TDM	Time Division Multiplex
TDMA	Time Division Multiple Access
TTI	Transmission Time Interval
UKM	Universiti Kebangsaan Malaysia
UPM	Universiti Putra Malaysia
USM	Universiti Sains Malaysia
WiFi	Wireless Fidelity
WiMax	Worldwide Interoperability for Microwave Access
WSN	Wireless Sensor Network

LIST OF SYMBOLS

T_X	Transmitter
R_X	Receiver
E_b/N_o	Energy per bit to noise spectral density ratio
E_s/N_o	Energy per symbol to noise spectral density ratio
f	Frequency
θ	Elevation angle
p	Percentage of exceedance time of the year
$R_{0.01}$	Rainfall rate at p=0.01%
k	First rain specific coefficient
α	Second rain specific coefficient
γ_{Rain}	Rain specific attenuation
r_H	Horizontal reduction factor
P_H	Horizontal projection
L_S	Slant path length
H_R	Rain height above sea level
H_S	Earth station height above sea level
E_R	Earth radius
V_F	Vertical adjustment factor
φ	Latitude
$A_{0.01}$	Rain attenuation at p=0.01%
L_E	Effective rain path length
A_{Rain}	Rain attenuation
L_H	Rainfall horizontal path length
H_0	0°C isotherm height
p'	Crane's modified p
R	Rainfall rate
fr_{pri}	Principal relaxation frequency
fr_{sec}	Secondary relaxation frequency
T	Temperature

ε	Dielectric permittivity of water contents
γ_{cloud}	Cloud specific attenuation
A_{cloud}	Cloud attenuation
RH	Relative humidity
σ_S	Standard deviation of the scintillation
A_{scint}	Scintillation fade depth
K	Rician factor
a	Amplitude of the direct signal
σ	Standard deviation
P_T	Power transmitted
G_T	Transmitter antenna gain
G_R	Receiver antenna gain
d	link distance
λ	wavelength
L	Packet length
K_{mob}	Rician factor during clear LOS
K_{rain}	Rain impairment on Rician factor
L_A	Total atmospheric loss
L_{sys}	system losses
N	Noise power
c	The speed of light in vacuum
BW	Bandwidth
R_S	Symbol rate
R_C	Code rate
$y(t)$	Channel output signal
$x(t)$	Channel input signal
$f_{LMS}(t)$	Land Mobile Satellite channel fading
$n(t)$	Channel noise
$m(t)$	Mobility impairments
$s(t)$	tropospheric scintillation impairment
f_t	Total impairments

N_P	number of signal paths
$r(t)$	Envelope of the reflected signals
$A_i(t)$	Reflected power of the i^{th} signals
$\Gamma_i(t)$	coefficient related to angular Doppler frequency
ω_D	Doppler frequency
β_i	angle of arrival
ϕ	Phase difference
$r_I(t)$	In-phase component of the Rayleigh distribution
$r_Q(t)$	Quadrature component of the Rayleigh distribution
I_S	Loss attributed to motion at different speeds
n_S	Sample number
N_S	Total number of samples
σ_{LOS}	standard deviation of multipath during LOS state
s	Satellite terminal speed
G_N	Normal distribution signal
M	Mean
Σ	Standard deviation of shadowing in dB
σ_{BL}	standard deviation during Blockage scenario
g	Antenna averaging factor
N_{wet}	Wet term of radio refractivity
e	Water vapor pressure
P_r	Power received
M_O	modulation order
K_{cloud}	impairments caused by cloud
σ_{TS}	Standard deviation of scintillation for different
F_M	Mean signal fade
γ_o	Oxygen specific attenuation
P	Pressure
r_p	Coefficients related to pressure
r_T	Coefficients related to temperature
L_O	Path length for oxygen

γ_W	Water vapor specific attenuation
ρ	Water vapor density
L_W	Effective water vapor path length
A_{Gases}	Gases attenuation
A_O	Attenuation due to oxygen
A_W	Attenuation due to water vapor

CHAPTER 1

INTRODUCTION

The chapter presents an overview of the research aspects and architecture. The overview of the channel modeling in satellite communication is presented taking into account the ideology with the drawbacks that motivated doing this research. The overview discusses how the problem statements were formed through the satellite communication technology development and became significant before listing the problems that are currently failed to be solved. The research scope and study module are then discussed before presenting the research aim and objectives. A brief methodology to overcome the aforementioned problems and to achieve the research objectives is then introduced, and then the research contributions are enlisted before ending the chapter with the thesis organization.

1.1 Channel characterization and modeling in satellite communication: Drawbacks and motivations

The information about the satellite channel performance and characteristics is needed to deploy appropriate error control or Fade Mitigation Technique (FMT) to maximize reliability while using a minimum of available communication resources [1]. The information can be obtained by either conducting practical channel performance measurements (which is difficult to be conducted in all the spots of the world and at different channel parameters and scenarios) or channel modeling. The channel model is a simplification of a real world, where we predict its characteristic in advance based on specific channel parameters and scenarios. Suitable metrics can be quantified such as the received signal strength, power of multipath components, noise spectral density, link quality, etc.

However, variations in the atmospheric conditions were shown to have a major effect on the earth sky channel performance especially at frequencies above 10 GHz [2-5]. Nonetheless, as the desire for more data to be sent with respect to time in satellite communication increased, the higher frequencies began to gain much more interest [6]. As a recent trend, Ku-band is typically used for high quality and advanced applications in multimedia transmissions because of its wider bandwidth compared with lower bands like L, S, and C bands, and has less noise margin and atmospheric effects compared with other higher bands like Ka and V bands [7, 8]. The rain attenuation at Ku-band has a paramount impact on signal attenuation in space, followed by clouds, water vapor and oxygen as a minor effect on signal level variation [5, 8].

Consequently, channel impairments increase the need for developing channel models in order to predict the atmospheric induced fade level as well as

proposing proper FMT. Several researchers have tried to analyze the atmospheric effects on the transmitted signal level [9-12]. Despite a small inaccuracy percentage, they have been able to build well formulated models for a better expectation of the phenomena impact according to the parameters related.
However, reliable statistics of rain attenuation at a number of locations throughout the world are required [13]. Furthermore, the atmospheric variations increased in the tropical regions compared to the temperate areas due to their different weather parameters [2, 14, 15]. With the increase of recent satellite communication technology applications throughout the tropical countries and lack of information regarding the atmospheric impairments characterization, measurements, and mitigation techniques [5, 16, 17], the extraction of an exclusive and accurate performance of the signal quality effects during highly natural tropical weather impairments has turned into a growing demand [4, 17-19]. This supplies the fact that modern satellite communication technology applications are being increasingly demanded in tropical countries and that there is a scarcity of information regarding the atmospheric impairments analysis [17, 19]. Furthermore, the lack of measured rainfall data and the use of the estimated data instead may cause inaccuracy in the rain attenuation prediction [20]. Therefore further experimental measurements are needed to be conducted in tropical regions [20].

The impairments analyses employed so far follow two possible methods. The first method is used to obtain the weather parameters effects on specific “single” geographical region or site using variable transmission parameters such as different elevation angles and/or frequencies. The second method tries to analyze and compare the weather induced impairments in different “Multi” regions in tropics by using different transmission parameters like elevation angles and frequencies which have major effects on the attenuation value during bad weather especially at high intensity rain periods.

Logically, comparing between two or more regions (in terms of their weather impairments) with different elevation angle and/or frequency will not give real indication of the exact dynamic weather effect at specified regions. Consequently, in order to restrict on the analysis of the atmospheric impairments out of other impairments for several tropical regions, a new method is needed to extract the weather parameters from the other parameters to provide actual estimation of the atmospheric induced impairments.

The Land Mobile Satellite (*LMS*) systems are gaining much interest in the current generation of wireless systems and are expected to gain more interest in the next generations due to the feasible services and their ability to serve many users over a wide area with low cost compared with the land mobile terrestrial (*LMT*) systems [21]. The significance of *LMS* systems is rapidly growing for a variety of applications such as navigation, communications, broadcasting, etc.

Recent applications and services based on satellite to land mobile terminal communication have resulted in demand for more bandwidth and higher data rate, and thus higher transmission frequency [22]. Therefore, *LMS* channel characterization and modeling at high frequency has become a necessity for the development of efficient adaptive transmission models and techniques as solutions for channel impairments [21, 22]. Considerable interest has been directed recently toward *LMS* communication at Ku-band [22].

The *LMS* channel condition at Ku-band depends on mobility impairments and tropospheric scintillation. The latter, which causes rapid fluctuations in satellite signal level, occurs due to the irregularities in radio refractivity as the wave travels along different medium densities in the troposphere [23, 24]. Nevertheless, Ku-band receivers require a high-gain directional antenna [22]. The accuracy of the *LMS* channel models has increased notably over time through the addition of several features for approaching the real-world environment along with recent *LMS* technologies and services. This condition has motivated researchers as well as this research, to design more reliable and accurate *LMS* channel models.

However, existing channel models (To be discussed in details in Sections 2.7.2 and 2.7.3) do not consider tropospheric scintillation under non-rainy conditions. This significantly affects the signal performance at Ku-band, particularly in high humidity regions, such as the tropical environment [23, 24]. The tropospheric scintillation should be considered and identified accurately in the design of satellite communication systems [24]. Moreover, these models do not consider the impairments caused by different vehicle speeds at Ku-band for systems utilizing mobile directional antenna. Therefore, a comprehensive approach with reduced Root Mean Square Error (RMSE) for *LMS* channel modeling that considers these significant impairments becomes a necessity. The accuracy of channel modeling is important since a slight error in channel performance reporting (reaches even 1 or 2 dB) may cause inappropriate decision for resource management and/or FMT [1, 21]. Consequently, the recent advances in satellite communication technologies in the tropical regions have led to significant increase in the demand for services and applications that require high channel quality for mobile satellite terminals [21]. Typically, the quality of service provided to customers is predicted by the radio engineers or network operators [13].

Moreover, modern satellite communication techniques, particularly the FMT, require accurate satellite channel model suitable for highly natural tropical weather dynamics [25]. The channel dynamics in tropical environments accompanied with the lack of accurate and reliable channel model for satellite networks in tropical regions increase the need to develop such channel model that is related to tropical regions, which will replace the existing channel models (will be discussed in details in section 2.7.3). To do so, the effective atmospheric impairments in the tropical regions, namely rain, cloud and the tropospheric scintillation, on the channel performance and quality should be considered in order to index the atmospheric induced fade level and to select the proper FMT [7, 26].

Regarding the rain impairment, more accurate rain impairment modeling for mobile terminal in tropical regions became a necessity and challenge since the model should approach the realistic measured channel impairments at different weather conditions. Besides, there is lack of channel impairments' measurement campaign for mobile terminal scenario at Ku-band conducted [25]. Therefore, the *LMS* channel performance measurements during rainy environment is highly needed [25] and can be added to the world's database. The data from the measurement campaign will also be useful to validate the accuracy of the proposed channel models. The rain-induced tropospheric scintillation is required to be taken into consideration in the design of the impairments produced in the rainy weather condition [25, 27].

The cloud impairments affect the signal propagated in the satellite to land stationary terminals channel, especially at frequencies above 10 GHz [28]. With the recent satellite to land mobile terminals network technologies and services that use these high frequencies, there is a lack of channel impairments modeling and analysis for such type of link. The effects of cloud on mobile scenarios have not been taken into consideration yet in the existing models (will be discussed in details in section 2.7.3). Subsequently, not considering the cloud effect may cause serious problems related to the accuracy of the model, particularly during cloudy weather [29]. This is supported by the fact that the cloud in tropical regions is more condensed and causes more attenuation than the clouds in temperate regions [30]. This context is what frames and motivates this research design a model and analysis such scenarios while considering dynamics of the atmospheric and transmission parameters.

Consequently, the lack of reliable investigations regarding accurate performance evaluation, experiments, and analyses on the satellite to tropical regions link under atmospheric impairments have made the accurate link budget and signal quality performance evaluation and assessment a necessity [21, 31]. The communication signal quality is used as a metric for adaptation techniques for modern satellite networks and to identify the effects of channel impairments on the service quality delivered to users.

1.2 Problem statements

From the drawbacks mentioned in the previous sections, three main problem statements are addressed in this research as follows.

- The existing multi-region analysis method fails to precisely extract a unique performance of the signal quality effects during highly natural weather impairments in tropical regions.

- The existing *LMS* channel models during non-rainy and non-cloudy environments did not consider the variable pointing loss effect, for the Ku-band system that utilizes directional antenna, as well as the tropospheric scintillation effect. Failing to consider these two impairments will reduce the accuracy, the reliability, and the comprehensiveness of the existing *LMS* channel models.

- There is a lack of reliable *LMS* channel model that is suitable for tropical regions in terms of their distinctive weather impairments on the received signal level performance, as well as the link quality assessment.

1.3 Research scope and study module

To achieve user requirement in satellite communication, a block cycle that represents the principal steps can be drawn as shown in Figure 1.1.

In satellite communications, qualified satellite services and applications should be provided in order to achieve the satisfaction of a satellite system user. The recent satellite network technologies and the current state of the telecommunication market are driven by the user requirement for multimedia applications and services, which require high data rates [13].

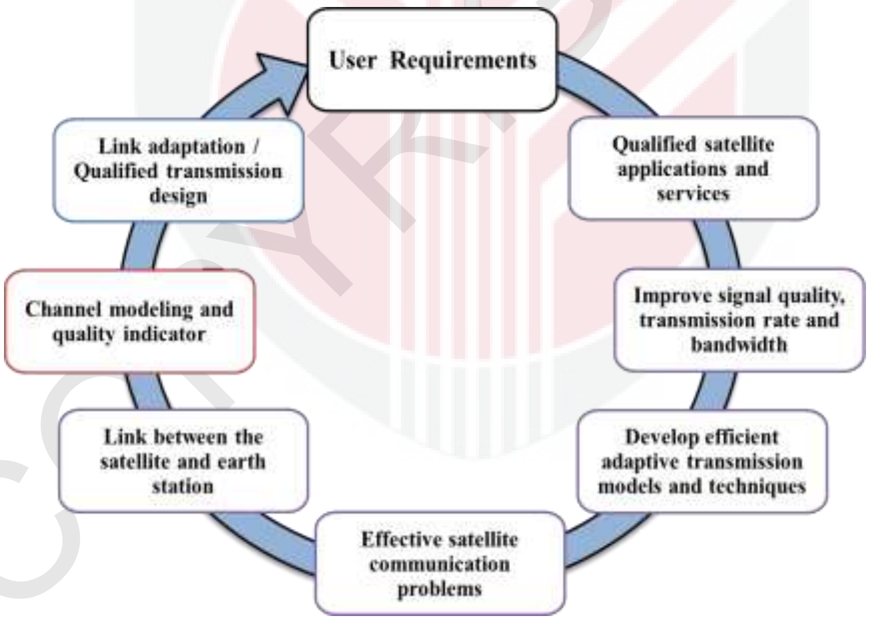

Figure 1.1: Research spot

The high data rate, in turn, requires high transmission frequency and wide bandwidth (such as Ku frequency band), qualified signal strength with less transmission errors, and high transmission rate. This can be achieved through developing an efficient and adaptive transmission systems and techniques.

However, several impairments may degrade the quality of the satellite signal and increase the transmission errors that can cause serious problems in the data received, such as mobility and atmospheric impairments. These impairments are produced in the link between the satellite and the earth station.

To this point the problems are addressed, and next is how the communication system designers deal with these problems to achieve user satisfaction. The channel modeling and quality indication, which are the scope of this research, are required especially in the recent satellite system technologies [13], that employs link adaptation as a fade mitigation technique. The channel state reporting is used in such types of system for quality improvement techniques and channel performance evaluation. These techniques have the ability to improve the signal quality under highly natural channel impairments to achieve end user satisfaction.

The channel modeling in this research considers and is limited to: “Ku-band” channel that links the “Geostationary Earth Orbit (GEO)” satellite to the land stationary and mobile terminals under dynamic tropical weather conditions. The study module and limitations are shown in Figure 1.2.

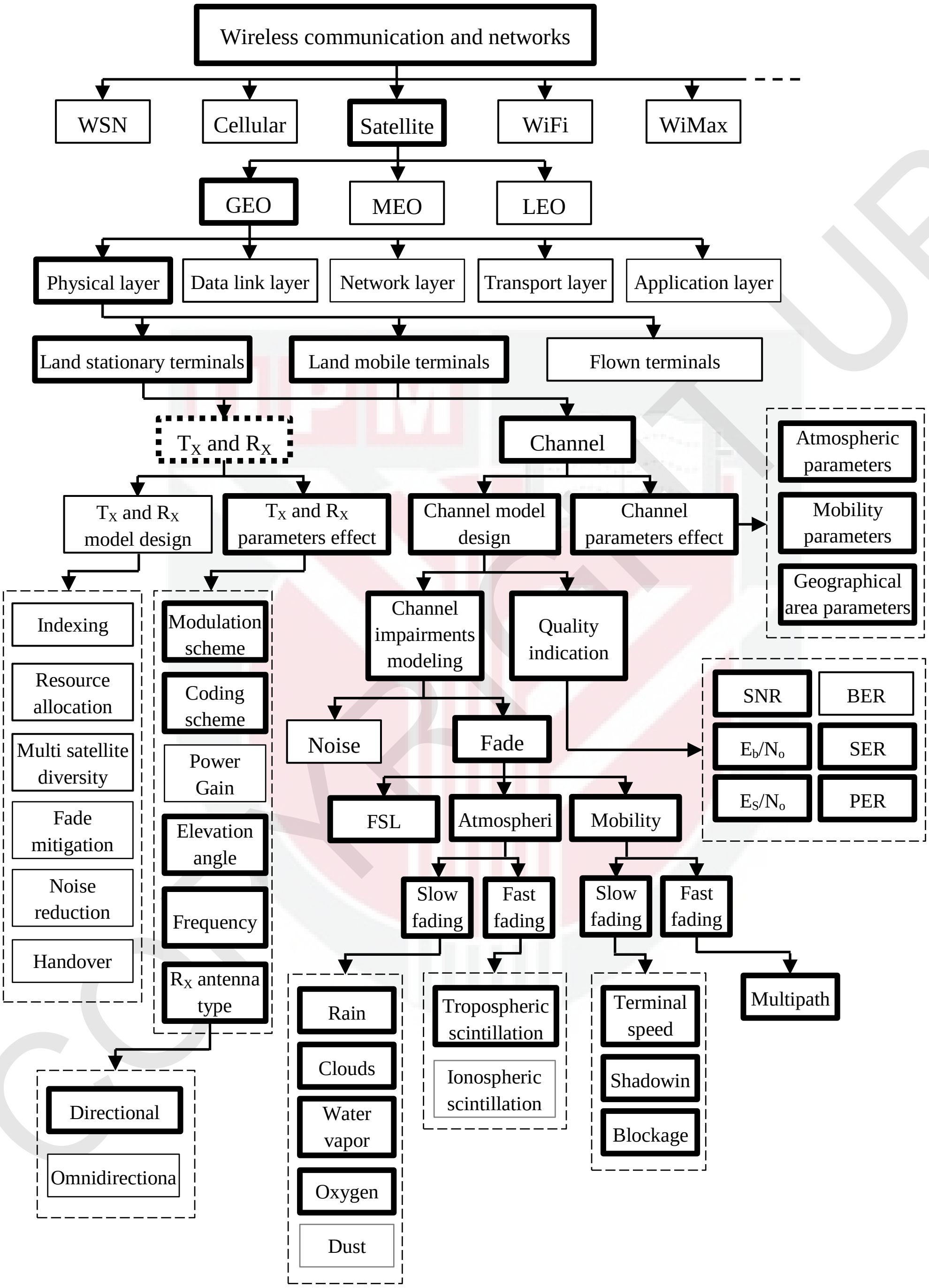

Figure 1.2: Study module

1.4 Research aim and objectives

The research aim is to achieve satellite to land channel characterization and modeling for advanced technology satellite communication systems that meet the dynamic tropical weather conditions. This is achieved through the following objectives:

- To develop and investigate a signal attenuation prediction method for extracting the impairments encountered during weather dynamics for multi-regions in tropics.
- To design and validate a new *LMS* channel model, with scintillation and tracking error awareness, for enhancing the comprehensiveness, accuracy, and reliability of *LMS* channel modeling based on actual experimental measurements.
- To design, investigate, and validate *LMS* channel model for tropical regions, based on actual experimental measurements, that considers the significant tropical weather impairments with indication of the performance quality level.

1.5 Research highlights

This research proposes a comprehensive model of atmospheric impairments to improve the estimation and the analysis of atmospheric effects on the signal quality in satellite communications using actual measured parameters. The model is composed of correlated modules that include channel modules and quality assessment extended module.

The research first presents a new method developed for appropriate analysis and realistic performance evaluation for satellite radiowave during the atmospheric conditions variations in 15 tropical areas from the four continents analyzed based on actual measured parameters. The method implementation includes signal attenuation, carrier to noise ratio, symbol energy to noise ratio, and symbol error rate at different areas and different modulation schemes. Furthermore, for improvement in analysis in terms of covering more remarkable regions in tropics, the research provides new measurements data with analysis for certain regions in tropics used as a test bed and to add measurement data of such area to the world's database for future researchers. The method comprises integrated aspects to improve the evaluation and analysis of effective atmospheric parameters on the signal quality at Ku-band in tropical regions.

The integrated aspects include: (i) presenting a new method called "*Extracted Atmospheric Impairments on Multi-Site (EAI-MS)*" which developed to extract the atmospheric impairments out of other impairments affecting signal quality, (ii) obtaining actual atmospheric and geographical parameters of substantial tropical regions, (iii) supplying the specified database with the first measured data of a remarkable region in the tropics, and finally (iv) presenting a newly developed Quality Indicator Module (QIM) extension to evaluate the satellite/Earth station quality performance regarding the effects of the abovementioned parameters. The observed link characteristics and performance analysis are presented with propagation measurements conducted in 3 tropical regions regarding rain attenuation in the tropics.

Nonetheless, several experimental measurements were conducted that considered stationary and mobile terminal scenarios in order to characterize the channel performance during dynamic link environments and validate the channel models proposed.

Moreover, the research presents *LMS* channel model at Ku-band with features that enhance accuracy, comprehensiveness, and reliability. The effect of satellite tracking loss at different mobile terminal speeds is considered for directional mobile antenna systems, a reliable tropospheric scintillation model for a *LMS* scenario at tropical and temperate regions is presented. Finally, a newly developed QIM for different modulation and coding schemes is included. The proposed model is designed based on actual experimental measurements and can be applied to narrow and wideband signals at different regions and at different speeds and multi-channel states.

The proposed channel model is called the *extended land mobile satellite channel (ELMSC)* model. The term “extended” refers to four new features included in the model design. First, improvement is based on actual signal measurements to enhance the accuracy and reliability of the previously developed multi-state *LMS* model at Ku-band. Second, model the effects of variable vehicular speeds concerning the clear Line-of-Sight (LOS) and shadowing scenarios. Third, an *LMS* tropospheric scintillation model for non-rainy environment is developed. Lastly, a quality indicator module is improved and added to the *ELMSC* model. The model consider tropospheric scintillation and vehicular environments as well as its application to narrow and wide-band signals worldwide because the *LMS* environment varies with respect to different regions in the world, particularly in temperate and tropical regions.

Finally, the research presents reliable channels model of satellite-to-land terminals that fills the gaps in the existing models. The proposed *Satellite-To-Tropics Channel (STROC)* model involves additional important features to the *ELMSC* model. These features include an increase in the channel model reliability by considering the effective tropical weather impairments for realistic link characterization, namely the impairments caused by rain, clouds, and rain-induced tropospheric scintillation.

The dynamic parameters of the rain and cloud and their effects on the Rician factor are modeled. The model involves modules that design multipath signals, multi-state mobility model, rain impairment model, cloud impairment model, tropospheric scintillation model, Link Budget Module (LBM), and QIM.

The research also developed an improved Packet Error Rate (PER) performance evaluation related to the degradations that occur in channel quality for different types of impairments (rain, clouds, mobility, and physical obstacles) using four modulation schemes, namely QPSK, 8-PSK, 16-QAM and 32-QAM.

1.6 List of contributions

The Research contributions are listed as follows.

- Specific analysis of the attenuation caused by rain, cloud, water vapor, and dry air has been made for various tropical atmospheric parameters with extraction of the effective channel impairments in tropical regions at Ku-band.

- Providing new experimental measurement data of instantaneous rain impairments at Ku-band and atmospheric parameters in three tropical regions located in the middle and north of Malaysia, namely Serdang and Bangi in Selangor, and Penang. The atmospheric parameters include the measurements of rain rate, temperature, humidity, and atmospheric pressure.

- Providing new database for measured atmospheric and site parameters in 15 tropical regions that can be used instead of the predicted database.

- Presenting new method for extracting the atmospheric impairments out of other impairments on satellite signal link for appropriate analysis and performance assessment of the rain attenuation in multi-regions in the tropics. The analysis includes channel performance and quality indication at several modulation schemes.

- Providing new experimental measurements data of signal attenuation for satellite to land mobile terminal moving at different speeds at clear LOS using mobile antenna system. Moreover, a database that contains the measurements of the effect of signal shadowing by roadside trees and signal blockage by obstacles, such as bridges and tunnels, is provided.

- Designing new *LMS* channel model during clear sky environment that fills the gaps of the existing models during the clear LOS, shadowing and blockage states. This is done by considering the effect of antenna tracking error during the mobility as well as the effect of the tropospheric scintillation on mobile terminal scenario.

- Presenting the first experimental measurements of the *LMS* channel performance under dynamic weather impairments in the tropical regions. The experimental measurements also include the measurements of the accumulated rainfall, temperature, relative humidity, and atmospheric pressure.

- Designing new *LMS* channel model that involves dynamic atmospheric impairments in tropical regions. The STROC model includes modeling the channel impairments attributed to rain, cloud impairments, and tropospheric scintillation[1].

- Presenting a quality indicator module which includes a method for *PER* approximation for satellite communication at higher *M-ary* modulation schemes for stationary and mobile terminal scenarios.

1.7 Thesis organization

The thesis is structured into five chapters; Chapter one presented the channel modeling characteristics and drawbacks with the motivation for the study, statement of the problems, research scope and study module, aim of the research and the objectives, before ending with the research highlights with a list of major contributions of the study. Chapter 2 gives an overview of the theories used in channel analysis, characterization and modeling for stationary and mobile terminals. This also includes discussing the effects of transmission parameters, atmospheric (rain, cloud, tropospheric scintillation, water vapor, and dry air) and mobility impairments and quality indication with a review of the previous works.

Chapter 3 presents the methodology of the research that includes the channel analysis techniques, experimental measurements for stationary and mobile terminals, channel modeling, and quality indication. Chapter 4 presents the obtained results regarding the proposed analytic method and channel modeling described in Chapter 3, along with the channel measurements, analysis, and quality indication. The thesis is ended with chapter 5 that include the conclusion of the research with some recommendations for future works.

[1] Rain-induced tropospheric scintillation has been included.

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