OPTIMUM ADAPTIVE CODING AND MODULATION CHARACTERISTICS ON BROADBAND SATELLITE COMMUNICATION SYSTEM IN TROPICAL NIGERIA

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DEDICATION

To my beloved Mother Aishatu M. Ruta

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ABSTRACT

Broadband satellite services operating at higher frequencies above 10 GHz are liable to atmospheric degradations. The effect atmospheric impairment is much higher in tropical and equatorial zones. The temporal and dynamic behaviours of precipitation has affected the optimum performance of satellite broadband applications using satellite very small aperture terminal (VSATs) for small offices and homes (SOHO). In order to improve the efficiency of satellite link operating in tropical rain zone, some propagation impairment mitigation technique (PIMT) can be employed. The objectives was to quantify the rain rate at 0.01%, quantify the rain and its effect on Ku-band frequency satellite link, examine the link attenuation level on 6 MHz and 2 MHz bandwidths and develop the optimum performance threshold for adaptive coding and modulation (ACM) in real-time operation for Nigcomsat ground station in Abuja, Nigeria. Two years measurement campaign was conducted from January 2016 to December 2018. This thesis shows that increasing the carrier power can improve the throughput, availability and reduction in the required bandwidth by 58%. This makes ACM a good candidate for bandwidth on demand applications which can greatly improve the design link for broadband satellite applications in tropical zone. This result will offer essential input to satellite operators to achieve the best spectral efficiency. The improvement in the total downtime from 2556 minutes recording the annual availability at 94.41% without ACM in 2016, to an excellent performance of 99.85%, recording annual downtime of only 42.8 minutes after the full implementation of ACM in 2018. This performance is the peak performance achievable by any satellite operator in recent time. The ITU-R P. 841-4 recommended 0.01% assurance of 99.99% to achieve an annual outage of 53 minutes. However, the achieved 42.8 minutes annual outage has satisfied the standard set by Nigcomsat of 99.7% and surpassed the requirements with the implementation of ACM. This is one of the best fit attained by Nigcomsat in meeting its customer's obligation ever in the last 7 years of Nigcomsat-1R satellite operation. This study has established the thresholds of performance for VSATs in tropical zone with seven (7) operating states of ACM in accordance with the atmospheric condition of Abuja, Nigeria.

ABSTRAK

Perkhidmatan satelit jalur lebar yang beroperasi pada frekuensi tinggi melebihi 10 GHz cenderung mengalami kemerosotan atmosfera. Kesan kemerosotan atmosfera lebih tinggi di zon tropika dan khatulistiwa. Tingkah laku hujan temporal dan dinamik telah mempengaruhi prestasi optimum aplikasi jalur lebar satelit dengan menggunakan terminal apertur satelit yang sangat kecil (VSAT) untuk pejabat dan rumah kecil (SOHO). Bagi meningkatkan kecekapan pengendalian pautan satelit di zon hujan tropika, beberapa teknik pengurangan gangguan perambatan (PIMT) boleh digunakan. Matlamatnya adalah untuk mengira paras hujan pada 0.01%, dan kesannya pada satelit frekuensi jalur-Ku, mengkaji tahap pelemahan satelit pada lebar jalur 6 MHz dan 2 MHz dan membangunkan ambang prestasi optimum untuk pengekodan dan modulasi boleh suai (ACM) dalam operasi masa nyata. Bagi stesen bumi Nigcomsat di Abuja, Nigeria. Kempen pengukuran dua tahun itu telah dijalankan dari Januari 2016 hingga Disember 2018. Tesis ini memperlihatkan bahawa meningkatkan kadar celus boleh meningkatkan daya tampung, ketersediaan dan pengurangan jalur lebar yang dikehendaki sebanyak 58%. Ini menjadikan ACM sebagai calon yang baik untuk aplikasi atas permintaan lebar jalur yang boleh meningkatkan reka bentuk satelit untuk aplikasi satelit jalur lebar di zon tropika. Hasilnya akan memberikan input penting bagi pengendali satelit untuk mencapai kecekapan spektrum terbaik. Peningkatan dalam jumlah masa henti dari 2556 minit mencatatkan ketersediaan tahunan sebanyak 94.41% tanpa ACM pada tahun 2016, kepada prestasi cemerlang 99.85%, merekodkan masa henti tahunan sebanyak hanya 42.8 minit selepas pelaksanaan ACM sepenuhnya pada tahun 2018. Prestasi ini adalah prestasi puncak yang boleh dicapai oleh mana-mana pengendali satelit pada masa kini. ITU-R P. 841-4 mengesyorkan jaminan 0.01% daripada 99.99% untuk mencapai 53 minit gangguan tahunan. Walau bagaimanapun, gangguan tahunan yang mencapai 42.8 minit telah memenuhi piawaian yang ditetapkan oleh Nigcomsat 99.7% dan melebihi keperluan dengan penggunaan ACM. Ini adalah salah satu langkah terbaik yang dicapai oleh Nigcomsat dalam memenuhi kewajiban pelanggannya dalam 7 tahun terakhir operasi satelit Nigcomsat-1R. Kajian ini telah menghasilkan ambang prestasi untuk VSAT di zon tropika dengan tujuh (7) keadaan operasi ACM mengikut keadaan atmosfera Abuja, Nigeria.

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LIST OF ABBREVIATIONS

ACM	-	Adaptive coding and modulation
ACTS	-	Advanced Communications Technology Satellite
ACU	-	Antenna control unit
ADU	-	Antenna drive unit
A_{eff}	-	Effective Area for antenna aperture
ALC	-	Automatic level control
APSK	-	Amplitude and Phase shift keying
ASCII	-	American Standard Code for Information Interchange
AVR	-	Automatic voltage regulator bus
AWM	-	Average worst month
AWS	-	Automatic Weather Station
AY	-	Average year
BER	-	Bit error rate
BUC	-	Block up-converter
BPSK	-	Binary phase shift keying
BW	-	Bandwidth
CAPPI	-	Constant Altitude Plane Position Indicator
CCDF	-	Complementary Cumulative Distribution Function
CCM	-	Constant coding and modulation scheme
CIR	-	Committed Information Rate
CNR	-	Carrier to noise ratio (C/N)
COST	-	Cooperation in Science and Technology
CR	-	Coding Rate
CW	-	Continuous wave in RF signal
dB	-	Deci-bel
DBR	-	Direct Broadcast Receiver
DC	-	Direct current battery power source
DID	-	Department of Irrigation and Drainage
DTH	-	Direct to home broadcast service
DR	-	Data Rate
DSD	-	Drop size distribution of rain

DVB-S2	-	Digital video broadcasting over satellite second generation
DVB-RCS	-	Digital Video broadcasting return channel via satellite
ECMWF	-	European Centre for Medium-Range Weather Forecasts
ECOWAS	-	Economic community of West African states
EIRP	-	Effective Isotropic Radiated Power
ELF	-	Extremely Low Frequency
ESA	-	European Space Agency
EW	-	East west for satellite station keeping operations
FEC	-	Forward error correction
FGM	-	Fixed gain mode
FIR	-	Finite Impulse Response
FSS	-	Fixed satellite service
FSO	-	Free space fibre optic
GEO	-	Geostationary earth orbit
GOES	-	Geostationary Operational Environmental Satellite
GHz	-	Gigahertz frequency range
GSO	-	Geosynchronous orbit
G_T	-	Gain of transmitter
HTTP	-	HyperText Transfer Protocol
ICMP	-	Internet Control Message Protocol
IF	-	Intermediate Frequency
IGMP	-	Internet Group Management Protocol
ISP	-	Internet service provider
ITALSAT	-	Italian Satellite
ITD	-	Inter-Tropical Discontinuity
ITU-R	-	International Telecommunication Union, Radio sector
ISP	-	Internet Service Providers
Kbps	-	Kilobits per second
KL	-	Kuala Lumpur
LAN	-	Local Area Network
$L_{(dB)}$	-	Loss in signal measured in decibel
LNB	-	Low Noise Block down Converter
LO	-	Local oscillator
LOS	-	Line of Sight

LPF	-	Low Pass Filter
M	-	Modulation Index
MATLAB	-	Matrix Laboratory
Mbps	-	Megabits per second
MCPC	-	Multichannel per carrier
MEASAT	-	Malaysia East Asia Satellite
MHz	-	Megahertz bandwidth
MODCOD	-	Modulation and coding scheme
NiMet	-	Nigeria Meteorological Agency
MMD	-	Malaysia Meteorological Department
NE	-	North-East
NOAA	-	National Oceanic and Atmospheric Administration
NS	-	North and South satellite station keeping operation
NWP	-	Numerical Weather Products
OBW	-	Occupied RF Bandwidth
OTS	-	Orbital Test Satellite
PDF	-	Probability Density Function
PIMT	-	Propagation Impairment Mitigation Technique
PLL	-	Phase lock loop
PNG	-	Papua New Guinea
P_R	-	Power received
P_T	-	Power transmitted
QoS	-	Quality of Service
QPSK	-	Quadrature Phase Shift Keying
RF	-	Radio frequency
RMS	-	Root Mean Square
SAM	-	Simple Attenuation Model
SatCom	-	Satellite Communication
SC	-	Stratiform-Convective
SCPC	-	Single channel per carrier
SFD	-	Saturated flux density
SIRIO	-	Satellite Italiano di Recerca Industriale e Operative
SLA	-	Service Level Agreement
SR	-	Symbol Rate

SST	-	Synthetic Storm Technique
SW	-	Southwest
TCP	-	Transmission control protocol
TDM	-	Time division multiplexing
TDMA	-	Time division multiple access
TT&C	-	Telemetry, Telecomm and Control
TR	-	Transmission rate
TRMM	-	Tropical Rainfall Measuring Mission
UDP	-	User Datagram Protocol
ULPC	-	Uplink Power Control
UPS	-	Uninterrupted Power Supply
UTC	-	Universal Time Coordinated
UTM	-	Universiti Teknologi Malaysia
VHF	-	Very high Frequency
VPN	-	Virtual Private Network
VSAT	-	Very small Aperture terminal
WINDS	-	Wideband Inter-Networking engineering test and Demonstration Satellite
ZDI	-	Zero degree Isothermal point

LIST OF SYMBOLS

A	–	Attenuation
γ_R	–	Rain attenuation
$A_{0.01}$	-	Specific Attenuation
C	-	Capacity
d, D	-	Duration of fades
$f\,n$	-	Cut-off frequency
$P\ (\%)$	-	Probability
Q	-	Standard cumulative distribution function
$R_{0.01}$	-	Rain intensity exceeded for 0.01%
Td	-	Time delay
λ	-	Wavelength of transmitted signal
ζ	-	Distance measured along satellite path
Δt	-	Time interval
C	-	Fade slope
A	–	Alfa (power law exponential coefficient)
K	-	Kappa (power law multiplier coefficient)
Xo	-	location of ground station
Ax	-	shift that account the path enters layer A
Hr	-	Rain height
hs	-	Height above mean sea level
θ	-	Elevation angle
f	-	Frequency
τ	-	Wave polarization
φ	-	Latitude and longitude of the earth station
Y	-	Specific attenuation
r	-	Apparent rain rate
v	-	Storm translation speed
η	-	NyQuist efficiency
$g(p)$	-	Relative diversity gain

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CHAPTER 1

INTRODUCTION

1.1 Background of study

Satellite communications operating and proving services at high frequencies above 10 GHz are expected to deliver a comprehensive capacity and higher data rate for broadband and multimedia services. Such services are disposed to atmospheric impairments essentially the rain effects. This distinct impairment is even worse in the tropical regions mostly characterized by heavy precipitation particularly when employed for VSAT services (J. S. Ojo *et al*, 2009). Abuja Nigeria is geographically located in the tropical region on latitude 9.06^{o}N and longitude 7.48^{o}E, where the rain attenuation and link outages is a predominant challenge for satellite service (T. V. Omotosho and C.O. Oluwafemi, 2009).

Satellite communication system operates on the principle of point to point and point to multipoint, with clear view from all form of obstructions including cloud, rain and tall vegetation cover along the propagation path (Louis J. Ippolito, Jr 2009). This is called clear line-of-sight (LOS) between the transmitting and receiving terminals of the communicating network (Robert Dybdal, 2009). The communication structure in broadband service uses a very small aperture terminal (VSAT) in two-way (duplex) transmission system via satellite link. Functionally the point to point or point to multipoint networks via fixed satellite service (FSS) is to provide a number of advantages. These advantages are especially more for difficult and mountainous terrain, Islands, high sea explorations and those unwired locations including disaster management (Teresa M. Braun, 2012). This study in its quest to evaluate the level of rain induced attenuation on NigComSat-1R satellite broadband service, employs the use tipping bucket rain gauge to conduct 2 years experimental measurements campaign to quantify the point rainfall rate ($R_{0.01}$) at Abuja ground station of NigComSat-1R. The second part is the use VSAT to evaluate the effects of rain attenuation on broadband service and to appraise for the mitigation of the rain induced attenuation on the satellite link.

Communication links are generally designed to meet certain performance specifications and threshold, usually a bit error rate (BER) for a digital link or a signal to noise ratio (S/N) to measure the performance of baseband channel (Gérard B. and Maurice C. 2006). The baseband channel BER or S/N ratio is determined by the carrier to noise ratio (C/N) level at the receiver terminal as a function of the radio frequency carrier power level received from the satellite within the footprint of the satellite of interest. The quality of satellite communication signal is the level of carrier power (C) above the system noise level (N) within the allocated bandwidth at the receiver input. This ratio defines the reliability of the link budget calculations as either closed link for margin value greater than zero or open link for margin value less than zero (Teresa M. Braun, 2012).

Broadcasting via satellite has been in use for decades long before the development into digital era, offering high capacity, wide coverage area, and simultaneously providing diverse service and application to millions of users across multiple countries and continents from satellites with global footprints to those underserved mountainous, high sea and Island areas independent of terrestrial networks. However, the significant cost of leasing satellite transponders has maintained a relatively high installation and operational costs for satellite content providers and internet service providers (ISPs) which is eventually transferred to end VSATs and direct broadcast TV user services fees. In view of such financial implications, several techniques are continuously been experimented to increase spectrum efficiency and subsequently increase the information throughput that can be transmitted over a given bandwidth. This study is focused on improving satellite link availability and spectral efficiency to achieve high data throughput while maintaining the allocated transponder bandwidth using adaptive coding and modulation (ACM) scheme.

Satellite communication system provides several type of connectivity that is physically diverse from terrestrial facilities such as terrestrial wireless networks, microwave point to point, coaxial cables or fiber optic networks. Amongst the advantages of satellite communications and services includes: Wide area of coverage at the same cost. High data transmission capacity providing up to 72 Mbps of data. Low error rates and better Carrier - to - noise ratio at radio frequency with link margin and Multi-User network capability (Gerard Maral, 2003). Effective application of satellite communications requires a robust link capacity to counter for the losses on the uplink and downlink signal propagation path with sufficient power margin to assure availability and system performance (L. J. Ippolito Jr. 2008). International telecommunication union (ITU-R) has made some recommendations to evaluate some of these atmospheric effects influencing satellite to earth propagation. These recommendations are (ITU-R.P. 618) for rain attenuation, (ITU-R.P. 837) for rain rate distributions, (ITU-R P. 838) for specific attenuation on the space to earth and (ITU-R P. 839) for rain height as well as fade dynamics among others.

Precipitation within the troposphere are generally classified as either liquid, solid or transition between liquid and solid segments especially at the melting ice layer. The liquid precipitation include rain and drizzle varying with in the degree of intensity, drop sizes and shapes. Heavy precipitation in the rain segment designates rainfall with a precipitation rate above 7.6 mm/h according to (Glossary of Meteorology 2012). Rainfall intensity is classified according to the rate of precipitation, which depends on the considered time and location (Monjo R, 2016). Some meteorological agencies considered precipitation as light when the rate is less than 2.5 mm/h and moderate for the rain rate is between 2.5 mm/h and 7.6 mm/h. while heavy when the rate is between 10 mm/h and 50 mm/h while precipitation above 50 mm/h is considered violent (American Meteorological Society, retrieved 2014). Correspondingly the central weather of Taiwan defines rain intensity as heavy rain when the 24-hour accumulated rainfall exceeds 80 mm, or 1-hour of rainfall exceeding accumulation of 40 mm (Taiwan meteorological regulation 2003). The United State of American geological survey categorized as heavy rain for intensities greater than 4 mm/h, but less than 8 mm/h (Howard Perlman, 2016).

The type of rain and its intensity equally depends on the local weather condition which is generally influenced by the rain height. Rain height on the other hand depends on the zero degree isothermal level (ZDI) and the melting layer relating to the local climatology. This will consequently affect the satellite link owing to the span of rain region along the elevation angle to the satellite, called the slant path (S. L Jong, *et al* 2015). The frequency of operation, local climatology, geography, the type of transmission parameters and elevation angle to the satellite has a greater effect during measurement of point rain rate (Van de Kamp 2003). The climate change factors is usually related to the point effects adding to complexity of transmission impairments. The prediction of rain rates and rain induced attenuation as it affects the satellite communication and signal propagations will vary with the rain height and the slant path to the satellite especially for low elevation angle (Timothy P, *et al* 2000). Above the ZDI point is where hydrometeors are more of ice flakes generating low specific attenuation (ITU-R P. 839-4, 2015). While Below ZDI is the melting layer of ice particles producing up to 4 times of specific attenuation compared to that of the related rain rate. However, varying ZDI height is yet to be consider as critical study area in the tropical regions where a combinations of both stratiform and convective thunder storm is most common (S. Solomon *et al* 2007). (Paulson and Al-Mreri, 2011) proposed the need to identify the increasing ZDI height trends across northern Europe, North America and central Asia with slopes ranging up to 10 meters annually. (Khairayu Badron *et al*, 2014) suggested for the improvement in the ITU-R P. 618 prediction method with the need to incorporate the local parameter in the satellite to earth link design. Recent studies have shown that for bi-seasonal tropical locations, the ZDI tends to be higher during wet season compared to the dry season period. For Abuja Nigeria this is usually between April to October for wet season and October through March annually. These variation in the ZDI height can increase the level of induced attenuation on the satellite to earth links due to increase in the slant path through the rain height (J. S Ojo *et al*, 2017).

To achieve good quality of service (QoS) and reliable link availability for both uplink and down link, a deliberate provision is required to mitigate the attenuation due to rain effects at high frequency bands (Ippolito L. J, 1999). Quantifying the downlink attenuation along the slant path as well as the total signal fade for broadband services providing mission critical assignment, emergency response, financial and security management, telemedicine services and control towers will require an instantaneous switching system to effect such mitigation control system. Satellite link designers and RF engineers have been utilizing one minute integration time (1-min) for statistical characterization of rain rates distributions and conversions of long term and worst-month statistics (Mandeep J. S *et al* 2012). It is therefore essential to specify communications link system parameters on a statistical basis when considering availability as affected by propagation impairments in the atmosphere. Statistically based performance parameters are usually specified on a percent of time in an average year or a particular month of the year. That the parameter is equal to or exceeds a specific value of 0.01% (ITU-R P.837). Most propagation effects probability models and fixed satellite services (FSS) requirements are specified on an annual basis. Broadband and broadcasting satellite service (BSS) generally specify the service availability monthly basis and taking note of the worst month of the year (ITU-R P.581). The worst month denotes the calendar month where the transmission impairments, primarily rain attenuation, produce the severest degradation on the system performance.

The concept of "worst month" (ITU-R P. 581-2) is such that the performance criteria for satellite communication systems be evaluated on month by month basis when the link outage is highest in regularity of occurrence and total cummulative duration when the service was lost. This worst month can be any month of the year often refer to "worst month" as the period of reference. That for the design of such systems it is necessary to have statistics of propagation effects that are relevant to the period of reference of the performance criteria. That consequently there is a need for an unambiguous definition for the period of reference. That the fraction of time during which a preselected threshold is exceeded in the worst month of a year is referred to as the annual worst-month time fraction of excess. That the statistic relevant for the performance criteria referring to "any month" is the long-term average of the annual worst-month time fraction of excess.

That the worst month of a year for a preselected threshold for any performance degrading mechanism, be that month in a period of twelve consecutive calendar months, during which the threshold is exceeded for the longest time. The worst month is not necessarily the same month for all threshold levels (ITU-R P. 581-2). Further studies in the review work shows wider inconsistencies of ITU-R recommended prediction method are observed to have underestimated the values of rainfall rate at 0.01% of time by 52.8% while overestimated for 0.001% of time exceedance with 7.6 %. This variations of cumulative distribution was recorded in Sumatra from an optical rain gauge measurement (Marzuki, H. *et al,* 2016). Most of the reviewed studies in general terms are more in agreement with the measurements campaigns compared to prediction in order to minimize the impact of rain induced attenuation on satellite link. For a total attenuation along the space to earth propagation link other factors such as cloud and fog can contribute to the overall link attenuation though may be very small effect. The total summation of all losses shall therefore be considered as other losses.

Clouds and fog mostly comprise of water droplets of less than 0.1 mm in width, whereas raindrops typically varies from 0.1 mm to 10 mm in width. Clouds are more of water droplets than water vapour, however, their relative humidity is typically near 100 % within the cloud when formed (Louis J. Ippolito, Jr, 2008) Clouds vary with distance from the equator. The cloudiest regions are the tropics and the temperate zones. Tropical cloud tops are substantially higher, extending between one and two kilometres higher than cloud tops in the mid-latitudes and more than two kilometres higher than the clouds over the subtropics and the poles. In the tropics exceptionally large thunderstorm is often formed extending from the surface to an altitude of between twelve and fifteen kilometres (Lorenzo Luini and Carlo Capsoni, 2014). Substantial fraction of the world's most intense thunderstorms occur in the tropics and subtropics, but the response of such storms to climate change remains uncertain and is often associated with precipitation and severe weather.

The frequency and strength of storms are also related to such climatic factors as average wind speed and direction, temperature, humidity, sunlight and topography (Gavin A. Schmidt, 2018). Comparison with rainfall measurements in an open area indicates high additional water input by cloud moisture depending on topography, cloud occurrence and wind speed. High daily and monthly variation of through fall are attributed to presence and quantity of cloud moisture, or absence of cloud moisture which can be influence by the wind direction, wind velocity and duration of storm (T. Stadtmuller, 1990). This can influence the accuracy of point rain rate measurement especially for single rain gauge.

1.1.1 Radio Frequencies Spectrum in Satellite Communication

Radio Frequency (RF) spectrum demand by users has been on the increase every year by different countries and satellite operators. The spectrum regulator the international telecommunications union on radio regulations (ITU-R) therefore categorize these frequency spectrum base on applications. These are further subdivided into bands for ease of utilization and allocations. The spectrum reserved for satellite applications therefore ranges from 1 GHz in L-band to 40 GHz in Ka-band. This frequency spectrum is divided into frequency bands based on applications. The most commonly used satellite frequency bands allocations from ITU-R are listed in the following Table 1.1 with commercial satellite service operating on C-band, Ku-band and Ka-band frequencies while L-band navigation operate in dual frequency of uplink in C-band and downlink in L-band frequency. V-band and W-band are under investigation for its viability and applications for satellite services.

Table 1.1: Satellite Operating Frequency [ITU-R Article 16]

BAND	FREQUENCY	DESCRIPTION/APPLICATIONS
L - Band	1 GHz to 2 GHz (0.5 to 1.5 GHz)	Long wave and Mobile satellite services
S - Band	2 GHz to 4 GHz	Short wave and Mobile satellite service
C - Band	4 GHz to 8 GHz	Compromise between S and X. Most commonly used in high rainfall areas such as, Asia and Latin America due to its tolerance to rain-fade
X - Band	8 GHz to 18 GHz	Used in WW II for fire control. Reserved for Military Applications
Ku - Band	12 GHz to 18 GHz	Under K - band; higher EIRP (power) VSATs and direct to home (DTH) services requiring small receive antennas in Broadcast service
K - Band	18 GHz to 26 GHz	K - band, where K - band stands for Kurtz
Ka - Band	26 GHz to 40 GHz	Above K - band provide high bandwidth capacity Highly susceptible to rain-fade and is being commercialized more and more

1.1.2 Rain Rate and Rain Attenuation.

Satellite service at higher frequencies above 10 GHz were observed to be influence by the rain effects resulting in rain attenuation of the propagating signal. Determining the rain effect troubling the current satellite service will improve the design of the upcoming satellite project to counter the challenges of the rain attenuation. This can be achieved by either prediction or measurement campaign to provide for the appropriate link margin. The prediction model from ITU-R P. 837 recommendations or employing the field measurement methods for certain locations where possible. The prediction method calculates the rainfall rate exceeded for a desired annual average. The probability of time exceedance at any given location on the surface of the earth using digital maps of the monthly total rainfall and monthly mean surface temperature were recommended. The annual rainfall rate exceeded for 0.01% of an average year $R_{0.01}$ (mm/h) is an integral part of the recommendation available on global rain maps. Several other prediction models were proposed by the research community but with varying degree of disagreement, mostly due to location of measurement and the parameters considered to achieve certain objective.

The rain attenuation model of ITU-R P. 618 series involve the computation of rainfall rate values at 0.1% to 0.001% of time availability when the link is interrupted by the rain event for a given location. A comparison between the prediction and measurement results to estimate attenuation due to rain plays an important role in satellite link design and link margin allocation. The estimates of attenuation for the long-term statistics along the slant path of satellite-to-earth attenuation at any location for frequencies from 4 GHz – 55 GHz is equally required for communications satellite payload design for the power budget. A number of studies have been undertaken to quantify and model the long-term rain attenuation statistics, however rain fade remains a concern especially for tropical and equatorial regions. Measurement data are not always available for research studies, where these measurement database are available, strict regulations are applied to its disclosures affecting the depth of contribution to knowledge. For this reason therefore, models are often adopted to predict the rain attenuation expected for a given system specification. Rain attenuation is majorly the cause of signal absorption or scattering, leading to significant performance degradation of the satellite link (J. E. Allnutt and F. Haidara, 2000).

Accordingly, Ku-band satellite services providing broadband applications are affected by signal fading and outage especially during mission critical operations including banking and security services. The duration of rain fade, the time of day when it is likely to occur, and the frequency of occurrence are all important design parameters (M Kolawole, 2003). To make operation of the satellite systems more reliable at frequencies above 10 GHz, a suitable propagation impairment mitigation techniques (PIMT) is necessary. Such PIMTs includes power control, diversity and carrier signal processing. The impact of rain on satellite signals could affect the performance stability and percentage of time availability (A. D. Panagopoulos, *et al* 2004). The parameters affected by the rain during signal propagation are the carrier to noise ratio (C/N) of the RF signal, where higher values of C/N provide better link performance, and bit error rate (BER) for digital systems due to the loss of energy in the link, in which a lower BER results in better link performance (Cheffena & Amaya, 2008).

Several rain attenuation models have been proposed, including those recommended by ITU-R study groups for the prediction of rain attenuation in satellite system design. These models tends to disagree with the real-time performance of satellite link and rain measurements in tropical regions of heavy rainfall (S. F. Abiola *et al*, 2013). In practice, satellite communication signals are modulated carriers, differing from beacon CW carriers in terms of required bandwidth and carrier power to achieve certain transmission rate (O. O. Obiyemi, *et al*, 2014). The percentage of service availability above 99 % and the quality of service, modulation scheme and error corrections are of equal concern in broadband satellite services for tropical locations.

1.2 Problem Statement

Users demanding for more bandwidths capacity to meet the market demand and the congestions, and luck of capacity at lower but must stable frequency band of C – band has been putting so much pressure on the satellite operators and service providers leading to the use of higher frequency bands in modern satellite communication technology. . Consequently, the Ku band and above, has been increasingly popular due to its advantages of using smaller size on-board equipment and interference reduction with terrestrial microwave communication links This however is accompanied by the challenges of atmospheric impairments for frequency bands above 10 GHz especially when employed for simplex direct broadcast television services or duplex very small aperture terminals (VSATs) and ultra-small aperture terminal (USAT) for broadband internet via satellite service to cover the underserved areas, Islands and high sea exploration towers.

Determination of an appropriate link margin and reliable fade mitigation technique can assure the availability of satellite link, and improve the optimum performance including worst month conditions (A. K. Maini and V. Agrawal, 2014). Accurate specifications of link budget parameters (transmit carrier power, uplink losses, transponder gain, downlink losses and receiver system gain). This requires the understanding of local atmospheric conditions to quantify the rain rate, carrier power and associated rain attenuation (A. Nandra, *et al* 2008). The link budget in essence is a process of correctly sizing the uplink and downlink parameters, earth stations needed, and potential atmospheric effects to optimized the satellite available EIRP, to create an acceptable link margin for optimum performance and higher throughput.

The overall performance of satellite communication network is generally presented in terms of carrier power level above the noise level (Sastri K. and Mario A, 2003). The carrier to noise ratio (C/N) of any radio frequency (RF) signal and the bit energy to noise spectral density ratio (E_b/N_o) are important performance parameters to achieve optimal data rate (Scott Carr Ken Lye *et al* 2014).

Studies have shown that link availability above the threshold (as defined by the type of service, usually 10^{-6} for digital signal bit error rate) is critical for quality of service assurance (O. O. Obiyemi, *et al*, 2014). For Ku band operating above 10 GHz, rain induced attenuation will require a measurement approach where possible to estimate the link margin. This is because predicted values of link margin has not performed optimally in tropical regions to compensate for the rain effect (J. S. Mandeep, *et al*, 2008). The rain rate therefore have a direct proportionality with the level of rain attenuation and the required link margin. Underestimation of rain rate will lead to underestimation of the attenuation depth, and unreliable fade margin while over estimation will attract higher cost of radio equipments. Hence, the need for more robust propagation impairment mitigation technique (PIMT) to compensate for the rain fade for real-time signal optimization (Lam H. Y *et al,* 2013).

There are several choices of impairment mitigation including site diversity, time diversity, space diversity, power control system and carrier parameter optimizations has been proposed. Each of the options is subject to the type of application and resource availability. The choice of PIMT is an important tool for satellite link design in broadband very small aperture terminal (VSAT) networks (Matricciani, E. 2006). The gradual changes in atmospheric parameters including rain rate, rain season duration as well as Onset and Cessation period in tropical region is affecting the prediction results (Meehl *et al,* 2007) and (Maraun *et al*, 2008).

(Kenji Nakamura, *et al*, 2017), suggested that the turbulence from regional climate is affecting satellite signal as it propagates through different atmospheric layers. The effects of refraction and depolarization from the melting ice layer can also affect the space to earth link. The consequences of a random fading influencing the receive signal at the VSAT terminal equally calls for time dependant PIMT. The issues of instability in the rain height leading to higher losses along the slant path of satellite link due to climate change is another factor to the dimensioning of link budget (H. Basarudin *et al,* 2016). The random variations in rain height, the annual and monthly variability in the overall rain profile will somehow undermine the prediction parameters.

Measurements campaign and designing for real-time PIMT can provide alternative to underestimations of margin during link design. This study therefore, has focused on quantifying the rain rate at Nigcomsat-1R satellite ground station in Abuja to improve the availability of broadband VSAT operating in forward and return link

.

1.2 Research Objectives

Objectives of this research are:

1. To quantify the point rain rate ($R_{0.01}$) for Abuja ground station using tipping bucket rain gauge to establish a rain rate database for NigComSat ground station to create rain rate time series model.
2. To examine the impact of rain induced attenuation on (Ku band) VSAT with respect to allocated bandwidth of 6 MHz and 2 MHz both in clear sky and rain fade.
3. To develop the performance thresholds for broadband satellite VSAT using Adaptive Coding and Modulation (ACM) based on Abuja rain rate for propagation impairment mitigation techniques (PIMTs).

1. 4 Scope of Work

This research study was conducted at Nigerian communications satellite (NigComSat) ground station located in Abuja Nigeria on latitude 9.06^{o} N and longitude 7.48^{o} E at 334 meters above sea level for the period of two years from January 2016 to December 2017. Two measurement activities were conducted, first was to quantify the rain rate using tipping bucket rain gauge. While the second setup was to evaluate the effect of the rain induced attenuation on broadband satellite signal, using very small aperture terminal (VSAT).

The two independent but concurrent measurements were collocated with the master control station of NigComSat-1R satellite. These measurement setups include: one unit of time stamped tipping bucket rain gauge installed on the rooftop. The measured point rain rate ($R_{0.01}$) was to be compared with rain rate prediction of ITU-R P.837 model. Two units of 1.8 meter VSAT antennas were installed in collocation with the tipping bucket rain gauge site. These

VSATs operates on uplink frequencies of 14124.5 GHz and downlink on 12624.5 GHz with bandwidth capacity of 6 MHz while the second terminal operates on uplink frequency of 14231.0 GHz and downlink on 12731.0 GHz with allocated bandwidth capacity of 2 MHz respectively. The VSATs are part of the larger VSAT network of Nigcomsat-1R broadband service designed to work in multiple carrier per channel (MCPC) in access technique of time division multiple access (TDMA) on return link and time division multiplexing TDM on forward link broadcasting from the network hub. TDMA enables multiple VSAT terminals to transmit and receive base on time slot on the same frequency and bandwidth capacity.

This is to examine the link fade status in both clear sky and rain fade condition. From the measurements results, this study will appraise the performance of adaptive coding and modulation (ACM) for improvement of link availability as PIMT. Nigeria is characterized by two seasons of dry and wet/rainy seasons. The rainy season starting between April and May and ending between October and November for Abuja annually with some minor variation... The scope of this work is to cover the following:

i. Assess and quantify the point rain rate ($R_{0.01}$) for Abuja ground station and measure the performance for worst month propagation condition.
ii. To evaluate the impact of rain induced attenuation on Ku-band VSAT with respect to the allocated to produce the attenuation model for 2 MHz and 6 MHz capacity.
iii. Examine the relationship between allocated bandwidth and carrier power to noise ratio.
iv. Evaluate the performance of adaptive coding and modulation (ACM) as propagation impairment mitigation technique (PIMT)
v. Estimate the bandwidth efficiency in ACM and without ACM

1.5 Research Contribution

The challenges of availability and performance of satellite link to meet the user's demands at frequencies above 10 GHz, especially when used for mission critical transmission on voice, video and data requires a more reliable PIMT for link improvements that could not be overcome by satellite link margin in VSAT networks. This requires a series of parameters to be reviewed especially the atmospheric parameters and carrier dependent factors. This study having considered the atmospheric effects and the satellite link margin on NigComSat-1R, reviewed the performance of Adaptive coding and modulation (ACM) to mitigate against the rain effect in real-time event to maintain the link availability. The improvement in the total downtime of 2556 minutes recording the annual availability of 94.41% in Table 4.14 to an excellent performance of 99.85% recording a downtime of only 42.8 minutes. This performance is almost the peak performance achievable by any satellite operator. The ITU-R P. 841-4 recommended 0.01% assurance of 99.99% was set to give an annual outage of 53 minutes. With 42.8 minutes meeting the Nigcomsat NSOG standard of 99.7% was surpassed by the implementation of ACM. This is one of the best feet attained by Nigcomsat in meeting its customer's obligation in service level agreements ever in the last 7 years. This study has established the thresholds of performance of VSATs for seven (7) operating state of ACM in accordance with the rain rate of Abuja Nigeria. This can be further expanded to include other rain characteristics of drop size distribution.

i. Quantifying the Rainfall rate for Abuja ground station of NigComSat-1R will improve the link budget and reference for planning.
ii. The worst month prediction will improve the resource allocation for technical support by the satellite service provider and save cost.
iii. The relationship between carrier power and bandwidth will help the satellite service provider and VSAT users to plan for capacity utilization in frequencies above 10 GHz.
iv. The performance thresholds in adaptive coding and modulation (ACM) will provide a good understanding for choice of propagation impairment mitigation technique (PIMT) for small offices and homes (SOHO) in tropical region to

improve the link availability in real time events including interactive sessions and news programs for video on demand.

v. The dependence of higher throughput on higher carrier power compared to bandwidth in digital transmission will help to define the quality of service and improve spectral efficiency in tropical region. Above are all contribution to knowledge for academic service and teaching purposes.

1.6 Thesis Organization

This thesis contains six chapters. Chapter 1 provides an overview of the research background on the topic, identifies the problem statements and outlines the objectives this research, scope of study and highlights the contributions to knowledge for academic and industry.

Chapter 2 Reviews some challenges associated with satellite communication link, discussed the core features of climatology characteristic relating to satellite propagation in tropical regions in general with particular interest on Nigeria. A review of the rainfall profile in terms of intensity, distribution and the models. The characteristics of specific attenuation with respect to microwave propagation, the slant path attenuation prediction models that has been developed and proposed in the literatures. To conclude this chapter is the implementation of propagation impairment mitigation techniques currently used by the advanced satellite communication system for better performance of broadband network.

Chapter 3 investigates the rain attenuation in tropical heavy rain zone of Nigeria for the worst month performance of broadband over satellite using two years of rain profiling at NigComSat ground station in Abuja Nigeria. The workflow of the scope of this study was presented. Details on the performance of broadband satellite link measurements and the seasonal and diurnal variations of precipitation. Synthetic Storm Technique (SST) and of the SC-EXCELL model for estimation of rain attenuation statistics was also considered for its importance on Earth-space links. Reference beacon signal of NigComSat-1R was also considered but for the restriction to the use of beacon real time data from the administration of NigComSat limited was only used for reference purpose due to the efficient performance even under worst rain condition. However as soon as the approval is secured will be consider for future study.

Chapter 4 presents the analysis of rainfall data collected for the two seasonal rainy periods as well as the two years broadband performance data, the relationship between beacon and broadband signals, the effect of rain attenuation on beacon and broadband with respect to their sensitivity and response. Also covered is the advantage of ACM over amongst other alternatives of PIMT due to its applicability to modulation scheme.

Chapter 5 presents the conclusion of the current study and proposed some future works. The main milestone achieved and constraints are summarized, some objective and important recommendations for the future work.

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B. C. Gremont, M. Filip, and E. Vilar, (2000) "Evaluation of CNR statistics for satellite link with multiple countermeasures," *Electron. Letter, vol. 36, no. 11, pp. 977–978, May 2000*

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APPENDICES

APPENDIX A:

List of Publications:

The following are the list of publications by the author: Published in Scopus index Journal:

A1.

Idrissa Abubakar, Hong Yin Lam and Jafri Din (2016) Implementation of Adaptive Coding and Modulation for Satellite Communication Links in Heavy Rain Region: an Operator's perspective. *ARPN Journal of Engineering and Applied Sciences. VOL. 11, NO. 12, JUNE 2016, ISSN 1819-6608 7585-7861*

Idrissa Abubakar, Jafri Din, Manhal Alhilali and Hong Yin Lam (2017) Interference and Electromagnetic Compatibility Challenges in 5G wireless Network Deployments. *Indonesian Journal of Electrical Engineering and Computer Science, Vol. 5, No 3, March 2017, pp. 612 -621 DOI: 10.11591/ijeecs.v5i3.pp612-621*

Idrissa Abubakar, Jafri Din and Hong Yin Lam (2017) Disparities in the Induced Rain Attenuation between Beacon (Narrowband) and Broadband Satellite Links in Tropical Zones. Indonesian Journal of Electrical Engineering and Computer Science Vol. 10, No. 3, June 2018, pp. ab~cd ISSN: 2502-4752, DOI: 10.11591/ijeecs.v10.i3.ppab-cd

Idrissa Abubakar, Jafri Bin Din, Lam Hong Yin, Manhal Alhilali (2018) Rain Attenuation in Broadband Satellite Service and Worst Month Analysis. International Journal of Electrical and Computer Engineering (IJECE) Vol. 9, No. 4, August 2019, ISSN: 2088-8708, DOI: 10.11591

A.2 Award Received:

3-Minutes Thesis Competition Faculty of Electrical Engineering UTM 9th March, 2016. **Second Prize Winner**

- Graduate Assistantship (GA) Scheme Award SEM II 2014/2015
- UTM International Doctoral Fellowship (IDF), Semester I 2015/2016
- UTM International Doctoral Fellowship (IDF), Semester II 2015/2016
- UTM International Doctoral Fellowship (IDF), Semester I 2016/2017
- UTM International Doctoral Fellowship (IDF), Semester II 2016/2017