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Contour Mapping for Rain Rate and Rain Attenuation in Microwave and Millimetre Wave Earth-Satellite Link Design in Tropical Tanzania

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Abstract

Rain rate and rain attenuation predictions are vital in the analysis of the performance of earth-satellite link at higher frequencies beyond 10 GHz for satellite system planning. This study intended to address lack of rain attenuation profile based on local rainfall data collected from various parts of the country. A one-minute integration time rainfall rate used to estimate the rain-induced attenuation was obtained by converting the annual rainfall data collected for 40 years from 22 locations in Tanzania using a combination of Chebil and refined Moupfouma-Martin methods. The International Telecommunication Union (ITU) standard was used to predict attenuation caused by one-minute rain rate. Contour maps for rain rate and rain attenuation were then generated over different percentages of times of 0.1% and 0.01% for both Ku and Ka-bands using the Kriging interpolation method in ArcGIS software. The maps show higher predicted rain rate values compared to the values given by the ITU in zones K, M and N. The developed maps can be used for rapid and precise estimation of link budget for satellite system design in Tanzania.

Keywords: contour maps, one-minute, rain attenuation, integration time, Ku-band and Ka-bands.

Introduction

In recent decades, satellite communications has played essential roles in global telecommunication systems. The growth of Very Small Aperture Terminal (VSAT) for Internet access, invention of Direct-to-Home (DTH) services, navigation, weather forecasting, disaster management, satellite network for fixed and broadcast service systems has increased the significance and use of satellite communication links over microwave propagation at higher frequencies, i.e. Ku-band, Ka-band, and V band at 12/14 GHz, 20/30 GHz and 40/50 GHz, respectively. In Tanzania, the VSAT technology is operating at Ku-band, but due to congestion experienced in this band, the higher frequency band (Ka-band) is now deployed (Linga et al. 2019).

At higher frequencies, radio waves have a shorter wavelength and hence liable for degradation by several factors, including clouds, rainy, atmospheric gas, to mention only a few. Among these, the factor that causes significant impairment to radio transmission is rainfall (Sakir 2017). As radio waves pass through a rainy medium, raindrops absorb the radio signals and scatter them, causing a change in amplitude and phase, resulting into signal attenuation which affects system reliability and availability. The degree of signal attenuation varies depending on rainfall rate, frequency and geographical location. Thus, areas with higher rainfall like the tropical, subtropical and equatorial regions suffer more severe attenuation than temperate regions (Durodola and Ogherehwo 2019). Tanzania has a tropical climate with regional variations due to topography, while its rain is convective, and is characterized by high intensity within a small area of occurrence. In Tanzania, rain attenuation profile based on local rainfall data is not available. To optimally plan and design earth-satellite communication systems, an in-depth understanding of rainfall physiognomies in a particular region is necessary to ensure that the required Quality of Services (QoS) is achieved (Abubakar et al. 2019, Christofilakis et al. 2020b).

The International Telecommunication Union Radio-wave sector (ITU-R) recommends the use of rainfall data collected using one-minute integration time to adequately estimate rain-induced attenuation. However, very few countries have sites that collect rainfall data using one-minute integration time. To date, in Africa, only a few such sites are found in Nigeria (Ononiwu et al. 2015), Rwanda (Sumbiri et al. 2016a) and South Africa (Ahuna et al. 2016). Elsewhere in the world, such studies have been done in other tropical countries such as Brazil (Karmakar et al. 2011), Sri Lanka (Sudarshana and Samarasinghe 2011), India (Kestwal et al. 2014), Malaysia (Selamat et al. 2014), Bangladesh (Sakir 2017), and Indonesia (Marzuki et al. 2020).

Rain rate data with one-minute integration time is generally not readily available worldwide, which prompted the International Telecommunication Union ITU-R P. 837 to provide global maps, through which data can be deduced using data from other regions. However, recent research shows that this method works better in temperate areas but has a tendency of underestimating or overestimating rain attenuation values when applied in tropical and equatorial regions (Rimven et al. 2018). Furthermore, it has been observed that better performance of rain attenuation is obtained when local factors like point rain rate, altitudes, elevation angle and thunderstorm ratio were used in prediction than interpolated values. Tanzania is placed in zones K, M and N by the Recommendation ITU-R P. 837-7 (2017); this causes the under-estimation of rain rate and rain-induced attenuation levels, causing an effect in the design of earth-satellite links above 10 GHz. Therefore, rain rate data with one-minute integration time is required for accurate estimation of rain-induced attenuation and hence fading. The designs in Tanzania, for Earth-Space communication links are based on either climate zone-based global ITU-R models or other models requiring the use of global coefficients which provide gross approximations, and usually under-estimate rain rate statistics.

One of the ways to present rain rate and rain attenuation in different climates is using contour maps. They provide the methodology for assessing rainfall rate and attenuation exceeded for other percentages of time depending on the availability objectives of the system. Climatic mapping has become popular and has been used in several countries including; South Africa (Ojo and Owolawi 2014), Colombia (Emiliani et al. 2004), Greece (Papatsoris et al. 2008), Bangladesh (Imran et al. 2015), Rwanda (Sumbiri et al. 2016b), Ethiopia (Diba et al. 2016), Turkey (Gunes et al. 1994) and Malaysia (Chebil and Rahman 1999). In this study, the annual rainfall data were used to obtain cumulative distribution presenting rainfall rate against the percentage of time exceeded in a year for 22 locations in Tanzania. The data used was collected for 40 years by Tanzania Meteorological Agency (TMA). The available rainfall data were converted to one-minute rain rate statistics for various locations scattered in Tanzania using refined Moupfouma-Martin method (Moupfouma and Martin 1995). Moreover, rain rate and rain attenuation contour maps were developed over 0.1 and 0.01% percentage of times for spatial interpolation for Ku and Ka-bands.

The purpose of this study was to develop contour maps as accurate tools that can assist system designers for earth-satellite links in tropical Tanzania. The maps developed are valuable in the initial design of terrestrial and earth-satellite microwave links, as they provide a comprehensive idea of rain attenuation to microwave engineers. Also, a review of the results for rain rate, rain attenuation and classification of climate zone campaigns is presented.

Materials and Methods

Rainfall climate and data availability over Tanzania

In this section, the geography, climatic characteristics and local rainfall data measurements are presented.

Geography and climatic characteristics

Tanzania is one of the five countries that constitute East Africa and lies between latitudes 1°20'S to 10°40'S and longitudes 29°40'E to 40°11'E. It borders Uganda and Kenya to the north, Mozambique, Malawi and Zambia to the south, the Indian Ocean to the east and the Democratic Republic of Congo, Burundi and Rwanda to the west. Tanzania occupies the larger part of the east coast of Africa and includes the Islands of Unguja, Pemba and Mafia. Figure 1 shows the topographic map of Tanzania and the location of measurement stations referred to in this study.

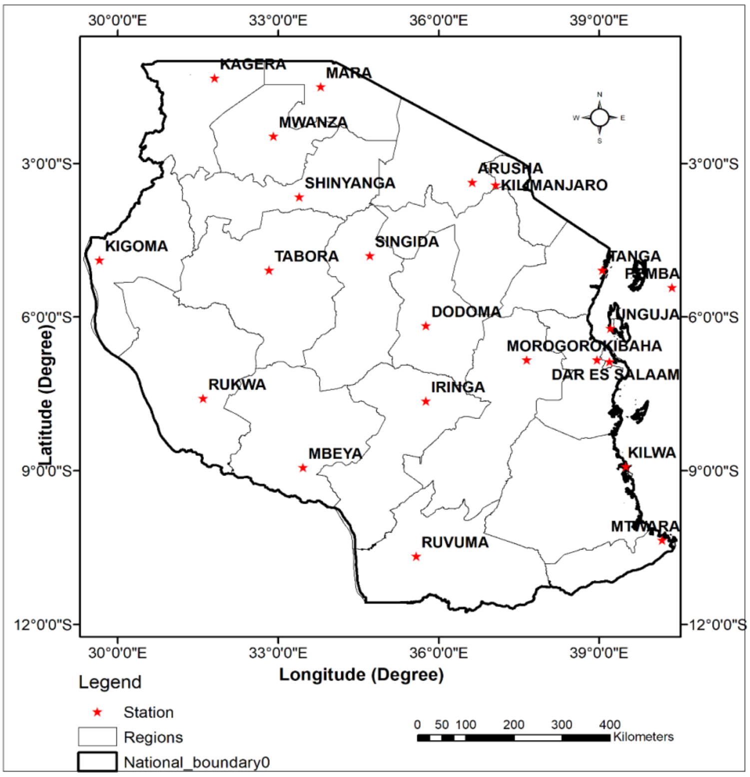

Figure 1: The topographic map of Tanzania showing the location of the measurement stations understudy.

Tanzania has four main climatic zones. These climates zones differ from one place to another depending on distance and altitude above the sea level, geographical location and type of vegetation cover. These zones are temperate highlands found in the north and south of the country, Lake Zone which is characterized by higher rainfall, semi-arid central plateau and hot and humid coastal plains. Due to the different climatic zones, Tanzania experiences various climatic conditions ranging from the hot humid coastal plain; the high-moist lake regions; the temperate southern and western highland and the semi-arid zone of the central plateau. All the islands of the Indian Ocean experience a tropical climate.

Influenced by the country's position near the equator and the influence of airstreams from the Indian Ocean, the country’s rainfall pattern shows a seasonal variation, with two main rain seasons. The rains begin in October - December in the most of southern parts of the country and March-May in the northern part of the country, while the lake zone experiences both seasons (Omeny et al. 2008). The dry season lasts for 5 to 6 months between May and October. These rainfalls are influenced by different systems including Inter-Tropical Convergence Zone (ITCZ), subtropical high-pressure systems, Indian Ocean Dipole (IOD), easterly/westerly waves, monsoon winds, Quasi-Biennial Oscillation (QBO), tropical cyclones, Southern Oscillation Index (SOI) and El Nino Southern Oscillation (ENSO). Apart from these systems, the rainfalls are also influenced by local features that tend to control weather and climate, leading to spatial rainfall variations. These local features include topography, Indian Ocean, presence of great lakes like Lake Tanganyika and Lake Victoria. The average annual precipitation ranges from 500 mm in the dry northern areas of Kilimanjaro to 2,600 mm in Bukoba along the western shore of Lake Victoria.

The Köppen- Geiger climate classification over Tanzania has many climate groups, based on the assumption that certain types of vegetation grow in a particular climate classification region (Peel et al. 2007). The available classifications are class A, Am and Aw (tropical), class B, Bsh (hot semi-arid), class C, Csb and Cwb (warm temperate); however, the most dominant classification in most zones is Aw. The Lake zone, Southern Highlands and Southern Western Highlands have two classes (Aw and Bsh for Lake Zone, Aw and Csb for Southern Highlands and Southern Western Highlands) but are mostly dominated by Aw. Northern Highlands, central area and the western area, have four classes (Csb, Cwb, Aw, Bsh), while the Northern coast with Unguja and Pemba has one class Aw.

Rainfall data availability

Ground base yearly rainfall data collected from 22 stations spread over the country were obtained from Tanzania Meteorological Agency. The dataset covered a period of 1978 to 2017. The locations and stations showing Köppen-Geiger climate classification over Tanzania are summarized in Table 1. The rain rate was measured using a tipping bucket with a diameter of 20 cm with the calibration of 0.2 mm of rainfall per tip. The raindrops were collected using low response rain gauges with higher integration time measured on an hourly basis, and then accumulation recorded after every 24 hours. The gauges qualify to the World Meteorological Organization standards.

Determination of rainfall statistics over Tanzania

The probability that a given average yearly rain rate over an hour has been exceeded is an essential parameter in computing rain-induced attenuation, which leads to fading. The ITU-R mandates that the probability above be obtained from complementary probability density function (CDF) of rainfall rate measurements using one-minute integration time. Most meteorological stations measure rainfall rate with longer integration time (5 minutes, 10 minutes, 30 minutes and 60 minutes).

Long integration time can be converted to a one-minute equivalent using physical, empirical and analytical methods (Emiliani et al. 2009). To localize the rain attenuation models for a particular location, the rainfall rate and experimental data for that location should be obtained. Empirical models are most widely used by most researchers, including ITU-R model. Empirical conversion models are used with global conversion coefficients if local measurement data enabling derivation of local coefficients are not available. The use of global conversion coefficients is necessarily a gross approximation where values of probabilities of rain rate exceeded for highly localized areas are needed (Obiyemi et al. 2017).

Table 1: Climatic characteristics for the study locations

Climate zone	Station name	Latitude (°S)	Longitude (°E)	Altitude (m)	Köppen class
Central Area	Dodoma	6°10'	35°46'	1120	Bsh
	Singida	4°48'	34°43'	1307	Bsh
Lake Victoria basin	Kagera	1°20'	31°49'	1144	Aw
	Mara	1°30'	33°48'	1147	Aw
	Mwanza	2°28'	32°55'	1140	Aw
	Shinyanga	3°39'	33°24'	1877	Aw, Bsh
Northern Coast with Unguja and Pemba Islands	Dar es Salaam	6°52'	39°12'	53	Aw
	Morogoro	6°50'	37°39'	526	Aw
	Pemba	5°25'	39°82'	46	Aw
	Pwani	6°50'	38°58'	167	Aw
	Tanga	5°5'	39°4'	49	Aw
	Unguja	6°13'	39°13'	18	Aw, Am
Northern Highland	Arusha	3°22'	36°38'	1372	Csb
	Kilimanjaro	3°25'	37°4'	891	Aw, Cwb
Southern Coast	Lindi	8°55'	39°30'	14	Aw
	Mtwara	10°21'	40°11'	113	Aw
South highland	Iringa	7°38'	35°46'	1428	Csb
	Mbeya	8°56'	33°28'	1758	Aw
	Rukwa	7°38'	31°36'	1824	Aw, Csb
South-western	Ruvuma	10°40'	35°35'	1036	Aw
Western Area	Kigoma	4°53'	29°40'	822	Aw
	Tabora	5°5'	32°50'	1182	Aw

Overview of rainfall rate prediction models

The widely used global methods are the Cranes model which was revised in 1996 (Crane 2003) and the ITU-R, which is now in its seventh edition (ITU-R. P. 837-7 2017). Other researchers have developed rain rate distribution models to compute one-minute integration time. Examples of these models include Rice and Holmberg (1973), Segal (1986), Moupfouma and Martin (1995), Chebil and Rahman (1999) and Ito and Hosoya (2006) amongst others.

In this paper, the combination of Chebil and refined Moupfouma-Martin methodologies have been used for analysis to estimate the one-minute integrated complementary cumulative distribution function of rain rate for various locations in Tanzania. This model was preferred because it provides a simple method for prediction of rain rate distribution for both tropical and temperate climates and allows for the inclusion of local climatic parameters as the key inputs that describe the distribution pattern. Furthermore, this model has been used to approximate a log-normal distribution for the low rain rates and a gamma distribution of a high rain rate.

According to the Moupfouma-Martin model, the one-minute rain-rate cumulative distribution can be expressed as follows:

$$P(R \geq r) = 10^{-4}\left(\frac{R_{0.01}}{r+1}\right)^{b} \exp(u[R_{0.01} - r]) \quad (1)$$

$$b = \left(\frac{r - R_{0.01}}{R_{0.01}}\right) \ln\left(1 + \frac{r}{R_{0.01}}\right) \quad (2)$$

Using this model, the estimation of *u* for tropical regions is given as follows:

$$u = \frac{4\ln(10)}{R_{0.01}} \exp\left(-\lambda\left[\frac{r}{R_{0.01}}\right]^{\gamma}\right) \quad (3)$$

Where: λ= 1.066 and γ =0.214.

For the temperate region, *u* is given as follows:

$$u = \frac{4\ln(10)}{R_{0.01}} \left(1 + \eta\left[\frac{r}{R_{0.01}}\right]^{\beta}\right)^{-1} \quad (4)$$

With η =1.066 and β = 0.214;

Where: ***r*** (mm/h) is the rain rate exceeded for a percentage of the time, $R_{0.01}$ is the rain intensity exceeded during 0.01% of time in an average year (mm/h). ***u*** defines the slope of the rain rate statistics in Equation (3) and is based on the local climatic conditions and earthly structures of the site of interest.

This method is determined by three main elements, λ, γ and $R_{0.01}$. The constants λ and γ have been provided. To compute $R_{0.01}$ a suitable model need to be selected. Thus, the Chebil technique which is the key input of Moupfouma-Martin model has been used to estimate $R_{0.01}$ (point rain rate exceeded at 0.01% of the time), from long term mean annual rainfall. The model uses power law relationship.

$$R_{0.01} = {}_{\alpha}M^{\beta} \quad (5)$$

Where α and β are the regression coefficients of 12.2903 and 0.2973, respectively obtained from the map in (Rice and Holmberg 1973), and M is the mean annual rainfall rate. The Chebil model was chosen because it produced the best estimate of the measured data compared to five other models used to obtain $R_{0.01}$ in tropical climate (Abdulrahman et al. 2010).

Modelling of one-minute rainfall statistics

This study has applied a more semi-empirical approach to producing results. This is a globally accepted practice in research related to rainfall rate and attenuation studies. Rainfall data covering 40 years have been obtained from the Tanzania Meteorological Agency for 22 sites in Tanzania. This data containing rainfall accumulation has been converted into a rainfall rate at a different percentage of time using the Chebil and Rahman model.

Development of rainfall rate contour maps

The contour maps of rainfall over Tanzania were developed based on the results of the cumulative distribution obtained from the combination of refined Moupfouma-Martin and Chebil models. The procedures described in Equations 1-5 were implemented in Matlab software. The results obtained from the cumulative distribution of one-minute rain rate data and coordinate location points for each station were exported to digital boundary file of Tanzania to create contour maps using the Kriging interpolation technique in Geographic Information System (ArcGIS) software platform.

Determination of rain attenuation over Tanzania

Numerous prediction models which use global coefficients to estimate rain-induced attenuation for terrestrial and satellite communication systems have been developed (Linga et al. 2019, Christofilakis et al. 2020a). Nowadays, the most applied methods for the prediction of rain attenuation are the ITU-R standards. However, there are other methods, such as the Crane method, mainly used in the United States of America (Crane 2003).

In this study, attenuation computation has adopted the methodology of the ITU-R described in Recommendation P. 618-13 (ITU-R 2017). Rain height was calculated according to Recommendation P. 839-4 ITU-R (2013), whereas the specific rain attenuation for 22 sites in Tanzania was obtained according to ITU-R Recommendation P. 838-3 (ITU-R

2005). This model was chosen because it produced the results that approximated the average predictions from the application of eight different methodologies (Emiliani et al. 2009). The climatic parameters used as inputs for the model are; the point rainfall rate for the location by 0.01% of an average year ($R_{0.01}$) in mm/hr, elevation angle (degrees), altitude/height above mean sea level of the earth station (km), frequency (GHz), the latitude of the earth station (degrees), and the effective radius of the earth (8500 km). The values of the parameters used for the model are presented in Table 2.

Table 2: Simulation parameter for rain induced attenuation prediction

Climate zone	Station name	Latitude (°S)	Longitude (°E)	Altitude (m)	Specific attenuation for Ku-band (dB/km)	Specific attenuation for Ka-band (dB/km)	Elevation angle
Central	Dodoma	6°10'	35°46'	1120	3.9139	10.6864	55.7
Area	Singida	4°48'	34°43'	1307	4.1040	11.1324	57.2
Lake	Kagera	1°20'	31°49'	1144	6.1365	15.7468	60.9
Victoria	Mara	1°30'	33°48'	1147	4.5788	12.2341	58.6
basin	Mwanza	2°28'	32°55'	1140	4.9336	13.0469	59.6
	Shinyanga	3°39'	33°24'	1877	4.4070	11.8373	58.9
Northern Coast	Dar es Salaam	6°52'	39°12'	53	4.9643	13.1169	51.8
with	Morogoro	6°50'	37°39'	526	4.4554	11.9494	53.5
Unguja	Pemba	5°25'	39°82'	46	5.5728	14.4917	52
and	Pwani	6°50'	38°58'	167	4.6645	12.4313	52
Pemba	Tanga	5°5'	39°4'	49	5.2063	13.6662	52.3
Islands	Unguja	6°13'	39°13'	18	5.7576	14.9051	52
Northern	Arusha	3°22'	36°38'	1372	4.4141	11.8537	55.2
Highland	Kilimanjaro	3°25'	37°4'	891	3.8163	10.4562	54.7
Southern	Lindi/Kilwa	8°55'	39°30'	14	4.7242	12.5683	51
Coast	Mtwara	10°21'	40°11'	113	4.9041	12.9797	49.8
South	Iringa	7°38'	35°46'	1428	4.6234	12.3368	55.4
highland	Mbeya	8°56'	33°28'	1758	4.6014	12.2861	57.5
	Rukwa	7°38'	31°36'	1824	4.4779	12.0014	60
South-western	Ruvuma	10°40'	35°35'	1036	4.8800	12.9248	57.6
Western	Kigoma	4°53'	29°40'	822	4.6455	12.3875	62.9
Area	Tabora	5°5'	32°50'	1182	4.6717	12.4477	59.3

Development of rain attenuation contour maps

To enable contour maps to be drawn in Tanzania, it is recommended that stations should be spread throughout the country. For this study, the cumulative distributions from Matlab software for rain-induced attenuation at 0.1% and 0.01% of exceedance were exported to create contour maps shown in Figures 5-8 using the Kriging interpolation technique in Geographic Information System (ArcGIS) software platform. The maps are used by radio system engineers to calculate the effects of the most radio wave propagation factor on earth satellite design.

The results obtained from the ITU-R model for Ku and Ka-bands of frequencies 11.356 GHz and 21.749 GHz on 7^{o}E EUTELSAT 7B satellite with horizontal polarization were exported to create contour maps using the Kriging interpolation method in ArcGIS software. These frequency values were referred to as centre frequencies of operation for downlinks were used for calculation. The 7^{o}E

EUTELSAT 7B satellite is among the few satellites in Tanzania operating at higher frequency bands above 10 GHz. To meet the operational challenges in the rapidly growing satellite broadband networks, attenuation contour maps were developed for the dedicated frequency bands. The Ka-band is more often used than Ku-band frequencies due to their capacity to provide higher bandwidth for the application they are expected to support. In addition, a Ka-band allows a higher return link data rate.

Results and Discussion

The simulation results of rain rate and rain attenuation for 22 locations in Tanzania were firstly estimated using Matlab software. Characteristically, these sites represent most parts of the country. After that, the obtained results were applied into an ArcGIS software to develop the rain rate and rain attenuation contour maps to demonstrate the spatial disparity of rain rate and rain attenuation over Tanzania.

Figure 2 represents the cumulative distribution of rain rates for all the 22 locations in Tanzania. The plots represent the percentage of time exceeded the one-minute rainfall rate in an average year. A brief description of locations with the highest and lowest values of $R_{0.01}$ for climate zones for average over 1000 mm per year is presented. For the coast areas including Unguja and Pemba Islands of the Indian Ocean which experience more tropical climate have higher rainfall of an average of 1100 mm per year. Unguja has the highest rain rate distribution at 0.01% of outage time with 111.7 mm/hr, while Morogoro has the lowest value of 90.48 mm/hr. In the Lake basin zone with an average rainfall accumulation of 1200 mm per year; the locations of Kagera and Shinyanga have 118.1 and 89.66 mm/hr as the highest and lowest rain rate values, respectively. For stations with lower average annual rainfall such as Dodoma, Singida, Kilimanjaro and Iringa, the $R_{0.01}$ values range from about 79.54 to 84.5 mm/hr depending on the geographical location.

The results in Table 3 obtained from refined Moupfouma-Martin model are compared with results from the ITU-R P.837-7 which classifies Tanzania with a specification of 60 mm/hr and falls under rain zone; K, M and N. However, based on the results from refined Moupfouma-Martin model, this study found out that Tanzania has rain climate which falls between ITU-R rain zones M, N and Q. It has been observed that the values deduced from the ITU-R model are lower than those computed from the refined Moupfouma-Martin model. For example, in Mtwara, the predicted ITU-R and refined Moupfouma-Martin rain rates for 0.01% were 68.7 and 98.41 mm/hr, respectively, resulting in a relative error of about 43%. Also, high difference up to about 54.84 mm/hr in Kagera, which is characterized in the M zone by the ITU-R model, results in a relative error of 87%. The location of Kilimanjaro has the least difference of about 21.04 mm/hr, which is characterized in the K zone by ITU-R instead of M zone based on the results obtained in this study.

The maps presented in Figures 3 and 4 show the variations of rain rate across the climatic zones at different percentages of time exceedance in Tanzania. Figure 3 shows that $R_{0.1}$ values vary from 16.5 to 26 mm/hr, while Figure 4, shows $R_{0.01}$ values vary from 85 to 108 mm/hr depending on geographical location. It can be seen that places lying around the coast area and Lake Victoria basin have the highest rainfall rate for all rain rate exceedance, making them more prone to rain attenuations which results into network outage and link failure than other locations. Locations with lower rain rates are observed at the central and northern highland.

Table 3: Point rain rate ($R_{0.01}$) using refined Moupfouma-Martin and ITU-R models

Climate zone	Station name	Latitude (°S)	Longitude (°E)	Annual rainfall (mm)	ITU-R (mm/h)	$R_{0.01}$ (mm/h)
Central Area	Dodoma	6°10'	35°46'	574	**46.42**	**81.23**
	Singida	4°48'	34°43'	655	**50.99**	**84.5**
Lake Victoria basin	Kagera	1°20'	31°49'	2022	**63.26**	**118.1**
	Mara	1°30'	33°48'	890	**52.65**	**92.56**
	Mwanza	2°28'	32°55'	1097	**55.47**	**98.49**
	Shinyanga	3°39'	33°24'	780	**51.6**	**89.66**
Northern Coast with Unguja and Pemba Islands	Dar es Salaam	6°52'	39°12'	1096	**71.22**	**98.48**
	Morogoro	6°50'	37°39'	824	**57.41**	**90.48**
	Pemba	5°25'	39°82'	1540	**87.02**	**108.9**
	Pwani	6°50'	38°58'	933	**66.04**	**93.87**
	Tanga	5°5'	39°4'	1274	**87.83**	**103**
	Unguja	6°13'	39°13'	1676	**84.7**	**111.7**
Northern-Highland	Arusha	3°22'	36°38'	803	**51.4**	**89.78**
	Kilimanjaro	3°25'	37°4'	534	**58.5**	**79.54**
Southern Coast	Kilwa/Lindi	8°55'	39°30'	959	**69.79**	**94.64**
	Mtwara	10°21'	40°11'	1094	**68.7**	**98.41**
South-Highland	Iringa	7°38'	35°46'	603	**45.06**	**82.45**
	Mbeya	8°56'	33°28'	929	**53.07**	**93.61**
	Rukwa	7°38'	31°36'	836	**49.36**	**90.86**
South-Western	Ruvuma	10°40'	35°35'	1064	**59.89**	**97.6**
Western Area	Kigoma	4°53'	29°40'	927	**55.34**	**93.68**
	Tabora	5°5'	32°50'	941	**55.38**	**94.12**

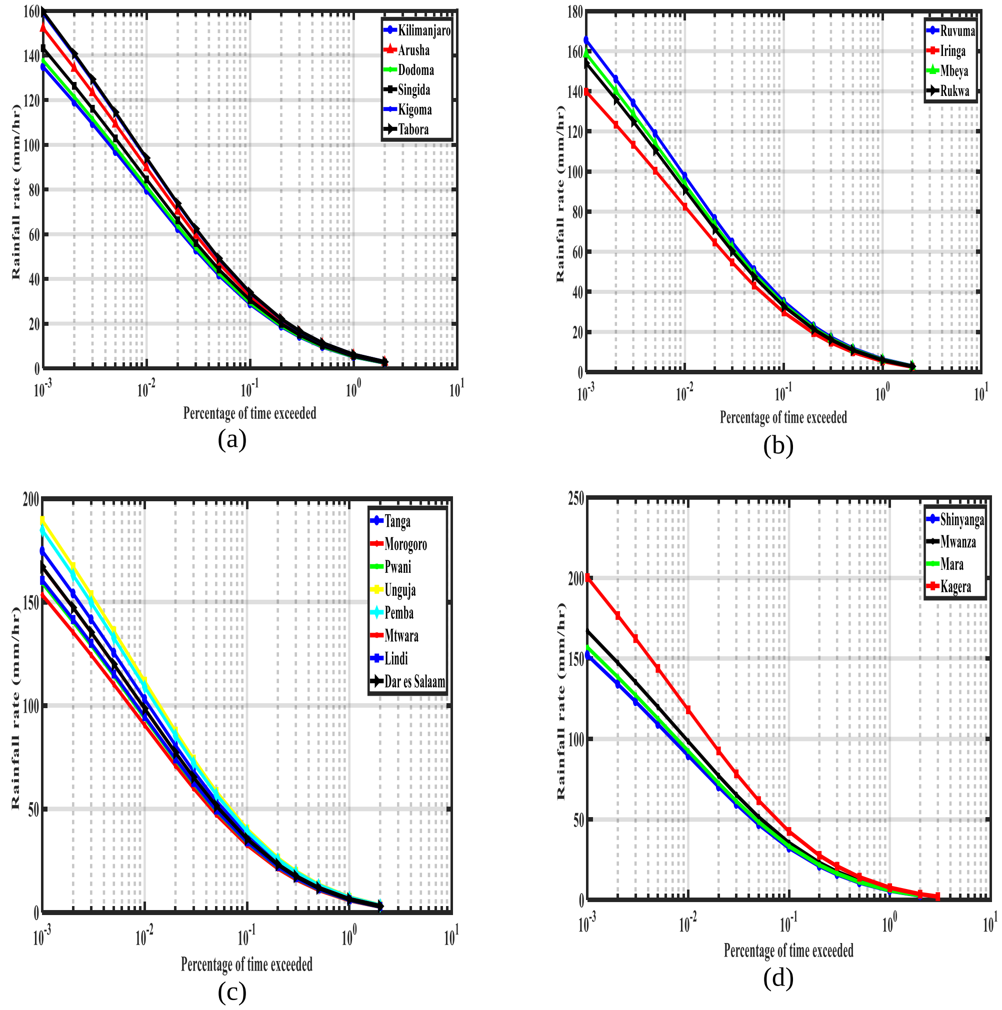

Figure 2: Cumulative distribution of rain rate at one-minute in Tanzania using refined Moupfouma-Martin model: (a) Northern highland, Central area and Western; (b) Southern highlands and southern western; (c) Coastal area with Unguja and Pemba islands; and (d) Lake Victoria basin.

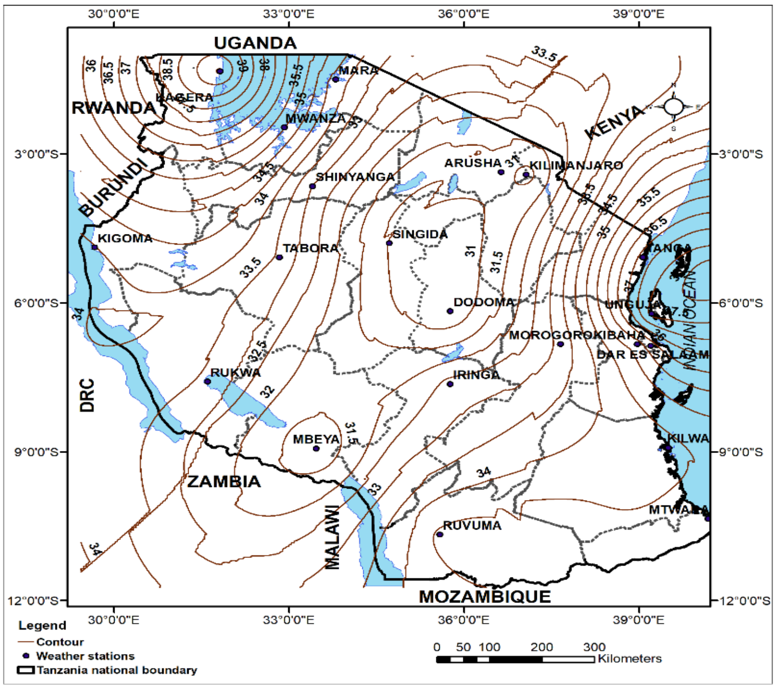

Figure 3: One-minute rain rate (mm/hr) contour map for 0.1% of the time in Tanzania.

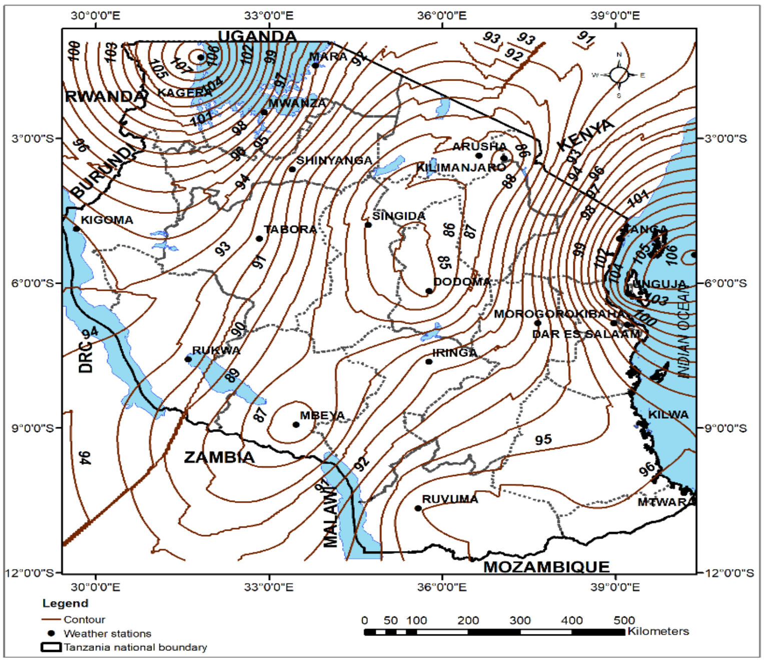

Figure 4: One-minute rain rate (mm/hr) contour map for 0.01% of the time in Tanzania.

Figures 5-8 present the contour maps for rain-induced attenuation at Ku and Ka-band frequency, respectively. Figures 5 and 7 present 99.9 % availability of time, while Figures 6 and 8 present 99.99% availability of time. The results portray a difference in both the Ku and Ka-band predicted attenuation values over each of the locations. For instance, for contour maps at 99.99 availability of time at Ku and Ka-bands, among the cities in the coastal zone with higher rainfall rates; Dar es Salaam has as high as for 49.34 dB for Ka-band, while it is 13.99 dB for Ku-band; this shows the difference of 35.35 dB between the two frequency ranges. The highest results of rain attenuation prediction in the Lake Victoria basin have a difference of 38.08 dB when compared with the highest results from the coastal zone.

In summary, for all zones, the predicted rain-induced attenuation values are lower for Ku-band when compared with Ka-band. Similarly, the rain-attenuation prediction differences and higher dB value do affect the availability of services. They can cause interruption of communication link performance in some areas as compared to others. To compensate for these differences, radio frequency modifications can be done by using appropriate fade mitigating techniques.

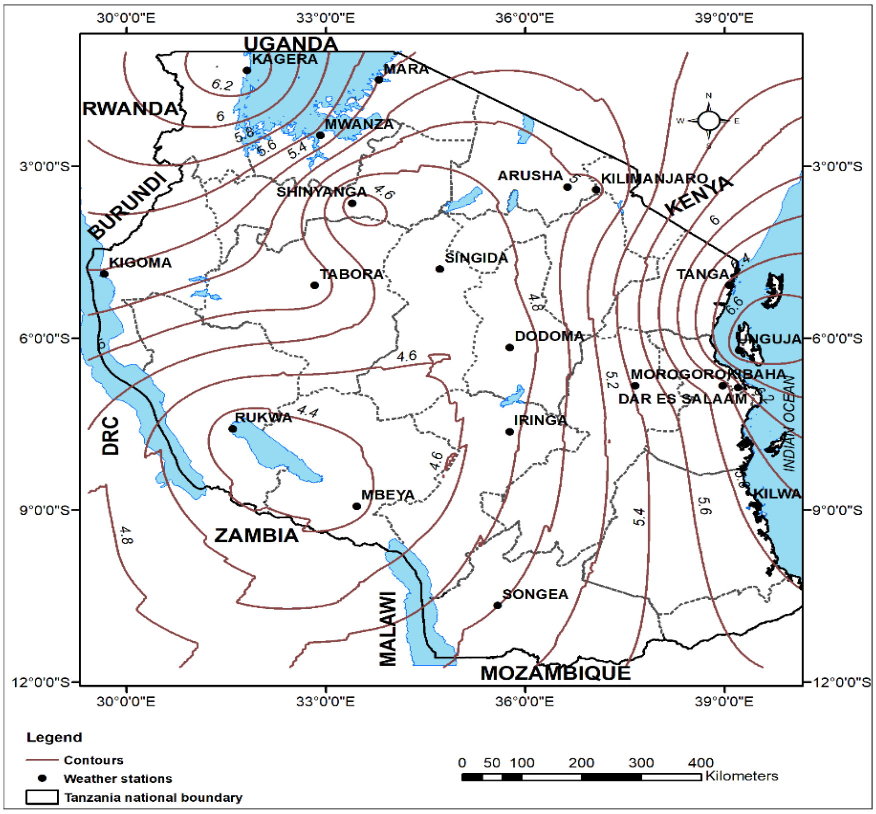

Figure 5: Rain attenuation distribution for 0.1% of the time for Ku-band in Tanzania.

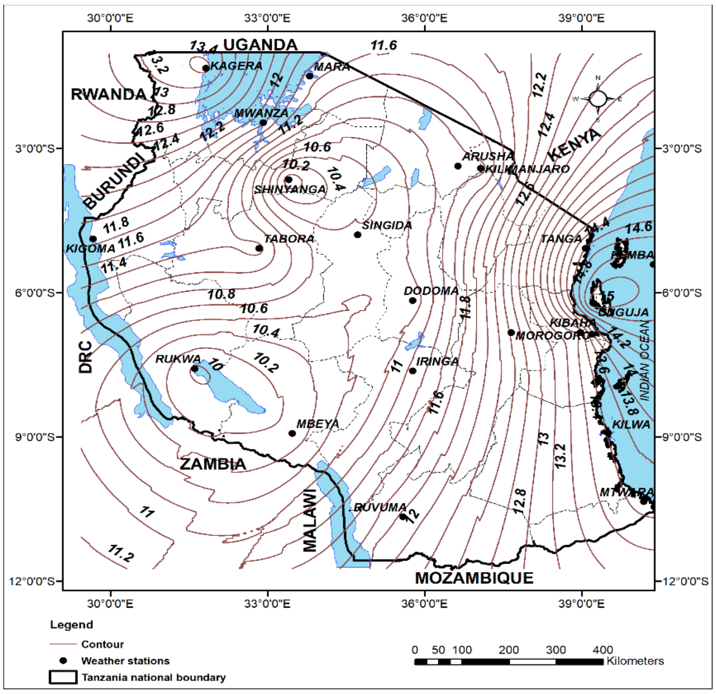

Figure 6: Rain attenuation distribution for 0.01% of the time for Ku-band in Tanzania.

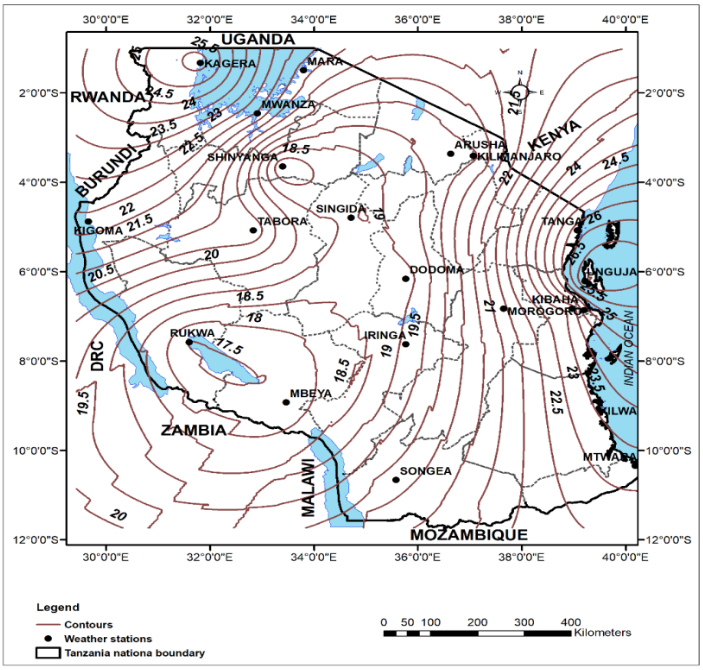

Figure 7: Rain attenuation contour map for 0.1% of the time for Ka-band in Tanzania.

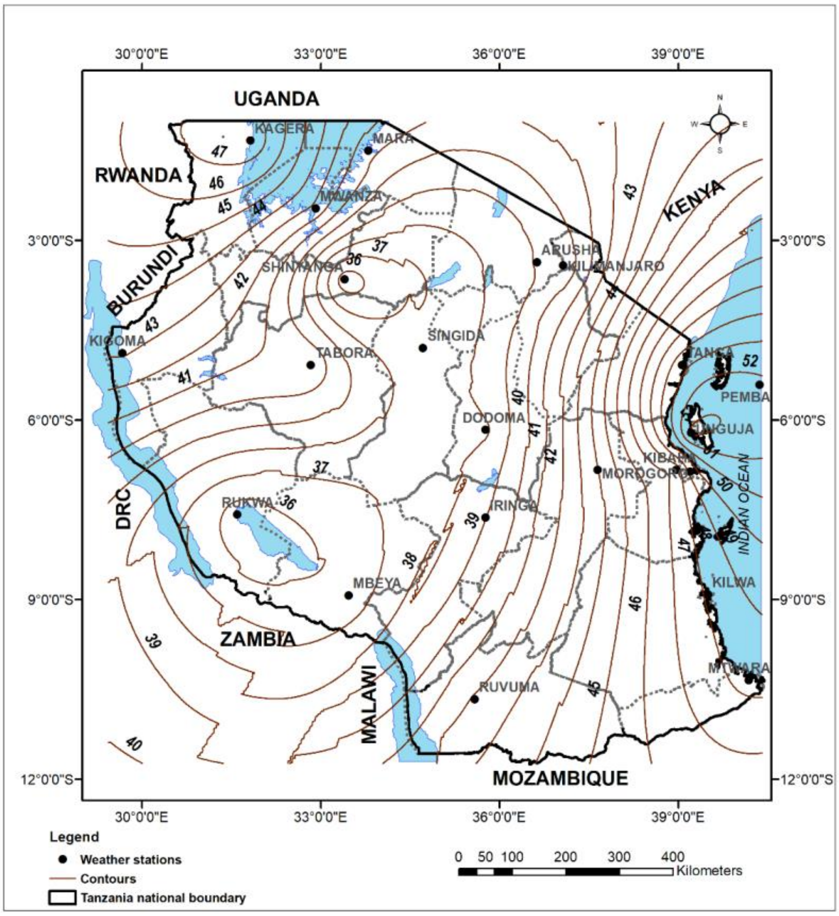

Figure 8: Rain attenuation contour map for 0.01% of the time for Ka-band in Tanzania.

Table 4 summarizes the results obtained from the ITU-R model for rain attenuations. The earth–satellite links over Tanzania at 99.99% availability need more fade margins to account for the rain attenuation incidences at the coast area. However, this is contrary to the central and southern highland zones which appeared to have the least fade margin to account for the effects of rain attenuation due to low annual rainfall occurring in this region.

Table 4: Rain induced attenuation at 99.9% and 99.99% availability for Ku-band and Ka-band

Climate zone	Location	Ku-band		Ka-band	
		0.1%	0.01%	0.1%	0.01%
Central Area	Dodoma	4.64	10.67	18.76	37.83
	Singida	4.707	10.65	19	37.71
Lake Victoria basin	Kagera	6.373	13.46	25.74	47.79
	Mara	5.396	11.69	21.73	41.31
	Mwanza	5.545	12.04	22.44	42.75
	Shinyanga	4.489	10.06	17.97	35.35
Northern Coast with Unguja and Pemba Islands	Dar es Salaam	6.167	13.99	24.78	49.34
	Morogoro	5.424	12.43	21.88	43.98
	Pemba	6.601	14.85	26.45	52.22
	Pwani	5.884	13.41	23.64	47.27
	Tanga	6.436	14.43	25.76	50.72
	Unguja	6.751	15.14	27.03	53.22
Northern- Highland	Arusha	5.004	11.2	19.89	39.09
	Kilimanjaro	4.952	11.11	19.87	39.14
Southern Coast	Lindi/Kilwa	5.869	13.62	23.65	48.14
	Mtwara	5.806	13.69	23.36	48.31
Southern- Highland	Iringa	4.767	11.07	19.14	38.99
	Mbeya	4.367	10.27	17.63	36.38
	Rukwa	4.301	9.963	17.47	35.48
Southern-Western	Ruvuma	4.999	11.85	20.27	42.13
Western Area	Kigoma	5.383	11.86	22.36	43.11
	Tabora	5.129	11.47	20.88	40.93

Conclusion

In this study, the cumulative distributions for rainfall rate obtained from the refined Moupfouma-Martin model were compared with results from the ITU-R model P.837-7. The results from the error margins indicate that the rainfall rate estimates from the climatic zones designated by ITU-R under-estimate rainfall rate at specific points of the probability of exceedance. Subsequent predictions over 22 various locations producing different rain attenuation estimates for earth satellite links across the seven climatic zones in Tanzania are presented. Inferences drawn from the predicted results were presented in the forms of contour maps. From the rain attenuation contour maps, earth satellite links in a coastal area, Lake Victoria basin and southern western of Tanzania are more affected by rain-induced attenuation and being more vulnerable to signal cut off and link outage compared to other parts of the country. On the contrary, the central and northern highlands of the country depict moderate rain-induced attenuation due to its low annual average accumulation of precipitation rate. Overall, the maps presented can be used by radio system engineers to rapidly and precisely determine the required link budget for satellite design.

For validation purposes, the need for ground-based measurement campaigns for rainfall rate and attenuation in the country is required. The availability of recommended one-minute rainfall data will be the most preferable. Also, sites falling under climatic zones N and Q are considered to be more susceptible to rain impairment and thus recommended as preliminary sites for rain rate and attenuation measurement campaign in Tanzania.

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