Rain Rate Statistics for Rain Attenuation for Western and Central African Subregions

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Abstract

Rain-induced attenuation serves as a substantial factor influencing link power sizing in both terrestrial and satellite-based applications. The absence of in-situ rain rate measurements for localized link designs has led to generalized assumptions about rain-induced attenuation, contributing to increased instances of signal impairments during rainfall events. This study addresses this challenge by quantifying rain rate statistics over country capitals in Western and Central Africa. The Chebil and Moupfouma models were employed to estimate essential rain rate statistics, including the point rainfall rate R0.01, utilizing a 32-year dataset of CRU rainfall accumulations. The results provide accurate rain-based statistics crucial for predicting, planning, and designing satellite and terrestrial links, especially for various microwave (MW) and millimeter-wave (mmW) technologies in specific locations. These rain rate insights are invaluable for engineers and designers working on communication systems, offering a comprehensive resource to enhance the accuracy of link budgeting and develop effective strategies for mitigating the impact of rainfall on signal quality. This research contributes to the optimization of communication systems, ensuring robust performance across diverse atmospheric conditions.

Keywords— rain attenuation, rain rate, rain rate statistics, link budget

Introduction

Higher frequencies are essential for modern communication applications for a variety of reasons, including the provision of a larger bandwidth, which means more data can be transmitted in each period; increased capacity to allow more users to share the same communication channel; and facilitating the miniaturization of communication devices such as mobile phones, tablets, and wearables. Although transmission at microwave and millimetric frequency bands experience less interference from other signals and sources, such as natural sources like lightning and human-made sources like power lines, they are however more susceptible to interference by hydrometeors, which include atmospheric gases, clouds, fog, snow, hail, glazing, and rain, which severely attenuate propagation at frequencies above 10 GHz (Ippolito Jr, 2017; Ojo et al., 2009).

Rain attenuation is unquestionably the most important propagation impediment at such high frequencies for tropical climates, with confirmed increases in attenuation with increasing operating frequency. Rain attenuation is known to increase with increasing operating frequency, making it one of the most significant propagation impairments in tropical regions at such high frequencies. Rain attenuation is the reduction in signal strength that occurs when electromagnetic waves at such frequencies pass through rain droplets in the atmosphere. At this frequency range, the attenuation due to rain is much higher than at lower frequencies, which can severely limit the range and reliability of wireless communication systems that operate in this frequency range.

The dearth of in-situ rain rate measurement as required in the required one-minute integration time across most countries in Africa (Ojo & Omotosho, 2013), particularly for localized practical link designs. This has increased generalizations of rain-induced attenuation, leading to inaccurate link budgeting with increasing occurrence of signal impairments during typical rainfall events. This shortcoming also impedes the development of domesticated models for specific climatic zones and the testing of other extant prediction models over such climates. Over the years, rain rate models have played significant roles in the design and operation of communication systems, particularly those that rely on satellite or wireless technology. These models can be used to estimate the expected attenuation in a given area and help engineers design more effective strategies for mitigating the effects of rain on signal quality. There are several types of rain rate models, but one of the most used is the ITU-R (International Telecommunication Union-Radiocommunication Sector) (ITU-R P.837-7, 2017) rain rate model. This model is based on empirical data and considers the specific frequency band being used for communication, as well as the percentage of time that rainfall rates exceed certain thresholds.

Rain rate statistics can be collected from ground-based rain gauge networks and space-based missions. While the ground-based rainfall monitoring networks are insufficient and unevenly dispersed for regional and national data coverage, space-based missions have proven useful for the provision of rainfall statistics, as required for driving necessary interventions through research, particularly in developing and undeveloped countries.

This work provides rain rate statistics over the central and western African subregions by quantifying the point rainfall rates from rainfall accumulations from a gauge-based global gridded precipitation dataset. These rain rate statistics are an important tool for radio engineers and designers of satellite/terrestrial communication systems. It will be useful for predicting the amount of attenuation that will occur in chosen regions, allowing for the development of more effective strategies for mitigating the effects of rain on signal quality.

Related Works

The study by (Chebil & Rahman, 1999) used the revised Moupfouma rain rate conversion models to synthesize 1-minute rainfall rate statistics from hourly and yearly rainfall data over the Malaysian Peninsula, producing contour maps with required rain rate statistics for quantifying the rain-induced attenuation over this region. The contribution by (Imran et al., 2015) provides 31 years of point rainfall intensity across Bangladesh, estimating total rain attenuation using various time percentages, distance, and frequency scenarios, with contour maps presenting rain attenuation statistics for planning links in the C, Ka, and Ku bands.

In (Ojo et al., 2008) similar statistics were presented over Nigeria as quantified from a 30-year rainfall data collection from diverse places. The validation of Nigeria's rain climate zone classifications using archival data from numerous ground-based observations and available TRMM precipitation index estimations from ITU-R and

Table 1: Rainfall accumulations and equivalent point rain rate estimates across locations

S/N	Country Name	Iso3 code	Location	Latitude (^{O} S)	Longitude (^{O} E)	Average monthly rain accumulation (mm)	Average yearly rain accumulation (mm)	Rainfall Rate at 0.01% (mm/h)	UN sub-region
1	Cameroon	CMR	Yaounde	3.8667	11.5167	135.5	1699.6	112.2	Central Africa
2	Central African Republic	CAF	Bangui	4.3667	18.5833	125.8	1557.3	109.3	
3	Chad	TCD	Ndjamena	12.1131	15.0492	44.3	555.5	80.5	
4	Congo	COG	Brazzavile	-4.2678	15.2919	122.8	1519.3	108.5	
5	Democratic Rep. of Congo	COD	Kinshasa	-4.325	15.3222	122.4	1535.2	108.8	
6	Equatorial Guinea	GNQ	Malabo	3.752064	8.7737	210.1	2635.8	127.8	
7	Gabon	GAB	Liberiville	0.3901	9.4544	190.0	2165.3	120.6	
8	Sao Tome and Principe	STP	Sao Tome	0.3361	6.6814	182.1	2284.7	122.5	
9	Benin	BEN	Porto-Novo	6.4972	2.605	116.8	1465.3	107.3	Western Africa
10	Burkina Faso	BFA	Ouagadougou	12.3572	-1.5353	64.4	808.1	89.9	
11	Cabo Verde	CPV	Praia	14.918	-23.509	25.2	316.5	68.1	
12	Cote d'Ivoire	CIV	Abidjan	5.3167	-4.0333	122.6	1517.6	108.5	
13	Gambia	GMB	Banjul	13.4531	-16.5775	77.9	964.3	94.8	
14	Ghana	GHA	Accra	5.55	-0.2	80.6	998.0	95.8	
15	Guinea	GIN	Conakry	9.5092	-13.7122	210.0	2635.0	127.8	
16	Guinea-Bissau	GNB	Bissau	11.85	-15.5667	130.9	1620.0	110.6	
17	Liberia	LBR	Monrovia	6.3133	-10.8014	228.9	2871.9	131.1	
18	Mali	MLI	Bamako	12.65	-8	73.8	913.4	93.3	
19	Mauritania	MRT	Nouakchott	18.1	-15.95	9.6	120.2	51.0	
20	Niger	NER	Niamey	13.5214	2.1053	43.3	542.9	79.9	
21	Nigeria	NGA	Abuja	9.0667	7.4833	97.9	1210.9	101.4	
22	Senegal	SEN	Dakar	14.6928	-17.4467	41.6	521.8	79.0	
23	Sierra Leone	SLE	Freetown	8.4844	-13.2344	232.9	2922.1	131.8	
24	Togo	TGO	Lome	6.1319	6.1319	92.4	1108.3	98.8	

Crane global radio-climatic models was documented in (Obiyemi et al., 2014). The study in (Ojo et al., 2009) provides similar statistics using contour maps for microwave-communications-system planning over Nigeria using the Moupfouma-Martin tropical rain-rate prediction model and the Rice-Holmberg model.

Local climatological data was translated into useful rain-rate statistics for rain attenuation prediction and communication system planning for selected locations across South Africa and the Southern African subregion (Obiyemi et al., 2022; J. S. Ojo & Owolawi, 2014). Long-term annual rainfall data for 10 years across 30 locations in Rwanda were used to quantify practical rain rates and attenuation estimates for terrestrial and satellite link designs across Rwanda (Sumbiri et al., 2016).

Although a number of the previous works have demonstrated the provision of rain-rate statistics for widespread application in the planning of terrestrial and satellite communications systems, applications however remain location-specific with the need for similar statistics for other locations within the region. This study, therefore, presents comprehensive rain rate statistics using the long-term precipitation dataset from the Climatic Research Unit (CRU) for planning, implementing and maintaining microwave (MW) and millimeter-wave (mmW) space-earth/terrestrial networks for the Western and Central Africa subregions.

Methodology

The study made use of CRU data from 25 different sites in the Western and Central African regions as shown in Figure 1. The capital cities of the countries under consideration are evaluated using the set of parameters listed in Table 1. This precipitation dataset is based on the long-term product from the CRU, which is a gauge-based global gridded precipitation dataset composed of monthly 0.50 latitude/longitude gridded series of climatic parameters over the periods 1901-2009 (Mitchell et al., 2002; Mitchell & Jones, 2005). The precipitation data from CRU were collected as NetCDF and .dat files from the CRU website. The monthly rainfall accumulation was extracted and tabulated in Excel using the Ferret software. Ferret is an interactive computer visualization and analysis tool for analyzing large and complex gridded datasets. The sites that are taken into account are the capital cities of the countries, with the characteristics listed in Table 1.

This study used a blend of the distribution function by Moupfouma (Moupfouma, 1993) and the rain rate model by Chebil (Chebil & Rahman, 1999) to predict the complementary cumulative distribution function (CCDF) of rainfall rates across 24 countries in the Western and Central African subregions. Using a 32-year rainfall dataset from CRU for each site, the point rain rate, R0.01, was estimated with the Chebil model, while the CCDF for

Figure 1. Map of the Central and Western Africa showing the study locations.

each location was developed by using the Moupfouma model for various exceedance values.

Equation (1) is the power-law function by Chebil (Chebil & Rahman, 1999), with β and α defined as constants derived based on rainfall measurements in tropical Singapore, Indonesia, Brazil, Malaysia, and Vietnam, and they are 0.2973 and 12.2903, respectively.

$$R_{0.01} = \alpha M^{\beta} \text{ [mm/h]} \tag{1}$$

The Moupfouma model, which prioritizes geographical and meteorological features, generated the rain rate distribution using (2), where R0.01 (mm/h) is the rainfall rate that is exceeded at 0.01%, r is the rainfall rate that is exceeded over some specific period of the time (mm/h), while b and u are respectively given as (3) and (4).

$$P(R \geq r) = 10^{-4}\left(\frac{R_{0.01}}{r+1}\right)^{b} \exp\left[u(R_{0.01} - r)\right] \tag{2}$$

$$b = \left(\frac{r}{R_{0.01}} - 1\right) ln\left(1 + \frac{r}{R_{0.01}}\right) \tag{3}$$

The parameter u in (2) is highly weather- and location-dependent, and so determines the slope of the cumulative distribution of the rainfall rate. It is defined in (4), with λ and γ expressed as 1.066 and 0.214 respectively as constants for subtropical and tropical climates.

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

Results and Discussion

Table 1 presents the estimated point rainfall rates for each reference site, as calculated using the Chebil power law. Figures 2 - 5 depicts the CCDF determined for locations in the Western African region based on the distribution function by Moupfouma, while Figure 6 and Figure 7 present similar estimates for locations in Central Africa. The average yearly rain accumulation (mm) over the 32-year observation over the Central Africa region is between 555.5 mm and 2635.8 mm respectively for Ndjamena, Chad (12.1131O N, 15.0492O E) and Malabo, Equatorial Guinea (3.752064O N, 8.773O

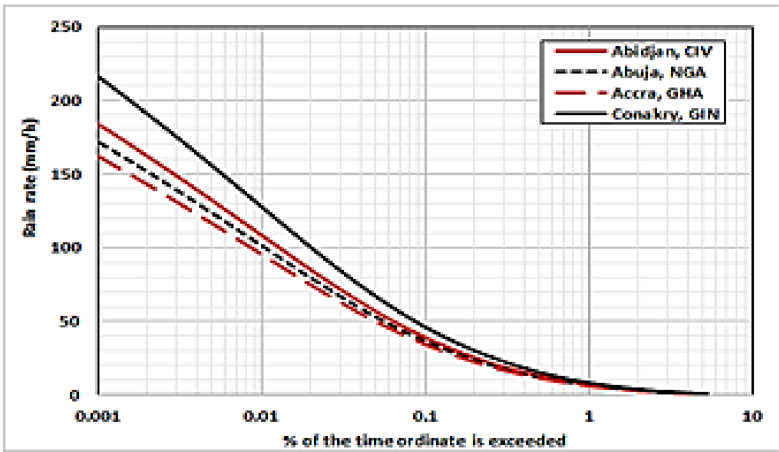

Figure 2: CCDF of the rainfall rates (mm/h) for Cote d'Ivoire, Nigeria, Ghana and Guinea

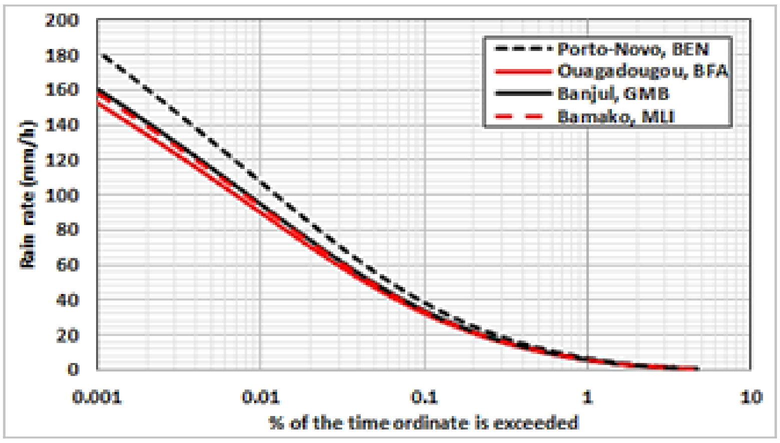

Figure 3: CCDF of the rainfall rates (mm/h) for Benin, Burkina Faso, Gambia, and Mali.

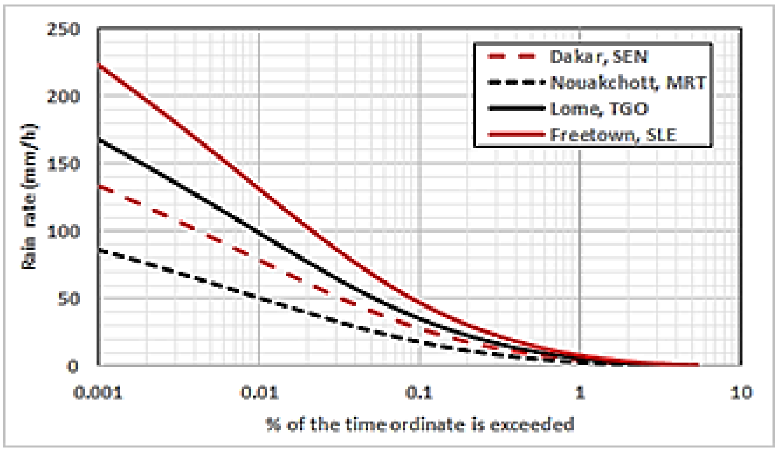

Figure 5: CCDF of the rainfall rates (mm/h) for Senegal, Mauritania, Togo, and Sierra Leone.

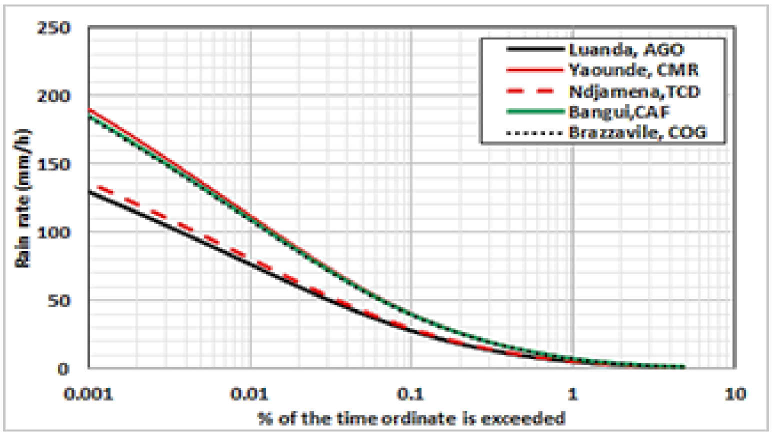

Figure 4: CCDF of the rainfall rates (mm/h) for Cameroon, Chad, Central African Republic, and Congo.

E), with corresponding point rainfall rates of 80.5 mm/h and 127.8 mm/h. For the West Africa region, the average yearly rain accumulation (mm) is between 521.8 mm and 2922.1 mm respectively for Dakar, Senegal (14.6928O N, 17.4467O W) and Freetown, Sierra Leone (8.4844O N, 13.2344O W), with corresponding point rainfall rates of 79 mm/h and 131.8 mm/h.

While the study utilized data from the capital cities across the Central and Western African Subregion, it is important to acknowledge that this may not provide an accurate representation of the rainfall distribution within each country. Variations in rainfall distribution can exist within the countries included in the study. The selection of case study locations primarily relied on the availability of reliable rainfall data for each specific location. However, future studies would benefit from exploring different regions within each country to obtain a more comprehensive understanding of rainfall patterns and their implications on satellite and terrestrial MW and mmW applications.

Figure 2 presents the CCDF of the rainfall rates (mm/h) for the capital cities of Cote d'Ivoire, Nigeria, Ghana, and Guinea. Figure 3 displays the CCDF of the rainfall rates (mm/h) in the capital cities of Benin, Burkina Faso, Gambia, and Mali. The CCDF of the rainfall rates (mm/h) in the capital cities of Cameroon, Chad, Central African Republic, and Congo is depicted in Figure 4. Similar rainfall rates (mm/h) statistics in the capital cities of Senegal, Mauritania, Togo, and Sierra Leone is presented in Figure 5. Figure 6 Shows the rainfall rates (mm/h) distribution in Guinea-Bissau, Cabo Verde, Liberia, and Niger’s capital cities. Figure 7 displays the CCDF of the rainfall rates (mm/h) for the capital cities of Gabon, Equatorial Guinea, Sao Tome and Principe, and the Democratic Republic of the Congo. The presented results for different locations and exceedance values of 1%, 0.1%, 0.01%, and 0.001% of the year can be used to infer the corresponding rainfall rate (mm/h).

Similar results earlier documented for some of the locations are 112mm/h (Ajayi & Ezekpo, 1988) and 94 mm/h (Omotosho & Oluwafemi, 2009) while 101.4mm/h was estimated from this present work for Abuja, Nigeria. Point rain rate estimate of 87.781 mm/h (Akobre et al., 2020) with 95.8 mm/h from this current work for Accra, Ghana. Results obtained for Yaounde, Cameroun 102 mm/h (Yeo et al., 2014) as

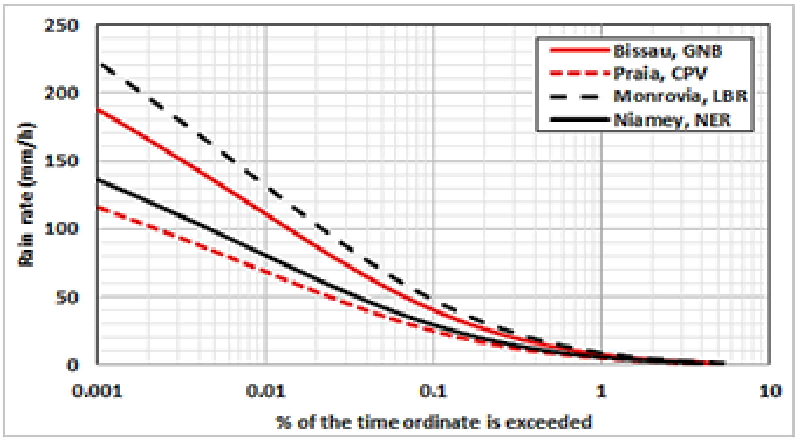

Figure 6: CCDF of the rainfall rates (mm/h) for Guinea-Bissau, Cabo Verde, Liberia, and Niger.

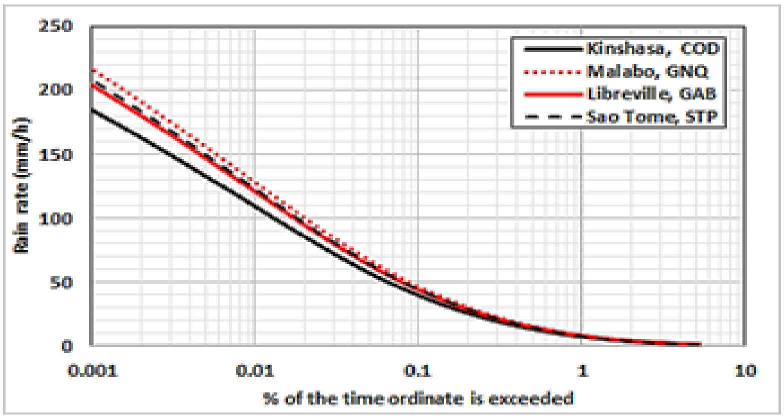

Figure 7: CCDF of the rainfall rates (mm/h) for Democratic Rep. of Congo, Equatorial Guinea, Gabon, and Sao Tome and Principe.

compared with the 112.2mm\h estimated from the current work.

Conclusion

In a concerted effort to minimize inaccuracies in link budgeting over microwave and millimeter waves and their consequential impact on diverse services and applications, this research focuses on quantifying crucial rain rate statistics over the country capitals in the West and Central African regions. Utilizing a 32-year dataset of CRU rainfall accumulations in specific capital cities, the Chebil and Moupfouma models are applied to estimate essential rain rate statistics, including the point rainfall rate R0.01 (mm/h). These statistics serve as invaluable resources for engineers and designers of satellite/terrestrial communication systems. The accurate prediction of attenuation levels in a given area plays a pivotal role in devising effective strategies to mitigate the impact of rainfall on the quality of transmitted signals. This research, by providing comprehensive rain rate insights, contributes to enhancing the reliability and performance of communication systems across the region, ensuring seamless and robust connectivity in various atmospheric conditions.

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