Estimation of Rain Attenuation over Microwave and Millimeter Bands for Terrestrial Radio Links in Ethiopia

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***Abstract*—while rainfall is a major cause of communication impairment at microwave and millimeter bands, the effect of rain attenuation in the Ethiopian microwave links, has so far remained as unstudied. Therefore, in this paper, the rain rate distribution at 15 minutes integration time is predicted for different percentage of time of the year based on two years of rain intensity data obtained from National Meteorological Agency (NMA) of Ethiopia. The rainfall rate for one minute integration time not exceeded 0.01% of the time is calculated using ITU-R and Chebil designations, it is found that the highest rainfall rate at 0.01 % of time for any location in Ethiopia, does not exceed 64 mm/h. The ITU-R model is then applied to estimate and analyze rainfall attenuation over terrestrial radio links for ten sites in Ethiopia. The attenuation is predicted for frequencies from 1-150 GHz, with variable distances. The results show that Bahirdar is predicted to experience the largest effect of rain attenuation whereas, Dubti, has the lowest attenuation.**

Keywords— Ethiopia; Rain rate; ITU-R model; microwave link; rain attenuation.

I. INTRODUCTION

Microwave and millimeter wave propagation at low latitude is a topic of interest for researchers and communication engineers. Due to high rainfall, humidity and temperature in low latitudes severe propagation effects may be seen over radio links [1]. Of all atmospheric effects on microwave and millimeter wave bands, rain attenuation is a serious problem. When the signal travels at microwave frequency through a rainy medium, the signal strength gets weakened due to the absorption and scattering of its amplitude and phase components by rain drops. In addition, rain droplets alter the polarization of the transmitted signal resulting in depolarization and unreliable effects at the receiver. In practice, notable parameters of rainfall rate and rain drop size are applied to improve the understanding of rainfall effects over wireless communications [2].

The study of radio wave propagation at microwave and millimeter bands is of immense interest to the International Telecommunications Union (ITU-R) and the International Union of Radio Science (URSI). The ITU-R, through Recommendation P 530-15 [3] and P 618-11 [4], provides basic Line-of-Sight (LOS) link design assumptions based on propagation prediction methods which are not suitable for tropical regions. It is therefore imperative that for these regions, experimentally determined parameters are obtained to modify or refine these propagation prediction methods. Such work has been done for clear-air and precipitation conditions within Southern Africa [5], [6], [7], Nigeria [8] and some tropical countries such as Malaysia [9] and Bangladesh [10]; however, other African tropical and equatorial regions have not been adequately studied.

Investigation of rain attenuation at microwave and millimeter bands in Ethiopia based on local data as recommended for every country is a motivation to this work. In this paper, the rain rates and the time percentage of exceedance are computed based on the data obtained from National Meteorological Agency (NMA) Ethiopia, with one minute rainfall conversion time developed at 0.01% for ten locations. Using ITU-R model, rain attenuation over ten Ethiopian radio links are estimated and analyzed.

II. GEOGRAPHY AND CLIMATE OF ETHIOPIAN LOCATIONS

Ethiopia is located in the Horn of Africa from 3^0 to 18^0N latitude and 33^0 to 48^0E longitude. The elevation generally ranges from 100 meters below sea level in Dallol depression of Afar to mountain peaks of over 4000 meters above sea level. The Rift Valley separates the western and eastern high lands, and these high lands gradually descend to the low land areas in the east, west and south of the country. The climate is temperate on the plateaus and hot in the low lands [11].

The climate variation over Ethiopia tends to depend on the unique characteristics of the area. The Köppen climate classifications (first proposed in 1931) is very useful in understanding this variation from the perspective of geographical elevation [12]. Thus, three major climate classifications obtained over Ethiopia are as follows: class A (As-, Aw-, Am) climates in the lowlands, which are of semi-humid to semi-arid characteristics surrounding the highlands; Class B (BWh-, BSh- and BSk) climate in the Afar-Triangle and the Somali Region; and class C (Cwb-, Cfb-, Cwc) climates in the Ethiopian highlands, which are of warm to cool mountainous with semi-humid to humid characteristics.

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The climate conditions covered in the locations of this paper include highlands, the Rift Valley, the lowlands in East,

TABLE I. LOCATIONS AND THEIR CLIMATE

LOCATIONS	LAT. (^{O}N)	LONG. (^{O}E)	M(mm)	KÖPPEN CLASS
Addis Ababa	9.02	38.45	1089	Cwb-warm temperate
Adama	8.33	39.17	904.2	Aw-Tropical
Arbaminch	6.03	37.33	820	Aw-Tropical
Bahir Dar	11.35	37.23	1480	Cwb-warm temperate
Dire Dawa	9.58	42.32	729.8	BSh-hot semi arid
Dubti	11.73	41.08	300	Bwh-hot arid
Jimma	7.40	36.49	1414	Cfb-warm temperate
Kombolcha	11.09	39.74	1139	Cwb-warm temperate
Negele Borana	5.33	39.58	550	Aw-Tropical
Mekele	13.28	39.32	601	Bsh-hot semi arid

Fig.1. Map of Ethiopia

west and south of the country, and swampy areas around Rift Valley Lakes, Lake Tana and the Blue Nile, and Dallol depression of Afar. Their climate conditions are discussed as shown in Table I. The average annual rainfall accumulation M is seen to be maximum in Bahirdar and minimum in Dubti. From the Köppen classification, it is seen that the locations Adama, Arbaminch and Negele Borena belong to A Köppen class; Diredawa, Dubti and Mekele belong to B Köppen class; whereas Addis Ababa, Bahir Dar, Jimma and Kombolcha belong to C Köppen class. All locations are shown in Fig.1.

III. RAINFALL RATE DISTRIBUTION IN ETHIOPIA

The statistical analysis for the ten main sites of Ethiopia is performed based on the Cumulative Distribution Function (CDF) for a period of two years on the data collected from NMA at 15- minute sampling rate. Fig. 2 shows the rainfall rate distribution for ten locations versus rainfall rate percentage of exceedance at 1%, 0.1%, and 0.01% for 15 minute values. From Fig.2, it is clear that the maximum $R_{0.01}$ (15min) is in Bahirdar at 23.6 mm/h while the minimum is recorded in Dubti at 8.5 mm/h.

TABLE II. R_{15min}(mm/h) for 99%, 99.9%,and 99.99% avaliability

LOCATIONS	Rain rate values at 1%,0.1% and 0.01% of time		
	1%	0.1%	0.01%
Addis Ababa	1.5	5.5	13
Adama	1.8	7.5	18
Arbaminch	1.7	6.5	17
Bahir Dar	2.3	10.5	23.6
Dire Dawa	1.3	5	13.5
Dubti	0.2	2.5	8.5
Jimma	2.2	13	21.5
Kombolcha	5	11	20.5
Negele Borana	1.3	5.6	11
Mekele	1.4	5.8	13.5

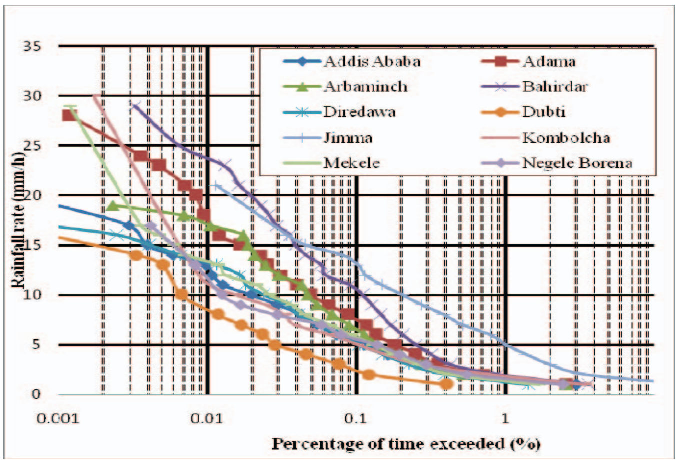

Fig. 2. Cumulative rain rate distribution at 15 minute sampling rate in Ethiopia

In the absence of comparable one minute rainfall rate data for any of the Ethiopian locations, it is important that only values at 0.01% are compared with one minute rainfall values from Chebil model [13] and from ITU-R 837.6 [14]. From the Chebil's model described in (1), $R_{0.01}$ at 1 minute time is estimated from long term mean annual rainfall (M) using known power low relationship:

$$R_{0.01} = \alpha M^{\beta} \tag{1}$$

α and β are regression coefficients. According to Chebil model, the typical values of regression coefficients α and β for Ethiopian location are 12.2903 and 0.2 respectively as obtained from the map in [15]. This model has been reported to provide better estimation than ITU-R P837.5 in tropical climate [16]. From Fig. 3, it is found that at 0.01% exceedance or (99.99% availability), the rainfall conversion rates over the investigated Ethiopian locations are given in (2) and (3) according to ITU-R and Chebil models respectively.

$$R_{1\min(0.01)} = 15.74 R_{15\min(0.01)}^{0.42} \tag{2}$$

$$R_{1\min(0.01)} = 12.616 R_{15\min(0.01)}^{0.5031} \tag{3}$$

The coefficients of determination (R^2) which indicate how much the data fit a statistical model are found to be 0.600 and 0.837 for the ITU-R and Chebil models respectively. This gives a 2.684 mm/h difference between the converted values of estimation. Results tend to agree with ITU-R and Chebil models. For future work, one minute data is needed to present the actual results.

TABLE III. $R_{0.01}$ OF ITU-R AND CHEBIL FOR DIFFERENT SITES

LOCATION	M (mm)	$R_{0.01}$(CHEBIL) (mm/h)	$R_{0.01}$(ITU-R) (mm/h)
Addis Ababa	1089	57.24	54
Adama	904.2	54.94	56
Arbaminch	820	53.78	50
Bahir Dar	1480	61.24	57
Dire Dawa	729.8	52.42	50
Dubti	300	43.10	45
Jimma	1414	60.63	64
Kombolcha	1139	57.8	54
Negele	550	49.25	48
Mekele	601	50.22	52

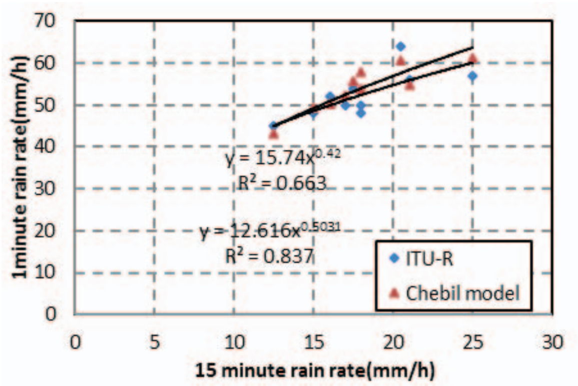

Fig. 3. ITU-R and Chebil rain rate for 1 minute values against measured 15 minute rain rate

VI. PREDICTION OF RAIN ATTENUATION OVER ETHIOPIA

A. Procedure for rain attenuation prediction

The important parameters for the calculation of attenuation due to rain are the specific attenuation (dB/km) of rain and the effective path length (km).The specific attenuation (dB/km) of rain rate is given by [17]:

$$\gamma_R = KR_{0.01}{}^{\alpha} \tag{4}$$

where γ_R is specific attenuation K and α are regression coefficients which are determined as a function of frequency as given in [17] for horizontal and vertical polarization respectively.

The effective path length (d_{eff}) of the link can be computed by multiplying the actual path length (d) with the distance factor where r is given by [3]:

$$r = \frac{1}{0.477\, d^{0.633} R_{0.01}{}^{0.073\alpha} f^{0.123} - 10.579\left(1-\exp\left(-0.024\, d\right)\right)} \tag{5}$$

where f is frequency (GHz) and α is regression constant in specific attenuation and r is less than or equal to 2.5.

The approximated path attenuation that is exceeded 0.01% of time is given by [3]:

$$A_{0.01} = \gamma_R d r \tag{6}$$

The attenuation exceeded for other percentage of time p in the range 0.001% to 1% can be computed using (7).

$$A_P = A_{0.01} C_1 P^{-[C_2 + C_3 \log_{10} P]} \tag{7}$$

$$C_1 = \left(0.07^{C_0}\right)\left[0.12^{(1-C_0)}\right] \tag{8}$$

$$C_2 = 0.855 C_0 + 0.546[1 - C_0] \tag{9}$$

$$C_3 = 0.139 C_0 + 0.043[1 - C_0] \tag{10}$$

$$C_0 = \begin{cases} 0.12 + 0.4\left[\log_{10}\left(\frac{f}{10}\right)^{0.8}\right] f \geq 10GHz \\ 0.12 f < 10GHz \end{cases} \tag{11}$$

The prediction procedure outlined above is considered to be valid in all parts of the world at least for frequencies up to 100 GHz and path lengths up to 60 km [3].

B. Determination of approximated specific attenuation of rain rate

The rain attenuation of terrestrial radio links depends on different factors such as rainfall rates, polarization of transmitted signal, propagation frequency and path length. Thus, the rain attenuation of microwave and millimeter bands will be studied from these perspectives. The first step in this investigation is to figure out specific rain attenuation, that is rain attenuation per kilometer in a rainy medium.

In Fig. 4a and 4b, the distribution of specific attenuation of rain versus frequency are determined for ten locations in Ethiopia, namely: Adama, Addis Ababa, Arbaminch, Bahirdar, Diredawa, Dubti, Jimma, Kombolcha, Mekele and Negelle Borena. In fact, these are typical sites which can represent most parts of the country. Fig. 4a shows specific rain attenuation for horizontal polarization for ten locations; while Fig. 4b is for vertical polarization. Fig. 4 shows that the specific attenuation increases sharply for frequency ranges to 50 GHz, followed by a more gradual increment from 50 to 100 GHz. Finally, these value remains practically constant for frequencies up to 150 GHz. It is seen from Fig. 4a that the maximum specific attenuation of 23 dB is observed in Bahir Dar, while the minimum of 18 dB is estimated in Dubti at 100 GHz. From Fig. 4b, the highest specific rain attenuation of 22 dB is observed in Bahirdar, with the lowest (17 dB) is observed in Dubti at frequency of 100 GHz.

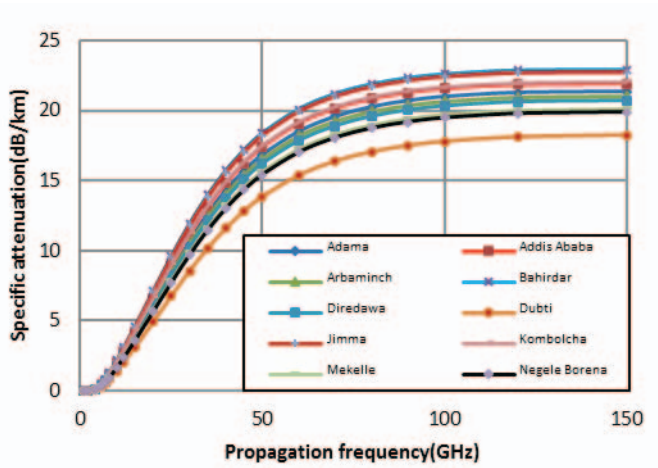

Fig.4a. Specific rain attenuation for Ethiopia against frequency (GHz) in horizontal polarization.

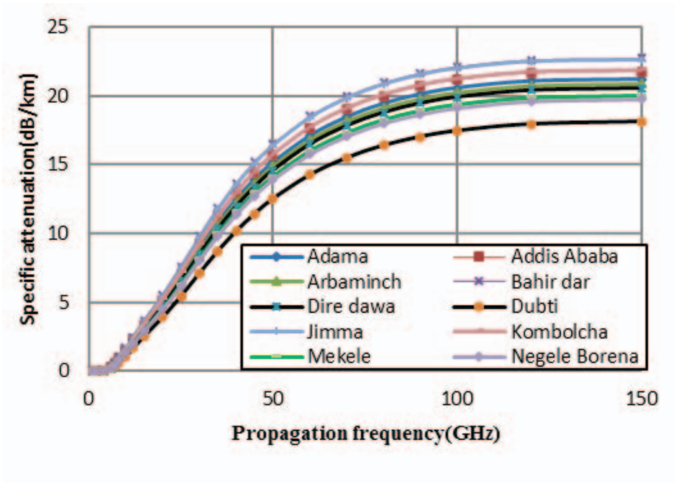

Fig. 4b. Specific rain attenuation for Ethiopia against frequency (GHz) in vertical polarization.

From Fig. 4 it is seen that the specific rain attenuation for horizontal polarization is greater than vertical polarization because of the fact that the raindrops have a non-spherical shape with flattened in the base and therefore, the horizontally polarized waves attenuated more than the vertically polarized waves.

C. Estimation of rainfall attenuation for Ethiopian Line –of-Site links.

Fig. 5a and Fig. 5b show the rain path attenuation for horizontal and vertical polarizations for 10 sites in Ethiopia over different distances. From these graphs, the rain attenuation rises sharply up to 40 km, then increases less sharply up to 50 km and finally the attenuation is getting almost constant. As the distance increases, the rain attenuation becomes non-uniform because of the fact that the effective path length does remain fixed for large actual path length. As seen in Fig. 5a with horizontal polarization at distance of 30 km, the maximum rain attenuation is in Bahirdar at 36 dB, while the minimum is in Dubt at 25 dB. For vertical polarization (Fig.5b) similar distribution of rain attenuation is observed: the highest value is 30 dB in Bahirdar, and lowest value is 22 dB in Dubti at 30 km. comparing the two graphs, vertical polarization has lower rain attenuation than horizontal polarization, as already stated.

Fig.6a and Fig. 6b show the increase in fade depth with propagation frequency up to 50 GHz as recommended by ITU-R, and this is valid only for distances up to 60 km; followed by gradual increase from 50 to 100 GHz and finally the rain attenuation getting nearly constant at 100 GHz and above. The estimated rain fade at 50 GHz for horizontal polarization is maximum in Bahirdar with a value of 25 dB and minimum in Dubti with 18 dB; while for vertical polarization the attenuation is 21 at dB Bahirdar and 15.6 dB at Dubti.

It is observed from the rainfall rate and attenuation that the North-west part of Ethiopia (Bahirdar and Jimma) experience intense effects of rain attenuation and hence, higher network outages. These results are seen to agree with the observation of Sami M Sharif in Sudan [18].

As seen from tables (IV and V) the rain fade decreases as availability move from 99.999% to 99%. The fade margin for rain attenuation prediction given in table IV and V can be used by engineers in designing terrestrial Line-of-Sight link.

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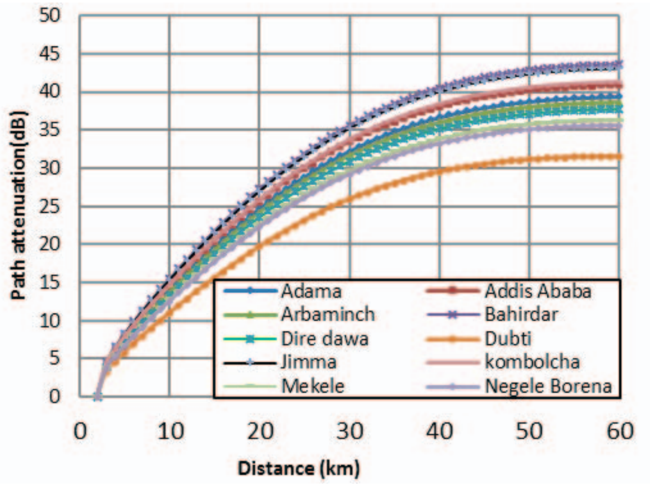

Fig. 5a. Rain attenuation for varying distance at frequency of 12GHz in horizontal polarization

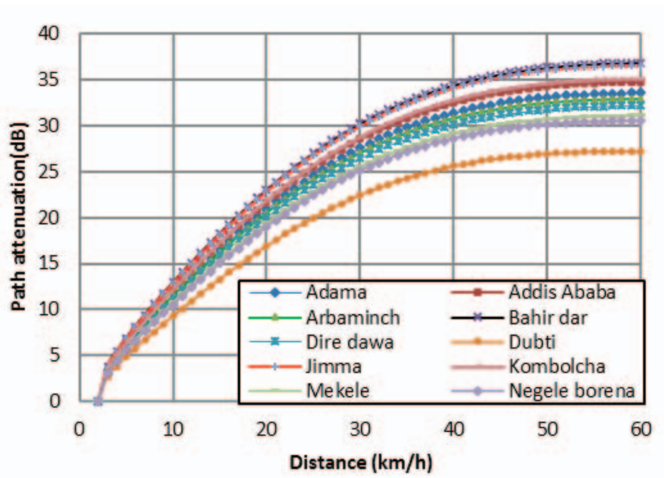

Fig. 5b. Rain attenuation for varying distance at frequency of 12GHz in vertical polarization

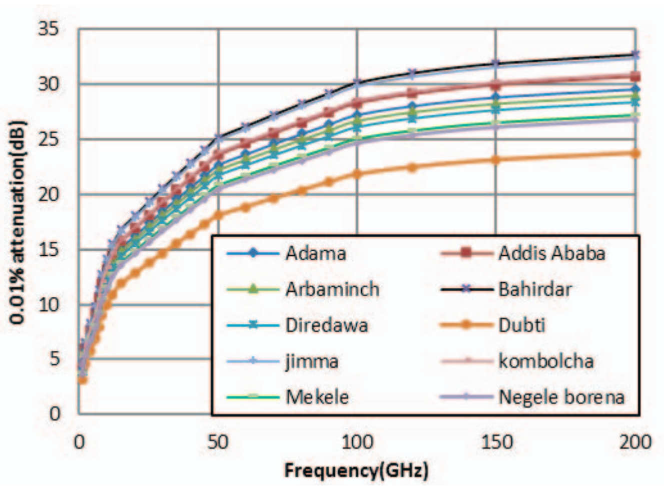

Fig. 6a. Estimated rain fade at different frequency in GHz for horizontal polarization

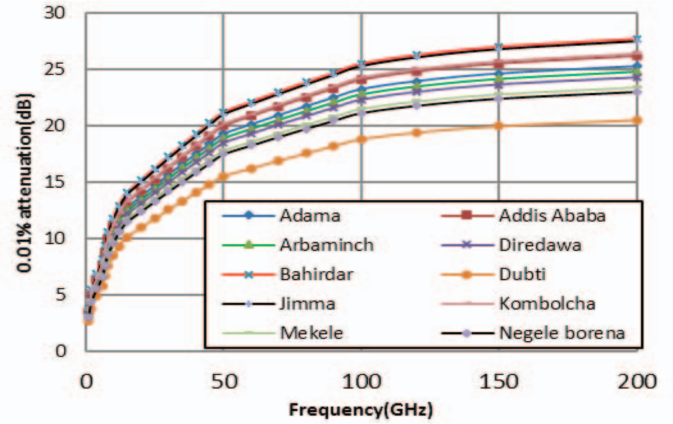

Fig. 6b. Estimated rain fades at different frequency in GHz for Vertical polarization

TABLE IV. RAIN FADE MARGIN AT PROPAGATION FREQUENCY OF 12GHZ AND PATH LENGTH OF 20 km IN HORIZONTAL POLARIZATION FOR 10 LOCATIONS IN ETHIOPIA.

LOCATIONS	Fade margin at different % of avaliability (dB)				
	99.99%	99.95%	99.9%	99.5	99%
Adama	26.37	13.79	10.03	4.36	2.93
Addis Ababa	27.39	14.32	10.41	4.53	3.05
Arbaminch	25.85	13.52	9.83	4.28	2.87
Bahir Dar	29.169	15.25	11.09	4.83	3.24
DireDawa	25.25	13.2	9.6	4.18	2.81
Dubti	21.08	11.02	8.02	3.49	2.34
Jimma	28.9	15.11	10.99	4.78	3.21
Kombolcha	27.65	14.45	10.51	4.57	3.07
Negele Borena	23.84	12.46	9.06	3.94	2.65
Mekele	24.27	12.69	9.23	4.02	2.7

TABLE V. RAIN FADE MARGIN AT PROPAGATION FREQUENCY OF 12GHZ AND PATH LENGTH OF 20 km IN VERTICAL POLARIZATION FOR 10 LOCATIONS IN ETHIOPIA.

LOCATIONS	Fade margin at different % of availability (dB)				
	99.99%	99.95%	99.9%	99.5%	99%
Adama	22.43	11.73	8.53	3.71	2.49
Addis Ababa	23.25	12.15	8.84	3.85	2.58
Arbaminch	22.02	11.51	8.37	3.64	2.45
Bahir Dar	24.66	12.89	9.37	4.08	2.74
DireDawa	21.53	11.26	8.18	3.56	2.39
Dubti	18.18	9.51	6.91	3.01	2.02
Jimma	24.44	12.78	9.29	4.04	2.71
Kombolcha	23.45	12.26	8.91	3.88	2.61
Negele Borena	20.4	10.67	7.75	3.38	2.27
Mekele	20.75	10.85	7.87	3.43	2.31

V. CONCLUSION

In this study, two year rain intensity data at 15 minutes sampling rain rate for ten geographical locations obtained from NMA, is used to determine the cumulative distribution of rain rate over Ethiopia. Furthermore, Chebil and ITU-R models are used to calculate $R_{0.01}$ at one minute integration time. Using ITU-R model, specific rain and total path rain attenuations for terrestrial Line- of- Sight links in Ethiopia are estimated. It is observed that the attenuation is maximum in Bahirdar followed by, Jimma, Kombolch, AddisAbaba, Adama, Arbaminch, Diredawa, Mekele, Negele Borena and Dubti in descending order. It is also seen that horizontally polarized signals suffer higher rain attenuation than vertically polarized signal. It is expected that further validation of these results will be undertaken using rainfall data of one minute integration time obtained from at least one location in Ethiopia. This is a subject of future work.

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