RAIN-INDUCED CROSS-POLARIZATION EFFECTS ON SATELLITE TELECOMMUNICATION IN SOME TROPICAL LOCATIONS

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Abstract

Rain- induced cross polarization is an important factor in the design of dual-polarization microwave radio communication systems. In this work, we present the scattering effect of oblate spheroidal raindrops on Earth-space wave communication in the frequency band 1–52 GHz in three tropical locations: Ile-Ife, Nigeria (4.34°E, 7.33°N), Douala, Cameroon (9.70°E, 4.05°N), and Nairobi, Kenya (36.75°E, 1.30°S). The present study employs the more realistic distribution of canting angles along the path. Results obtained show that the XPD improves by about 4-7dB over those based on the equi-orientation model. Elevation angles of 23° and 55° are assumed for wave propagation in the regions. The incident waves are assumed to be linearly polarized. The tropical lognormal raindrop size distribution model has been used to estimate the raindrops number density. The specific attenuation and specific phase shift are calculated in terms of the power law relationship between attenuation and rainfall rate since measured cumulative distribution of rain rates are available from the locations. The calculation of the propagation parameters is based on the measured Mean Annual (MA) and Mean Worst Month (MWM) rainfall rates in each location. The predicted copolar attenuation (CPA), and cross-polarization XPD for Cameroon is closer to those obtained for Nigeria than that for Kenya. At the elevation angle of 55°, and for links over the Atlantic Ocean Region (AOR), the CPA and XPD are higher in Cameroon than Nigeria by about 24% at the most. At the elevation angle of 23°, and for links over the Indian Ocean Region (IOR), the percentage difference between CPA and XPD in Cameroon is higher than in Nigeria by about 1136%. Therefore, it can be safely said that rain induced degradation of Earth-space communication will be most severe in Cameroon and least in Kenya.

Keyword: *Cross-polarization discrimination, co-polar attenuation, specific attenuation, specific phase shift*

Introduction

To increase channel capacity without increasing bandwidth, orthogonal polarization (linear or circular) may be independently used for transmission at the same frequency over the same path. However, "frequency re – use" may be impaired by the possibility that in propagating through the atmosphere, some of the energy transmitted in one polarization state can be transferred to the orthogonal polarization state thus causing interference between the two channels (CCIR, 1986). Rain and other hydrometeors may cause this phenomenon. This is usually referred to as cross polarization. Cross - polarization may occur during periods of multipath propagation. Additionally, cross - polarization may arise due to the characteristics of the antenna systems at each terminal, and this cross – polarized component will then exist at a base level. When two orthogonal polarization 'a' and 'b' (Fig 1a) are transmitted at the same level, the ratio of the co – polarized signal ('ac' or 'bc') in a given receiving channel to the cross – polarized signal ('bx' or 'ax') in that channel (ac / bx), is known as the cross – polarization isolation (XPI). This is of prime importance in system design. The two-ratio ac/bx and bc/ax are not necessarily the same. Propagation experiment, on the other hand, usually measure cross polarization discrimination (XPD = ac/ax) which is the ratio of the co – polarized received signal 'ac' to the cross – polarized received signal 'ax' when one polarization only, 'a' is transmitted (ITU-R, 1994) . That is the co – polar signal ac and the cross –polar signal ax is each measured independently and in the absence of any orthogonal polarized transmitted signal 'b'. In the context of rain – induced cross - polarization, the above expressions ac/bx, bc/ax and ac/ax may be considered to be the same (Oguchi, 1975, Watson et al, 1974). Both the cross polarization isolation (XPI) and cross - polarization discrimination (XPD) are normally expressed in decibels. A dual – polarized receiver that is designed to receive orthogonal channels simultaneously will detect both wanted, or co – polarized, signals ac and bc and the unwanted, or cross – polarized signals bx and ax. The isolation in channel a will be the ratio ac/bx. In general, experiment use only mono – polarized transmissions and so what is measured is the discrimination ratio ac/ax or bc/bx.

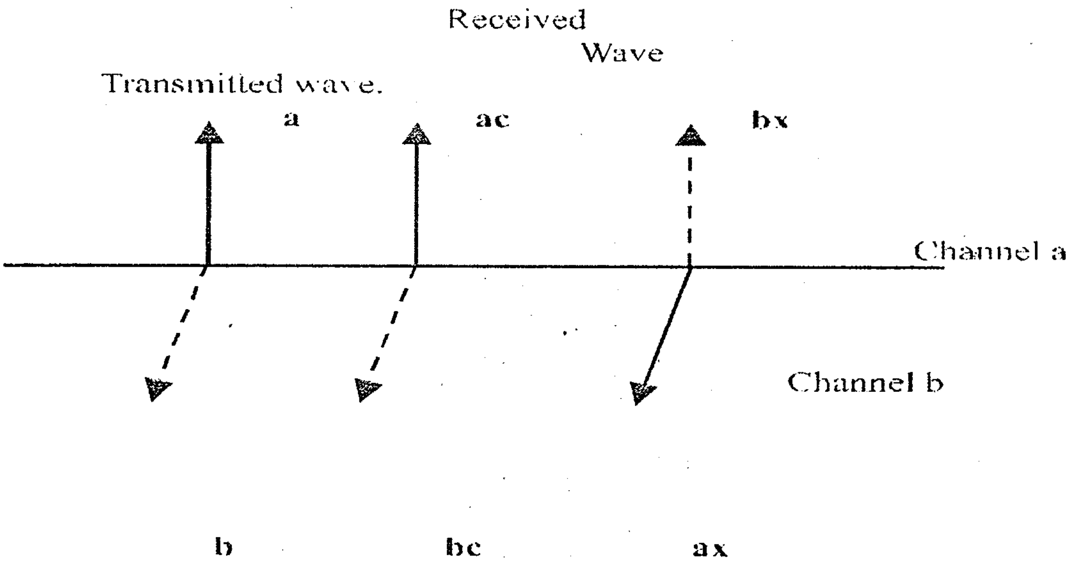

Fig. 1a: Term used to define the difference between XPD and XPI (ac and bc are the co – polarized components of signal transmitted in channels a and b, respectively. ax and bx are the cross – polarized components of signals transmitted in channels a and b respectively).

Computational Method

The propagation constant associated with wave transmission through rain is defined as the rate of wave attenuation per unit distant and the rate of phase dispersion per unit distance. It means that the propagation constant will provide information for the specific attenuation and phase shift of a radio signal. It is generally expressed as

$$\gamma = aR^{b} + hR^{k}$$

Table 1: Rainfall rate $R_{0.01}$ exceeded for 0.01% of time in Ile-Ife (Nigeria), Douala (Cameroon) and Nairobi (Kenya). Source (McCarthy et al., 1994 a, b, c)

Location	Mean annual rainfall rate for 0.01% time	Mean worst month rainfall rate for 0.01% time
Ile-Ife (Nigeria)	108mm/h	130mm/h
Douala (Cameroon)	126mm/h	160mm/h
Nairobi (Kenya)	65mm/h	100mm/h

Table 2: Some parameters relevant to the study

Elevation angle of 55 degree

Location	height above sea level /km	Polarization	Latitude	Longitude	Rain height /km	slant path Length /km
Ile-ife	0.274	horizontal	4.34	7.33	4.5	5.159
Douala	0.015	horizontal	9.7	4.05	4.5	5.475
Nairobi	1.8	horizontal	36.75	1.3	4.5	3.296

Elevation angle of 23 degree

Location	height above sea level /km	Polarization	Latitude	Longitude	Rain height /km	slant path Length /km
Ile-ife	0.274	horizontal	4.34	7.33	4.5	10.816
Douala	0.015	horizontal	9.7	4.05	4.5	11.478
Nairobi	1.8	horizontal	36.75	1.3	4.5	6.91

The Total slant path attenuation

The ITU–R P.618-8 (2003) procedure for calculating long-term rain attenuation statistics from point rainfall rate at a given location for frequency up to 55 GHz was used for calculating the total slant-path attenuation for 0.01% of time and the scaling formulation for slant-path attenuation for other percentage of time for 0.001 and 0.1% of an average year.

Cross Polarization Discrimination Used In This Work

Based on small argument approximations, Olsen (1981) proposed a semi-empirical model for calculating XPD and CPA. The expressions were derived from the earlier work of Oguchi (1977). Thus XPD is expressed approximately as

$$XPD \cong -20\log(l\cos^2\in|\Delta k|e^{-2\sigma^2}\sin\frac{|\phi-\tau|}{2} \quad (1)$$

and

$$CPA \cong \left[A_H + A_V + (A_H - A_V)\cos^2\in e^{-2\sigma^2}\cos 2(\phi-\tau)\right]\frac{l}{2} \quad (2)$$

where A_H and A_V are the specific attenuation associated with the principal planes of the raindrops axis i.e major and minor axes of the raindrop.

$$|\Delta k| = |k_H - k_V| = (\Delta\alpha^2 + \Delta\beta^2)^{\frac{1}{2}} \quad (3)$$

where $\Delta\alpha$ and $\Delta\beta$ are the differential attenuation, and differential phase shift, respectively. ϕ defines the effective canting angle (we use10^0) and τ is the polarization tilt angle ($\tau = 0$ for horizontal polarization and $\frac{\pi}{2}$ for vertical polarization) σ is the effective standard deviation of the canting angle distribution (10^0 for 0.01%), $\in$ represents the path elevation angle (for this work 23^0 and 55^0) and l is the path length through uniform rain. The specific attenuation has been calculated using the power law relationship between attenuation and rain rate proposed by Olsen et al.,(1985). This is expressed as $A = aR^b$, R is rainfall rate and the parameters a and b are taken from the work of Ajayi (1985). A similar power law relationship has been used to calculate the specific phase shift. The phase shift is expressed as

$$\phi = hR^k.$$

Results and Discussion

Specific attenuation

The specific attenuation due to rain has been calculated at some frequencies for rain rates exceeded for 0.01% of time at three stations, Nigeria, Cameroon and Kenya .The mean annual (MA) and mean worst month (MWM) rainfall rates used are shown in

Table 1. Oblate spheroidal raindrops are assumed. Generally the specific attenuation increases with increasing frequency with highest attenuation in Douala for both MA and MWM. The reason is due to the higher rainfall rate in Douala as shown in Table 1 compared to the other two stations.

Specific phase shift

The specific phase shift has been calculated for the three stations in the frequency range 1-52GHz band for the two rain rates shown in Table 1. The slant path lengths (calculated using ITU-R P 618 2003) are shown in Table 2. The specific phase shift increases with frequency up to a maximum and then decreases after the peak frequency. The peak frequency for the three stations is 25GHz. The reason is due to the high rainfall rate in the three stations as shown in Table 1, the rainfall rates are greater than 50 mm/h, hence the more intense the rainfall the smaller the peak frequency.

Differential attenuation and differential phase shift

The results of the differential attenuation and differential phase shift are presented using the mean annual rainfall rate and the mean worst month rain rate. The results show that the differential attenuation increases with frequency in the three locations and peaks around the frequency of 40GHz (as shown in figs 1b and 2). The differential phase shift on the other hand peak around 20GHz in the three stations. It crosses over to negative values around the frequency of 30 - 31 GHz for Nigeria and Cameroon while in Kenya it becomes negative around the frequency of 32 - 38 GHz for both rain rates MA and MWM respectively. The reason for this is not far fetched the phase shift decreases rapidly after attaining a peak around the frequency of 24-25 GHz at the locations. Therefore the difference between the two low values become negative at frequencies higher than about 24GHz. Results are also presented for the two rainfall rates, MA and MWM respectively.

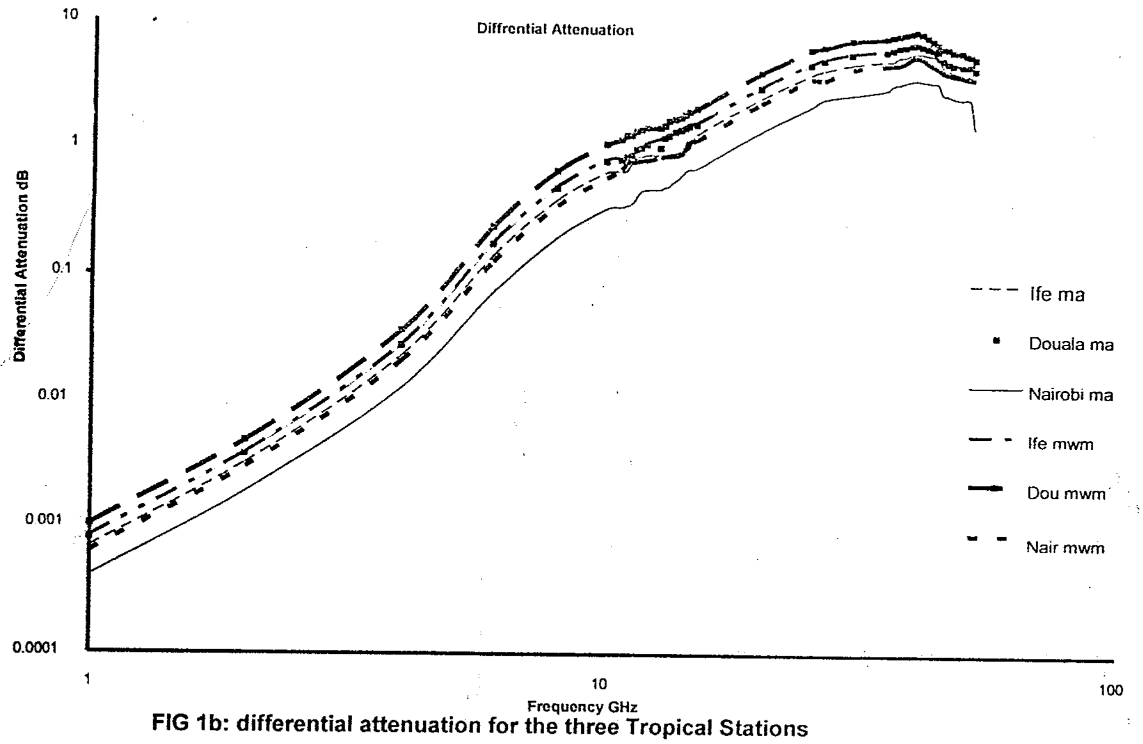

FIG 1b: differential attenuation for the three Tropical Stations

Ile-ife ma=108 mwm=130mm/h, Douala ma=126 mwm=160mm/h,Nairobi ma=65, mwm=100mm/h

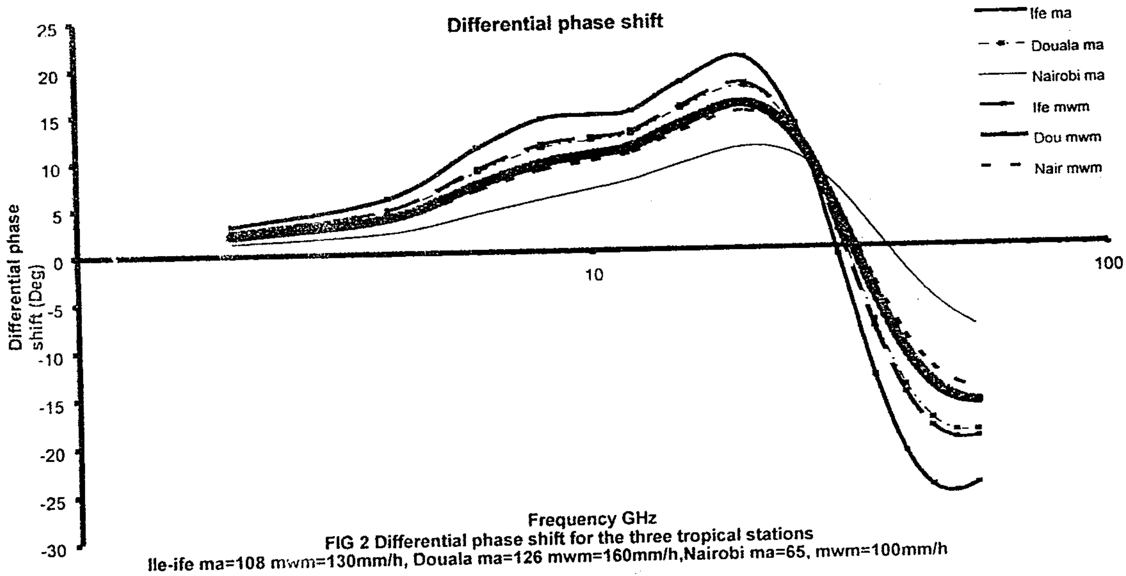

FIG 2 Differential phase shift for the three tropical stations
Ile-ife ma=108 mwm=130mm/h, Douala ma=126 mwm=160mm/h,Nairobi ma=65, mwm=100mm/h

Normalized differential attenuation and normalized differential phase shift

The normalized differential attenuation and normalized differential phase shift with respect to vertical attenuation show some peaks, which decrease with increasing frequency; these peaks arise from the fact that the horizontal attenuation at those frequencies is greafer than the vertical attenuation. The first peak is around the frequency 6 GHz at the three stations. This peak is not of much practical significance because of the low attenuation in both polarizations. The second peak is around the frequency of 25 GHz for Nigeria and Cameroon and at a frequency of 26.5 GHz in Kenya. The third peak occurs around the frequency of 39GHz in Nigeria, and Cameroon, and at a frequency of 38 and 39 GHz in Kenya MA and MWM rainfall rate data respectively (as shown in figs 3 and 4). The normalized differential phase shift per decibel of vertical attenuation at the three locations s show sharp decrease with increasing frequency and above 10 GHz the normalized differential phase shift is negligible. But below 10 GHz is the major contributor to depolarization. However above 10 GHz the differential attenuation is the major contributor to depolarization.

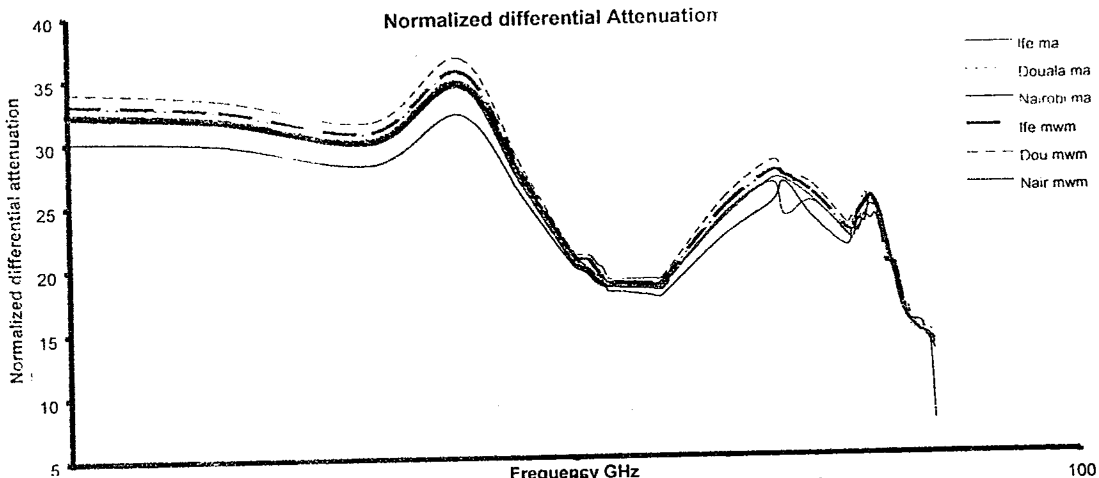

Fig 3: Normalized differential attenuation for the three tropical stations
Ile-ife ma=108 mwm=130mm/h, Douala ma=126 mwm=160mm/h,Nairobi ma=65, mwm=100mm/h

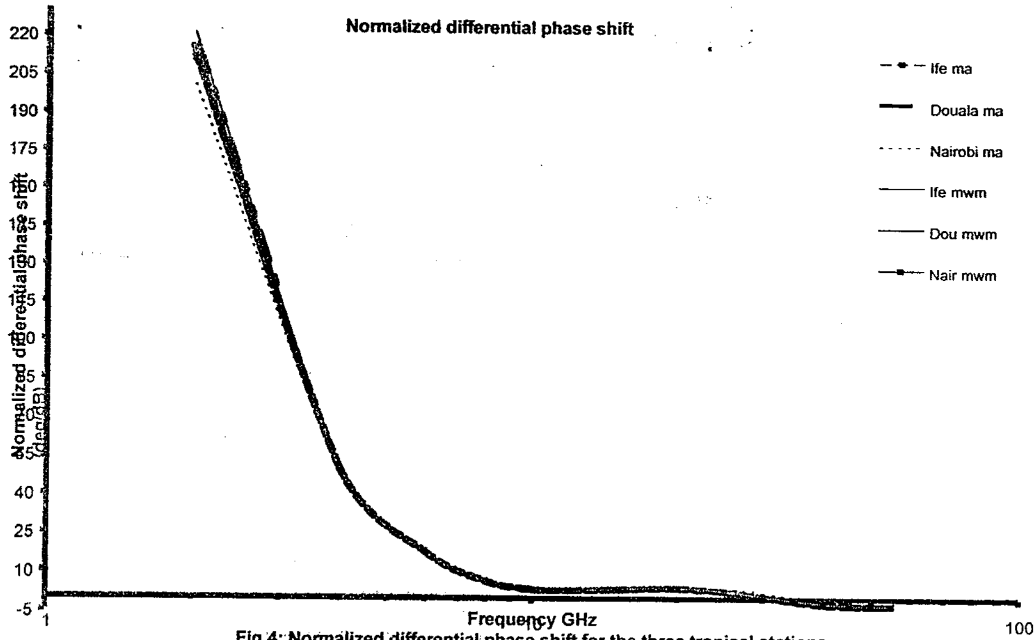

Fig 4: Normalized differential phase shift for the three tropical stations
Ile-ife ma=108 mwm=130mm/h, Douala ma=126 mwm=160mm/h,Nairobi ma=65, mwm=100mm/h

Total slant path attenuation

The total slant path attenuation has been calculated for the three stations in the frequency range 1-52GHz for the two rain rates that is the mean annual (MA) and mean worst month (MWM) rain rates, and at two elevation angles 23 ^{0}and 55^0 . The frequency characteristics of the total slant path attenuation (for 55^0 and 23^0) at the two rainrate for the three locations are presented in Figs 5 and 6. It should be remembered that from Table 2 the slant path lengths to the rain region in the locations are 10.82km (Ile-Ife), 11.47km (Douala) and 6.91km (Nairobi) respectively. Hence the total slant path attenuation is lowest in Nairobi due to its short distance to the rain region. The total slant path attenuation increases with frequency and decrease with increase in elevation angle, since generally the lower the elevation angle, the longer the path length through rain.

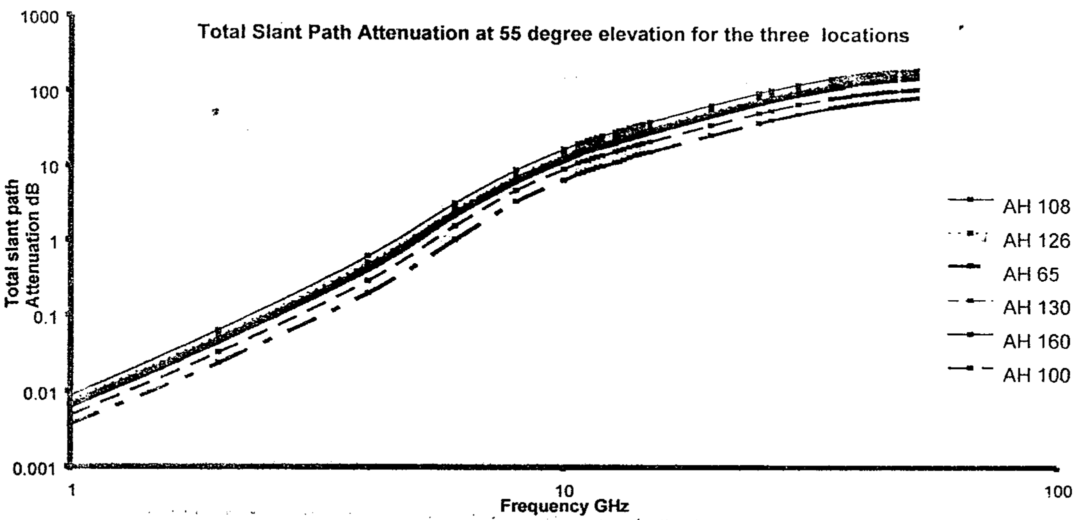

Fig. 5: Total Slant path attenuation for the three tropical stations AH horizontal polarization
Ile-ife ma=108 mwm=130mm/h, Douala ma=126 mwm=160mm/h,Nairobi ma=65, mwm=100mm/h

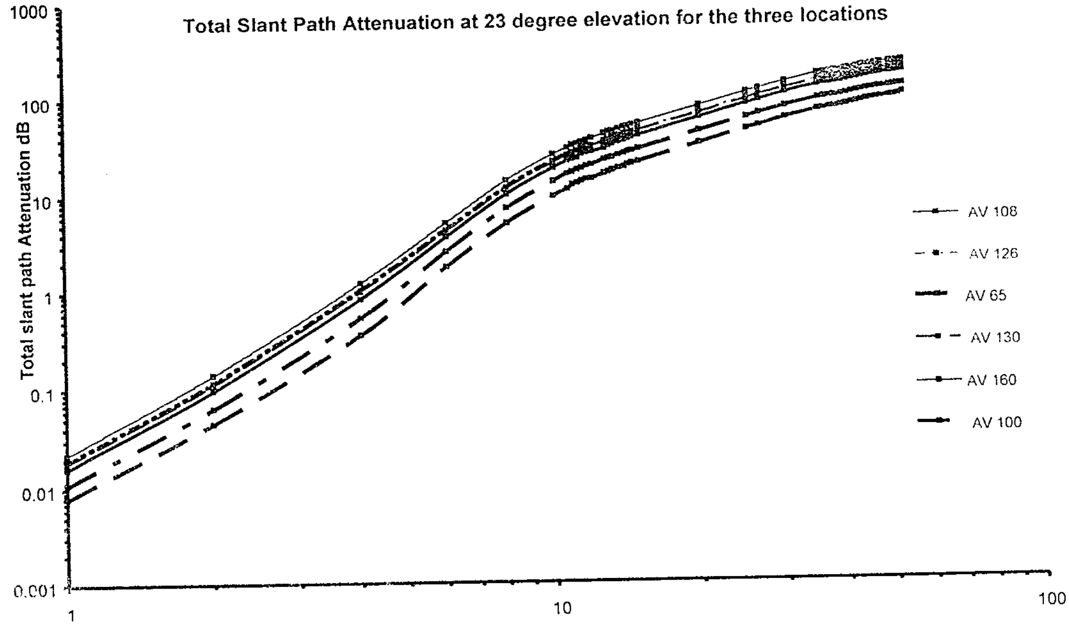

Fig 6: Total slant path attenuation for the three tropical stations, AV vertical polarization
Ile-ife ma=108 mwm=130mm/h, Douala ma=126 mwm=160mm/h,Nairobi ma=65, mwm=100mm/h

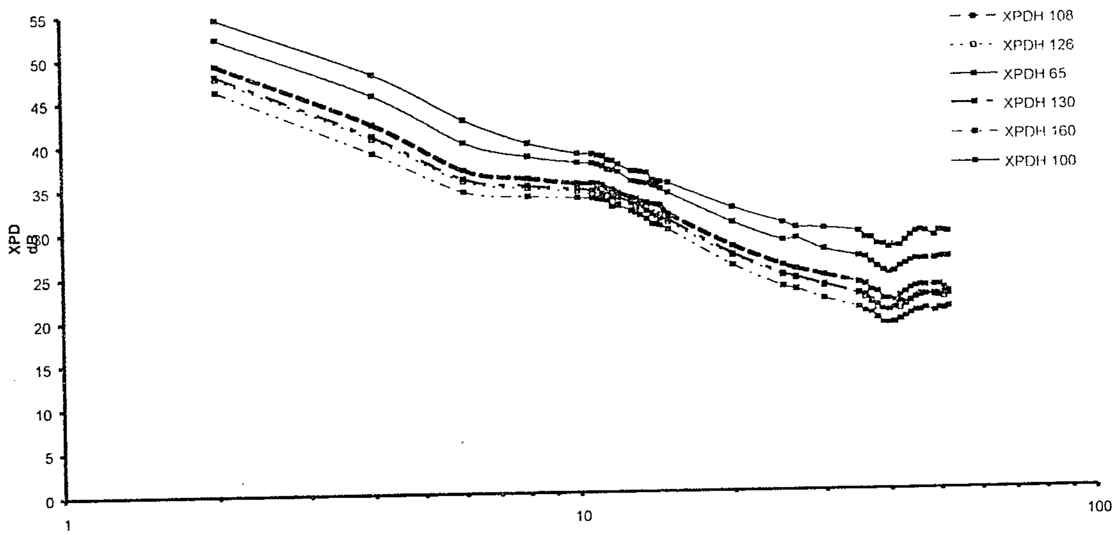

Fig 7: XPD using effective canting angle 10 and standard deviation of 10 for 0.01% , XPDH horizontal polarization
Ile-ife ma=108 mwm=130mm/h, Douala ma=126 mwm=160mm/h,Nairobi ma=65, mwm=100mm/h.

Comparison of the total slant path attenuation

The result of the total slant path attenuation in Cameroon and Kenya are compared with Nigeria at the two-elevation angle and for the mean annual and worst month rain rates. The predicted attenuation for Cameroon is generally higher than Nigeria. At elevation angle of 55^0, the slant path attenuation using the mean annual rain rate in Cameroon is higher than Nigeria by about 16 % at frequencies higher than 10GHz. It is lower in Kenya by about 45%. Using the mean worst month rain rate, Cameroon is higher by about 20 % at frequencies above 5GHz, whereas it is lower in Kenya by about 26%. The higher rain rates in Cameroon in addition to the higher total rainfall are responsible for this difference. At the lower elevation angle of 23^0 and at frequencies higher than 10GHz, using the mean annual rain rate, Cameroon is higher than Nigeria by about 13%, it is lower in Kenya by about 44 %. Using the mean worst month rain rate, at frequencies higher than 10GHz. The total slant path attenuation in Cameroon is higher than Nigeria by about 24% at frequencies higher than 10GHz and it is lower in Kenya by about 44 %. The higher rain rate in Cameroon in addition to the higher total rainfall is responsible for this difference.

Cross Polarization Discrimination

The frequency characteristics of the Cross-Polarization Discrimination (XPD) are shown in Figs 7 and 8 for two elevation angles investigated. Generally, the XPD decreases with increasing frequency, and rain rate for the locations. It also decreases with decreasing elevation angle. XPD for vertical polarization is worst by about 16 dB compared to horizontal polarization at all frequency for 55^0 elevations in all the three station. At 23^0 elevations XPD horizontal is about 16 dB better than the vertical for frequencies higher than 10GHz, in the three stations. The XPD decreases to negative values at frequencies higher than about 25 GHz for vertical polarization at 23^0 elevations in, Nigeria and Cameroon. This is due to higher rain rate of the two-country compare to Kenya. The results of the cross polarization discrimination from the three locations are also compared. The results show that the predicted Cross Polarization Discrimination (XPD) in Kenya is generally higher than that of Nigeria and Cameroon; this is due to higher rain fall rates in the two stations. It implies that satellite signals will experience more depolarization in Cameroon and Nigeria. At elevation angle of 55^0, using the mean annual rain rate XPD in Cameroon is lower than Nigeria by about 8 % at frequencies higher than 10 GHz. It is higher in Kenya by about 16%. Using the mean worst month rain rate, Cameroon is lower by about 9 % at frequencies about 5 GHz, whereas it is higher in Kenya by about 21%. The lower rain rate in Kenya in addition to the lowest total rainfall is responsible for this difference. At lower elevation angle of 23^0 and at frequencies higher than 10GHz, using the mean annual rain rate, Cameroon is lower than Nigeria by about 81%, it is higher in Kenya by about 54 %. Using the mean worst month rain rate, at frequencies higher than 10GHz, Cameroon is lower than Nigeria by about 31% at a frequency of 10GHz and it is higher in Kenya by about 14 %. The lower rain rate in Kenya in addition to the lowest total rainfall is responsible for this difference. We can conclude that;

(1). The XPD values for Cameroon at 55^0-elevation angle are comparable to Nigeria than that of Kenya.

(2). The minimum XPD for most communication systems is between 20 – 30 dB for discriminating the unwanted polarization during a severe rainfall. It can be seen that from the results for Kenya at 55^0 elevations, and frequencies between 38 – 42 GHz, the XPD for horizontal polarization decreases to a minimum value of 27dB this is closer to 30 dB.

(3). For Nigeria it decreases to a minimum of 21 dB between the frequencies 39 – 41 GHz and at Cameroon it decreases to a minimum of 20 dB between the frequencies 38 – 42 GHz.

(4). But at 23^0 elevation, the XPD for horizontal polarization is much more poorer, above 20 GHz and it reduces to a minimum values of 17 dB for Kenya, while for Nigeria above 15GHz it reduces to a minimum of 11dB, for Cameroon above 13.625 GHz it reduces to a minimum of 10 dB.

(5). Generally at all frequencies (1 – 52GHz) XPD horizontal polarization for 55^0 elevation is 10 dB better than XPD 23^0 horizontal polarization.

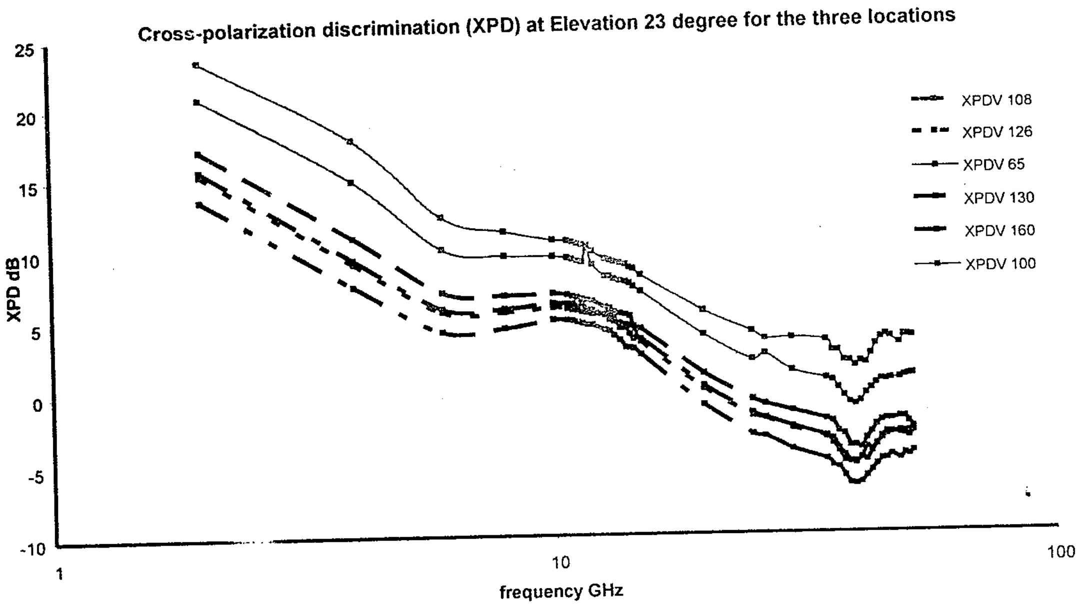

Fig 8: XPD using effective canting angle 10 and standard deviation of 10 for 0.01% ,XPDV vertical polarization

Ile-ife ma=108 mwm=130mm/h, Douala ma=126 mwm=160mm/h,Nairobi ma=65, mwm=100mm/h.

Co – polar Attenuation

The copolar attenuation, which is the attenuation of the wanted signal after depolarization are shown in Figs 9 and 10. The result shows that CPA increases with increasing frequency, rain rate and also increases with decrease in elevation angle.

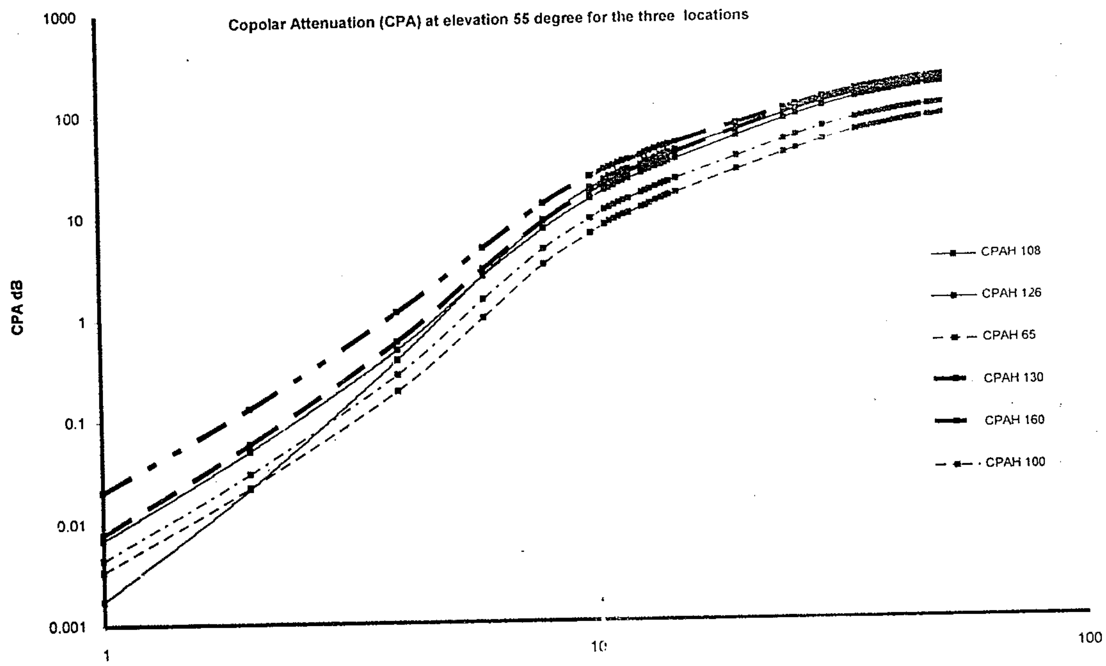

Fig 9: Copolar attenuation for the three tropical stations, CPAH horizontal polarization

Ile-ife ma=108 mwm=130mm/h, Douala ma=126 mwm=160mm/h,Nairobi ma=65, mwm=100mm/h

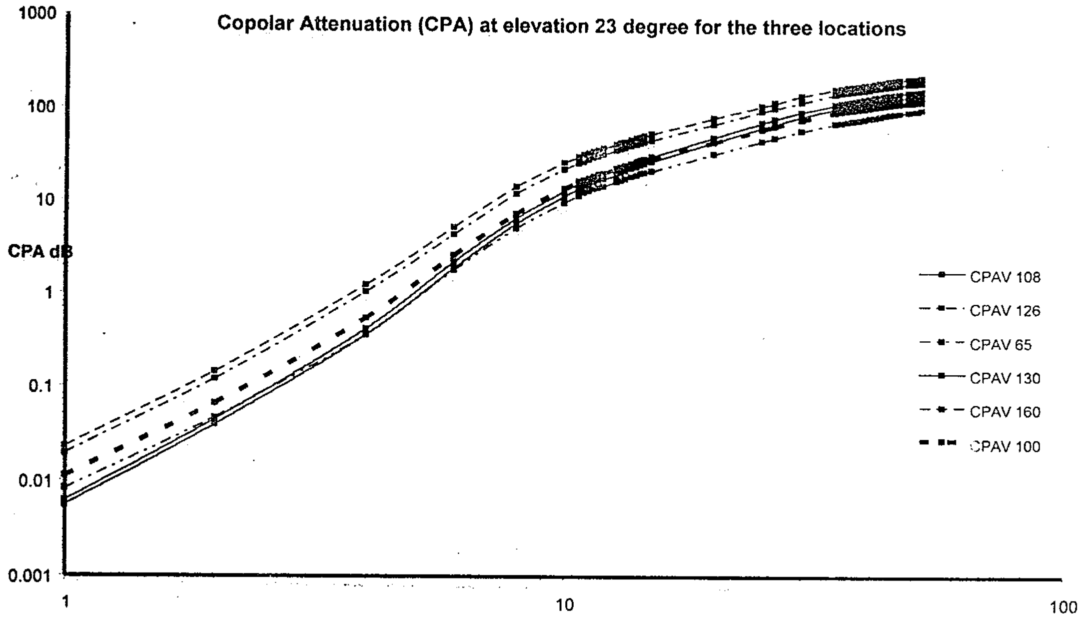

Fig 10: Copolar attenuation for the three tropical stations, CPAV vertical polarization Ile-ife ma=108 mwm=130mm/h, Douala ma=126 mwm=160mm/h,Nairobi ma=65, mwm=100mm/h

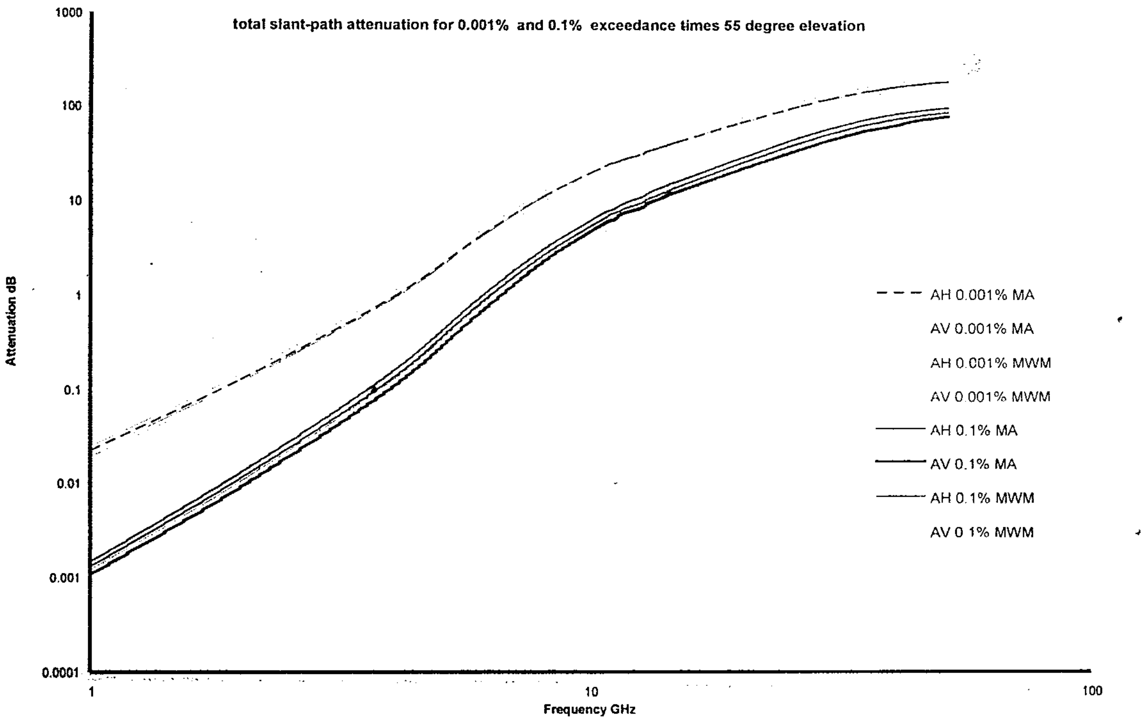

Fig. 11:

The results of the co - polar attenuation (CPA) for Cameroon and Kenya were compared with Nigeria; the result shows that the predicted CPA of Cameroon is generally higher than Nigeria. At elevation angle of 55^0, the CPA using the mean annual rain rate in Cameroon is higher than Nigeria by about 13 % at frequencies higher than 10 GHz. It is lower in Kenya by about 54%. Using the mean worst month rain rate, Cameroon is higher by about 16 % at frequencies above 5 GHz, whereas it is lower in Kenya by about 26%. The higher rain rate in Cameroon in addition to the higher total rainfall is responsible for this difference. At lower elevation angle of 23^0 and at frequency higher than 10 GHz, using the mean annual rain rate, Cameroon is higher than Nigeria by about 13%, it is lower in Kenya by about 44 %. Using the mean worst month rain rate, at frequency higher than 10 GHz, Cameroon is higher than Nigeria by about 15% at frequency of 10 GHz and it is lower in Kenya by about 26 % for the same frequency. The higher rain rate in Cameroon in addition to the higher total rainfall is responsible for this difference.

Scaling Formulation

So far the results presented are for rain rate exceeded for 0.01% of time XPD, CPA and slant path attenuation. Sometimes the slant path attenuation may be needed for the other time percentages, scaling formula for estimating the total slant path attenuation for other time percentages unavailability in the range 0.001% to 5% as published in the ITU – Recommendation P. 618 – 6 was used to predict the total slant path attenuation for other time percentages unavailability such as 0.001% and 0.1%. For other exceedance % times, the attenuation for other % of time is estimated in terms of the attenuation exceeded for 0.01% of time. Results are presented for exceedance times of 0.001% and 0.1%, which are also sometimes relevant to propagation studies Fig 11(shown only for Ife-ife.)

Conclusion

This study presents the theory and evaluation of some rain induced cross-polarization effects on satellite telecommunication in three tropical locations Nigeria, Cameroon and Kenya. In order to account for rain induced differential attenuation and phase shift, the oblate spheroidal raindrop shape is assumed and the frequency range of the study is 1–52 GHz (including 26 practical frequencies). The tropical raindrop size distribution model was used. The power law regression parameters "a and b" and "h and k "calculated by Ajayi (1985) were used to calculate the specific attenuation and phase shift. The result of the specific attenuation was then used to evaluate the total slant path attenuation for 0.01% of time unavailability or exceedance time (99.99% availability). Also the result of the specific attenuation was used in the evaluation of the Co – Polarized attenuation (CPA) using the Mean Annual (MA) and Mean Worst Month (MWM) rain rates and at two elevation angles 23^0 and 55^0. The results of specific attenuation and phase shift were then used in calculating the differential attenuation and phase shift and their normalized components with respect to the vertical attenuation. The results of the differential attenuation and phase shift were used to calculate the Cross–Polarization Discrimination (XPD). The values of the predicted CPA, and XPD for Cameroon, and Kenya were compared with Nigeria. The results show that the predicted slant path attenuation, CPA, and XPD at elevation angle of 55^0 for Cameroon are within about 24% of that for Nigeria when the MA rain rate exceeded for 0.01% of time is used. It is about 36% when the MWM rain rate exceeded for 0.01% of time is used. At the elevation angle of 23^0, the values are unusually high and are about 1136% and 466% respectively.

Recommendations

In the framework of brotherliness and for the purpose of quick integration and expansion of telecommunications services in the region, further studies are recommended particularly in Cameroon where there is a dearth of information on propagation studies. There is very little interaction between or cooperation between scientists in radio communication in these regions, therefore an intergovernmental platform can be created to bring researchers in these countries together for the development of Africa. Furthermore, the available experts in Nigeria can be encourage to assist their colleagues in Cameroon and Kenya to measure and analyze propagation parameters relevant to Earth-space communication in their region. This is with the view to improving the quality of telecommunication deliverables across the region.

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