Investigation of Depolarization and Cross Polarization over Ku-band Satellite Links in a Guinea Savanna Location, Nigeria

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Abstract

In communication systems engineering, designers tend to optimize the channel capacity of radio links through frequency re-use by deploying dual independent orthogonally polarized channels in the same frequency band. Such frequency re-use techniques via linear or circular polarization are severely impaired by the interference of cross-polarized signals, because the energy from one polarization is transferred to the other orthogonal state. Depolarization effects on satellite links are described in terms of cross polar discrimination (XPD). The parameters mainly responsible for causing depolarization at Ku-band due to scattering by oblate spheroid raindrops were computed from satellite beacon footprint data. Measured data from Ku-band, EUTELSALAT (W4/W7) at a frequency of 12.245 GH_Z and elevation angle of 036^0 E over Jos (9.8965^0 N, 8.8583^0 E, 1192 m) were analyzed. Also the distribution of one minute rain rate was obtained from Davis Vantage Vue weather station. These data were applied to the ITU-R procedure in recommendation 618-7, to estimate the cross polarization discrimination due to rain on earth satellite path. Result gave useful models and thresholds values for radio communication planning in the region For positive values of XPD, threshold of rain rate was 37mm/h, while the threshold for co-polar attenuation was found to be 6.7 dB. Also, the results showed very low XPD values of about -100dB, indicating that very high incidences of interference and cross talks occur in the region; and inhibits frequency re-use in Guinea Savanna region of Nigeria.

Keywords: Guinea Savanna region, Ku- frequency band, Depolarization, Cross polarization discrimination (XPD).

1. INTRODUCTION

Signal depolarization inhibits the re-use of the frequency of systems with two orthogonal channels for radio communication. Depolarization of satellite signal are caused by the anisotropy of the propagation medium due to the oblateness of raindrops and the melting layer along the earth space propagation path. It is due to the non-spherical symmetry of the raindrops (the top and bottom are flattened), along with their tendency to have a preferred orientation. Depolarization results in cross talk between two orthogonal polarized channels, transmitted on the same path and frequency band (Kaustav and Animesh, 2011). Signal depolarization inhibits the re-use of the frequency of systems with two orthogonal channels for radio communication. Cross polarization discrimination (XPD) indicates the isolation between the two communication channel with orthogonal polarization (Barclay, 2003) and may be used to measure the effect of depolarisation interference. A high value of XPD implies less interference, while low values of XPD signify high occurrences of interference (Muhammed *et al.*, 2011). The attenuating effects of rain on RW propagation may be traced to the micro-physical characteristics of rain, such as rain intensity (Durodola et al., 2017), velocity (Oguchi, 1994), size (Ajewole et al.,, 1999; Roddy, 2006), shape (Garg and Nayar, 2002) and canting angle (Rytir, 2009; Animesh, and Arpita, 2011) among others. Thus, the amount of rain depolarisation depends on rain rate, signal frequency, size, shape and the relative orientation of the rain drops (Appolito, 1981).

1.1 Rain Shape

Garg and Nayar (2002) demonstrated that the shape of the rain-drop varies from spherical to oblate spheroid as it drops from the sky and increases in size. The Raindrop changes shape as it falls from the sky in the presence of drafts and aerodynamic forces. This change in shape is responsible for the depolarisation effect of rain on radiowaves as they propagate through the atmosphere. Raindrops less than 1 mm in size are not severely distorted and are therefore modelled as spheres. Oguchi (1973) described the deformation from sphericity with the empirical linear expression in equation (1):

$$\frac{a}{b} = 1 - \frac{0.41}{4.5} a_0 \qquad (1)$$

where, a and b are the semi-minor and semi-major axes of the raindrop, and a_0 is the equi-volumic radius in mm. Equation (1) was used by Ajewole (1997) to compute various phase shifts, scattering and attenuation parameters of tropical rainfall for frequencies between 1 and 100 GHz in Nigeria.

1.2 Rain Canting Angle

Canting angle of the rain drop is defined as the angle between the major axis of the drop and the local horizontal, denoted as **ξ,** in Figure 1. It is important for the determination of depolarisation characteristics of rain. Due to aerodynamic forces around them, non-spherical raindrops wobble, change orientation, and cant away from the vertical and remain on axial orientations different from the vertical, as shown in Figure 2(c). The canting angle for each raindrop is different and constantly changing as it drops to the ground, varying from -15^o to +15^o with a mean canting angle of +7^o. The distribution in channels is usually modelled as a deterministic or a stochastic distribution with a mean and standard deviation. The aerodynamic forces are more severe in convective types of rain and so they experience greater depolarisation effects. For modelling rain depolarisation, a canting angle distribution is obtained and the cross-polarization discrimination (XPD) is computed using the mean value of the canting angle.

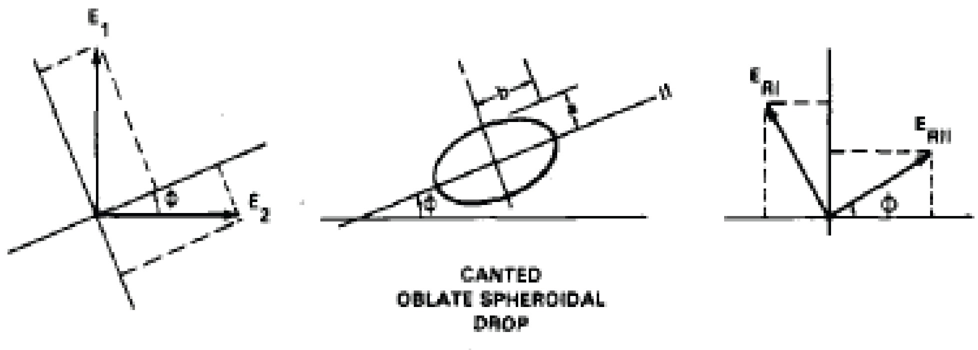
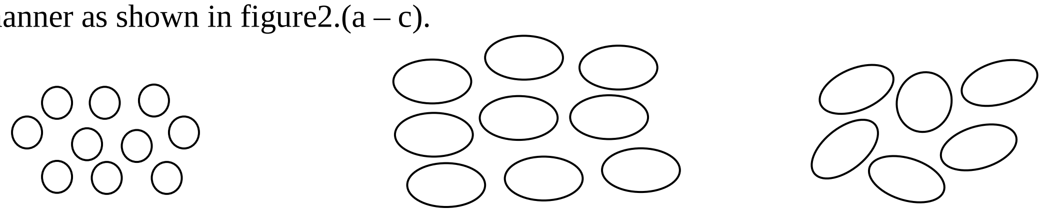


Figure 1: Canting effect of deformed raindrop: Vector relationship for a depolarizing medium. a) co- and cross-polarized waves for linear transmission and b) classical model for a canted oblate spherical rain drop. (Appolito, 1981).

2.0 DEPOLARIZATION DUE TO RAIN

The orientation of the line of electric flux in an electromagnetic field is referred to as wave polarization; while a change in the orientation of the electric field of satellite signal is termed depolarization. Depolarization is induced by rain and multipath propagation. While multipath induced depolarization is limited to terrestrial links, depolarization on satellite paths is caused by rain and ice. The wave while passing through the anisotropic medium experiences attenuation and phase shift that alters its polarization state. Ajewole (1997) computed various phase shifts, scattering and attenuation parameters of tropical rainfall for frequencies between 1 and 100 GHz in Nigeria.

During rainfall, as rain gets more intense the size shape and orientation of the raindrop varies as shown in Figure 2. Consequently, rain drop size distribution (DSD) plays major role in determining satellite signal depolarization (Senzo, 2014). When a radiowave propagates through a non-spherical hydrometeor, the rain drop changes the polarization of the radiowave. Rain depolarisation refers to the deformity experienced by the RW signal passing through falling raindrops. Small raindrops are spherical in shape, but as the raindrops grow larger, they become oblate spheroids (flattened underneath by air-resistance opposing the downward movement of the drops). Also the axis of symmetry of symmetry of the drop is vertical, for vertically falling raindrops, but aerodynamic forces cause some canting and tilting of the drops in a randomized manner as shown in figure2.(a – c).



a) Small rain-drops are spherical

b) Larger rain-drops are flattened by air resistance

c) Raindrops with randomized canting/tilting angles due to aerodynamic forces

Figure 2: Variation in raindrop size, shape and angle during rain events (Roddy, 2006)

2.1 Cross-polarization due to rain

Some communication systems use orthogonal polarization to isolate between channels. Heavy rainfall will alter the polarization of the transmitted wave by generating an orthogonal component and introduce a cross-polarized component, which may disrupt system performance. Figure 2(b) and 2(c) show large raindrops that are oblate-spherical in shape, flattened at the bottom, falling with their major axis almost horizontal at various canting angles. The horizontal component of the wave will be more attenuated when it propagates through the rain. In Figure 3 are the horizontal and vertical components of the resolved radiowave, and the consequent change in its polarization (Rytir, 2009).

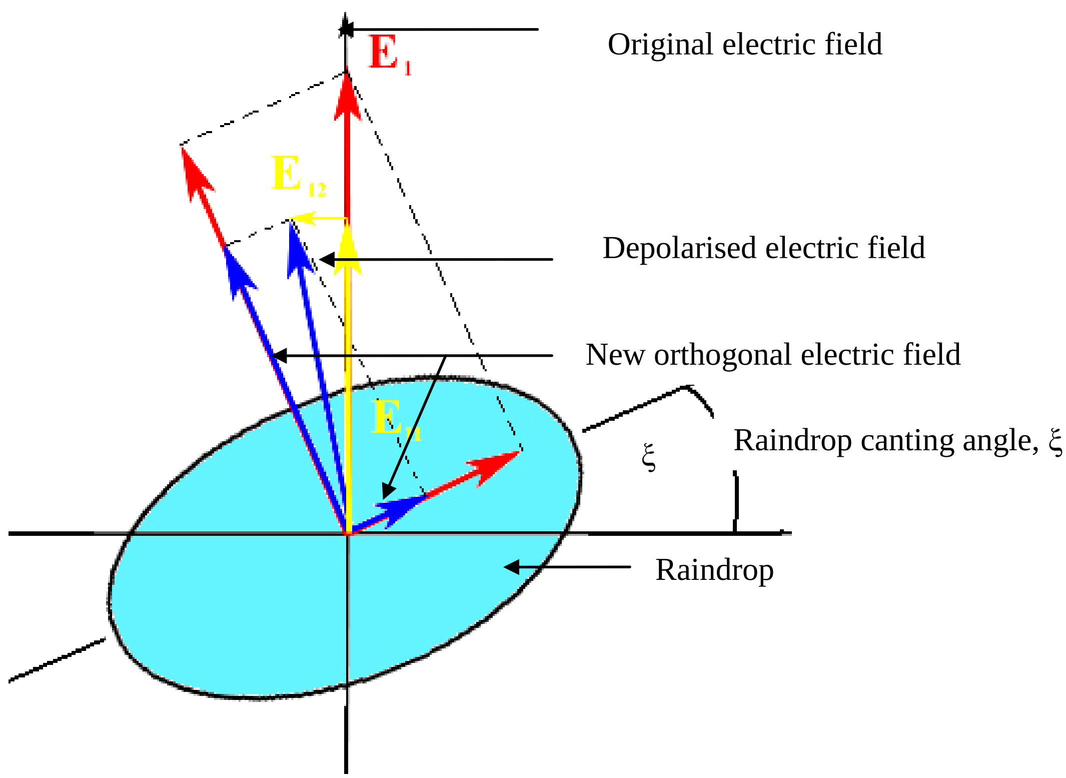


Figure 3: Depolarization of signal E_1, through an oblate shaped raindrop (Rytir, 2009)

As two orthogonal vectors $\boldsymbol{E_1}$ and $\boldsymbol{E_2}$ propagate the rain filled medium in figure 4, cross polarisation of each vector towards the other component occurs. As such, power is transferred from desired polarization state to the undesired orthogonal polarization state, resulting in interference and crosstalk. Depolarisation degradations such as crosstalk and interference are most common with horizontal and circular polarization, because of the differential attenuation and differential phase shift experienced with non-spherical raindrops along the radio path

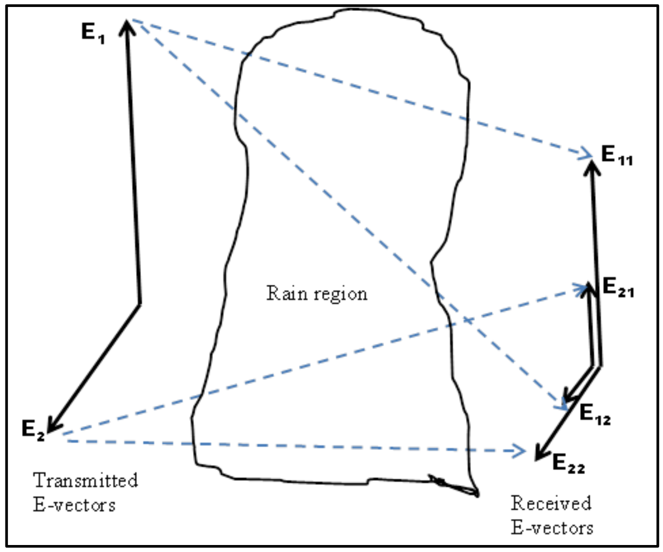


Figure 4: Cross-polarization of radio-waves due to depolarization through a rain region

Equations describing *cross polarisation discrimination* (XPD) are derived from Figure 4 and measured in dB as the power ratio of the wanted (co-polar) to the unwanted (cross-polarized). This is define mathematically as:

$$XPD = 20\log\left[\frac{Magnitude\ of\ Co-polar\ component, E_{11}}{Magnitude\ of\ Cross-polar\ component, E_{12}}\right] \quad (2)$$

$$XPD = 20\log_{10}\left|\frac{E_{11}}{E_{12}}\right| = 20\log_{10}\left|\frac{E_{co}}{E_{cross}}\right| \quad (3)$$

With respect to the co-planar attenuation, the cross-polarisation discrimination may be expressed in terms of the radio-path dependent parameters U and V:

$$XPD = U - V\log A \quad (4)$$

Where: U and V are dependent on frequency, f, elevation angle, θ, and canting angle, ξ (See Figure 3). XPD is evaluated for both horizontal and vertical polarizations.

$$XPD_H = 20\log\left[\frac{(1-G)\tan\vartheta}{G+\tan^2\vartheta}\right] \quad (5)$$

$$XPD_V = 20\log\left[\frac{(1+G)\tan\vartheta}{1+G+\tan^2\vartheta}\right] \tag{6}$$

Where: ϑ is the canting angle and G is the differential propagation factor for terrestrial and satellite links are defined as:

$$G = \begin{cases} exp[-(\Delta A + j\Delta\emptyset)L \times \cos^2\varphi]; & terrestrial \\ exp\left[-(\Delta A + j\Delta\emptyset)L \times \frac{1}{2} \times (\mathrm{e}^{-2\sigma'^2}\cos 2\varphi)e^{-2\sigma^2}\right]; & satellite \end{cases} \tag{7}$$

Where: θ is the elevation angle of the signal, which is 0^o for terrestrial; σ' is the standard deviation of the angles; and σ is the standard deviation of the canting angles, which is 0^o for terrestrial and 10^o for satellite paths. The symbols ΔA and $\Delta\emptyset$ are differential attenuation and phase shift defined by Ajewole (1997) as:

$$\Delta A = A_H - A_V \tag{8}$$

$$\Delta\emptyset = \emptyset_H - \emptyset_V \tag{9}$$

Radio propagation equipment required for empirical determination of these phase shifts, scattering and attenuation parameters are not readily available. However, Muhammed *et al.*, (2011) derived equations to compute cross polarization discrimination (XPD) from rain attenuation, which was expressed as:

$$XPD = U - V log_{10}(A) dB \tag{10}$$

Where,

$$U = 30\log(f) - 40\log(cos\theta) - 10log\, {}^1\!/_2\, \left(1 - cos(4T)\right)e_m^{-k^2} \tag{11}$$

and θ is the satellite elevation angle, T is the local polarization tilt angle, k_m^2 relates to the variance, σ of the canting angle distribution ($k_m^2 = 0.0024\,\sigma_m^2$). Equations (2 to 11) are similar to the procedure prescribed ITU-R P. 618-7 (2001) for computing rain XPD for circular, vertical and horizontal polarizations of transmitted waves (Muhammed *et al.*, 2011). The ITU-R P.618-7 (2001) procedure was therefore to compute the rain XPD in the region (See section 3.1).

3.0 EXPERIMENTAL SITE AND METHODOLOGY

The measurement taken at experimental sites are described in Durodola et al, 2017. Table 1 presents the characteristics of the experimental site and the parameters for the Ku-band satellite receiver at location. The experimental set up was used to concurrently measure and record rain-rate, rain attenuation, signal loss, at the locations. The rainfall rates were used to formulate a models that relates the distribution of rainfall intensities to the impairments caused by rain depolarisation on line of sight (LOS) satellite links in Northern Guinea Savanna location in Nigeria.

Table 1: Characteristics of the experimental site and specification of parameter for the Ku-band link

Measurement site	Unijos, plateau state (9.8965^0 N, 8.8583^0 E; 1192 meters)
Climate region of the site	Guinea Savanna
Max / Ave / Min Temperatures	29.8^0C / 22.8^0C / 07^0C
Satellite Name/ Number	Eutelsalat; W4/ W7 (DSTV Multi-choice)
Satellite signal frequency / Polarization	12.245GHz / Horizontal
Symbol rate	27, 509bps
satellite elevation (orbital)	036E
Satellite Geo-station Lookup	056.5E
Antenna diameter	90cm
Rain Equipment / Integration time	Davis Vantage Vue Integrated Sensor Suite (ISS) weather station and Weather Link

3.1 Procedure for XPD Calculation (ITU-R, P. 618-7, 2001)

Parameters needed to calculate long-term statistics of depolarization from rain attenuation statistics include:-

A_p: rain attenuation (dB) exceeded for the required percentage of time, *p*, for the path in question, commonly called co-polar attenuation (CPA)

τ: tilt angle of the linearly polarized electric field vector with respect to the horizontal (for horizontal, vertical and circular polarizations use $\tau = 0°$, 90° 45° respectively)

f: frequency (GHz)

θ: path elevation angle (degrees).

ITUR P. 618-7 (2001) used five basic components to be computed to arrive at the value of XPD due to rain as expressed by equation (12). These include frequency-dependent factor C_f, attenuation factor C_A, polarization factor C_τ, elevation factor C_ϑ and canting angle factor C_σ.

Rain XPD not exceeded for *p*% of the time is given as:

$$XPD_{rain} = C_f - C_A + C_\tau + C_\theta + C_\sigma \quad \text{dB} \qquad (12)$$

Where, the frequency-dependent term is:

$$C_f = 30 \log f \qquad \text{for } 8 \le f \le 35 \text{ GHz} \qquad (13)$$

The rain attenuation dependent term is:

$$C_A = V(f) \log A_p \qquad (14)$$

Where, $V(f) = 12.8 f^{0.19}$, for $8 \le f \le 20$ GHz

Polarization improvement factor is:

$$C_\tau = -10 \log [1 - 0.484 (1 + \cos 4\tau)] \qquad (15)$$

Where, $C_\tau = 0$ for circular polarization and reaches a maximum value of 15 dB for horizontal and vertical polarizations respectively. The elevation angle-dependent term is:

$$C_\theta = -40 \log (\cos \theta) \qquad \text{for } \theta \le 60° \qquad (16)$$

The canting angle dependent term is:

$$C_\sigma = 0.0052\, \sigma^2 \qquad (17)$$

Where, σ is the standard deviation of the raindrop canting angle distribution, expressed in degrees; σ takes the value 0^o, 5^o, 10^o and 15^o for 1%, 0.1%, 0.01% and 0.001% of the time, respectively.

4.0 RESULTS AND DISCUSSION

Figure 5 presents the cumulative distribution of one minute rain rate over Jos (September 2013 – September 2017). It can clearly be seen that the higher rainfall intensities occur between for 0.01 and 0.001% and it is during such times that maximum attenuation due to rainfall can be

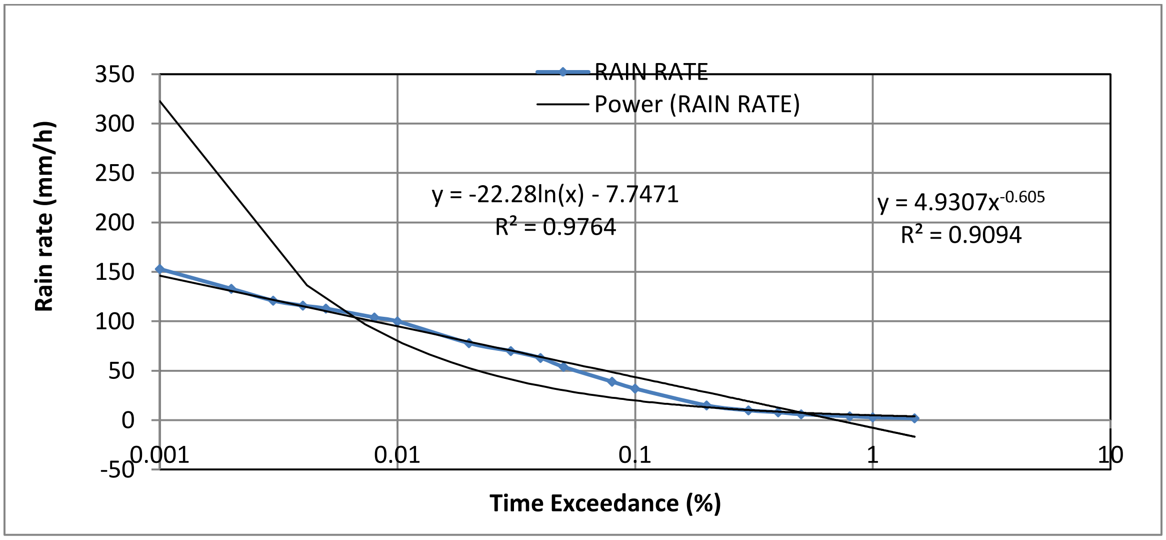


Fig.5. Distribution of rainfall intensities in Jos

best estimated. Also Figure 5 indicates that the distribution of rainfall intensities, R_p at a specified percentage of time, *p%* could be adequately modelled with a logarithm expression in equation (18) having an agreement factor of 98%:

$$R_p = -22.3\ln(\mathrm{p}) - 7.75 \quad (18)$$

On the other hand, modelling rainfall intensities with the power law model produced a lower agreement factor of about 91%.

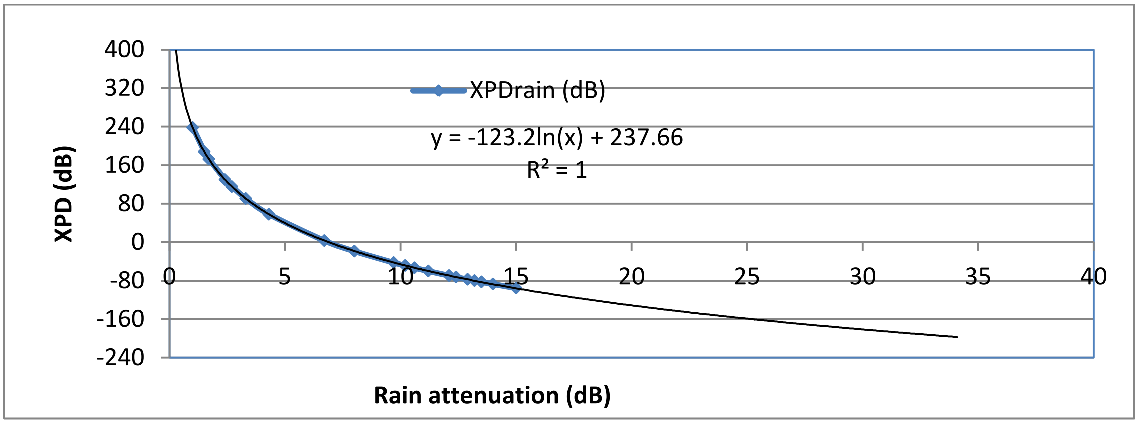


Fig. 6: Variation of Cross Polarization Discrimination (XPD) with Rain Attenuation (C_A)

Figure 6 shows the variation of the XPD with rain attenuation exceeded for the required period of time, often called the co-polar attenuation over the elevation angle at 12.245 GHz. The cross polarization discrimination degrades with increasing co-polar attenuation. The logarithm model in Figure 6 clearly shows that the signal degradation as a result of XPD is more enhanced by CPA for given fade as seen in the negative slope (or coefficient = -123) of degradation in equation (19).

$$XPD_{rain} = -123\ln(\mathrm{A_p}) + 234 \quad (19)$$

When $XPD_{rain} = 0$, $A_p = e^{1.9} = 6.7\,dB$ (20)

Since the relationship between XPD_{rain} and CPA has a perfect correlation of $R^2 = 1$, equation (19) could be used as a perfect model for deriving rain induced XPD at any given level of attenuation in the region.

Equation (20) indicates that XPD_{rain} will be completely degraded to zero, when the co-polar attenuation reaches 6.7 dB in the location. This means that the amount unwanted cross polarized signals equals the wanted signal and the signal is completely overshadowed by interfering signals and crosstalk within the orthogonal frequency band. This scenario creates undesirable degradation in the channel that demand for development of mitigation techniques.

Also Figure 6 shows negative values of rain-induced XPD for attenuation values above 6.7 dB. This implies that the values of unwanted cross-polarized signals, (interference and crosstalk) are higher than the level of the desired signal. At such instances only the crosstalk and interferences are received at the receiver station of the satellite link. It is desirable to develop mitigation techniques to arrest such degradation.

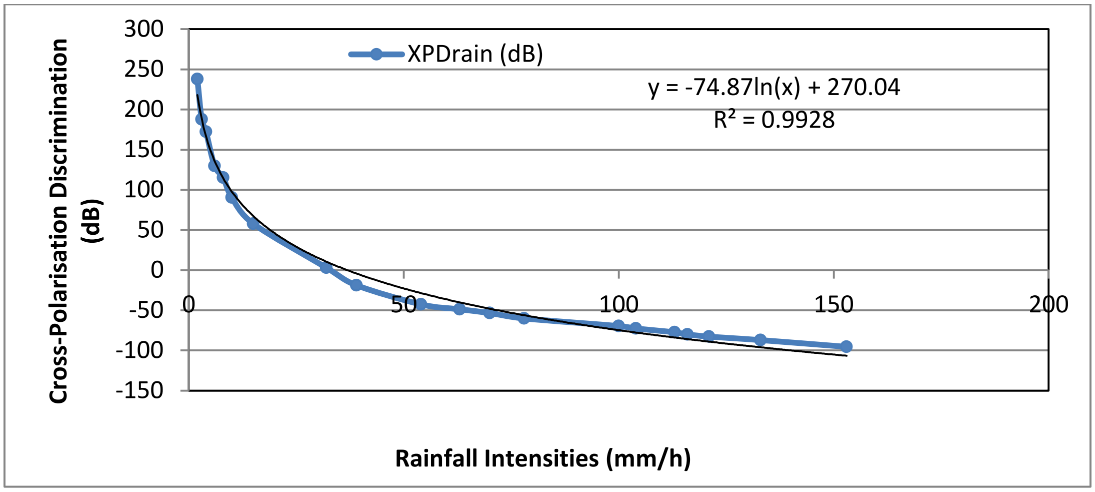


Fig. 7. Variation of Cross polarization discrimination (XPD) with Rain rate

Figure 7 show the variation of XPD with rain rate at 12.245 GHz. As rain rate increases, XPD decreases. This results in very high interference level in the orthogonal channels. A relation was observed between the XPD and rain rate, which showed an almost perfect fit of 99%, as seen in logarithm expression in equation (21):

$$XPD_{rain} = -75\ln(R_p) + 270, \qquad R^2 = 0.99 \qquad (21)$$

When $XPD_{rain} = 0$, $R_p = e^{3.6} = 36.6$ mm/h (22)

The implication of equation (22) is that when rainfall intensities of about 37 mm/h, interferences and crosstalk become prevalent at the receiver end of the Ku-link and communication is completely impaired. Mitigation techniques must therefore be implemented to cater to cross-polarization defects and improve throughputs of the link.

Consider the temporal distribution of cross-polarization over Jos, Figure 8 shows that all percentages of time above 0.1% experience positive cross polarization, while all finer percentages of time below 0.1 % experience negative cross-polarization. As explained earlier, a negative value of XPD means that unwanted interference and crosstalk are prevalence in the region. The operations of most satellite links are significant at finer time percentages between 0.05 and 0.001 for acceptable quality of service; but this is the period when degradation (crosstalk and interference) is most prevalent. Thus, in the Guinea Savanna region of Nigeria, it is difficult to optimize the channel capacity of radio links through frequency re-use by deploying dual independent orthogonally polarized channels in the same frequency band.

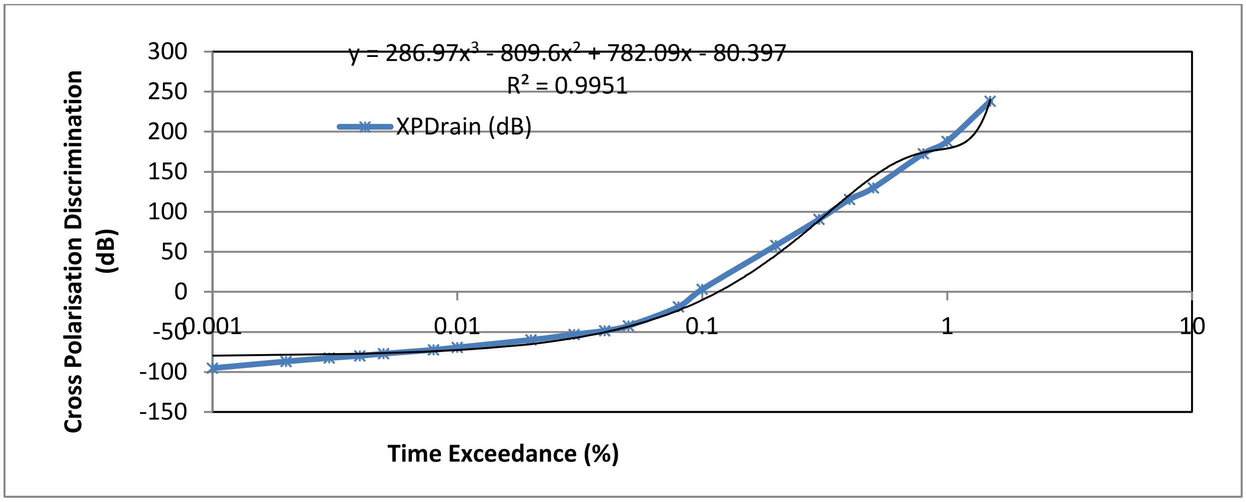


Fig. 8: Temporal distribution of Cross Polarization Discrimination (XPD) over Jos

5.0 CONCLUSION

This paper present some features of propagation phenomena observed with a Ku-band signal over earth space path. These data were applied to the ITU-R procedures in recommendation 618-7 (ITU-R,2001) to estimate the cross polarization discrimination due to rain on earth satellite path. From the results, simple logarithm equations were derived to relate XPD to rain rates, rain attenuation and percentages of time. Threshold of rain rate for positive values of XPD was 37mm/h, while the threshold for co-polar attenuation was found to be 6.7 dB. These values are useful for radio communication planning in the region. Finally, results obtained show that negative values of XPD value of about -100 dB occurred. which imply very high incidences and cross talks are prevalent in the region. As such frequency re-use is difficult in Guinea Savanna region of Nigeria.

6.0 ACKNOWLEDGEMENT

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