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PREDICTION OF CROSS POLARIZATION DISCRIMINATION AT MILLIMETER WAVE BAND DUE TO DUST STORMS

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ABSTRACT

Microwave links performance during dust storms has received considerable interest in recent time with emphasis on signal attenuation. However, phase shift and cross polarization have not been tackled enough. This paper investigates the cross polarization discrimination (XPD) induced by dust storms at millimetre wave band. It introduces simple models of wave propagation through dust storms. The models are developed based on the forward scattering amplitude of dust particles using Rayleigh method. Three conditions are set to validate the suitability of the Rayleigh approximation for the model. It is shown that the method is valid for determining the scattering of ellipsoidal dust particles for the particle sizes and frequency range considered. The scattering coefficients are derived and mathematical models for phase shift and attenuation are proposed in terms of relative permittivity and visibility. Results of the proposed model compared with some published results show close agreement. Differential phase shift and attenuation are computed and XPD introduced by dust storms in such links are predicted using the model parameters as inputs. Attenuation in dry dust is only significant when the visibility becomes severe. XPD at such visibility also becomes significant i.e. numerically low. A similar trend is found as the frequency increases.

Keywords: cross polarization, millimetre wave, dust storms, differential attenuation, Rayleigh approximations, differential phase shift, wave propagation.

1. INTRODUCTION

Two orthogonal polarizations can be used to make the optimum use of frequency spectrum. The method of transmitting two separate polarizations while using the same frequency to increase channel capacity without increasing bandwidth has become an attractive technique at conventional or higher frequencies. This has received much attention in the literature. Furthermore, increasing attention is being paid to millimetre wave (MMW) bands because of the congestion of the radio spectrum in the lower frequency ranges. However, the very difficult propagation conditions at higher frequencies make this technique a challenge to microwave system engineers who are interested in signal degradations such as fading-outages (attenuation), cross polarization and interference due to scatter [1].

It is imperative to consider all potential sources of signal degradations in order to achieve an optimum design of a system. An electromagnetic wave propagating through a dispersed dust particles experiences attenuation and phase shift (rotation) that are capable of causing communication system outages [2-7]. Differential attenuation and phase shift occur when orthogonal communication channel passes through dust particles. This is apparently because the dust particles are not spherical in shape [1] but eccentric.

A number of investigators have presented models to compute microwave attenuation in dust storms. [2-3], [8-9]. These investigators concluded that attenuation by dust storms is not serious except for very dense storms. It has also been shown [10-17] that complex permittivity, visibility and frequency have major impact on microwave propagation in dust storms.

Bashir *et al*., [18] were the first to calculate cross polarization in dust storm and found it to be dependent on shape of the particles. The problem of dust-induced cross polarization was also investigated by Ansari and Evans [3], Ghobrial and Sharief [4], McEwan and Bashir [19] as well as other investigators [20-22]. McEwan and Bashir [19] assumed all dust particles to be ellipsoids with axes ratios equal to the average axes ratios of some 100 particles that were studied using microscopic measurements. The results were given in terms of the relative volume occupied by dust. However, this quantity is difficult to directly measure in practice. Ghobrial *et al*., [4], gave a simple expression for the XPD for waves with circular polarization and calculated the cross polarization of microwave propagation in dust storms around 10 GHz. It was found that the cross polarization can have a significant effect on the wave propagation in dust storms. None of these investigators however tackled the problem of cross polarization beyond *X* band (i.e., wavelength, λ = 3 cm).

In this work, XPD in dust storm is treated at MMW bands. Rayleigh approximation method is validated for solving electromagnetic wave scattering at such bands. The scattering coefficients are derived and mathematical models for phase shift and attenuation in dust storm are proposed in terms of relative permittivity and visibility rather than mass of dust per unit volume of air. Visibility is readily measurable and is usually taken as the measure of storm severity. Lastly, the Rayliegh-scatterer approximation's results are used as inputs to XPD at MMW bands.

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2. METHODOLOGY

2.1 Application of Rayleigh approximation method to complex scattering

Scattering and absorption by dust particles can cause attenuation of radio waves [23]. Solutions to the exact integral expression of scattering amplitude function are difficult. The function depends on the local field inside the particle and its permittivity. However, the local field is generally unknown; hence, certain approximations like Rayleigh, Born, Wentzel-Kramers-Brillouin (WKB) etc. [24] are usually required to overcome the difficulty.

Rayleigh approximation method gives an analytical solution of Maxwell's equations for the scattering of electromagnetic waves by dielectric particles. The Rayleigh type of scattering occurs when the particle is electrically small. The scattering is a function of the electric polarizability of the particles. The method is validated for solving electromagnetic wave scattering at MMW bands. Firstly, the approximation is valid when the external field is homogeneous and continuous, which occurs if the particle radius, a satisfies the condition $a \leq 0.05\lambda$ (or $ka \ll 1$) in which λ is the wavelength and k is the propagation constant.

Another condition is that the incident field penetrates so fast inside the particle that the static polarization is established in a short time compared to the wave period. i.e., $k\,|\overline{m}|a \ll 1$, in which $\overline{m}$ is the particle refractive index [25]. Bashir [26] added that the Rayleigh approximation is valid when the phase is also homogenous. For the phase to be the same inside and outside the particle, $\frac{2\pi a}{\lambda}|\varepsilon - 1| \ll 1$; in which ε is the permittivity.

Setting 0.5 as the limit when defining much less than 1 [27] and the value of $\varepsilon = 3.8 - j0.038$ adopted from [19], the above three conditions are tested and implemented in this work. For instance, the values of ka and $k|\overline{m}|a$ even at 100 GHz are of the order of 0.2 and 0.4 respectively. The third condition holds for only the millimetric wavelength of the order of frequency less than 85GHz. In summary, these suggest the validity of Rayleigh approximation for dust particles up to 0.1 mm radius and frequency 85 GHz.

2.2. Microwave attenuation and phase shift

The definition of complex refractive index $\overline{m}$ of a scattering medium given by Van De Hulst, H. C. [28] is referred to for derivation of attenuation and phase shift of microwave propagation in dust storm.

$$\overline{m} = 1 - j2\pi k^{-3} N S(0) \tag{1}$$

in which $S(0)$ is the complex forward scattering amplitude function and k is the free space phase constant. The path is considered to be intersected by a slab containing many particles. Under the Rayleigh approximation, the complex forward direction scattering is

$$S(0) = jk^3 p_i \tag{2}$$

in which p_i is the complex polarizability.

The propagation constants depend on the shape of the scattering particles and their orientation relative to the wave polarization [18]. Considering the shape of the particles as ellipsoid and the particles orientation in such a way that the field is applied along one of the axes (i = 1, 2, 3), the polarizability is expressed [28] as

$$p_i = \frac{v}{4\pi}\psi_i \tag{3}$$

in which v is the volume of the ellipsoids ($v = \frac{4}{3}\pi a^3$) and

$$\psi_i = \left[l_i + \left(\frac{1}{\varepsilon - 1}\right)\right]^{-1} = \psi_i' - j\psi_i'' \tag{4}$$

in which l_i are three factors such that $l_1 + l_2 + l_3 = 1$
Therefore, (3) can be expressed as

$$p_i = \frac{v}{4\pi\left[l_i + \left(\frac{1}{\varepsilon - 1}\right)\right]} \tag{5}$$

Substituting (5) into (2),

$$S(0) = jk^3 . \frac{v}{4\pi\left[l_i + \left(\frac{1}{\varepsilon - 1}\right)\right]} \tag{6}$$

Chu [2] expressed the number of dust particles per cubic meter ($\# / m^{\uparrow}3$) as

$$N = \frac{\alpha_0}{6.5\left(\frac{4}{3}\pi a^2\right)} \tag{7}$$

in which α_0 is the optical attenuation coefficient (*dB/m*) and a is the radius of the particle. Substituting (6), (7) and the volume of ellipsoid into (1), the complex refractive index of scattering medium may now be expressed as

$$\overline{m} = 1 + \frac{\alpha_0 a}{13}\psi i$$

$$= 1 + \frac{\alpha_0 a}{13}(\psi_i' - j\psi_i'') \tag{8}$$

Therefore,

$$\mathrm{Re}\,(\overline{m} - 1) = \frac{\alpha_0 a}{13}\,\mathrm{Re}[\psi_i] \tag{9}$$

Multiplying (9) through by free space constant k, the phase shift, β_i, is obtained thus

ARPN Journal of Engineering and Applied Sciences

β_i = k Re (m^{-1})

$$= \frac{k}{13}\alpha_0{}^a \quad \mathrm{Re}[\psi_i] \; rad/m$$

$$= \frac{k}{13}\alpha_0{}^a \quad \mathrm{Re}[\psi_i] \left(\frac{180}{\pi}\right) \; deg/m \qquad (10)$$

Similarly, the attenuation, α_i , is thus obtained

α_i = k Im($\overline{m}$)

$$= -\frac{k}{13}\alpha_0{}^a \quad \mathrm{Im}[\psi_i] \; Np/m$$

$$= -\frac{k}{13}\alpha_0{}^a \quad \mathrm{Im}[\psi_i] \; (8.68) \; dB/m \qquad (11)$$

Equations (10) and (11) can be expressed in terms of volume fraction, v_f defined [2] as

$$v_f = \frac{4}{3}\pi a^3 N \qquad (12)$$

Substituting the value of α_0 (which can easily be obtained from (7)), (12), as well as the value of *k* into (10) and (11), the phase shift coefficient (β_i) and the attenuation coefficient (α_i) are obtained in terms of volume fraction.

$$\beta_i = 6\times 10^5 . f_{GHz} . v_f \; [Re(\psi_i)] \; [deg/km] \qquad (13)$$

$$\alpha_i = -9.0896\times 10^4 . f_{GHz} . v_f \; [Im(\psi_i)] \; [dB/km] \qquad (14)$$

in which f is the frequency (GHz), $Re(\psi_i)$ is the real part of the i-th value of the dielectric constant and $Im(\psi_i)$ is the imaginary part of the i-th value of the dielectric constant.

2.3. Visibility

The concentration number of particles per unit volume or volume fraction, v_f , is difficult to measure or obtain in dust storms. Meteorologically, dust storms are observed and majorly characterized using visibility. Therefore, our methods for evaluating phase shift and attenuation during dust storm are finally treated in terms of visibility which is more realistic.

A relation between visibility and dust concentration was given by Chepil [29], Gillett [30] and Goldhirsh [31]. The relations provide ease of application to a range of dust storms characteristics. Goldhirsh [31] defined the relative mass of dust per cubic volume of air and was given as

$$M = \rho_0 v_r \; [\text{Kg of dust}/m^3 \text{ of air}] \qquad (15)$$

in which v_r is the relative volume (also referred to as the volume fraction, v_f) and ρ_0 is the solid density of dust.

Similarly, the mass of suspending dust per unit volume of air was related to visibility by [30]

$$M = \frac{C}{V^{\gamma}} \qquad (16)$$

in which V is the visibility (km), C and γ are constants that depend on the type of land from which the storm originated as well as the climatic conditions. This suggests why different values of C and γ are employed by different investigators thereby leading to different value of M .

From (15) and (16),

$$v_f = \frac{\frac{C}{V^{\gamma}.1}}{\rho_0} \qquad (17)$$

If the values of C and γ are taken as 3.44×10^{-4} and 1.25 respectively [29], substituted into (17) and the resultant expression is divided by the value of solid density of dust ($2.65\times 10^3 \frac{kg}{m^3}$), volume fraction is obtained as expressed in (18).

$$v_f = \frac{1.297\times 10^{-7}}{V^{\gamma}} \qquad (18)$$

Finally, (18) is substituted into (13) and (14) and the expressions are given below, respectively.

$$\beta_i = (7.78\times 10^{-2})\left(\frac{f}{V^{\gamma}}\right)[Re(\psi_i)] \; [Deg/km] \qquad (19)$$

$$\alpha_i = -(1.18\times 10^{-2})\left(\frac{f}{V^{\gamma}}\right)[Im(\psi_i)] \; [DB/km] \qquad (20)$$

in which $Re(\psi_i)$ and $Im(\psi_i)$ are the real and the imaginary parts of the i-th value of the dielectric constant. i =1, 2 corresponds to horizontal polarization wave and i = 3 corresponds to vertical polarization wave. Therefore (19) and (20) are the expressions for the phase shift and the attenuation encountered by signal propagating through a dusty medium when the particle shapes are considered as ellipsoids.

3. CROSS POLARIZATION DISCRIMINATION

The particle drop distortion explains why the complex forward direction scattering, S (0), takes different values for horizontal and vertical polarizations. To this end, there exists differential phase shift and differential attenuation between these polarizations resulting in cross polarization. Since the two axes of the ellipsoidal particle are randomly oriented in the horizontal plane, the phase shift and the attenuation constants for horizontal polarization wave can be written as

$$\beta_h = \frac{\beta_1 + \beta_2}{2} \tag{21}$$

$$\alpha_h = \frac{\alpha_1 + \alpha_2}{2} \tag{22}$$

For vertical polarization wave, both the phase shift and the attenuation are unchanged and can be respectively expressed as

$$\beta_v = \beta_2 \tag{23}$$

$$\alpha_v = \alpha_2 \tag{24}$$

Against this premise, the differential phase shift and the differential attenuation between the vertical and horizontal polarizations is expressed thus

$$\Delta\beta = \beta_h - \beta_v \tag{25}$$

$$\Delta\alpha = \alpha_h - \alpha_v \tag{26}$$

The fact that attenuation and phase constants for vertical and horizontal polarizations in a given storm are not the same causes cross polarization to be induced. The XPD [32] for a circular polarized wave and a linear polarization of 45^0 wave propagating in a medium with suspending dust particles is given by

$$XPD = 20\log_{10}\left|\frac{1+\gamma}{1-\gamma}\right| \tag{27}$$

in which γ is the differential phase shift and differential attenuation between the channels (1/km) and can be determined for a wave propagating in a storm as

$$\gamma = e^{-(\Delta\alpha - j\Delta\beta)L} \tag{28}$$

in which $\Delta\alpha$ is the differential attenuation (Np/km), $\Delta\beta$ is the differential phase shift (deg/km) and L is the propagation path length in storm (km). Thus, XPD depends not only on the amount of dust in air or visibility but also on the shape as well as the orientation of the particles.

4. RESULTS AND DISCUSSIONS

4.1. Validation of the proposed model

The proposed model is validated and then implemented in this section. Meaningful comparison of data is often difficult since data obtained by different investigators are presented in different forms [25]. However, to overcome this problem and establish a comparison basis, the parameters are usually considered to vary around the reported data. For ease of setting attenuation as a function of visibility, Alhaider [16], Ahmed [25] and Goldhirsh [31] are chosen for the validation.

Alhaider [16] derived attenuation formula for microwave propagation in dust storms using ten-year visibility data. The formula is expressed in (29)

$$\alpha = \frac{0.189}{V_b}\frac{r}{\lambda}\frac{3\varepsilon''}{[(\varepsilon'+2)^2+\varepsilon''^2]} \tag{29}$$

in which λ is wavelength (m), V_b is the visibility in (km) and r is the particle radius in (mm). Rayleigh approximation was also used by Ahmed [25] to derive a general formula suitable for any particle size distribution for microwave propagation in dust storms which is expressed by

$$\alpha = 0.629 \times 10^3\left[\frac{FG''}{V_0}\right]a_e \tag{30}$$

in which F is the frequency (GHz), V_0 is the visibility (km), a_e is the effective particle radius (m) and G'' is the imaginary contributions of the relative dielectric constant of the dust particles. Goldhirsh [31] derived another attenuation formula for microwave propagation in dust storms as expressed

$$\alpha = \frac{2.317\times10^{-3}.\,\varepsilon''}{[(\varepsilon'+2)^2+\varepsilon''^2].\,\lambda}\cdot\frac{1}{V\gamma}\left[{}^{dB}/_{km}\right] \tag{31}$$

in which λ is the wavelength (m), V is the visibility (km), γ is a constant equal to 1.07 and ε' and ε'' are the real and the imaginary contributions of the relative dielectric constant of the dust particles, respectively.

To validate the proposed model, the calculations consider permittivity ε = 3.8 - j0.038 at 0% moisture content [19]. Thus (20) is validated against the published models using the vertical component. Figure-1 shows the comparison of attenuation in dust storms at frequency of 10GHz. An excellent agreement is observed among the models and this suggests a successful bench marking.

Of all the attenuation models considered, Alhaider model and Ahmed model produce a higher value of wave attenuation, and the calculated results show conformity. However, Goldhirsh model has a lower value of wave attenuation. More agreement of all the models is noticed as the visibility gets better.

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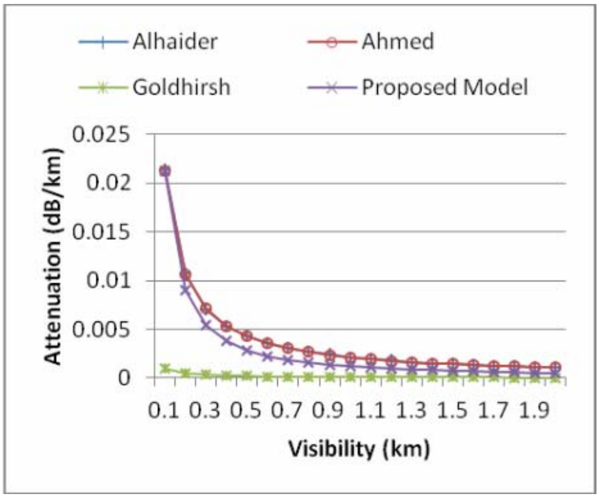

Figure-1. Proposed model validation.

4.2. Implementation of phase shift and attenuation model

Upon the validation of the proposed model, the phase shift and the attenuation components are thus implemented. Illustrative values of the phase shift and the attenuation are presented in Figure-2 for different visibility and frequency. Here, the calculation considers ellipsoidal particles with $l_1 = 0.2$, $l_2 = 0.3$ and $l_3 = 0.5$ [33]. In Figures 2(b) and 2(c), both vertical and horizontal phase shift and attenuation are illustrated respectively at frequency of 85 GHz. They show the relation with visibility to be linearly dependent. The wave attenuation generally decreases as the visibility improves. Least attenuation value is recorded at 1 km visibility and so very negligible. Another important result of the phase shift and the attenuation calculation is the linear dependence on frequency as shown in Figure-2(a).

It should be pointed out that the attenuation is worsened when severest storm situation is considered. In other word, at visibility less than 100 m as is the case in some regions that experience dust storm phenomenon. The attenuation could be very severe if 1 m visibility is calculated at 85 GHz.

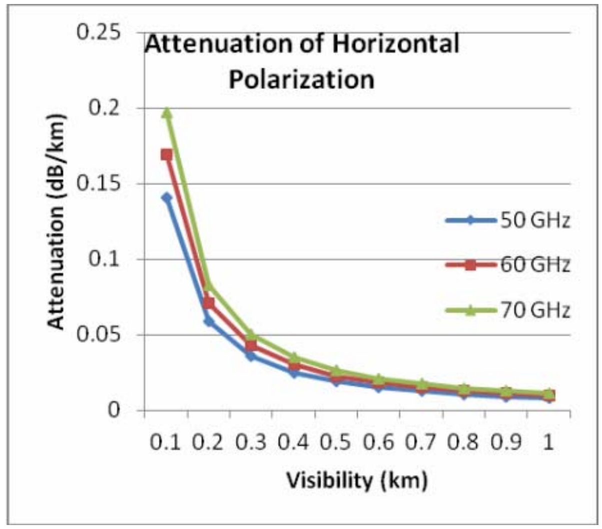

Figure-2(a). Attenuation of horizontal polarization wave at 50 GHz, 60 GHz and 70 GHz.

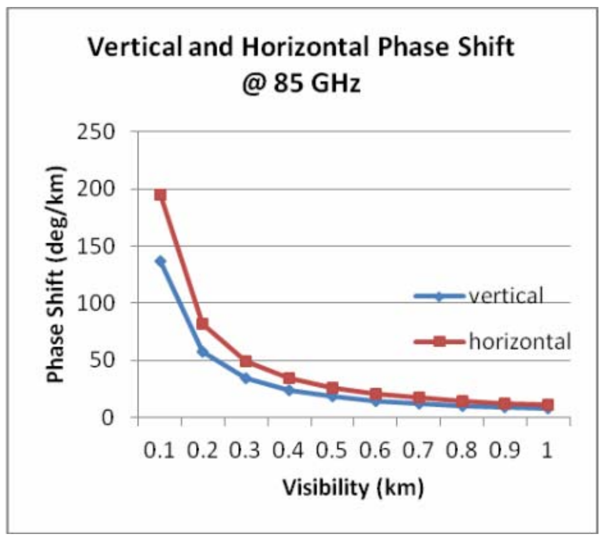

Figure-2(b). Phase shift of vertically and horizontally polarized waves @ 85GHz as a function of visibility.

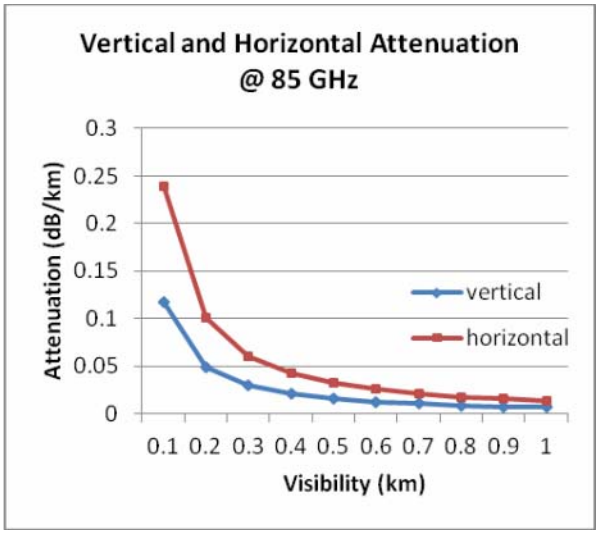

Figure-2(c). Attenuation of vertically and horizontally polarized waves @ 85GHz as a function of visibility.

4.3. Differential phase shift and differential attenuation

Prediction of XPD requires the determination of differential phase shift and differential attenuation. When particles are assumed to have ellipsoidal geometry, dust particles align with the shortest axis, vertical, under stationary air conditions. Cross polarization is induced by particles having such orientation. The differential phase shift and the differential attenuation which are inputs to XPD are calculated using (25) and (26). Figures 3(a) and 3(b) respectively give the differential phase shift and the differential attenuation at 50 GHz and 85 GHz for different values of visibility.

4.4. Cross polarization discrimination

Cross polarization discrimination (XPD) induced by dust storms at MMW bands is evaluated using the values obtained from the proposed mathematical formulation for the prediction of signal attenuation and phase shift. Using (27) and (28) and the results obtained from the preceding sections, XPD is evaluated for different visibilities. The XPD prediction is carried out for dry dust conditions and the result is presented in Figure-4.

From the calculated results, XPD due to dust storm depends on visibility, frequency and dielectric constant. Thus XPD is a function of both attenuation and phase shift. There is a linear relationship between XPD and visibility. Increase in visibility leads to an increase in XPD. Similarly, increase in frequency apparently results in an increase in the attenuation and in turn, lower values of XPD are obtained. This is when cross polarization is said to be severe.

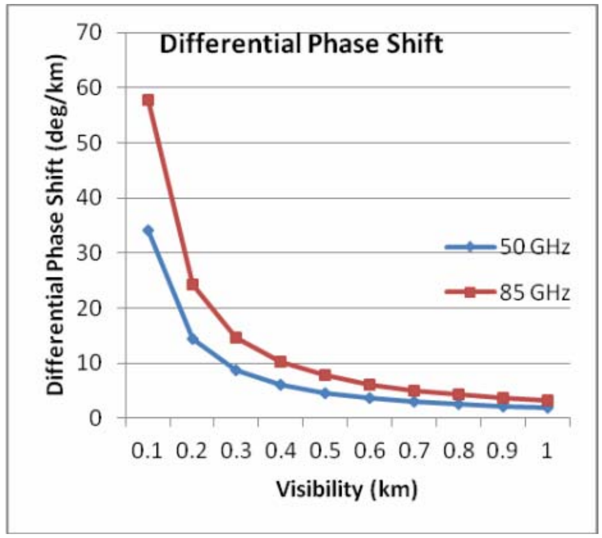

Figure-3(a). Differential phase shift between vertical and horizontal polarization.

It is seen that the variation in the evaluated XPD would be from 10 dB to 31 dB for the frequency between 50 GHz and 85 GHz, visibility between 0.1 km and 1km and along path link of 1 km. The severity of XPD becomes higher as the path length is increased.

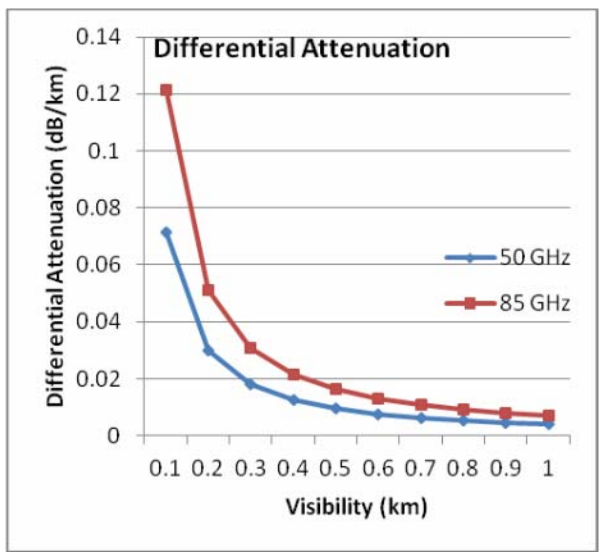

Figure-3(b). Differential attenuation between vertical and horizontal polarization.

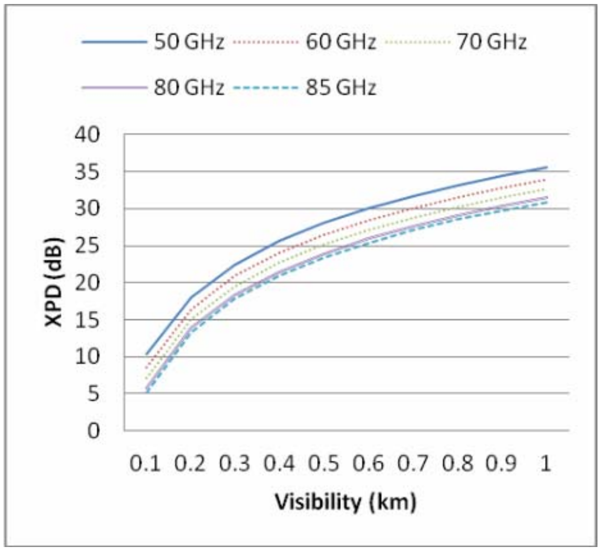

Figure-4. Cross polarization discrimination @ 1 km path length for 50 GHz, 60 GHz, 70 GHz, 80 GHz and 85GHz.

5. CONCLUSIONS

The cross polarization effect on the performance of the links during dust storm is seldom tackled at MMW bands despite the adoption of methods of transmitting two separate polarizations (linear or circular) while using the same carrier frequency to increase channel capacity.

In this work, it has been shown that the Rayleigh approximation is valid for determining the scattering of ellipsoidal dust particles for MMW bands. To this end, mathematical model as contained in (19) and (20) is developed to evaluate the phase shift and the attenuation of linearly polarized waves. The simple proposed model was derived in terms of visibility, frequency and dielectric constant. The phase shift and the signal attenuation caused by dust storm vary directly with the frequency and dielectric constant but are inversely proportional to the visibility. During severe dust storms, attenuation becomes significant but negligible as the visibility increases.

Perfect agreement is found between the proposed models and the published theoretical results. The results are used as inputs to the XPD prediction. The phase shift, the attenuation and the cross polarization introduced by dry dust storms have been estimated for different reference visibility. The attenuation increases from 0.004 dB/km to 0.07 dB/km when the visibility decreases from 1 km to 100 m at 50 GHz. Similarly, the attenuation varies from 0.07 dB/km to 0.12 dB/km for visibility range of 1 km and 100 m at 85 GHz.

Finally, it is found that circular and 45^0 linear cross polarization values in dry regions will not be significant even when visibility reduces to 100 m. They however become significant when visibilities fall below 100m over about 10km or below 10m over about 1 km of link path. At frequency of 50GHz, visibility of 100 m and 1 km path length, XPD of 10.3 dB is predicted. It can be concluded that for dry dust storm, the XPD is fairly good for use in dual polarization systems.

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