A Review of Microwave Cross Polarization in Sand and Dust Storms

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Abstract —This paper presents a review of cross polarization in sand and dust storms (SDS). Relevant past works have been identified and their contributions to microwave cross polarization have been highlighted. Attention was given to semi-empirical models since they are used most readily for statistical predictions in design applications. The cross polarization mechanisms and parameters are also presented as well as a discussion about the advantages and the constraints of some of the models and their methodologies. Modified cross polarization discrimination (XPD) models for both terrestrial and slant links are proposed. Besides, the gaps in knowledge are established and the outlook of this topic in future is also suggested.

Index Terms—Cross polarization, microwave, attenuation, phase rotation, cross polarization discrimination, sand and dust storms, propagation

I. INTRODUCTION

Most of the existing frequency spectrums are already crowded and demand for high data rate communication links is on the increase as the information age evolves. To address this challenge and meet the demand for high data rate, frequency reuse technique is being adopted [1], [2]. A dual polarization frequency reuse transmits two orthogonally polarized signals and independent data streams (using right-hand and left-hand circular polarizations). This scheme allows for optimal utilization of frequency spectrum. This concept however comes with some deleterious effects from precipitations such as dust, rain, ice etc.

One of the causes of depolarization especially on earth-satellite links is the presence of ice crystals in clouds at high altitudes. Unlike rain depolarization, ice depolarization is not accompanied with significant co-polarized attenuation. The rain effects have already received adequate attention by many researchers such as [3], [4]. Literature on rain have been considered in this review even though the emphasis of the review is on the dust effects because the precipitations exhibit strong similar characteristics.

The wave propagating in a non-spherical particle along a propagation path changes its polarization as it progresses [5], [6]. This results in cross-polar interference, a situation where a part of the propagated energy or power emitted in one polarization interferes with the orthogonally polarized signal. Depolarization changes a part of signal with a given polarization to a different polarization. When a left-hand circular polarization is depolarized, a small amount of the left-hand circular polarization wave energy interferes with the right-hand circular polarization wave energy. While the wanted polarization, i.e. left-hand circular polarization, is known as the co-polarization, the unwanted polarization i.e. right-hand circular polarization is known as the cross polarization (XP). Thus, a major problem posed by depolarization to dual polarization frequency reuse communication link is the drop in cross polarization isolation (XPI) and the cross polarization interference along the propagation path.

Another limiting factor to performance of communication systems is the cross talk between channels i.e. unwanted signal in the channel. Cross talk is a form of interference which depends on the isolation or discrimination between two polarizations. Thus, XPI or cross polarization discrimination (XPD) is a parameter for quantifying dual polarization frequency reuse link performance. The XPD is the ratio of energy levels of the wanted co-polarization signal to that of the unwanted XP signal. While the XPI appears to be frequently used in system design, the XPD is commonly used in propagation experiments. Both XPI and XPD are synonymously used in this paper.

A few dust parameters such as permittivity of dust particles, particle shape and sizes etc. are used as inputs to evaluate the effects of dust storms on microwave propagation. A comprehensive review of some of these parameters have been carried out [7], [8]. Dust-induced microwave attenuation has also been investigated [9]-[11]. The problem of dust-induced depolarization has also been investigated [12]-[14] and many more. However, this work is a review which describes the principles of approach and methodology of some of the existing investigations. Besides, their strengths and the drawbacks are highlighted, and a modified model is also proposed. The gaps in the existing knowledge and outlook for future are also given.

II. SAND AND DUST STORMS

Sand and dust storms (SDS) have been discussed by [7] and [15]-[16]. Particles driven by winds and that rarely

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rise higher than 2m are sometimes called sand storms. The diameters of sand storm particles are usually greater than 0.08mm and may be between 0.15mm and 0.3mm [15]. On the other hand, the diameters of dust particles are usually within the range of 10μm and 80μm. The fall speeds of such particles can obscure the sun for extended periods. When the visibility is less than 1km, it may be termed as dust storm, or referred to as severe dust storm if the visibility is below 500m. Further classifications and different types of storms are summarized in Table I. The classification is based on both the duration of the storm and the wind speed during storms. The Table I also presents other important characteristics and features of SDS such as visibility and height during storms.

TABLE I: SAND AND DUST STORMS CLASSIFICATION [7], [15], [16]

Types	Wind speed (m/s)	Height (km)	Visibility (km)	Duration (hrs)
Haboob	11 – 21.5	0.5 – 12	0.2 – 0.4	0.5 – 6
Dust devils	5 – 10	0.5 – 2	< 1	0.1 – 0.5
Diurnal wind cycle	8 – 12	< 1	0 – 1	< 1
Frontal	9 – 17	1 – 5	0 – 1	1 – 8

III. CROSS POLARIZATION MECHANISMS AND PARAMETERS

The XP in clear air and SDS conditions depend on some parameters and physical mechanisms which have been investigated using either theoretical or experimental techniques [17], [18]. The mechanisms may be dependent or independent of the cross polar patterns. The parameters which the XPD depends on include the frequency of operation, particle shape and orientation, canting angle, scattering and reflection from the surface along the propagation path as well as the complex permittivity of the particles. XPD in circular polarization is a function of the refractive index of the surface material, even though multipath fading of the co-polar signal could cause more severe XPD deterioration.

Investigations of SDS induced XP [12], [14] have shown that differential attenuation and differential phase rotation from non-spherical scatterers are responsible for signal depolarization. Complex permittivity of dust particles is an important component in predicting microwave attenuation and phase rotation, and in turn, XP. A few investigators have measured the permittivity of sand and dust samples [19], [20]. It is a function of moisture content, chemical composition and frequency. Difference in particle sizes does not result in change in the permittivity except because of different chemical compositions [21].

Information on particle drop shape has been given [5], [21], [22]. It is important to mention that the non-sphericity of falling particles and their tendency to align in a direction at a given time remain the major factors responsible for depolarization. It has also been established that vertical wind gradients cause canting. [23] developed a model to investigate dependence of the canting on particle size and wind shear. While XPD decreases as the canting angle increases, the canting angle decreases as the particle sizes increase.

Equation (1) has been used by [24]-[27] to describe the XPD variation.

$$XPD = \boldsymbol{U} - \boldsymbol{V} \log_{10} A \tag{1}$$

where A is attenuation, U and V are propagation coefficients which depend on parameters such as the frequency of operation, path elevation angle, tilt and canting angles etc. and other parameters mentioned earlier.

IV. CROSS POLARIZATION MODELS AND PREDICTION OF CROSS POLARIZATION DISCRIMINATION

XP models have continued to evolve even as much works are still being expected. Oguchi’s general theory [3] formed the basis for most of the evolving XP models as demonstrated by [28]-[30] and few others. Some of the XP models discussed in this section are semi-empirical and are premised on the rain techniques. They also stemmed from further simplifications of the relevant fundamental theories. These simplifications enhance practical applications of the models.

One of the simplifications of the popular Oguchi theory was presented by [30] in his work.

$$XPD \approx -20 \log\left(L \cos^2 \epsilon \, |\Delta k| e^{-2\sigma^2} \sin 2 \frac{|\phi-\tau|}{2}\right) \tag{2}$$

$$CPA \approx \left[A_H + A_V + (A_H - A_V) \cos^2 \epsilon e^{-2\sigma^2} \cos 2(\phi - \tau)\right] L/2 \tag{3}$$

where A_H and A_V are the specific attenuations (horizontal and vertical), τ is the polarization tilt angle, ϕ is the effective canting angle, σ is the effective standard deviation of the canting angle distribution, L is the path length, ϵ is the path elevation angle and

$$|\Delta k| = |K_H - K_V| = (\Delta\alpha^2 + \Delta\beta^2)^{1/2} \tag{4}$$

where K_H and K_V are propagation constant for horizontal and vertical polarizations, $\Delta\alpha$ is the differential attenuation and $\Delta\beta$ is the differential phase rotation.

For terrestrial link applications, the theory may be said to be most readily adaptable. A disadvantage of this equation, however, is the fact that $|\Delta k|$ is sensitive to particle size distribution. A concept of dual cross-coupling between orthogonally polarized signals as suggested by Oguchi was also used by [29] to study XP effects. This attempt is another simplification of Oguchi’s theory.

Bashir *et al.* [31] made the first attempt to calculate XP in SDS. The work considered particles as oblate spheroids and an axial ratio of 0.95 was approximated. All the symmetry axes of the particles were assumed to be aligned in the same direction. They could display canting angles of 1, 3 and 6 degrees with respect to the vertical polarization and horizontal polarization of a terrestrial microwave link. At 9.4GHz and using point matching method, the prediction showed small attenuation but phase rotation of typically 1.5 deg/km resulting in an XPD of 51dB over a 1km path length. Although the paper demonstrated the possibility of significant XP due to differential phase rotation, later measurements indicated higher eccentricity.

Another known investigation on XP in SDS by [32] considered communication at 37GHz. With visibilities around 100m and dry dust, the effect was small for linear polarization. In humid areas and during severe storms, however, the effect especially for circular polarization could be very significant. This shows a suitable performance of dual polar systems for linear XP, while that of circular polarization is unsatisfactory. Lack of information on shape and alignment of dust particles was noted in this work. This uncertainty was also noted by [5] and attempt was made to address it. In this work, however, expression was given in terms of relative volume of dust. This quantity is difficult to measure directly. Besides, overestimation of the inertial forces was observed. The slant path's prediction was severe, and on 1km path length, 16dB was recorded.

XP was also treated by Ghobrial and Sharif [21]. The work also emphasized dust particles shape, dimensions and alignment as particularly significant in XP computations, while noting their associated problems. Like [31], particles were assumed to be spheroid having axis ratios of 5:1 (in oblate and prolate). The results showed that the XPD reduced by about 10dB as the water content increased from 0% to 20%. An increase in the axial ratio from 1.1:1 to 2:1 reduced the XPD by about 20dB, while subsequent increase to 5:1 reduced it by nearly 8dB. This further confirms that for linear polarization, the effect of SDS is negligible unless there is an increase of moisture contents. However, the model is limited by problem of phase dissimilarity between the two linearly polarized waves creating circular polarization, i.e. $\phi < 20^0$. Lastly, aside the fact that the dust particles permittivity used in obtaining the expression is bulk (i.e. not scaled), it may also not be universally applicable.

Based on an oblate-spheroidal shape model, a complicated expression was proposed by [27]. Although this effort was an attempt to improve accuracy of predictions (especially in rain), it however failed to serve as an improvement because the relation deviated in the specified frequency range (i.e. 10GHz – 30GHz). Besides, the oblate-spheroidal shape adopted has been shown to be less accurate when checked against Oguchi's work.

CCIR 1978b [33] adopted a semi empirical model as expressed in (5).

$$XPD = 30\log(f) - 10\log\tfrac{1}{2}\left[1-\cos(4\delta)e^{-0.0024\sigma_m^2}\right] - 40\log(\cos\epsilon) + 0.0053\sigma_\theta^2 - \boldsymbol{V}\log A \quad (5)$$

where

$$\boldsymbol{V} = \begin{cases} 20, & 8 < f \leq 15\,GHz \\ 23, & 15 < f \leq 35\,GHz \end{cases} \quad (6)$$

f is the frequency, δ is an angle which may depend on both the tilt angle of the linearly polarized electric field and the mean canting angle, σ_θ is the standard deviation, σ_m is an angle variance and ϵ is the elevation angle of the slant path.

The performance accuracy of this model was however questioned by [28]. Perhaps, the need for improving the model and other important considerations necessitated the Simple Isolation Model (SIM) proposed by Stutzman and Runyon.

$$XPD = 9.5 + 17.3\log(f) - 42\log(\cos\epsilon) - 10\log\left\{\tfrac{1}{2}\left[1-\cos(4\delta)e^{-0.0024\sigma_m^2}\right]\right\} + 0.0053\sigma_\theta^2 - 20\log(F_0) - 19\log(A) \quad (7)$$

where F_0 is a shape factor.

Like many other XPD models, SIM is a model for predicting XPD from attenuation. It was developed for satellite communication links applications between 10GHz to 30GHz. Unlike most other models, however, SIM was derived by curve fitting the values generated from the multiple scattering model by varying the parameters involved. SIM is an important improvement on existing models such as the CCIR. The consideration of shape factor term is another merit of SIM. The rigor of developing the model may however make it susceptible to error.

Interpolation was used to obtain the values of necessary propagation coefficients for other frequencies different from those used by Oguchi. Considerable variability in some of the values obtained or employed by different investigators may be due to meteorological factors like the wind direction etc.

Fenn and Rispin's work [1] simulated a satellite-earth link in a dual polarization frequency reuse technique at K-band (specifically between 17.7GHz and 21.2GHz). Excellent XPI suitable for evaluating dual polarization frequency reuse scheme (especially during clear air) was recorded. [34] used (8) and (9) for prediction of XPD due to canting angle of falling particle and non-spherical shape of the drops for both horizontal and vertical polarizations.

$$XPD_h = \left(\frac{H-V}{2}\right)\frac{\sin 2\theta}{H\cos^2\theta + V\sin^2\theta} \quad (8)$$

$$XPD_v = \left(\frac{H-V}{2}\right)\frac{\sin 2\theta}{V\cos^2\theta + H\sin^2\theta} \quad (9)$$

where θ is the canting angle and H and V are as defined.

$$H = e^{-A_h L} \quad (10)$$

$$V = e^{-A_v L} \quad (11)$$

A_h and A_v are the horizontal and vertical attenuations, and L is the path length.

Ghobrial and Sharief [21] gave the circular polarized wave as:

$$XPD = 10\log_{10}\left|\frac{1+2m\cos\phi + m^2}{1-2m\cos\phi + m^2}\right|\,[dB] \quad (12)$$

where ϕ is a phase difference of 90^0 and m is the ratio of the amplitudes of the two linearly polarized waves producing the circular polarization.

Equation (13) has been obtained from (12), derivation details of which can be understood from [21].

$$XPD = 91.6 - 20\log_{10}(f.L) + 21.4\log_{10}V \ [dB] \quad (13)$$

where L is the path length (km), f is the frequency (GHz) and V is the visibility (km).

It has been observed that larger elevation angles come with better isolation. While addressing the effect of random depolarizing factors on XPD, [35] modified the Ghobrial formula and derived (14) for XP caused by SDS in earth-satellite links.

$$XPD = -69.5 + 14.4\log_{10}h - 21.4\log_{10}V - 20\log_{10}\lambda + 40\log_{10}\cot(\theta) \quad (14)$$

where h is the dust storm height, θ is the elevation angle, V is the visibility and λ is the wavelength.

However, a further consideration of (14) necessitated a slight modification as shown in Section V. While observing that circular polarization and linear polarization at 45^0 do experience most severe XPD, [36] presented an expression as a function of differential attenuation and phase rotation between dual channels denoted as γ in (15) and (16).

$$XPD = 20\log_{10}\left|\frac{1+\gamma}{1-\gamma}\right| [dB] \quad (15)$$

where γ is further expressed as:

$$\gamma = e^{-(\Delta A - j\Delta\varphi)L} \quad (16)$$

where L is the path length, ΔA is the differential attenuation and $\Delta\varphi$ is the differential phase rotation.

[37], [38] also investigated XP and calculated the XPD at 10GHz. The amplitudes of polarized waves and the phase change at a given path length were considered. [38] employed the circular polarized wave XPD expression given by [21] in (12). The quantities m and ϕ can be evaluated for a wave propagating in an SDS as follows:

$$m = \exp[-|A_v - A_h|L] = \exp(-\Delta A.L) \quad (17)$$

$$\phi = |\varphi_h - \varphi_v|L = \Delta\varphi.L \quad (18)$$

where L is the propagation path length, A is the attenuation, φ is the phase rotation, ΔA is the differential attenuation, $\Delta\varphi$ is the differential phase rotation.

TABLE II: SOME CROSS POLARIZATION WORKS IN SAND AND DUST STORMS

Investigator	Approach	Strength	Drawback
[2]	Used the existing theoretical basis and oblate shape.	Inclusion of canting angle. Expression in terms of differential phase rotation and attenuation.	Assumption of equal orientation.
[5]	Particle alignment and ellipsoidal shape were considered.	Attempted theoretical alignment of dust particle.	Inertial forces overestimated. Equation expressed in volume fraction.
[13]	Derived depolarization equation using scattering by dipole and back scattering concept	Microwave and millimeter wave frequency range	Left out particle canting angle
[14]	Used the Van de Hulst approach to determine the XPD inputs (attenuation and phase rotation).	Expressed XPD in differential attenuation and phase rotation.	Low frequency range (10GHz). Assumed equi-orientation. Neglected canting angle.
[21]	Based on suspending particles, XPD for circular polarization is expressed in terms of visibility.	Easy to calculate. Expression in visibility.	Used bulk permittivity. Expression unsuitable for phase rotation, ϕ >20^0.
[31]	Calculated XPD and its inputs using Point Matching Technique	First to calculate XPD in SDS	Lower frequency range (9.4GHz). Canting angle assumption.
[32]	Used Rayleigh approximation method to determine the scattering of spheroidal particles – XPD input.	Frequency range extended to 37 GHz.	Canting angle and particle shape assumptions.
[35]	Derived XPD expression for Earth-satellite link by modifying Ghobrial formula.	Consideration of dust height and Earth-satellite link.	Assumed canting angle. Equation valid for a phase rotation < 20^0.
[37]	Evaluated XPD and its inputs using Rayleigh.	Equation given in terms of visibility	Neglected the particle orientation.
[38]	Evaluated XPD and its inputs using Rayleigh and Ghobrial & Sharief methods.	Clear definition of propagating parameters.	Neglected the particle orientation.
[40]	Probability density of Iraqi storms was used.	High frequency range.	Neglected particle alignment

At some point of evolvement of this field, while it has been established that XP can significantly affect wave propagation in SDS, it was however observed that the particle orientation and the canting angle calculations were left out. In the application of the particle symmetry axes, the eccentricity was under estimated and the inertial forces responsible for the dust particle alignment were overestimated as mentioned earlier. It became apparent that further investigation of XP and XPD predictions was necessary. These problems were later addressed by [2], [23] and [39].

Summary of some of the investigated works on XP in SDS are shown in Table II, highlighting the approaches adopted by the authors and stating the strengths as well as the drawbacks.

V. Modified XPD Model for Terrestrial and Earth–Satellite Links

Using (19) given by [21], XPD models for both terrestrial and earth–satellite links leading to (27) and (36) can be derived.

$$XPD = 20\log\left(\frac{\Delta\phi D}{2}\right) \tag{19}$$

where

$$\Delta\phi D = (\phi_h - \phi_v)D \tag{20}$$

$$\phi_h = 0.33D/\lambda V^{\gamma} \tag{21}$$

and

$$\phi_v = 0.24D/\lambda V^{\gamma} \tag{22}$$

From (20), (21) and (22),

$$\Delta\phi D = (\phi_h - \phi_v)D = \frac{0.09D}{\lambda V^{\gamma}}\ (deg) \tag{23}$$

or

$$\Delta\phi D = \frac{1.57\times10^{-3}}{\lambda V^{\gamma}} D\ (rad) \tag{24}$$

Further simplification of (24) produces (25).

$$\frac{\Delta\phi D}{2} = \frac{7.85\times10^{-4}}{\lambda V^{\gamma}} D\ (rad) \tag{25}$$

Equation (25) is substituted into (19) to obtain (26)

$$XPD = 20\log\left(\frac{7.85\times10^{-4}}{\lambda V^{\gamma}} D\right) \tag{26}$$

Thus, (26) can be re-written as shown in (27).

$$XPD = 62.1 - 20\log\left(\frac{D}{\lambda}\right) + 21.4\log V \tag{27}$$

where D is the distance, λ is the wavelength of the operation, V is the visibility, and γ is a constant taken as 1.07.

Similar model was derived by Ghobrial [21] for evaluation of XPD of a terrestrial link. A closer approach demonstrated in (27) can be followed to obtain model for the Earth–satellite XPD.

Recalling (19) and rewriting (24) as (28),

$$\Delta\phi = \frac{1.57\times10^{-3}}{\lambda V^{1.07}} (rad/km) \tag{28}$$

In this case,

$$V = V_0\left[\frac{h}{h_0}\right]^{0.26} \tag{29}$$

where V_0 is the reference visibility, h is the storm's height and h_0 is the reference height [35].

Similarly,

$$\Delta\phi(h)_\theta = \Delta\phi(h)\cos^2\theta \tag{30}$$

In the same vein, if

$$D \cong \frac{h}{\sin^2\theta} \tag{31}$$

Norinpel [41] also confirmed (31). Equation (28) is substituted into (30) to obtain (32).

$$\Delta\phi(h)_\theta = \frac{1.57\times10^{-3}}{\lambda V^{1.07}}\cos^2\theta \tag{32}$$

Equation (33) is obtained when (29) is substituted into (32).

$$\Delta\phi(h)_\theta = \frac{1.57\times10^{-3}\cos^2\theta}{\lambda\left[V_0\left(\frac{h}{h_0}\right)^{0.26}\right]^{1.07}} \tag{33}$$

Taking

$$\frac{\Delta\phi D}{2} \cong \frac{\Delta\phi(h)_\theta D}{2} \tag{34}$$

From the foregoing, it means that the XPD can be expressed as

$$XPD = 20\log\left(\frac{\Delta\phi(h)_\theta D}{2}\right) \tag{35}$$

When (31) and (33) are substituted into (35) and taking the value of h_0 to be $0.015\ km$ (being the reference height for visibility measurements by meteorology departments [35]), (35) can be further simplified to become

$$XPD = -72.3 + 14.4\log_{10} h - 21.4\log_{10} V - 20\log_{10}\lambda + 40\log_{10}\cot(\theta) \tag{36}$$

The proposed expression in (36) is the modified Jervase XPD model for Earth–satellite link, where h is the dust storm height, θ is the elevation angle, V is the visibility and λ is the wavelength.

VI. Knowledge GAP and Outlook

To provide better understanding of depolarization in SDS, improvement of the existing semi-empirical models is suggested. Simulations and where possible, actual experiments to further investigate and measure XPD under different propagation conditions should be carried out. The experimental approach may be system design oriented or model oriented. The experimental set up of the former may be like a typical radio system and involves measuring XP directly (i.e. obtaining XPD or XPI as the case maybe). The latter characterizes the depolarizing medium's physical properties to develop models that can be used in systems design. A combination of the two approaches may as well be expected as real experimental measurements hardly follow either of the extremes.

There is a strong possibility of significant XP, mainly due to differential phase rotation, on circularly polarized links; and of course, due to dust particle alignment and canting on linear polarizations. Outlook in the future, therefore, points towards more investigations on these important parameters, such as differential phase rotation, attenuation and canting angles, necessary for the dust-induced XP. Where such has taken place, further refinements can be expected to develop and propose models which attract global applicability and universal acceptance.

Attention is expected to be focused on direct measurement of canting angle especially during turbulent conditions and determination of other relevant empirical parameters under different conditions and their relative importance on depolarization. Furthermore, since single scattering albedo of falling particles increases at higher frequencies, incoherent depolarization effect is expected to attract further attention.

The challenge associated with lack of measured data and knowledge of pooling such data to further enhance accurate model development of XPD are being addressed. Although some predictions may not agree well with measurements, some of the innovative techniques used enhance other measurements that are model-oriented.

VII. Conclusion

No doubt, XP is a significant effect of SDS especially for slant communication links and during severe storm. However, the SDS XP models are not as well developed as in rain. They are still evolving as some progress are being recorded in development of models that enhance solutions to problems of XP in SDS. Against this premise, an overview of XP in SDS is carried out in this article to enhance understanding of the topic and development of better propagation models (theoretical and semi-empirical). Some of the important XP parameters have been highlighted. More emphasis was placed on the semi-empirical models that are readily applied in statistical predictions in design applications. Under this, an attempt was made to modify one of the existing models for further improvement.

Directions for further works on microwave XP in SDS include direct measurements of canting angle especially during turbulent conditions and XPD under different propagation conditions. Besides, further refinements of relevant models that can attract global applicability and universal acceptance are also expected.

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