Alqalam Journal of Medical and Applied Sciences. 2026;9(7):2187-2192
https://doi.org/10.54361/ajmas.269749

Original article

Modeling and Simulation of Dust-Induced Cross-Polarization Based on Differential Phase Shift in Terrestrial and Earth–Satellite Links

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Abstract
This paper presents analytical models for estimating cross-polarization discrimination (XPD) in dust-laden propagation environments over Libya. Two models are formulated based on differential phase shift (DPS): a terrestrial model for ground-based links and a satellite model for slant-path Earth–satellite links. The models incorporate key propagation parameters, including operating frequency, visibility, link distance, elevation angle, and dust storm height. The results show that XPD decreases with increasing frequency and dust concentration, while improving significantly with higher visibility. Under severe dust conditions (V ≈ 0.01 Km), XPD falls below 15 dB, indicating strong depolarization, whereas values exceeding 30 dB are obtained under clearer atmospheric conditions. These findings provide practical engineering insights into link performance degradation in Libyan environments. The developed models provide a physically consistent and region-specific framework for the design and optimization of reliable terrestrial and Earth–satellite communication systems operating under dust-laden propagation environments
Keywords. XPD, DPS, Dust-Laden Propagation, Terrestrial Links, Earth–Satellite Links, Predictive Modeling.

Introduction

The radio-frequency (RF) spectrum is becoming increasingly congested due to the growing demand for high-data-rate communication services driven by modern information technologies. To improve spectral efficiency and accommodate this demand, frequency reuse techniques have been widely adopted [1,2]. Among these, dual-polarization frequency reuse enables the simultaneous transmission of two orthogonally polarized signals carrying independent data streams, such as right-hand and left-hand circular polarization, thereby effectively doubling channel capacity without requiring additional bandwidth. Despite these advantages, the performance of dual-polarized communication systems is significantly affected by atmospheric impairments, including rain, fog, and airborne dust particles. In dust-laden environments, signal degradation is not limited to attenuation; depolarization also plays a major role in degrading system performance. Depolarization results from the interaction between electromagnetic waves and non-spherical dust particles suspended in the propagation medium. As the wave propagates through such environments, its polarization state gradually changes, causing part of the transmitted co-polarized power to be converted into the orthogonal polarization. This cross-polarization interference reduces channel isolation and degrades communication performance [3,4]. Cross-polarization discrimination (XPD) is a key parameter for quantifying depolarization in dual-polarized communication systems. It is defined as the ratio of the received co-polarized power to the received cross-polarized power. Lower XPD values indicate stronger depolarization, resulting in increased interference between orthogonal channels and reduced link reliability and system capacity. Extensive research has been conducted on electromagnetic wave propagation in random and atmospheric media. Classical studies established the theoretical foundations of wave scattering and propagation in random media [5,6], while later investigations proposed empirical and semi-empirical models to estimate propagation impairments, including depolarization, under various atmospheric conditions [7-13]. Among the mechanisms responsible for depolarization, differential phase shift (DPS) has been identified as one of the dominant contributors in particulate media. Dust particle characteristics, including complex permittivity, particle shape, and size distribution, strongly influence microwave and millimeter-wave propagation. Although several studies have investigated dust-induced depolarization [14-19], most existing models are not specifically adapted to the environmental conditions encountered in Libya. Consequently, the behavior of XPD under Libyan dust conditions remains insufficiently investigated, with only limited studies reported in the literature [20,21]. To address this gap, this paper develops analytical models for estimating XPD in dust-laden environments over Libya. The proposed approach is based on DPS and incorporates key propagation parameters, including operating frequency, visibility, link distance, elevation angle, and dust storm height. It comprises a terrestrial model for ground-based links and a satellite model for slant-path Earth–satellite links, providing a physically consistent and region-specific framework for evaluating depolarization effects and supporting the design of reliable terrestrial and Earth–satellite communication systems.

Methodology

This section describes the adopted methodology for developing the proposed XPD models. The analysis is based on the phase shift induced by dust-laden environments over Libya, which affects both orthogonal polarization components, as reported in [20]. The DPS between the two polarization components is derived and employed as the key parameter for characterizing cross-polarization effects. The resulting DPS is then incorporated into the proposed analytical models to estimate XPD under different dust conditions.

Received*: 18-05-2026 -* ***Accepted****: 16-07-2026 -* ***Published****: 21-07-2026*

Differential Phase Shift in Dust-Laden Environments

As an electromagnetic wave propagates through a dust-laden medium, interactions with suspended particles induce DPS between the orthogonal polarization components.

The corresponding phase shifts for the horizontal and vertical polarizations are expressed as functions of operating frequency and visibility [20].

$$ps_h = 0.0129 \frac{f}{V^{\gamma}} \quad (1)$$

$$ps_v = 0.0091 \frac{f}{V^{\gamma}} \quad (2)$$

The DPS between the horizontal and vertical polarizations is defined as:

$$D_{PS} = ps_h - ps_v \quad (3)$$

By substituting (1) and (2) into (3), the expression becomes:

$$D_{PS} = 0.0038 \frac{f}{V^{\gamma}} \quad deg \quad (4)$$

For analytical consistency, the above expression can be converted into radians as:

$$D_{PS} = 6.63 * 10^{-5} \frac{f}{V^{\gamma}} \quad rad \quad (5)$$

These formulations emphasize the dependence of DPS on operating frequency and visibility, enabling a quantitative description of polarization behavior in dust-laden propagation environments.

XPD Model Development

XPD in dust-laden environments is governed by several physical mechanisms and environmental parameters that have been extensively investigated through theoretical and experimental studies [6,13]. These include operating frequency, particle size, shape, orientation, canting angle, scattering effects along the propagation path, and the complex permittivity of dust particles, which strongly influences depolarization characteristics. In practical propagation scenarios, XPD can be expressed as a function of the phase difference between two orthogonal polarization components. Accordingly, it is commonly modeled as a function of DPS, as given in [8,22]:

$$\mathrm{XPD} = -20 \log_{10}(D_{PS} d/2) \quad (6)$$

where D_{PS} is the DPS per unit length, and *d* is the propagation path length.

Terrestrial Model (Ground-Based Links)

Substituting Eq. (5) into Eq. (6) yields the logarithmic XPD model for terrestrial links:

$$\mathrm{XPD} = 89.6 - 20 \log_{10}(d.f) + 21.4 \log_{10}(V) \quad (7)$$

where *f* is the operating frequency (GHz), *V* is the visibility (km), and the exponent of the visibility term is based on an experimentally derived constant γ=1.07 [22].

Satellite Model (Slant-Path Links)

For Earth–satellite links, the slant propagation path and the variation of dust properties with altitude must be considered. The visibility variation with height is expressed as [23,24]:

$$V = V_{ref}\left[h/h_{ref}\right]^{0.26} \quad (8)$$

where V_{ref} is the reference visibility, h is the dust storm height, and h_{ref} Is the reference height. The effect of the elevation angle is incorporated through [25]

$$D_{PS}|_{\theta} = D_{PS}.\cos^2\theta \quad (9)$$

Substituting Eqs. (8) and (9) into Eq. (5) gives

$$D_{PS}|_{\theta} = \frac{6.63*10^{-5}.f.\cos^2\theta}{\left[V_{ref}\left(\frac{h}{h_{ref}}\right)^{0.26}\right]^{1.07}} \quad (10)$$

For slant-path propagation, the effective path length is approximated by: $d = h/\sin\theta$. Substituting this expression together with Eq. (10) into Eq. (6), and assuming $h_{ref} = 0.010$ km, yields the logarithmic XPD model for Earth–satellite links:

$$: \mathrm{XPD} = 100.73 - 20\log(f) + 21.4\log(V) + 20\log(K_{\theta}) - 14.4\log(h) \quad (11)$$

where $K_{\theta} = cos\,\theta\, cot\,\theta\theta$ is the elevation angle (degrees), *h* is the dust storm height (km), *V* is the visibility (km), and *f* is the operating frequency (GHz).

Received*: 18-05-2026 -* ***Accepted****: 16-07-2026 -* ***Published****: 21-07-2026*

Results and Discussion

This section presents and discusses the results obtained using the proposed analytical XPD models. Figures 1–3 are generated from the Earth–satellite model given by Eq. (11), whereas Figure 4 is obtained using the terrestrial model of Eq. (7). The results demonstrate the influence of the principal propagation parameters on XPD and provide insight into the depolarization behavior of electromagnetic waves in dust-laden environments.

Satellite XPD Performance

(Figure 1) Shows the variation of XPD with operating frequency for an elevation angle of θ = 45° and a dust storm height of h = 2 *km*. The results indicate a clear reduction in XPD as the operating frequency increases. This trend is attributed to the stronger interaction between electromagnetic waves and suspended dust particles at higher frequencies, leading to an increase in the DPS between the orthogonal polarization components and consequently stronger depolarization. Quantitatively, for the lowest visibility (V = 0.01 *km*), XPD ranges from approximately 30 to 21 dB over the microwave band (10–30 GHz) and further decreases from approximately 21 to 11 dB over the millimeter-wave band (30–100 GHz). These results indicate that communication systems operating at millimeter-wave frequencies are considerably more susceptible to polarization degradation under dusty atmospheric conditions.

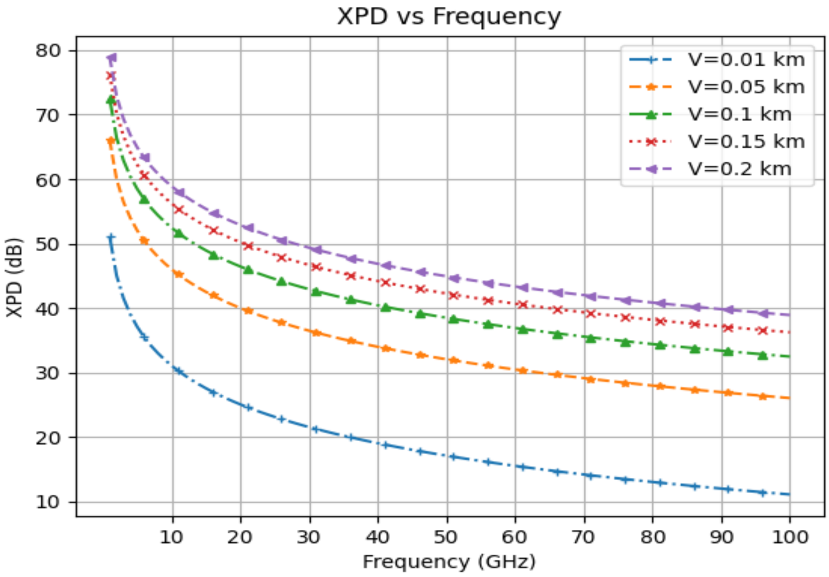
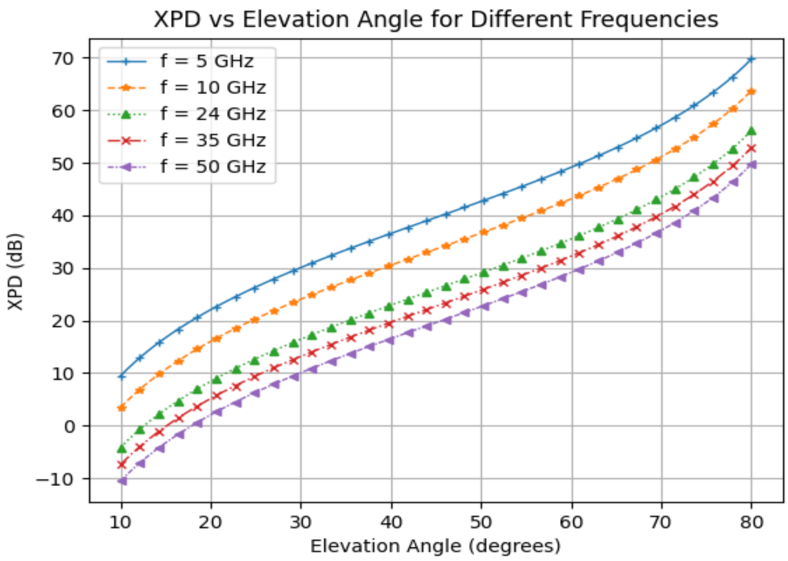


Fig. 1. Variation of XPD with frequency using the satellite model at θ = 45° and h = 2 km.

(Figure 2) Presents the variation of XPD with elevation angle for a visibility of *V*=0.01 *km* and a dust storm height of *h*=2 *km*. The results show that XPD increases as the elevation angle increases. This behavior is consistent with the proposed analytical model, in which larger elevation angles reduce the effective propagation path through the dust layer, thereby weakening depolarization effects and improving polarization discrimination. Although higher elevation angles improve XPD, the predicted values remain below approximately 20 dB under the considered low-visibility conditions, indicating that severe dust storms continue to produce noticeable depolarization even for relatively large elevation angles.



***Received**: 18-05-2026 - **Accepted**: 16-07-2026 - **Published**: 21-07-2026*

Fig. 2. Variation of XPD with elevation angle using the satellite model at V = 10 m and h = 2 km.

(Figure 3) Illustrates the variation of XPD with operating frequency for different dust storm heights at a fixed visibility of V = 0.01 *km* and an elevation angle of θ = 45°. The results show that XPD decreases as both the operating frequency and dust storm height increase. This behavior is attributed to the longer propagation path through the dust-laden medium at higher storm heights, which increases the DPS between the orthogonal polarization components and consequently enhances depolarization. For a dust storm height of h = 2 *km*, XPD decreases from approximately 35 dB to 14 dB over the investigated frequency range. These results indicate that higher dust storm heights intensify polarization degradation, with the effect becoming increasingly pronounced at higher operating frequencies..

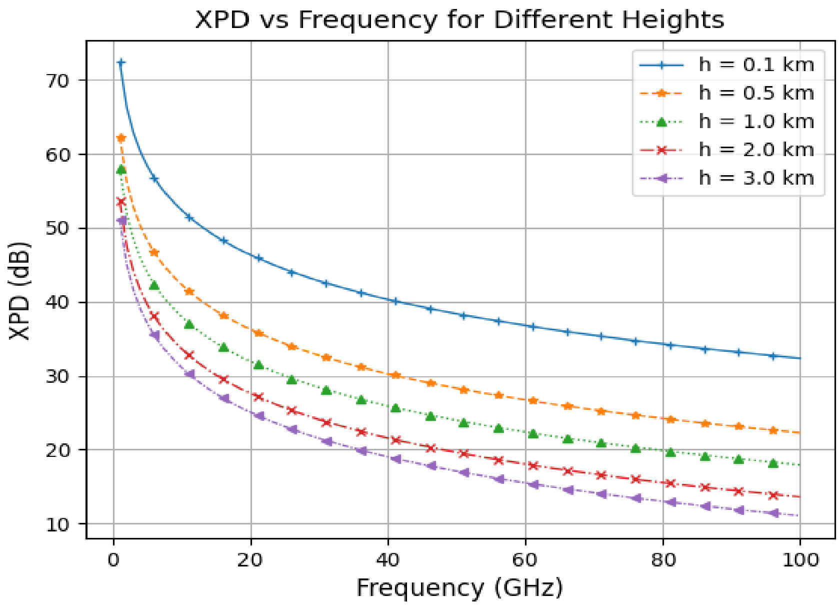


Fig. 3. XPD versus frequency using the satellite model at V = 10 m and θ = 45°.

Terrestrial XPD Performance

(Figure 4) Presents the predicted XPD for terrestrial communication links with a propagation distance of d = 1 *km*. Similar to the satellite model, the results indicate that XPD decreases with increasing operating frequency and improves with increasing visibility. Under severe dust conditions (V ≈ 0.01 *km*), XPD decreases from approximately 25 dB to 10 dB over the investigated frequency range, indicating significant depolarization and reduced polarization isolation. As visibility increases to (V ≈ 0.09 *km*), XPD ranges from approximately 45 dB to 27 dB, reflecting substantially weaker depolarization and more reliable dual-polarized communication. These results confirm that visibility is one of the dominant parameters governing polarization performance in terrestrial dust-laden propagation environments.

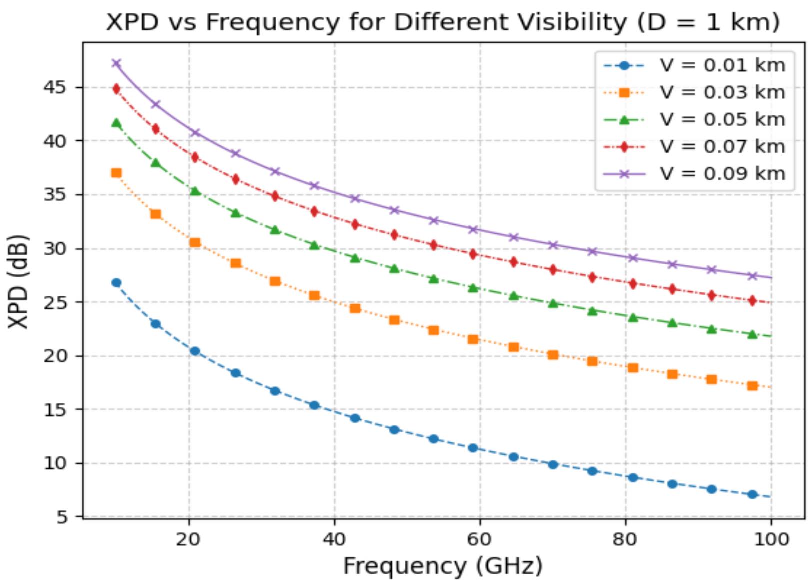


Fig. 4. XPD versus frequency using the terrestrial model at d = 1 km

***Received**: 18-05-2026 - **Accepted**: 16-07-2026 - **Published**: 21-07-2026*

https://doi.org/10.54361/ajmas.269749

Conclusion

This paper presented two analytical models for predicting XPD in terrestrial and Earth–satellite communication links operating under dust-laden propagation environments representative of Libyan conditions. The proposed formulations are derived directly from DPS, which represents the fundamental physical mechanism responsible for dust-induced depolarization. The developed models incorporate the principal propagation parameters affecting polarization degradation, including operating frequency, visibility, propagation path length, elevation angle, and dust storm height, thereby providing a practical framework for estimating XPD under dusty atmospheric conditions. The obtained results demonstrate that XPD is strongly influenced by both environmental and propagation parameters. In particular, increasing operating frequency and decreasing visibility significantly indicate stronger depolarization and increased interference between orthogonal polarization components. For Earth–satellite links, the analysis further shows that elevation angle and dust storm height also influence polarization discrimination through their effect on the effective propagation path. The predicted trends are physically consistent with the expected behavior of electromagnetic wave propagation through dust-laden media. By relating XPD to DPS, the proposed models provide a physically meaningful description of dust-induced depolarization rather than relying solely on empirical relationships. The resulting formulation offers a simple and practical mathematical framework for evaluating depolarization in dust-laden propagation environments and supports the design, performance evaluation, and optimization of dual-polarized microwave and millimeter-wave terrestrial and Earth–satellite communication systems operating under severe dust conditions.

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***Received**: 18-05-2026 - **Accepted**: 16-07-2026 - **Published**: 21-07-2026*

https://doi.org/10.54361/ajmas.269749

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***Received**: 18-05-2026 - **Accepted**: 16-07-2026 - **Published**: 21-07-2026*