Geometry-Based Modeling of Cross-Polarization Discrimination in HAP Propagation Channels

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Abstract—This paper proposes a three-dimensional (3-D) geometry-based reference model for cross-polarization discrimination (XPD) in narrowband fading channels, when high altitude platforms (HAPs) are involved. Both line-of-sight (LoS) and non-line-of-sight (NLoS) propagation conditions are assumed in the transmission links from a HAP to a terrestrial mobile station (TMS). Based on this model, the cross-polarization discrimination (XPD) is derived as a function of critical model parameters, such as the elevation angle of the platform and the distribution of the scatterers.

Keywords—Cross-polarization discrimination (XPD); high-altitude platform; polarized channels; Rician fading; 3-D scattering

I. INTRODUCTION

The growing demand for ubiquitous broadband wireless communications has prompted the development of terrestrial and satellite networks. In recent years, the high-altitude platforms (HAPs) have also emerged [1]. HAPs are airships or aircrafts flying in the stratosphere capable of alternatively or complimentary fulfill the vision of optimal connectivity at low cost, while they attain network flexibility and adaptability due to their rapid deployment and movement on demand. As modern communication services demand increasingly higher data rates, the multiple-input multiple-output (MIMO) technology [2], [3] has played an important role in enhancing the achievable data throughput.

The prerequisite so that HAP configurations successfully adopt MIMO techniques is the existence of sufficient antenna spacing, as well as a rich scattering environment. Previous theoretical studies suggested that the size of a single HAP allows for the accommodation of at least two antennas [4]-[6], whereas the antenna spacing at the mobile terminal has to be at least half a wavelength to achieve reasonably low correlation. Nevertheless, a HAP-based channel is expected to be Rician in its general form, i.e., both line-of-sight (LoS) and non-line-of-sight (NLoS) links exist. Hence, other ways of de-correlating MIMO branches are desired, in case of environments dominated by strong LoS component. A promising, attractive, and potential strategy due to the recent advances in MIMO compact antennas [7] to achieve low correlation and increased channel capacity in free-space communications is to exploit the benefits of polarization diversity via dual-polarized (DP) antennas [8]-[12]. Then, the two spatially separated single-polarized (SP) antennas are replaced by a single antenna structure employing two orthogonal polarizations. The cross-polarization discrimination (XPD) factor is the usual evaluation parameter [12] and estimates the depolarization effects that arise due to the scattering mechanisms.

To comprehensively understand HAP-DP systems, modeling of the underlying dispersive channel is important. Since HAPs are placed in the stratosphere and mobile users are often located lower than the surrounding scatterers, the waves may travel in both horizontal and vertical planes. Therefore, three-dimensional (3-D) channel modeling is required to ideally characterize the propagation environment and accurately represent important aspects of polarized HAP-DP channels. Several 3-D channel models have been developed for fixed-to-mobile (F-to-M), e.g., [13], mobile-to-mobile (M-to-M), e.g., [14], and HAP-based [6] channels, but they do not account for channel polarization. In [15], 3-D models for XPD in F-to-M and M-to-M channels were proposed. Nevertheless, these models consider only the first tier of scatterers lying on the surface of one (F-to-M) or two (M-to-M) cylinders, which is unrealistic for HAP-based communication systems [6].

Based on the geometrical theory of channel depolarization introduced in [15], this paper proposes a 3-D geometry-based single-bounce (GBSB) reference model for narrowband HAP-DP channels. From this model, the XPD is derived, under 3-D non-isotropic scattering, as a function of the model parameters, i.e., the distribution of the scatterers and the elevation angle of the platform. Numerical calculations demonstrate the theoretical derivations.

The remainder of the paper is organized as follows. Section II introduces the 3-D model for HAP-DP fading channels, while Section III derives the corresponding XPD. Numerical results are provided in Section IV. Finally, conclusions are drawn in Section V.

II. A 3-D GEOMETRY-BASED MODEL FOR NARROWBAND HAP-DP FADING CHANNELS

This section presents the geometrical characteristics of the proposed model for XPD, which considers a quasi-stationary and free of local scattering HAP and a terrestrial mobile station (TMS). Contrary to previous work that deals with compact MIMO antenna array configurations in conjunction with multiple HAP constellations [16], this paper utilizes the polarization diversity from a single HAP. Fig. 1 defines the Cartesian coordinate system and shows the LoS and NLoS
paths for a downlink HAP-DP Rician channel, where the local effective scatterers are non-uniformly distributed within a cylinder. The radius of the cylinder corresponds to the maximum distance $R_{S,\text{max}}$ between TMS and an effective scatterer, whereas the height of the cylinder $H_{S,\text{max}}$ stands for the maximum scatterer height. A multi-element antenna version of this model was previously proposed in [6], but it was not used to study XPD. Note that shadowing is neglected, while rain effects are insignificant at frequency bands well below 10 GHz utilized in this scenario.

According to Fig. 1, the $x$-axis is the line that connects coordinate origin $O$ (the projection of the HAP antenna to the $x$-$y$ plane) and $O'$ (lower center of the cylinder), while $O_{T}$ and $O_{R}$ represent the position of the HAP and TMS antennas, respectively. To aid our analysis, we denote $d(a,b)$ the distance between two points $a$ and $b$. Then, $d(O,O') = D$. In addition, $d(O,O_{T}) = H_{T}$ is the height of the HAP antenna and $d(O',O_{R}) = H_{R} < H_{T}$ is the height of the TMS antenna. The elevation angle of the HAP relative to $O_{R}$ is $\beta_{R} \approx \arctan(H_{T} / D)$. The distance between the projection $S$ of the scatterer $S$ to the $x$-$y$ plane and $O'$ is $d(O',S) = R_{S} \in (0,R_{S,\text{max}}]$ and the height of the scatterer is $d(S,S) = H_{S} \in (0,H_{S,\text{max}}]$. Moreover, $a_{T}$ denotes the azimuth angle of departure (AAoD) of the waves that impinge on the scatterer $S$, while $a_{R}$ and $\beta_{S} \approx \arctan(H_{S} / R_{S})$ are the azimuth angle of arrival (AAoA) and the elevation angle of arrival (EAAoA) of the waves scattered from $S$, respectively. Furthermore, TMS is moving with speed $v_{R}$ in the direction determined by the angle $\gamma_{R}$.

Due to the 3-D scattering conditions, a vertically (horizontally) polarized wave emitted from the HAP gives rise to a horizontally (vertically) polarized wave being received at the TMS. The vector $V$ in Fig. 1 represents the vertical polarization vector of a wave transmitted from the HAP and $V'$ denotes the vertical polarization vector of the wave reflected by the scatterer $S$. Note that $V'$ is not entirely vertically polarized, but has also cross-polarization components. This effect is called depolarization and is significantly affected by the distribution of the scatterers. One observes that the HAP, the TMS, and the scatterer define a plane for each wave that is emitted from the HAP and received at the TMS. The polarization angle $\xi_{V}$ of $V$ for this plane is defined as the angle between $V$ and the line that includes the projection of $V$ on that plane. Then, the angle between $V'$ and its projection line on the same plane is $\pi - \xi_{V}$ [17]. The polarization vector $V'$ can be decomposed into the vertical (perpendicular to the plane) and horizontal (parallel to and thus included in the plane) polarization components. The case of horizontally polarized antennas at the HAP and TMS can be similarly analyzed, but it is intentionally omitted to reduce the complexity of the illustration of the proposed system.

Figure 1. The 3-D cylindrical scattering model for XPD on Rician HAP-DP fading channels.

Observing Fig. 1 and considering a vertically polarized wave from the HAP, the amplitude of the received wave at a vertically polarized TMS antenna can be written as

$$A_{VV} = A_{r} f_{VV},$$

where $A_{r}$ is the amplitude of $V'$ at the TMS and the channel polarization function $f_{VV}$ is given by

$$f_{VV} = \left| \cos \left( \xi_{V} + \left( \pi - \xi_{V} \right) \right) \right| = \left| \cos \left( \xi_{V} - \xi_{V} \right) \right|. \quad (2)$$

Similarly, one can express the equation for the amplitude of the horizontal polarization component that is received from a vertically polarized transmitted plane as follows

$$A_{HH} = A_{r} f_{HH} = A_{r} \left| \sin \left( \xi_{V} - \xi_{V} \right) \right|. \quad (3)$$

Due to the symmetry in the co- and cross-polarization functions, for the case a horizontally polarized plane wave transmitted from the HAP, we obtain $A_{HH} = A_{r} f_{HH} = A_{H} f_{VV}$ and $A_{HH} = A_{H} f_{HH} = A_{H} f_{VV}$, where $A_{H}$ is the amplitude of $H'$ at the TMS and $H'$ is the horizontal polarization vector of the wave reflected by the scatterer $S$.

Using the cosine law, we obtain the angles $\xi_{V}$ and $\xi_{V}$ as functions of the model parameters as follows

$$\xi_{V} = \arccos \left( \frac{\cos \xi_{V} - \cos \xi_{V} \cos \beta_{S}}{\sin \xi_{V} \sin \beta_{S}} \right), \quad (4)$$

$$\xi_{V} = \pi - \xi_{V}, \quad (5)$$
where
\[ \xi_2 = \arccos \left( \frac{(H_T / \sin \beta_T)^2 + R_s^2 - \left[ d^2(O, S) + H_T^2 \right]}{2(H_T / \sin \beta_T) R_s} \right), \]
\[ \xi_3 = \arccos \left( \frac{(R_s / \cos \beta_s)^2 + (H_T / \sin \beta_T)^2 - d^2(O_T, S)}{2(R_s / \cos \beta_s)(H_T / \sin \beta_T)} \right), \]
\[ d(O_T, S) \approx \left[ (H_T / \tan \beta_T + R_s \cos \alpha_R)^2 + (R_s \sin \alpha_R)^2 \right]^{1/2}, \]
\[ \xi_4 = \arccos \left( \frac{\cos \xi_5 - \cos \xi_6 \cos \xi_7}{\sin \xi_5 \sin \xi_7} \right), \]
\[ \xi_5 = \arccos \left( \frac{\left( 2^2 \left( O, S \right) + H_T^2 \right) + (H_T / \sin \beta_T)^2 - R_s^2}{2d(O_T, S)(H_T / \sin \beta_T)} \right), \]
\[ \xi_6 = \arccos \left( \frac{d^2(O_T, S) + (H_T / \sin \beta_T)^2 - (R_s / \cos \beta_s)^2}{2d(O_T, S)(H_T / \sin \beta_T)} \right), \]
\[ \xi_7 = \arccos \left( \frac{d^2(O_T, S) + \left[ d^2(O, S) + H_T^2 \right] - (R_s \tan \beta_s)^2}{2d(O_T, S)\left[ d^2(O, S) + H_T^2 \right]^{1/2}} \right). \]

(6)

III. XPD IN HAP-DP FADING CHANNELS

Considering vertically polarized HAP and TMS antennas and \( N \) scatterers, the \( n \)-th scatterer is denoted by \( \mathbf{S}^{(n)} \) and the complex low-pass channel impulse response is given by
\[ h_{VV}(t) = h_{VV}^{L_S}(t) + h_{VV}^{N_L}(t), \]
where
\[ h_{VV}^{L_S}(t) = A_{V,L_S} \exp \left[ j\phi_L(t) \right], \]
\[ h_{VV}^{N_L}(t) = A_{V,N_L} \exp \left[ j\phi_N(t) \right]. \]
are the LoS and NLoS components, respectively, \( A_{V,L_S} \) and \( A_{V,N_L} \) denote the amplitude of the LoS and NLoS component, respectively, of \( V' \) at the TMS, and
\[ \phi_L(t) = 2\pi \left( f_c + f_D^{L_S} \right)(t - H_T / (c_0 \sin \beta_T)), \]
\[ f_D^{L_S} = \cos \beta_T f_{R,max} \cos \gamma, \]
\[ \phi_N(t) = 2\pi \left( f_c + f_D^{N_L} \right)(t - \left[ d^{(n)}(O_T, S) + R_s \sin \alpha_R \right] / c_0 + \phi^{(n)}), \]
\[ f_D^{N_L} = f_{R,max} \cos \left( \gamma + \phi^{(n)} \right), \]
where \( f_c = c_0 / \lambda \) is the carrier frequency, \( c_0 \) is the light velocity, \( \lambda \) is the carrier wavelength, and \( f_{R,max} = v_R / \lambda \) is the maximum Doppler frequency associated with TMS. It is assumed that phases \( \{\phi^{(n)}\} \) are independent and identically distributed (i.i.d.) uniform random variables on the interval \((-\pi, \pi)\) and are independent from the other random variables.

For large number of local scatterers, central limit theorem implies that \( h_{VV}(t) \) is a complex Gaussian random process. Then, using (7)-(9), the received power through the VV channel at the TMS is obtained as
\[ P_{VV} = P_{VV}^{L_S} + P_{VV}^{N_L}, \]
where
\[ P_{VV}^{L_S} = \frac{1}{2} \left| A_{V,L_S} \right|^2, \]
\[ P_{VV}^{N_L} = \frac{1}{2} \mathbb{E} \left[ \left| h_{VV}^{N_L}(t) \right|^2 \right], \]
and \( K \) denotes the Rician \( K \)-factor. Note that the channel is assumed locally wide-sense stationary, i.e., the locations of the scatterers with respect to the TMS will remain the same, provided that the TMS moves over small distances.

Since \( \beta_s \approx \arctan \left( H_S / R_S \right) \), (13) becomes a function of \( a_R^{(n)}, R_S^{(n)}, \) and \( H_S^{(n)} \). For an infinite number of scatterers, i.e., \( N \rightarrow \infty \), these discrete random variables can be replaced with the continuous random variables \( a_R, R_S, \) and \( H_S \) with joint probability density function (pdf) \( f(a_R, R_S, H_S) \). From Fig. 1, \( a_R, R_S, \) and \( H_S \) are independent. Thus, the joint pdf can be decomposed to \( f(a_R) f(R_S) f(H_S) \) and we obtain
\[ P_{VV}^{N_L} = \frac{1}{2} \mathbb{E} \left[ \left| h_{VV}^{N_L}(t) \right|^2 \right] \times f(a_R) f(R_S) f(H_S) da_R dR_S dH_S. \]

In this paper, we use the von Mises pdf\cite{18} to characterize the random variable \( a_R \). The von Mises pdf was empirically justified in\cite{19} and is defined as
\[ f(a_R) = \frac{\exp \left[ k \cos \left( a_R - \mu_R \right) \right]}{2\pi I_0(k)}, \]
where \( k \leq a_R \leq \pi, \) (15)
where $I_0(\cdot)$ is the zeroth-order modified Bessel function of the first kind, $\mu \in [-\pi, \pi]$ is the mean angle at which the scatterers are distributed in the $x$-$y$ plane, and $k \geq 0$ controls the spread around the mean. To characterize $R_S$, we use the hyperbolic pdf [20]. This pdf was empirically justified in [21] and is defined as

$$ f(R_S) = \frac{a}{\tanh(a R_{S,\text{max}}) \cosh^2(a R_S)}, \quad 0 < R_S \leq R_{S,\text{max}}, \quad (16) $$

where $\tanh$ and $\cosh$ are the hyperbolic tangent and hyperbolic cosine, respectively, and the parameter $a \in (0, 1)$ controls the spread of the scatterers around the TMS. Finally, we adopt the log-normal pdf [22], [23] to characterize the random variable $S_H$. This pdf matched data values obtained from measurements of building heights and is defined as

$$ f(S_H) = \exp \left[ -\frac{1}{2\sigma^2} \ln^2 \left( \frac{S_H}{S_{H,\text{mean}}} \right) \right]/H_S \sqrt{2\pi}, \quad 0 < S_H \leq S_{H,\text{max}}, \quad (17) $$

where the parameters $S_{H,\text{mean}}$ and $\sigma$ are the mean and standard deviation of $S_H$, respectively.

The power at the TMS with a horizontally polarized TMS antenna and a vertically polarized HAP antenna (HV channel), a vertically polarized TMS antenna and a horizontally polarized HAP antenna (VH channel), and horizontally polarized TMS and HAP antennas (HH channel), which are denoted by $P_{HV}$, $P_{VH}$, and $P_{HH}$, respectively, can be similarly expressed using (11) and (14) and changing the indices. By taking into account the statistical distribution of scatterers, the total power of the vertical and horizontal polarization components can be derived via the superposition of the LoS and NLoS components by averaging over the pdfs defined in (15)-(17). The XPD is defined as the ratio of the co-polarized average received power to the cross-polarized average received power and is given by

$$ \overline{\text{XPD}}_{HV/HV} = \frac{P_{VV}}{P_{HV}}, \quad (18) $$

$$ \overline{\text{XPD}}_{HH/VH} = \frac{P_{HH}}{P_{VH}}. \quad (19) $$

IV. NUMERICAL RESULTS

This section provides results to illustrate the theoretical derivations. Unless indicated otherwise, the values of the model parameters used to obtain the curves are $H_T = 20$ km, $\beta_T = 60^\circ$, $k = 3$, $\mu = \pi / 3$, $R_{S,\text{max}} = 200$ m, $a = 0.01$, and $H_{S,\text{max}} = 80$ m. In addition, a typical densely built-up district (London [23]) is considered, i.e., the surrounding buildings act as scatterers, and we set $H_{S,\text{mean}} = 17.6$ m and $\sigma = 0.31$.

Fig. 2 depicts the XPD as a function of the elevation angle $\beta_T$ for different degrees of local scattering (in the azimuth domain) at the TMS. One observes that the XPD drastically decreases, as the elevation angle increases. Fig. 2 also implies that as $k$ increases, the scattering becomes increasingly non-isotropic, the depolarization is directly affected, and the XPD increases. For highly concentrated scatterers around the angle $\mu$, i.e., for $k = 20$, the XPD takes its highest values.

Fig. 3 shows the XPD as a function of the spread of the scatterers around the TMS, which is controlled by the parameter $a$ (hyperbolic distribution), for different elevation angles $\beta_T$. It is evident that increasing $a$ decreases the spread of the scatterers and increases the XPD. Note that $a$ values of 0.01, 0.02, 0.03, 0.04, and 0.05 correspond to an average distance between the TMS and a scatterer of approximately 60 m, 34 m, 23 m, 17 m, and 14 m, respectively.
for different means of the scatterer height. One observes a variety of radio propagation environments and can be used to validate the utility of this model. Future research efforts could also include the channel modeling and measurement data to validate the utility of this model. Notwithstanding, future work could be devoted to collecting and XPD, without any aid of measurement data.

facilitate the practical exploitation of channel depolarization and XPD, without any aid of measurement data. Notwithstanding, future work could be devoted to collecting measurement data to validate the utility of this model. Future research efforts could also include the channel modeling and performance analysis of HAP-DP systems accommodating two spatially separated DP antennas, which form 4-antenna arrays.

V. CONCLUSION

In this paper, a 3-D reference model for XPD in HAP-DP narrowband fading channels has been proposed. Based on this model, the XPD has been studied. The numerical results have shown the relation between XPD and the 3-D non-isotropic distribution of scatterers in the vicinity of the TMS. These results have also underlined that the XPD strongly depends on the elevation angle of the platform with respect to the TMS. The reference model is parametric and adaptable to a wide variety of radio propagation environments and can be used to facilitate the practical exploitation of channel depolarization and XPD, without any aid of measurement data. Notwithstanding, future work could be devoted to collecting measurement data to validate the utility of this model. Future research efforts could also include the channel modeling and performance analysis of HAP-DP systems accommodating two spatially separated DP antennas, which form 4-antenna arrays.

ACKNOWLEDGMENT

This work is co-financed by the European Union and Greek national funds through the Operational Program “Education and Lifelong Learning” of the National Strategic Reference Framework (NSRF) – THALES Research Program: MIMOSA.

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