Spatially Correlated 3-D HAP-MIMO Fading Channels

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Abstract—This paper proposes a three-dimensional (3-D) scattering model for multiple-input multiple-output (MIMO) land mobile stratospheric multipath-fading channels. Analytical and closed-form expressions for the spatial and temporal correlation functions between two arbitrary sub-channels are derived, assuming non-isotropic or isotropic scattering environments. This model can be used to estimate the required High Altitude Platform (HAP) antenna separation to achieve an uncorrelated HAP-MIMO channel matrix. Numerical calculations have been carried out to demonstrate theoretical derivations. The proposed model is useful to design, analyze and test future HAP-MIMO based 3G communication systems with line-of-sight (LOS) and non-line-of-sight (NLOS) components.

Keywords—Stratospheric platform, HAP, multiple-input multiple output (MIMO), fading channels, three dimensional scattering environment, spatial correlation, antenna separation, LOS, NLOS, 3G communications

I. INTRODUCTION

High altitude platforms (HAPs) have been a new alternative to traditional terrestrial and satellite communications infrastructures that can exploit the best features of both systems and can promise access to broadband modern telecommunication services [1], [2]. The term HAPs defines quasi-stationary platforms flying at an altitude ranging between 17 and 22 Km above the ground, in the stratosphere. The ITU has licensed several frequency bands for communications through HAPs for the world wide 4G communications systems [3], [4] and for 3G communications systems [5]. Coverage zones of a HAP based system depend on elevation angle of the receiver. High elevation angles imply the presence of a predominant radio wave path of line of sight [6], but also multipath propagation should be considered when evaluating the telecommunication system performance [7].

The challenge nowadays is to investigate the application of Multiple-Input Multiple-Output (MIMO) techniques to the Land Mobile Stratospheric communication systems [8], [9]. Some models using multiple HAP constellations [10], [11] have shown that capacity can be significantly increased by using highly directional user antennas to spatially discriminate between HAPs in different parts of the sky. Moreover, in [12] a physical statistical Land Mobile-HAP propagation channel model was described that can predict joint statistical time series and power-spatial-delay profile data in a multi-antenna mobile, multi-HAP scenario whereas the potential gain of using various compact MIMO antenna array configurations in conjunction with HAP diversity techniques was studied in [13].

This paper focuses on the design of a MIMO channel model for 3G communications (2 GHz frequency band) based on a stratospheric platform, a mobile user and the presence of infinite scatterers around a cylinder. This implies that the radio propagation environment is characterized by 3-D scattering with line-of-sight (LOS) or non-line-of-sight (NLOS) propagation conditions between the free of local scattering HAP and the mobile user. Studies on the Terrestrial 3-D MIMO channel modeling include Aulin’s 3-D cylinder model [14] and improved SISO, SIMO, MISO [15], [16] and MIMO fixed-to-mobile [17] or mobile-to-mobile versions [18], without the LOS component.

The rest of the paper is organized as follows. In Section II the 3-D geometrical model is described. From this model the corresponding space-time correlation function is derived in section III. Section IV presents numerical results for this model relative to different parameters. Conclusions are drawn in Section V.

II. THE 3-D LAND MOBILE HAP-MIMO CHANNEL MODEL

This paper considers a downlink MIMO Land Mobile Stratospheric communication channel with $L_{SBS}$ transmit and $L_{TMS}$ receive antenna elements. All antennas are fixed, omni-directional, without beamforming and are numbered as $1 \leq p \leq q \leq L_{SBS}$ and $1 \leq l \leq m \leq L_{TMS}$, respectively. The $L_{SBS}$ elements of the Stratospheric Base Station (SBS) are situated 17-22 Km above the ground and it is assumed that the $L_{TMS}$ elements of the Terrestrial Mobile Station (TMS) are in motion.
Even though HAPs can provide quasi-stationary communication platforms, several points should be examined carefully in the design of the model [1]. Aircrafts usually fly on a tight circle (about 2km radius or more), while airships can theoretically stay still and they only have to compensate the winds or pressure variations. The ITU has specified that a HAP should be kept within a circle of 400m radius, with height variations of ±700m [19], so that services are available almost all the time. In practice, HAPs may move in any direction at a varying speed and the movements can be horizontal/vertical displacement with respect to x, y and z-axis as well as yaw, pitch and roll (6 degrees of freedom) [20]. Drift on the x or y-axis have similar effects on the ground, but vertical displacement, roll and pitch can be bypassed, based on a study of the winds statistics and the respective HAPs instability model [21], which indicates that the most important component is the horizontal displacement and the vertical winds are almost insignificant. For this work we consider that the HAP is kept within a circle of radius RHAP.

The geometrical characteristics of our model and the definition of the Cartesian coordinate system are discussed in the following figures. Fig. 1 shows the LOS paths of the 3-D model for a 2×2 MIMO channel with Ls=Rs=2 antenna elements. Fig. 2 shows the NLOS paths for the channel in Fig. 1. This elementary 2x2 antenna configuration can be used to form Uniform Linear Arrays (ULA) with arbitrary number of antenna elements. As shown in the Figs. 1 and 2, the y axis is the line that connects coordinate origin O (centre of the projections p and q of the SBS antenna elements p and q to the X−Y plane) and O′ (the centre circle of the cylinder). To aid our analysis we denote D_{a,b} as the distance between two points a and b. Then, the distance between O and O′ is D_{o,o′} and the elevations of the SBS and TMS antennas are H = D_{o,o_0} and D_{o,o_0′}, respectively. Furthermore, the elevation angle of SBS relative to the O′ is β_{HAP}.

The proposed model assumes N fixed emitting scattered waves that impinge on the TMS antenna elements from a random position S around the cylinder (not inside it). Then the nth scatterer is denoted by S^{(n)}. The elevation angle of S^{(n)} relative to the O′ is β_{S}^{(n)} and the azimuth angle is α_{S}^{(n)}. It is assumed that radius R is much smaller than the distance D_{o,o′}, i.e., R ≪ D_{o,o′} (Local Scattering Condition). The spacing between two adjacent antenna elements at the SBS and TMS is denoted by δ_{s} and δ_{r}, respectively. It is assumed that δ_{s} and δ_{r} are much smaller than the radius R, i.e., max{δ_{s}, δ_{r}} ≪ min R. Angles θ_{s} and θ_{r} represent the orientation of the transmitter and receiver antenna arrays respectively, relative to the x-axis and angle ψ describes the elevation angle of the TMS antenna array.
The symbols $\alpha_{p}^{\text{LOS}}$, $\alpha_{s}^{(s)}$ and $\alpha_{s}^{(n)}$ denote the angle of arrival (AoA) of the LOS paths, the angle of departure (AoD) of the wave that impinge on the scatterer $S^{(s)}$ and the AoA of the wave scattered from $S^{(n)}$, respectively. Moreover, we assume that SBS and TMS are moving with speeds $u_s$ and $u_t$ in the directions determined by the angles $\gamma_s$ and $\gamma_t$, respectively.

Based on the geometrical model described above, the impulse response $h_{pl} (t)$ of the sub-channel $p-l$ is a superposition of the LOS and NLOS rays and can be written as follows

$$h_{pl} (t) = h_{pl, \text{LOS}} (t) + h_{pl, \text{NLOS}} (t).$$

In the 3-D reference model, the number of local scatterers is infinite ($N \to \infty$). Consequently the impulse response $h_{pl, \text{NLOS}}$ can be modeled as a low pass zero mean complex Gaussian process and therefore its envelope $|h_{pl, \text{NLOS}}|$ is Rayleigh distributed (central limit theorem) [22].

The impulse responses of the LOS and NLOS components are, respectively

$$h_{pl, \text{LOS}} (t) = \frac{K_{pl} \Omega_{pl} e^{j2\pi f_{r,\text{max}} (x_{\text{max}} - t)}}{K_{pl} + 1} e^{j2\pi f_{r,\text{max}} (x_{0} - t)}.$$

$$h_{pl, \text{NLOS}} (t) = \sqrt{\frac{\Omega_{pl}}{K_{pl} + 1}} \lim_{N \to \infty} \sum_{n=1}^{N} \frac{1}{\sqrt{N}} e^{j2\pi f_{r,\text{max}} (x_{\text{max}} - t)} e^{j2\pi f_{r,\text{max}} (x_{0} - t)} e^{j2\pi f_{r,\text{max}} (x_{\text{max}} - t)},$$

where $f_{r,\text{max}} = u_s / \lambda$ and $f_{r,\text{max}} = u_t / \lambda$ are the transmitter’s and receiver’s maximum Doppler frequency respectively and $\lambda$ is the carrier wavelength. It is assumed that phase $\phi^{(s)}$ is random variable uniformly distributed in the interval $[-\pi, \pi]$ and independent from AoD and AoA. In (2) and (3), $K_{pl}$ and $\Omega_{pl}$ denote the Ricean factor and the transmitted power of the subchannel $p-l$ respectively.

The distances $D_{p,s}$, $D_{n,s}$ and $D_{s,j}$, can be expressed as functions of the angles $\alpha_{p}^{(s)}$, $\alpha_{s}^{(n)}$ and $\beta_{s}^{(n)}$

$$D_{p,s} = \frac{H}{\sin \beta_{AOD}} \frac{\delta_s \cos \theta_s - \delta_s \Delta \sin \theta_s \sin \alpha_{s}^{(n)}}{2 \cos \beta_{AOD} 2 \cos \beta_{AOD}},$$

$$D_{s,j} = R - 0.5 \delta_s \sin \psi \sin \beta_{s}^{(n)} - 0.5 \delta_s \cos \psi \cos \beta_{s}^{(n)} \sin \alpha_{s}^{(n)},$$

$$D_{s,j} = R - 0.5 \delta_s \sin \psi \sin \beta_{s}^{(n)} - 0.5 \delta_s \cos \psi \cos \beta_{s}^{(n)} \sin \alpha_{s}^{(n)},$$

where $\Delta = \arcsin \left( R / D_{0,0} \right) = R / D_{0,0}$ is the narrow angle of spread, when $D_{0,0} \gg R \gg \max (\delta_s, \delta_s)$. Then, from Fig. 2, $\alpha_{s}^{(n)} \leq \arcsin \left( R / D_{0,0} \right)$ is small angle. Derivations of (4)-(6) are omitted for brevity.

Using (4)-(6), assuming that the total transmit power is unity and applying the sine law to the triangle $O S^{(n)} O'$ the impulse responses of the LOS and NLOS components become respectively

$$h_{pl, \text{LOS}} (t) = \frac{K_{pl}}{K_{pl} + 1} e^{-\frac{j2\pi f_{r,\text{max}}}{\alpha_s^{(n)}} \left( x_{\text{max}} - \gamma_s \right)} e^{-\frac{j2\pi f_{r,\text{max}}}{\alpha_s^{(n)}} \left( x_{0} - \gamma_s \right)} e^{-\frac{j2\pi f_{r,\text{max}}}{\alpha_s^{(n)}} \left( x_{\text{max}} - \gamma_s \right)}.$$

$$h_{pl, \text{NLOS}} (t) = \frac{1}{K_{pl} + 1} \lim_{N \to \infty} \sum_{n=1}^{N} \frac{1}{\sqrt{N}} a_{p,s} b_{s,j} e^{j2\pi f_{r,\text{max}} (x_{\text{max}} - t)} e^{j2\pi f_{r,\text{max}} (x_{0} - t)} e^{j2\pi f_{r,\text{max}} (x_{\text{max}} - t)}.$$

where

$$a_{p,s} = e^{-\frac{j2\pi f_{r,\text{max}}}{\alpha_s^{(n)}} \left( x_{\text{max}} - \gamma_s \right)} e^{-\frac{j2\pi f_{r,\text{max}}}{\alpha_s^{(n)}} \left( x_{0} - \gamma_s \right)} e^{-\frac{j2\pi f_{r,\text{max}}}{\alpha_s^{(n)}} \left( x_{\text{max}} - \gamma_s \right)}.$$

$$b_{s,j} = e^{-\frac{j2\pi f_{r,\text{max}}}{\alpha_s^{(n)}} \left( x_{\text{max}} - \gamma_s \right)} e^{-\frac{j2\pi f_{r,\text{max}}}{\alpha_s^{(n)}} \left( x_{0} - \gamma_s \right)} e^{-\frac{j2\pi f_{r,\text{max}}}{\alpha_s^{(n)}} \left( x_{\text{max}} - \gamma_s \right)}.$$

III. SPACE-TIME CORRELATION FUNCTIONS

The space-time correlation function between two sub-channels $h_{pl} (t)$ and $h_{qm} (t)$ is defined as:

$$R_{pl,qm} (\delta_s, \delta_t, \gamma_s) = E\left[ h_{pl} (t) h_{qm} (t + \tau) \right] = E\left[ h_{pl, \text{LOS}} (t) h_{qm, \text{LOS}} (t + \tau) \right] + E\left[ h_{pl, \text{NLOS}} (t) h_{qm, \text{NLOS}} (t + \tau) \right] = R_{pl,qm}^{\text{LOS}} (\delta_s, \delta_t, \gamma_s) + R_{pl,qm}^{\text{NLOS}} (\delta_s, \delta_t, \gamma_s),$$

where $(\cdot)^*$ denotes complex conjugate operation, $E[ \cdot ]$ is the statistical expectation operator, $p, q \in \{1, \ldots, L_{\text{subs}}\}$ and $l, m \in \{1, \ldots, L_{\text{sub}}\}$.
Using (2) and (7), space-time correlation function of the LOS component can be written as

\[
R_{\text{LOS}}^{\text{LOS}}(\delta_1, \delta_2; \tau, t) = E\left[ h_{\text{LOS}}(t) h_{\text{LOS}}^*(t + \tau) \right] = \\
\sqrt{\frac{K_n}{K_p}} \int_{\beta_0}^{\beta_0} \frac{K_m}{K_m} e^{-j2\pi \Delta (D_{12})_k} \frac{e^{-j2\pi \Delta (D_{12})_k}}{\Delta} \frac{1}{2} e^{j2\pi \frac{\Delta}{\lambda} \sin \theta_{\text{LOS}} \sin \phi_{\text{LOS}}} \frac{1}{2} e^{j2\pi \frac{\Delta}{\lambda} \sin \theta_{\text{LOS}} \cos \phi_{\text{LOS}}} \frac{1}{2} e^{j2\pi \frac{\Delta}{\lambda} \cos \theta_{\text{LOS}} \sin \phi_{\text{LOS}}} \frac{1}{2} e^{j2\pi \frac{\Delta}{\lambda} \cos \theta_{\text{LOS}} \cos \phi_{\text{LOS}}} d\phi_{\text{LOS}} d\theta_{\text{LOS}}.
\]

(12)

Assuming that \( \max \{ \delta_1, \delta_2 \} \ll D_{12,0} \), we obtain that \( \alpha_{\text{LOS}}^{(s)} = \alpha_{\text{LOS}}^{(s)} = \pi \). Based on this approximation, equation (12) can be simplified to

\[
R_{\text{LOS}}^{\text{LOS}}(\delta_1, \delta_2; \tau, t) = \sqrt{\frac{K_n}{K_p}} \int_{\beta_0}^{\beta_0} \frac{K_m}{K_m} e^{-j2\pi \Delta (D_{12})_k} \frac{1}{2} e^{j2\pi \frac{\Delta}{\lambda} \sin \theta_{\text{LOS}} \sin \phi_{\text{LOS}}} \frac{1}{2} e^{j2\pi \frac{\Delta}{\lambda} \sin \theta_{\text{LOS}} \cos \phi_{\text{LOS}}} \frac{1}{2} e^{j2\pi \frac{\Delta}{\lambda} \cos \theta_{\text{LOS}} \sin \phi_{\text{LOS}}} \frac{1}{2} e^{j2\pi \frac{\Delta}{\lambda} \cos \theta_{\text{LOS}} \cos \phi_{\text{LOS}}} d\phi_{\text{LOS}} d\theta_{\text{LOS}}.
\]

(13)

Moreover, using (3) and (8)-(10), space-time correlation function of the NLOS component can be written as

\[
R_{\text{NLOS}}^{\text{NLOS}}(\delta_1, \delta_2; \tau, t) = E\left[ h_{\text{NLOS}}(t) h_{\text{NLOS}}^*(t + \tau) \right] = \\
\frac{1}{N} \int_{\beta_0}^{\beta_0} \frac{1}{N} \sum_{i=1}^{N} \left[ e^{-j2\pi \Delta (D_{12})_k} \frac{1}{2} e^{j2\pi \frac{\Delta}{\lambda} \sin \theta_{\text{NLOS}} \sin \phi_{\text{NLOS}}} \frac{1}{2} e^{j2\pi \frac{\Delta}{\lambda} \sin \theta_{\text{NLOS}} \cos \phi_{\text{NLOS}}} \frac{1}{2} e^{j2\pi \frac{\Delta}{\lambda} \cos \theta_{\text{NLOS}} \sin \phi_{\text{NLOS}}} \frac{1}{2} e^{j2\pi \frac{\Delta}{\lambda} \cos \theta_{\text{NLOS}} \cos \phi_{\text{NLOS}}} d\phi_{\text{NLOS}} d\theta_{\text{NLOS}} \right].
\]

(14)

Since the number of scatterers is infinite, the discrete AoA \( \alpha_{\text{s}}^{(s)} \) and the elevation angle \( \beta_{\text{s}}^{(s)} \) can be replaced with continuous random variables \( \alpha_{\text{s}}^{(s)} \) and \( \beta_{\text{s}}^{(s)} \) with probability density functions \( f(\alpha_{\text{s}}) \) and \( f(\beta_{\text{s}}) \), respectively. Thus, equation (14) becomes

\[
R_{\text{NLOS}}^{\text{NLOS}}(\delta_1, \delta_2; \tau, t) = \frac{1}{N} \int_{\beta_0}^{\beta_0} \frac{1}{N} \sum_{i=1}^{N} \left[ e^{-j2\pi \Delta (D_{12})_k} \frac{1}{2} e^{j2\pi \frac{\Delta}{\lambda} \sin \theta_{\text{NLOS}} \sin \phi_{\text{NLOS}}} \frac{1}{2} e^{j2\pi \frac{\Delta}{\lambda} \sin \theta_{\text{NLOS}} \cos \phi_{\text{NLOS}}} \frac{1}{2} e^{j2\pi \frac{\Delta}{\lambda} \cos \theta_{\text{NLOS}} \sin \phi_{\text{NLOS}}} \frac{1}{2} e^{j2\pi \frac{\Delta}{\lambda} \cos \theta_{\text{NLOS}} \cos \phi_{\text{NLOS}}} d\phi_{\text{NLOS}} d\theta_{\text{NLOS}} \right].
\]

(15)

where \( \beta_{s,max} \) is random scatterer’s maximum elevation angle. Assuming that the scattering environment is non-isotropic, we adopt Von Mises distribution \([23]\) for \( f(\alpha_{\text{s}}) \) and Parson’s recommended p.d.f. \([15]\) for scatterer’s elevation angle. The Von Mises p.d.f. is defined as

\[
f(\alpha_{\text{s}}) = \frac{1}{2\pi I_0(\kappa)} \exp[k \cos(\alpha_{\text{s}} - \mu)], \quad -\pi \leq \alpha_{\text{s}} \leq \pi,
\]

(16)

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 on the azimuth, and \( k \) controls the spread around the mean. Setting \( k = 0 \) incurs isotropic scattering \( (f(\alpha_{\text{s}}) = 1/(2\pi)) \). Parson’s p.d.f. is defined as

\[
f(\beta_{\text{s}}) = \frac{\pi}{4\beta_{\text{s,max}}^2} \cos\left(\frac{\beta_{\text{s}}}{2\beta_{\text{s,max}}}\right).
\]

(17)

where \( 0 < \beta_{\text{s,max}} < \pi/2 \). Parameter \( \beta_{\text{s,max}} \) is the absolute value of random scatterer’s maximum elevation angle and according to \([24]\) can take values between 0° and 20° for the terrestrial “street canyon” type of propagation and between 20° and 80° for over the roof propagation, where the base station is elevated above the roofs of the buildings.

Using the aforementioned p.d.f.s and the integral

\[
\int_{a}^{b} e^{ax}(b+a) e^{bx} \, dx = 2\pi I_0 \left(\sqrt{a^2 + b^2}\right) [25, eq. 3.384-4],
\]

space-time correlation function of the NLOS component becomes

\[
R_{\text{NLOS}}^{\text{NLOS}}(\delta_1, \delta_2; \tau, t) = \frac{1}{N} \int_{\beta_0}^{\beta_0} \frac{1}{N} \sum_{i=1}^{N} \left[ e^{-j2\pi \Delta (D_{12})_k} \frac{1}{2} e^{j2\pi \frac{\Delta}{\lambda} \sin \theta_{\text{NLOS}} \sin \phi_{\text{NLOS}}} \frac{1}{2} e^{j2\pi \frac{\Delta}{\lambda} \sin \theta_{\text{NLOS}} \cos \phi_{\text{NLOS}}} \frac{1}{2} e^{j2\pi \frac{\Delta}{\lambda} \cos \theta_{\text{NLOS}} \sin \phi_{\text{NLOS}}} \frac{1}{2} e^{j2\pi \frac{\Delta}{\lambda} \cos \theta_{\text{NLOS}} \cos \phi_{\text{NLOS}}} d\phi_{\text{NLOS}} d\theta_{\text{NLOS}} \right].
\]

(18)

where

\[
a_i = -j2\pi f_{\Delta} \sin \gamma_i - j2\pi f_{\Delta} \Delta \sin \gamma_i + j2\pi \delta_{\Delta} \Delta \sin \theta_i \Delta \cos \beta_{\text{FOP}} + j2\pi \delta_{\Delta} \beta_{\text{FOP}} \Delta \cos \theta_i \sin \phi_i \sin k \sin \beta_i,
\]

(19)
\[ a_s = -j 2 \pi f_{s,\text{max}} \cos \gamma_s + j \frac{2 \pi}{\lambda} \delta_s \cos \psi \cos \beta_s \cos \theta_s \]

\[ + k \cos \mu, \quad (20) \]

\[ a_i = \pi / 2 \beta_{s,\text{max}}, \quad (21) \]

\[ a_s = \frac{2 \pi \delta_s \cos \theta_s}{\lambda \cos \beta_{s,HAP}} - j 2 \pi f_{f,\text{max}} \cos \gamma_s, \quad (22) \]

\[ a_i = j \frac{2 \pi}{\lambda} \delta_s \sin \psi. \quad (23) \]

To obtain the space-time correlation function of the NLOS component, the integral in (18) has to be evaluated numerically, since there is no closed-form solution.

Finally, the space-time correlation function between two subchannels \( h_{ni}(t) \) and \( h_{n'i}(t) \) becomes a summation of the space-time correlation function of the LOS component \( R_{\text{LOS}}(\delta_r, \delta_s, \tau) \) and the space-time correlation function of the NLOS component \( R_{\text{NLOS}}(\delta_r, \delta_s, \tau) \) defined in (13) and (18)-(23), respectively.

The general formulas of the Land Mobile Stratospheric MIMO channel space-time correlation function can be further simplified for the cases of SIMO and MISO channels. In MISO channels, we consider multiple SBS antenna elements and one TMS antenna element \( (\delta_s = 0) \). In that case, the closed form of the spatial correlation function \( (\tau = 0) \) between two subchannels \( h_n(t) \) and \( h_m(t) \) with isotropic scattering \( (k = 0) \) is the following

\[ R_{\text{NLOS}}^{\text{SIMO}}(\delta_r) = \frac{1}{K_{\text{pl}} + 1} \frac{1}{K_{\text{qw}} + 1} \left\{ e^{-\left(\frac{1}{K_{\text{pl}}} + \frac{1}{K_{\text{qw}}} + 1\right) a_s \Delta \tan \theta_s} \right\}. \quad (24) \]

In SIMO channels, we consider one SBS antenna element \( (\delta_r = 0) \) and multiple TMS antenna elements. In that case, the spatial correlation function \( (\tau = 0) \) between two subchannels \( h_n(t) \) and \( h_m(t) \) with isotropic scattering \( (k = 0) \) is the following

\[ R_{\text{NLOS}}^{\text{SIMO}}(\delta_s) = \frac{1}{K_{\text{pl}} + 1} \frac{1}{K_{\text{qw}} + 1} \left\{ K_{\text{pl}} \sqrt{K_{\text{qw}} e^{a_s \Delta \tan \theta_s}} \right\} \]

\[ + a_s e^{a_s \Delta \tan \theta_s} \int_{-\beta_{s,\text{max}}}^{\beta_{s,\text{max}}} \cos (a_s \beta_s) e^{a_s \Delta \tan \theta_s} \left( \frac{a_s}{\tan \psi} \cos \beta_s \right) d \beta_s. \quad (25) \]

IV. NUMERICAL RESULTS

This section provides numerical results of the 3-D HAP-MIMO 2x2 cylinder model. The effect of spatial correlation is investigated, as well as the impact of the antenna spacing and arrangement is demonstrated in non-isotropic and isotropic scattering environments.

In all examples, we used the following model parameters:

- SBS elevation was \( D_{\text{e},0} = 20 \text{ Km} \), SBS elevation angle was \( \beta_{s,HAP} = 60^\circ \), the distance between \( O \) and \( O' \) was \( D_{\text{e},0'} = D_{\text{e},0} / \tan \beta_{s,HAP} = 11.5 \text{ Km} \), the radius of the cylinder was \( R = 80 \text{ m} \) and the narrow angle of spread was \( \Delta = \arcsin \left( R / D_{\text{e},0} \right) = 0.4^\circ \). Unless indicated otherwise, other model’s parameters were chosen to be \( \theta_s = \theta'_s = 90^\circ \), \( \psi = 0^\circ \), \( \beta_{s,\text{max}} = 45^\circ \), \( \tau = 0 \) and \( k = 0 \). Moreover, in order to estimate the required HAP inter-element distance to achieve an uncorrelated HAP-MIMO channel matrix, we set Ricean factor \( K = 0 \).

The effect of non-isotropic scattering for a HAP-MIMO channel with two SBS antennas and one TMS antenna is observed in Fig. 3, for \( \mu = 60^\circ \). The correlation increases as the scattering becomes more non-isotropic, which corresponds to an increase in \( k \). At 2 GHz, assuming an isotropic scattering environment \((k = 0)\), the SBS antennas require a separation of around 14 meters, which suggests that MIMO techniques are applicable in a single HAP.

The correlation functions of one SBS antenna and two uniformly and vertically placed TMS antennas for a HAP-SIMO channel are plotted in Fig. 4 for several \( \beta_{s,\text{max}} \) values. As \( \beta_{s,\text{max}} \) changes from 10° to 45°, the correlations between the two subchannels reduces dramatically. When TMS antennas are horizontally placed, their correlation is significantly small and is almost the same with different \( \beta_{s,\text{max}} \).

![Figure 3. The correlation of a HAP-MISO channel with two SBS antennas and one TMS antenna in terms of the degree of local scattering at the TMS.](image-url)
shown if Fig. 5 and those of the uniformly and vertically placed TMS antennas in Fig. 6. It is clear that the correlation functions of the MIMO channels are significantly affected not only by the spacing but also by the arrangement of the antenna elements. This suggests that low correlations can be obtained, if we carefully arrange the SBS and TMS antenna elements, such that their correlation falls in the “valleys” of the plots.

V. CONCLUSIONS

In this paper, a reference model for a Land Mobile Stratospheric Ricean MIMO channel is introduced. Spatial correlation functions of this model have been analyzed under a 3-D cylinder fading environment. General formulas as well as specific closed-form expressions have been derived for the spatial correlation between two arbitrary sub-channels. Extensive numerical calculations have been carried out to demonstrate theoretical derivations and estimate the required inter-element distance for an uncorrelated HAP-MIMO channel matrix. Our procedure provides a useful framework for designing and testing future HAP-MIMO based 3G communication systems and studying the channel capacity of HAP-MIMO based channels, with LOS and NLOS components.

REFERENCES


