Performance Analysis of MIMO MRC in 3D Mobile-to-Mobile Double-Correlated Channels

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Abstract—In this paper, we consider multiple-input multiple-output (MIMO) maximal ratio combining (MRC) systems and assess the system performance in terms of average symbol error probability (SEP), outage probability and ergodic capacity in double-correlated Rayleigh-and-Lognormal fading channels. In order to derive the receive and transmit correlation functions needed for the performance analysis, a three-dimensional (3D) MIMO mobile-to-mobile (M-to-M) channel model, which takes into account the effects of fast fading and shadowing is used. Numerical results are provided to show the effects of system parameters, such as maximum elevation angle of scatterers, orientation angle of antenna array in the x-y plane, angle between x-y plane and the antenna array orientation, and degree of scattering in the x-y plane, on the system performance.

I. INTRODUCTION

In wireless communication systems, such as cooperative multiple-input multiple-output (MIMO) networks, mobile Ad-hoc networks and vehicle-to-vehicle communication systems, transmitters and receivers may both be in motion, and the channel is a mobile-to-mobile (M-to-M) channel. For M-to-M communication systems equipped with low elevation antennas and multi-antenna mobile transceivers, in rich-scattering environments where scattered waves do not travel horizontally, a three-dimensional (3D) geometrical model has been proposed in [1] to describe the corresponding multipath fading channel, which can be characterized by the two-cylinder model, consisting of one cylinder around the transmitter and another around the receiver. Recently, the space-time correlation function of 3D MIMO M-to-M fast fading channels has been derived in [2], and used to assess its influence on the capacity in the scenario with no channel state information (CSI) at the transmitter and perfect CSI at the receiver, through simulations.

In the above-mentioned works on M-to-M channel modelling, only the effects of fast fading factors caused by multipath, such as random phase shift, propagation delay and Doppler shift, were considered in the modelling of the time-varying channel impulse response. In this paper, we investigate the effects of fast fading and shadowing on the 3D MIMO M-to-M channel modelling, and derive the space-time correlation function on the basis of the space-time correlation without consideration of shadowing and the correlation model for shadow fading provided in [3].

3D M-to-M channels can be considered as a general kind of double-correlated fading channels, where the transmit and receive correlations are due to scattering and shadowing. Herein, we consider MIMO maximal ratio combining (MRC) over 3D M-to-M double-correlated fading channels. MIMO MRC systems implement transmit-beamforming (TB) through full CSI availability at the transmitter, and can achieve high system capacity and full diversity gain. The performance of MIMO MRC systems in uncorrelated and semi-correlated Rayleigh fading channels was analyzed in [4], [5], respectively. In addition, the performance of such systems over double-correlated Rayleigh fading has been investigated in [6]. In the latter, the cumulative distribution function (CDF) and probability density function (PDF) of the output signal-to-noise ratio (SNR), which are related to the transmit and receive correlation functions, were provided and used for deriving the average symbol error probability (SEP) in the special case with two antennas at either the transmitter or the receiver, i.e., for $2 \times n_T$ or $n_T \times 2$ MIMO configurations, where $n_T$ and $n_R$ are the numbers of transmit and receive antennas. Because the CDF expression of the output SNR in [6] is too complex to achieve tractable performance analysis, an approximation in the low SNR range was used in [7] for the $n_T \times n_R$ MIMO configuration.

In this paper, the effect of spatial correlation on the performance of the M-to-M MIMO MRC system under study is assessed in the transmission scenario over double-correlated Rayleigh-and-Lognormal fading channels considering fast fading and shadowing. We derive the average SEP as a function of the average SNR per receive antenna, $\gamma$, in the $2 \times 2$ MIMO MRC system configuration using an approach which is much simpler than that in [6]. Besides, the performance of M-to-M MIMO MRC is investigated in terms of outage probability and ergodic capacity, for which analytical expressions are derived.

In the remainder of this paper, Section II introduces the M-to-M MIMO MRC system under study. In Section III, the space-time correlation function of 3D MIMO M-to-M channels is presented taking into account fast fading and shadowing. Then, the performance of M-to-M MIMO MRC is analyzed in Section IV in terms of average SEP, outage probability and ergodic capacity. Numerical results and comparisons are presented in Section V, followed by concluding remarks provided in Section VI.

II. SYSTEM MODEL

Consider a MIMO system, equipped with $n_T$ transmit and $n_R$ receive antennas, to operate under TB and MRC. The received signal model can be expressed as

$$y = H w x + n,$$  \hspace{1cm} (1)

where $x$ denotes the transmitted symbol with average power $P_0$, $w$ refers to the $n_T \times 1$ unit-energy TB weight vector, and
$n$ is the $n_R \times 1$ noise vector with elements belonging to independent and identically distributed (i.i.d.) complex Gaussian distribution $CN(0, N_0)$ that is uncorrelated with transmitted symbols. In (1), $H$ is the $n_R \times n_T$ channel gain matrix, which follows the common Kronecker structure, according to

$$H = \Phi_R^{1/2} H_n \Phi_T^{1/2} \sim CN_{n_R,n_T}(0_{n_R,n_T}, \mathbf{I}_{n_R} \otimes \mathbf{I}_{n_T})$$

where $H_n \sim CN_{n_R,n_T}(0_{n_R,n_T}, \mathbf{I}_{n_R} \otimes \mathbf{I}_{n_T})$ with $\mathbf{I}_n$ denoting the identity matrix of size $n \times n$, and $\Phi_R$ and $\Phi_T$ are the receive and transmit correlation matrices, respectively. Accordingly, the channel is called double-correlated fading channel. Let $\lambda_{max}$ be the largest eigenvalue of the double-correlated complex Wishart matrix $H^H H$, then the output SNR of the MIMO MRC system is given by, $\gamma = \gamma_{\lambda_{max}}$, where $\gamma$ denotes the average SNR per receive antenna. In the scenario with shadowing, $\gamma$ is assumed to be Lognormally distributed according to the PDF

$$p_\gamma (\gamma) = \frac{\xi}{\sqrt{2\pi} \Gamma} \exp \left[ - \frac{(\log \gamma - \eta_P)^2}{2\Gamma^2} \right]$$

(3)

where $\sigma$ denotes the shadowing standard deviation, $\xi = 10/\ln 10$, $\eta_P = 10\log_{10} \left( \frac{P_0 (D/d_0)^{-\gamma}}{N_0} \right) - L_0$, with $r$ representing the pathloss exponent, $d_0$ denoting the close-in reference distance which is determined from measurements close to the transmitter, and $L_0$ expressing the pathloss in [dB] at distance $d_0$.

As for $\lambda_{max}$, its exact CDF and PDF are derived in [6]. However, the provided expressions are too complex to achieve tractable performance analysis. Herein, we concentrate on the special case with $2 \times 2$ MIMO MRC configuration in double-correlated channels, for which the CDF of $\lambda_{max}$ is given by [6]:

$$F_{\lambda_{max}} (\gamma) = \frac{\omega_1 \omega_2 \sigma_1 \sigma_2}{\lambda (\sigma_2 - \sigma_1)} (\omega_2 - \omega_1) \times \sum_{i=1}^{2} (-1)^i \prod_{j=1}^{2} (\frac{\omega_j}{\sigma_j} + \frac{\lambda}{\omega_j-\sigma_j} - 1)$$

(4)

where $\omega_1 < \omega_2$ and $\sigma_1 < \sigma_2$ are the eigenvalues of $\Phi_R$ and $\Phi_T$, respectively. Finally, the CDF and PDF of the output SNR $\gamma$ can be obtained as follows

$$F_\gamma (\gamma) = \int_0^{\infty} F_{\lambda_{max}} (\frac{\omega}{\gamma}) p_\gamma (\gamma) d\gamma$$

(5)

$$p_\gamma (\gamma) = \frac{1}{\gamma} F_{\lambda_{max}} (\frac{\omega}{\gamma}) p_\gamma (\gamma) d\gamma$$

(6)

where $p_{\lambda_{max}} (\cdot)$ denotes the PDF of $\lambda_{max}$.

III. SPACE-TIME CORRELATION FUNCTION

In this section, we derive the receive and transmit correlation matrices, $\Phi_R$ and $\Phi_T$, of a narrow-band MIMO M-to-M system. The transmitter and receiver are mobile and denoted by $T_x$ and $R_x$, respectively. We consider a 3D scattering environment with non-line-of-sight (NLOS) propagation, which can be characterized by the two-cylinder model illustrated in [1, Fig. 1].

1 Due to space limitation this figure is not reproduced here.

$T_x$, denoted by $S^{(p)}_R (p = 1, 2, ..., P)$ following notations in [1]. Also, $Q$ fixed omnidirectional scatterers $S^{(q)}_R (q = 1, 2, ..., Q)$ are located on the surface of the cylinder with radius $R_x$ around $R_x$. Let $D$ denote the distance between the centers of $T_x$ and $R_x$ cylinders. For brevity, we focus on the scenario with $n_T = 2$ and $n_R = 2$, and denote the distance between the antenna elements at $T_x$ and $R_x$ by $\delta_T$ and $\delta_R$, respectively. It is assumed that $\max \{R_T, R_R\} \leq D$ and $\max \{\delta_T, \delta_R\} \leq \min \{R_T, R_R\}$. Tilt angles $\theta_T$ and $\theta_R$ represent the orientation of $T_x$ and $R_x$ antenna arrays in the x-y plane, respectively, with respect to the x-axis. Analogously, angles between the x-y plane and the orientation of $T_x$ and $R_x$ antenna arrays are denoted by $\zeta_T$ and $\zeta_R$, respectively.

As for the scatterer orientation, the azimuth angle of departure (AaOD) and the azimuth angle of arrival (AaOA) are expressed as $\omega_T^{(p)}$ and $\omega_R^{(q)}$, respectively. The symbols $\beta_T^{(p)}$ and $\beta_R^{(q)}$ denote the elevation angle of departure (EaOD) and the elevation angle of arrival (EaOA), respectively. Furthermore, it is assumed that $T_x$ and $R_x$ move with speeds $v_T$ and $v_R$, according to the direction angles $\psi_T$ and $\psi_R$ with respect to x-axis in the x-y plane, respectively.

Herein, we take into account fast fading and shadowing in the MIMO M-to-M channel modelling. Since the fast fading and shadowing are uncorrelated random processes, the space-time correlation function between two complex faded envelopes corresponding to transmission links $A_T^{(k)} A_R^{(n)}$ and $A_T^{(k)} A_R^{(n)}$ can be written as

$$\rho_{nk,\tilde{n}k} (\delta_T, \delta_R, \tau) = \gamma_{Sh} (\delta_T, \delta_R, \tau) \rho_{nk,\tilde{n}k}^{NS} (\delta_T, \delta_R, \tau)$$

(7)

where $\rho_{nk,\tilde{n}k}^{NS} (\delta_T, \delta_R, \tau)$ represents the space-time correlation without consideration of shadowing, and $\gamma_{Sh} (\delta_T, \delta_R, \tau)$ is the correlation component with shadowing only, given by [3]

$$\gamma_{Sh} (\delta_T, \delta_R, \tau) = e^{-\eta \lambda (f_{\max} T_R + f_{\max} T_T) \tau} \left[ A \cos (\Delta_{nk,\tilde{n}k}) + B \right]$$

(8)

where $\lambda_c$ denotes the carrier wavelength, and $\eta$ is a propagation-related coefficient (a value of $\eta = 1/20$ is suggested for suburban and urban environments [8]). $A$ and $B$ are two non-negative coefficients satisfying $A + B \leq 1$. In order to calculate the geometrical angle between the two links $A_T^{(n)} A_R^{(n)}$ and $A_T^{(k)} A_R^{(n)}$, i.e., $\Delta_{nk,\tilde{n}k}$, we start by presenting the coordinates of the transmit and receive antennas:

$$A_T^{(k)} = \frac{-\delta_T (n_T + 1 - 2k)}{2} \cos \zeta_T \sin \theta_T, \frac{-\delta_T (n_T + 1 - 2k)}{2} \cos \zeta_T \cos \theta_T$$

(9)

$$A_R^{(n)} = \frac{D - \delta_R (n_R + 1 - 2n)}{2} \cos \zeta_R \sin \theta_R, \frac{D - \delta_R (n_R + 1 - 2n)}{2} \cos \zeta_R \cos \theta_R$$

(10)

Then, based on the coordinates of $A_T^{(k)}$ and $A_R^{(n)}$, cos($\Delta_{nk,\tilde{n}k}$) can be calculated using cos($\Delta_{nk,\tilde{n}k}$) =
\[
\left( A_T^{(k)} A_R^{(n)} , A_T^{(k)} A_R^{(n)} \right) / \left| A_T^{(k)} A_R^{(n)} \right| \ \left| A_T^{(k)} A_R^{(n)} \right| , \quad \text{where}
\]
\[
\left( A_T^{(k)} A_R^{(n)} , A_T^{(k)} A_R^{(n)} \right) \text{ denotes the inner product of } A_T^{(k)} A_R^{(n)} \text{ and } A_T^{(k)} A_R^{(n)} .
\]

We adopt the von Mises distribution for \( \alpha_T \) and \( \alpha_R \) \[1\]
\[
p(\alpha_T) = \frac{1}{2\pi I_0(k_T)} \exp[k_T(\alpha_T - \mu_T)],
\]
\[
p(\alpha_R) = \frac{1}{2\pi I_0(k_R)} \exp[k_R(\alpha_R - \mu_R)],
\]
where \( I_0(\cdot) \) refers to the zeroth-order modified Bessel function of the first kind, \( \mu_T \) and \( \mu_R \) denote the mean value of \( \alpha_T \) and \( \alpha_R \), respectively, and \( k_T \) and \( k_R \) represent the degrees of scattering. For as \( \beta_T \) and \( \beta_R \), their PDFs are given by \[1\]
\[
p(\beta_T) = \frac{\pi}{4 |\beta_T^\text{max}|} \cos \left( \frac{\pi |\beta_T|}{2 |\beta_T^\text{max}|} \right) , \quad |\beta_T| \leq |\beta_T^\text{max}| \leq \frac{\pi}{2},
\]
\[
p(\beta_R) = \frac{\pi}{4 |\beta_R^\text{max}|} \cos \left( \frac{\pi |\beta_R|}{2 |\beta_R^\text{max}|} \right) , \quad |\beta_R| \leq |\beta_R^\text{max}| \leq \frac{\pi}{2},
\]
where \( \beta_T^\text{max} \) and \( \beta_R^\text{max} \) are the maximum elevation angles of the scatterers around \( T_x \) and \( R_x \), respectively.

Consequently, the overall space-time correlation function taking into account fast fading and shadowing can be obtained by substituting (8) and \[2, \text{eq. (14)}\] into (7), thus yielding
\[
\rho_{nk,\bar{n}k} (\delta_T, \delta_R, \tau) \approx e^{-\eta k_0 (\Delta_{n,k}^\text{max} + \Delta_{\bar{n},k}^\text{max})} \left[ A \cos \left( \Delta_{nk,\bar{n}k} \right) + B \right]
\]
\[
\times I_0 \left( \sqrt{\frac{2\pi}{k_T}} \right) \frac{2\pi_{\alpha_T}^{\text{max}}}{\lambda_x} \sin \zeta_T
\]
\[
\times I_0 \left( \sqrt{\frac{2\pi}{k_R}} \right) \frac{2\pi_{\alpha_R}^{\text{max}}}{\lambda_x} \sin \zeta_R
\]
\[
\times \frac{\Delta_{nk,\bar{n}k}^\text{max} \sin \zeta_R}{\lambda_x},
\]
where parameters \( y_T, z_T, y_R \) and \( z_R \) are given in \[2, \text{eq. (13)}\]. Moreover, elements of the receive and transmit correlation matrices can be respectively expressed as
\[
\Phi_R_{n\bar{n}} = \frac{1}{\eta_T} \sum_{k=k=1}^{n_T} \rho_{nk,\bar{n}k} (\delta_T, \delta_R, 0),\ (16)
\]
\[
\Phi_T_{k\bar{k}} = \frac{1}{\eta_R} \sum_{n=n=1}^{n_R} \rho_{nk,\bar{n}k} (\delta_T, \delta_R, 0).\ (17)
\]

Remark 1: The cross-correlation of shadowing, \( A \cos \left( \Delta_{nk,\bar{n}k} \right) + B \), can be divided into two kinds: angle-independent \( (A = 0) \) and angle-dependent \( (A \neq 0) \) \[9\]. It is noticed that the geometrical angle \( \Delta_{nk,\bar{n}k} \) is infinitesimally small if \( \max \{ \delta_T, \delta_R \} \ll D \). When parameters \( A, B \) are such that \( A + B = 1 \), the impact of the shadowing on the receive and transmit correlations specified in (16) and (17) becomes negligible.

IV. PERFORMANCE ANALYSIS

In this section, we derive the average SEP, outage probability and ergodic capacity of MIMO MRC systems under the above-described 3D M-to-M channel propagation model.

A. Average SEP

The general expression of average SEP for many modulation formats can be expressed as \[10\]
\[
P_s = E_\gamma \left\{ aQ \left( \sqrt{2b\gamma} \right) \right\},
\]
where \( Q(\cdot) \) represents the Gaussian Q-function, and \( a \) and \( b \) are modulation-specific constants. A useful alternative expression for (18) using integration by parts is given by
\[
P_s = \frac{a\sqrt{b}}{2\sqrt{\pi}} \int_0^\infty \frac{e^{-bu}}{\sqrt{u}} F_{\gamma}(u) \, du
\]
\[
= \int_0^\infty \left[ \frac{a\sqrt{b}}{2\sqrt{\pi}} \int_0^\infty \frac{e^{-bu}}{\sqrt{u}} F_{\gamma}(u) \, du \right] p_\gamma(\gamma) \, d\gamma.
\]
(19)

Let \( P_s(\gamma) = \frac{a\sqrt{b}}{2\sqrt{\pi}} \int_0^\infty \frac{e^{-bu}}{\sqrt{u}} F_{\gamma}(u) \, du \), which can be expressed as
\[
P_s(\gamma) = \frac{a\sqrt{b}}{2\sqrt{\pi}} \int_0^\infty \frac{e^{-bu}}{\sqrt{u}} F_{\gamma}(u) \, du
\]
\[
\times \left( \lambda_{\min} \right)^2 \frac{2}{\sigma_2 - \sigma_1} \sum_{i=1}^{2} \frac{(-1)^i}{(\sigma_2 - \sigma_1)(\sigma_2 - \sigma_1)^{2/3}} \right)
\]
\[
\times \left( \frac{1}{(\sigma_2 - \sigma_1)^{2/3}} + \frac{b}{(\sigma_2 - \sigma_1)^{2/3}} + 2 \right) \left( \frac{1}{(\sigma_2 - \sigma_1)^{2/3}} + \frac{b}{(\sigma_2 - \sigma_1)^{2/3}} + 2 \right) \}
\]
\[
= \int_0^\infty e^{-bu} u^{\gamma-3/2} \left( \exp \left( \frac{-1}{(\sigma_2 - \sigma_1)^{2/3}} u \right) - 2 \sum_{j=1}^{2} \exp \left( \frac{-1}{(\sigma_2 - \sigma_1)^{2/3}} u \right) + 1 \right) \, du.
\]
(21)

It is noticed that
\[
\int_0^\infty u^{\gamma-3/2} e^{-au} \, du = \left( \frac{-2u^{\gamma-2} e^{-au}}{\sigma_2 - \sigma_1} \right)^{\infty} - 2a \int_0^\infty u^{\gamma-2} e^{-au} \, du
\]
\[
= \left( \frac{-2u^{\gamma-2} e^{-au}}{\sigma_2 - \sigma_1} \right)^{\infty} - 2\sqrt{\pi} a,
\]
(22)

where \( [x(t)]_{t=0}^\infty \triangleq \lim_{t\to\infty} x(t) - \lim_{t\to-\infty} x(t) \). Thus, the integral \( \mathcal{Z} \) (21) can be rewritten as
\[
\mathcal{Z} = \sum_{j=1}^{2} 2 \sqrt{\pi} \left( \frac{b + \frac{1}{(\sigma_2 - \sigma_1)^{2/3}}}{\frac{1}{(\sigma_2 - \sigma_1)^{2/3}} + \frac{b}{(\sigma_2 - \sigma_1)^{2/3}} + 2} \right)
\]
\[
- 2 \sqrt{\pi} \left( \frac{b + \frac{1}{(\sigma_2 - \sigma_1)^{2/3}}}{\frac{1}{(\sigma_2 - \sigma_1)^{2/3}} + \frac{b}{(\sigma_2 - \sigma_1)^{2/3}} + 2} \right) - 2\sqrt{\pi} b.
\]
(23)
Then, substituting (23) into (20), we obtain the following expression for the average SEP given $\bar{\gamma}$
\[
P_s(\bar{\gamma}) = \frac{a \sqrt{\bar{\sigma}_1 \sigma_2 \bar{\gamma}}}{2 \pi (\sigma_2 - \sigma_1)} \sum_{i=1}^{2} (-1)^i \left\{ \sqrt{\pi} \sum_{j=1}^{2} \left[ \left( \frac{1}{\omega_i - j + 1 + \sigma_j \bar{\gamma}} + b \right) - b \right] \right\} + 2 \sum_{j=1}^{2} \sqrt{\pi} \left[ b + \frac{1}{\omega_i - j + 1 + \sigma_j \bar{\gamma}} \right] - 2 \sum_{j=1}^{2} \sqrt{\pi} \left[ b + \frac{1}{\omega_i - j + 1 + \sigma_j \bar{\gamma}} \right],
\]
(24)
which can be used to assess the performance of M-to-M MIMO MRC systems.

B. Outage Probability

This metric denotes the probability that the output SNR, $\gamma$, drops below a predefined SNR threshold $\gamma_{th}$. Using the CDF expression of $\lambda_{max}$ in (4), the outage probability as a function of $\bar{\gamma}$ for M-to-M MIMO MRC systems in double-correlated Rayleigh-and-Lognormal fading channels can be expressed as
\[
P_{out}(\gamma_{th}, \bar{\gamma}) = \frac{\omega_1 \omega_2 \sigma_1 \sigma_2 \bar{\gamma}}{\gamma_{th} (\sigma_2 - \sigma_1)} \sum_{i=1}^{2} (-1)^i \left[ e^{-\frac{\gamma_{th}}{\omega_i - j + 1 + \sigma_j \bar{\gamma}}} + \frac{\gamma_{th}}{\omega_i - j + 1 + \sigma_j \bar{\gamma}} - 1 \right].
\]
(25)

C. Ergodic Capacity

The ergodic capacity of M-to-M MIMO MRC systems in double-correlated Rayleigh-and-Lognormal fading channels can be obtained by averaging the capacity expression given $\bar{\gamma}$ over the distribution of $\bar{\gamma}$, i.e.,
\[
C(\bar{\gamma}) = \frac{1}{\bar{\gamma}} \int_{0}^{\infty} C(\gamma) p_\gamma(\gamma) d\gamma,
\]
where $C(\bar{\gamma})$ denotes the ergodic capacity as a function of $\bar{\gamma}$, which can be expressed in [bits/s/Hz] as
\[
C(\bar{\gamma}) = \frac{\omega_1 \omega_2 \sigma_1 \sigma_2 \bar{\gamma}}{\gamma_{th} (\sigma_2 - \sigma_1)} \sum_{i=1}^{2} (-1)^i \left\{ e^{-\frac{\gamma_{th}}{\omega_i - j + 1 + \sigma_j \bar{\gamma}}} + \frac{\gamma_{th}}{\omega_i - j + 1 + \sigma_j \bar{\gamma}} - 1 \right\}.
\]
(26)

V. NUMERICAL RESULTS

In this section, we present numerical results illustrating the effect of the spatial correlation on the average SEP, outage probability and ergodic capacity of M-to-M MIMO MRC systems. Herein, we assess the performance as a function of the average SNR per receive antenna, $\bar{\gamma}$. It is assumed that the system operates at 800MHz, thus the wavelength is $\lambda_c = 0.375m$. We set the number of transmit and receive antennas to $n_T = n_R = 2$, the distance between the centers of $T_x$ and $R_x$ to $D = 200m$, and the parameters of normalized shadowing correlation function to $A = B = 0.5$. Unless otherwise specified, the other system parameters are as follows: $\delta_T = \lambda_c$, $\delta_R = \lambda_c/10$, $\beta_T^{max} = \beta_R^{max} = \pi/12$, $\theta_T = \theta_R = \pi/4$, $\zeta_T = \zeta_R = \pi/3$, $\psi_T = 0$, $\psi_R = \pi$, $k_T = k_R = 10$, $f_T^{max} = f_R^{max} = 5$, $\mu_T = \pi/2$, and $\mu_R = 3\pi/2$.

Fig. 1 illustrates the impact of the degree of scattering around $T_x$ in the $x$–$y$ plane, i.e., $k_T$, which controls the spread of scatterers around the mean values of $\alpha_T$, on the average SEP.
for $\bar{\gamma} = 20 \text{dBi}$ in the case when $a = 4$ and $b = 0.5$, i.e., for QPSK modulation, compared to that in the uncorrelated fading channel case. As observed, the larger $k_T$ is, the higher the average SEP will be due to the higher non-isotropic scattering.

Fig. 2 plots the outage probability versus the orientation angle $\theta_T$ of $T_x$ antenna arrays in the x-y plane, taking $\zeta_T$ as a parameter, for $\bar{\gamma} = 20 \text{dBi}$ and $\gamma_{th} = 10 \text{dBi}$. It can be observed that the outage probability depends on the relative angles between the antenna array and the local scatterers around $T_x$ and $R_x$, i.e., $|\theta_T - \mu_T|$ and $|\theta_R - \mu_R|$, similar to the phenomenon observed in the outage capacity results presented in [2]. Furthermore, the angles between x-y plane and the orientation of the $T_x$ and $R_x$ antenna arrays, i.e., $\zeta_T$ and $\zeta_R$, play an important effect on the performance of outage probability. For the case with $\zeta_T = \pi/3$, when $\zeta_T = \pi/2$ the outage probability is the lowest and $\theta_T - \mu_T$ has no influence on it. A value of $\zeta_T = 0$ results in the highest outage probability. On the other hand, as $\zeta_T$ decreases, the outage probability drops dramatically with increasing values of $|\theta_T - \mu_T|$. Similar observations apply when by fixing the value of $\zeta_T$ and varying that of $\zeta_R$.

Finally, the ergodic capacity as a function of the average SNR per receive antenna is shown in Fig. 3. It is observed that increasing the maximum elevation angle $\beta_T^{\text{max}}$ yields a favorable influence on the ergodic capacity. Additionally, shadowing results in a reduction in the ergodic capacity; a decrease that is not of major significance as it can be seen from the plots. In this figure, results corresponding to the case with no CSI at the transmitter and perfect CSI at the receiver, pertaining to the MIMO system with no MRC, are plotted to serve as reference and illustrate the advantages of MRC. Further analysis on the effect of different parameters on performance are presented in [12].

VI. CONCLUSION

In this paper, the performance of M-to-M MIMO MRC systems in double-correlated channels, taking into account fast fading and shadowing, was evaluated in terms of average SEP, outage probability and ergodic capacity. Numerical results show that the larger the degree of scattering around the transmitter in the x-y plane is, the higher the average SEP will be due to the higher non-isotropic scattering. On the other hand, increasing the maximum elevation angle of scatterers yields a favorable influence on the ergodic capacity, whereas shadowing results in a reduction in the ergodic capacity.

REFERENCES


