On the 3-D MIMO Channel Model Based on Regular-Shaped Geometry-Based Stochastic Model

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***Abstract*—This paper proposes a novel three-dimension multiple-input multiple-output (MIMO) channel model based on Regular-Shaped Geometry-Based Stochastic Model (RS-GBSM), which is called Geometrical Multi-Ellipsoid Based Stochastic Model (GMEBSM). Scatterers are assumed to be distributed on the surface of the ellipsoids whose foci are at the center of transmitter and receiver ends. Ellipsoids with different propagation delays are assumed to obey exponential distribution. By using the von Mises Fisher (VMF) distribution, the proposed model has the ability to jointly consider the azimuth and elevation angles. Assuming in 3-D non-isotropic scatting model, the expression for the space-time correlation function (STCF) between each two sub channels is derived. Finally, simulation results of the derived CF are presented.**

Keywords—Channel modeling; multiple-input multiple-output; Angle of Arrival; space-time correlation function; geometry-based stochastic model

I. INTRODUCTION

In recent years, multiple-input multiple-output (MIMO) wireless systems have attracted much attention. The system can provide a potentially huge gain in capacity and promise a high spectral efficiency by using multiple antennas at both receiver and transmitter ends. However, performance of wireless communication systems depends on the statistical characteristics of angular components of the received signal. Thus, a channel model which is capable of providing the directional information of the received multipath waves is extremely in need. It is known that rays reflected from scatterers exhibit different delays and angles at the receiver, so that the statistic characteristics of different multipath components are strongly dependent on the distribution of the scatterers around the wireless link [1]. Therefore, a geometric based channel model, which can characterize the distribution of scatterers, can be used to describe the angle of arrival (AoA) statistics accurately.

In previous publications, several two-dimensional (2-D) and three-dimensional (3-D) geometrical scattering channel models have been proposed, such as elliptical scattering model in [2-5]; single-bounce two-sphere model in [6]; a combination of two-sphere model and an elliptic-cylinder model in [4]; 3-D ellipsoid scattering model in [7-8].

2-D models ([2] [3] [5]) assumed that waves travelled only in the horizontal plan and ignored the vertical components, while in reality, waves do travel in 3-D space. Reference [7-8] introduced a 3-D ellipsoid model which assumed uniform distribution of scatterers were inside an ellipsoid. They developed a 3-D geometry-based scattering channel model for wireless communication environments, in which the AoA of the received multipath waves took place in both the azimuth and the elevation angles. They also assumed that the azimuth angle and elevation angle were independent and should be analyzed separately.

In this paper, the Geometrical Multi-Ellipsoid Based Stochastic Model (GMEBSM) is developed, which is a 3-D geometrical scattering channel model. The proposed model is on the basis of ellipsoid model and the foci of the model are the center of transmitter and receiver ends. The model assumes that the scatterers are distributed on the surface of the ellipsoids. Different ellipsoids lead to different transmission delays, which is assumed to obey exponential distribution. In the previous reported ellipsoid models, scatterers are assumed to be uniform distributed in space. This assumption is acceptable only for certain environments. To jointly consider the azimuth and the elevation angles of the angle-of-arrival (AoA), we apply the von Mises-Fisher (VMF) distribution as the scatterer distribution. The VMF distribution can be considered to be the analogue of the multivariate Gaussian distribution [8].

The proposed model can be utilized both for outdoor micro-cell and pico-cell as well as indoor environment where scatterers significantly impact the transmitter and receiver characteristics.

The rest of the paper is organized as follows. Section II proposes the novel GMEBSM for non-isotropic MIMO channels. The model is the combination of line-of-sight (LoS) components and non-line-of-sight (NLoS) components. The analysis of channel statistic properties is in Section III. In Section IV, the simulation results and analysis are presented. Finally the conclusion will be derived in Section V.

II. DESCRIPTION OF GMEBSM

The proposed GMEBSM is equipped with M transmitter and N receiver antenna elements at each ends. The radio propagation environment is characterized by 3D effective scattering components between the Tx and Rx. We define the effective scatterers as scatterers that are capable of reflecting incident waves and the power of which can be effectively received by receiver.

In the ellipsoid model, the base station (BS) and mobile station (MS) are located on the x-axis at the foci and are separated by a distance $D = 2f$, where f is the ellipsoid's focal length. Cartesian coordinates of the receiver and the

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transmitter are $(f,0)$ and $(-f,0)$, respectively. Note that the ellipsoid is made of the ellipse rotating around the x axis.

As shown in Fig.1, the proposed GMEBSM is the combination of line-of-sight (LoS) components and N_i ellipsoid models.

Scatterers are distributed in the space with density function around the communication link. For graphical simplicity, only two scatterers on two ellipsoid-models are shown in Fig.1 and they are denoted by S_1, S_2. The spherical coordinates of the scatterer S_1, which is on $Ellipsoid-i$ $(El-i)$, with respect to the receiver can be expressed as (r,θ,ϕ) and the ellipsoid can be described as

$$\frac{\left(r\sin\theta\cos\phi+\frac{D}{2}\right)^2}{a_i^2}+\frac{\left(r\sin\theta\sin\phi\right)^2}{b_i^2}+\frac{\left(r\cos\theta\right)^2}{b_i^2}=1 \qquad (1)$$

where co-elevation and azimuthal angles of arrival at receiver are denoted by θ and ϕ, with $0 \le \theta \le \pi$ and $-\pi \le \phi \le \pi$. The parameter r denotes the distance from the scatter S_1 to Rx.

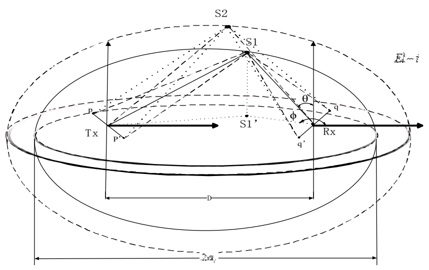


Fig. 1. The GMEBSM Model

The transmission delay which is caused by the reflection of the scatterers on the $El-i$ can be denoted as τ_{SB_i}. We assume that the transmission delay caused by the reflection of different ellipsoids obey exponential distribution [8], shown as

$$f_\tau\left(\tau_{SB_i}\right)=\frac{\tau_0}{\sigma}e^{-\frac{\left(\tau_{SB_i}-\tau_0\right)}{\sigma}} \qquad (2)$$

where σ is the root-mean square delay spread (RDS).

The distribution shown in (2) is related to the parameter η_{SB_i} shown in equation (3).

$$\eta_{SB_i}=F_\tau\left(\tau_{SB_{i+1}}\right)-F_\tau\left(\tau_{SB_i}\right) \qquad (3)$$

$F_\tau\left(\tau_{SB_i}\right)$ is the cumulative distribution function (CDF) of $f_\tau\left(\tau_{SB_i}\right)$. The parameter η_{SB_i} specifies how much the single-bounced rays reflected by $El-i$ contribute to the total scattered power.

The antenna spacing at Tx and Rx are respectively designated by δ_T and δ_R. Note that the assumption $\min\{D,a,f\} \gg \max\{\delta_T,\delta_R\}$ is applied in this theoretical model. The tilt angles with respected to x axis of the multi-element antennas are denoted by γ_T and γ_R. The Co-EAoD (co-elevation angle of departure) and AAoD (azimuth angle of departure) of the waves that impinge on the effective scatterers are designated by θ_T and ϕ_T. The Co-EAoA (co-elevation angle of arrival) and AAoA (azimuth angle of arrival) of the wave traveling from an effective scatterer are denoted by θ_R and ϕ_R, respectively. θ_R^{Los} and ϕ_R^{Los} denotes the AoA of a LoS path.

In the next section, we will present the derivation of the reference model and derive the correlation function of the GMEBSM.

III. THE STATISTICAL PROPERTIES OF THE GMEBSM

A. The derivation of the proposed model

The 3D MIMO fading channel can be described by a matrix $\mathrm{H}(t)=\left[h_{pq}(t)\right]_{M\times N}$, with the size of $M\times N$. The subscripts p and q denote the antenna elements at Tx and Rx. The received complex fading envelope between the p-th $(p=1,\cdots,\mathrm{M})$ Tx antenna and the q-th $(q=1,\cdots,N)$ Rx antenna at the carrier frequency f_c is a superposition of the LoS and single-bounced components, which can be expressed by the following equation

$$h_{pq}(t)=h_{pq}^{LoS}(t)+\sum_{i=1}^{Ni}h_{pq}^{SB_i}(t) \qquad (4)$$

In Eq. (4), the components can be expressed as

$$h_{pq}^{LoS}(t)=\sqrt{\frac{K}{K+1}}e^{-j2\pi f_c\tau_{pq}-j2\pi t(f_{T_{max}}A_{LoS}+f_{R_{max}}B_{LoS})} \qquad (5)$$

$$h_{pq}^{SB_i}(t)=\sqrt{\frac{\eta_{SB_i}}{K+1}}\lim_{N_s\to\infty}\sum_{n=1}^{N_s}\frac{1}{\sqrt{N_s}}e^{-j(\psi_n-2\pi f_c\tau_{pq,n})-j2\pi t(f_{T_{max}}A_{SB_i,n}+f_{R_{max}}B_{SB_i,n})} \qquad (6)$$

where

$$A_{LoS}=\cos\left(\theta_T^{LoS}\right)\cos\left(\phi_T^{LoS}\right) \qquad (7)$$

$$B_{LoS}=\cos\left(\theta_R^{LoS}\right)\cos\left(\phi_R^{LoS}\right) \qquad (8)$$

$$A_{SB_i,n}=\cos\left(\theta_T^{SB_i,n}\right)\cos\left(\phi_T^{SB_i,n}\right) \qquad (9)$$

$$B_{SB_i,n}=\cos\left(\theta_R^{SB_i,n}\right)\cos\left(\phi_R^{SB_i,n}\right) \qquad (10)$$

with $\phi_T^{LoS}\approx 0$, $\phi_R^{LoS}\approx\pi$, $\theta_T^{LoS}\approx\theta_R^{LoS}\approx\frac{\pi}{2}$, $\tau_{pq}=\varepsilon_{pq}/c$ and $\tau_{pq,n}=\left(\varepsilon_{pn}+\varepsilon_{nq}\right)/c$. Supposing there are N_s effective scatterers around the Tx and the Rx lying on the surface of the i-th ellipsoid model. Here, K is the Ricean factor. The phase ψ_n is independent and identically distributed (i.i.d) random variable with uniform distributions over $[-\pi,\pi)$.

$f_{T_{max}}$ and $f_{R_{max}}$ are the maximum Doppler frequencies of Tx and Rx, respectively.

Based on the cosine theorem and small angle approximations, we can obtain

$$\varepsilon_{pq} \approx D - \frac{\delta_T}{2}\cos\gamma_T + \frac{\delta_R}{2}\cos\gamma_R \tag{11}$$

$$\varepsilon_{pnq} \approx 2a \mp \frac{\delta_T}{2}\cos(\phi_T - \gamma_T)\sin\theta_T \mp \frac{\delta_R}{2}\cos(\phi_R - \gamma_R)\sin\theta_R \tag{12}$$

One ellipsoid of the GMEBSM is shown in Fig.2. The distance between the scatterer S and the center of transmitter Tx is ε_{Tn} and the distance between S and the receiver Rx is ε_{nR}, respectively. Each scatterer on the surface of ellipsoid is located on an ellipse (Ellipse-1 in Fig.2) which is the same with Ellipse-0. Based on the basic principle of ellipse and the cosine theorem, the distance ε_{Tn} and ε_{nR} can be denoted as

$$\varepsilon_{Tn} = \sqrt{{\varepsilon_{nR}}^2 + D^2 - 2\varepsilon_{nR} D\cos\phi_R \sin\theta_R} \tag{13}$$

$$\varepsilon_{nR} = \frac{4a^2 - D^2}{2\left(2a - D\cos\phi_R \sin\theta_R\right)} \tag{14}$$

On the basis of Eq. (13-14), the relationship between the AoDs and AoAs could be derived as

$$\cos\theta_T^{SB,n} = \frac{\varepsilon_{nR} \times \cos\theta_R^{SB,n}}{\sqrt{{\varepsilon_{nR}}^2 + D^2 - 2\varepsilon_{nR} D\cos\phi_R^{SB,n}\sin\theta_R^{SB,n}}} \tag{15}$$

$$\cos\phi_T^{SB,n} = \frac{D - \varepsilon_{nR}\cos\phi_R \sin\theta_R^{SB,n}}{\sqrt{{\varepsilon_{nR}}^2 + D^2 - 2\varepsilon_{nR} D\cos\phi_R^{SB,n}\sin\theta_R^{SB,n}}} \tag{16}$$

As scatterers tend to infinity, the discrete variables such as EAoD $\theta_T^{SB,n}$, AAoD $\phi_T^{SB,n}$, EAoA $\theta_R^{SB,n}$ and AAoA $\phi_R^{SB,n}$, can be replaced by continuous random variables θ_T^{SB}, ϕ_T^{SB}, θ_R^{SB}, and ϕ_R^{SB}.

To jointly consider the impact of the azimuth and elevation angles on channel statistics, VMF PDF are applied to characterize the distribution of the scatterers which impact the AoA statistics of the received signal. The VMF can be considered as the analogue of the multivariate Gaussian distribution, which is given by

$$f_p\left(\mathbf{\Omega}; \boldsymbol{\mu}, \kappa\right) = C_p\left(\kappa\right)\exp\left(\kappa \boldsymbol{\mu}^T \mathbf{\Omega}\right) \tag{17}$$

$$C_p\left(\kappa\right) = \frac{\kappa}{4\pi \sinh\left(\kappa\right)} \tag{18}$$

where Ω represents the direction of scatterers which can be expressed as $\left(\sin\theta\cos\phi, \sin\theta\sin\phi, \cos\theta\right)^T$, and μ which is indicated as $\left(\sin\theta_0\cos\phi_0, \sin\theta_0\sin\phi_0, \cos\theta_0\right)^T$, points to the center of the cluster. The parameter κ indicates the concentration of the distribution about the mean direction vector. The distribution becomes isotropic when $\kappa \to 0$, and extremely non-isotropic while $\kappa \to \infty$.

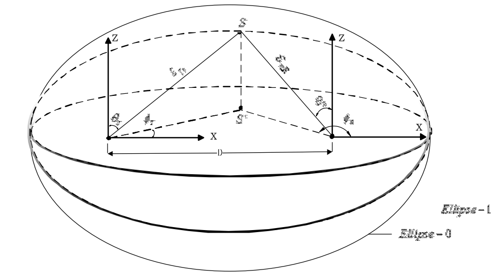


Fig. 2. Single Ellipsoid of GMEBSM

B. The Correlation Function of the 3D MIMO model

In this section, the statistical properties of the multi-ellipsoid model will be derived.

Correlation among antenna elements is an important factor to affect AoA characteristics and the performance of the receiver when using multiple antenna systems and antenna arrays [8].

The space-time correlation function plays an important role in MIMO communication channels. The normalized ST CF between any two complex fading envelopes $h_{pq}\left(t\right)$ and $h_{p'q'}\left(t\right)$ is defined as

$$\begin{aligned}\rho_{h_{pq}h_{p'q'}}\left(\tau\right) &= \frac{E\left[h_{pq}\left(t\right)h_{p'q'}^*\left(t-\tau\right)\right]}{\sqrt{\Omega_{pq}\Omega_{p'q'}}} \\ &= \rho_{h_{pq}^{LoS}h_{p'q'}^{LoS}}\left(\tau\right) + \sum_{i=1}^{Ni}\rho_{h_{pq}^{SB_i}h_{p'q'}^{SB_i}}\left(\tau\right)\end{aligned} \tag{19}$$

Substituting Eq. (19) for Eq. (5) and Eq. (11), we can then acquire the CF of the LoS component as

$$\rho_{h_{pq}^{LoS}h_{p'q'}^{LoS}}\left(\tau\right) = \frac{K}{K+1}e^{-j\frac{2\pi}{\lambda}\overline{\varepsilon_{pq}}} \times e^{-j2\pi\tau\left(f_{T_{max}} - f_{R_{max}}\right)} \tag{20}$$

$$\overline{\varepsilon_{pq}} = 2D\cos\gamma_R \tag{21}$$

Substituting Eq. (19) for Eq. (6) and Eq. (12), we can then obtain the CF of the single-bounce component as

$$\rho_{h_{pq}^{SB_i}h_{p'q'}^{SB_i}}\left(\tau\right) = \frac{\eta_{SB_i}}{K+1} \times \int_0^{2\pi}\int_0^{\pi} e^{-j\frac{2\pi}{\lambda}\bar{d} - j2\pi\tau\left(f_{T_{max}}A_{SB_i,n} - f_{R_{max}}B_{SB_i,n}\right)} d\theta d\phi \tag{22}$$

$$\bar{d} \approx \delta_T\cos\left(\phi_T - \gamma_T\right)\sin\theta_T + \delta_R\cos\left(\phi_R - \gamma_R\right)\sin\theta_R \tag{23}$$

The parameters $A_{SB_i,n}$ and $B_{SB_i,n}$ are shown in (9) and (10).

IV. SIMULATION RESULTS AND ANALYSIS

To establish a verification of the theoretical Space-Time Correlation Function of the proposed reference model, we present some simulation results in this section.

The parameters in Fig.3 and Fig.4 are set as Table.1.

TABLE I. DEFINATION OF PARAMETERS IN SIMULATION IN FIG.4 AND 5

parameters	description	detail
D	The distance between the Tx and Rx	$D = 30m$
f_c	operation frequency	$f_c = 2.4GHz$
λ	wavelength	$\lambda = c/f_c$
γ_T, γ_R	The tilt angles of the multi-element antenna at Tx and Rx	$\gamma_T = \gamma_R = \pi/4$
f_T, f_R	Identical maximum Doppler frequencies at transmit side and receive side	$f_T = 50Hz$ $f_R = 90Hz$
δ_T, δ_R	The antenna spacing at transmit side and receive side	$\delta_T = \delta_R = \lambda/2$

The omnidirectional antennas are employed at both sides. The space-time correlation function of the proposed reference model is illustrated as follows.

Fig.3 illustrates the CFs of Single-Bounce (S-B) reflected from different ellipsoids, which own different propagation delays. CF-SB1 represents the ellipsoid with $\tau_{SB} = 0.1\mu s$, CF-SB2 with $\tau_{SB} = 0.2\mu s$ and CF-SB3 with $\tau_{SB} = 0.3\mu s$, respectively. The figure shows that the proposed channel have small correlations when the propagation delay increased.

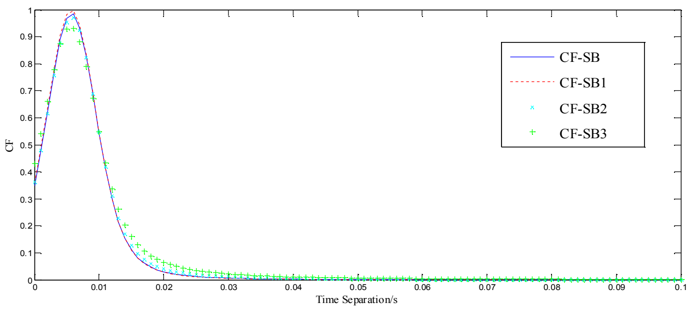
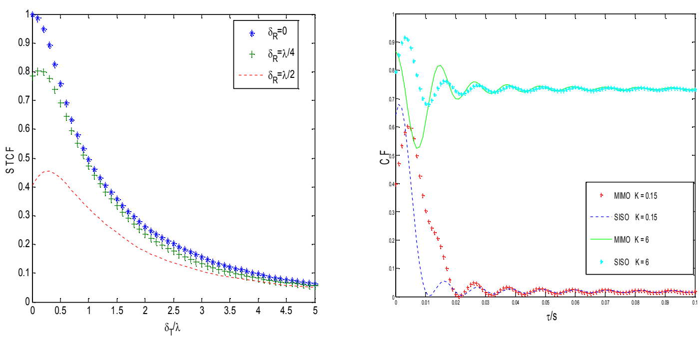


Fig. 3. The CF of single-bounce



(Fig. 4.1) (Fig.4.2)

Fig. 4. The CF of the proposed reference model

The 2-D space-time correlation function for channels proposed in [6] suggests that two vertically placed antennas are completely correlated and no diversity gain is available. The space-time correlation function of the proposed 3-D channel model shows that vertically placed antennas have small correlations, as illustrated in Fig.4.1. The STCF decreases when the antenna spacing at Tx and Rx increases.

Fig.4.2 shows the CF including LoS components and S-B components with Ricean factor $K = 0.15$ and $K = 6$. K becomes small when the density of scatterers surrounding the Rx and Tx is high, as the NLoS components play a major role in the propagation environment. The CF is higher when LoS component has dominant power.

V. CONCLUSION

In this paper, we have proposed a novel 3-D RS-GBSBM for Rayleigh fading MIMO channels called GMEBSM. The proposed model has the ability to analyze the joint impact of the azimuth and elevation angles on channel statistics. Furthermore, the model has the advantage that parameters are well defined and we can compare the performance of the MIMO system over different propagation conditions.

The Space-Time Correlation Functions for 3-D non isotropic scattering environment have been derived in this paper. Our future work will focus on evaluating the ToA characteristics and MIMO capacity with this model.

REFERENCES

[1] Hamalainen J., Savolainen S., Wichman R. and Ruotsalainen, K., Ylitalo J., "On the Solution of Scatter Density in Geometry-Based Channel Models". IEEE Transactions on Wireless Communications, 2007. 6(3): p. 1054-1062.

[2] A. Intarapanich, Padam L. Kafle, "Geometrically Based Broadband MIMO Channel Model With Tap-Gain Correlation". IEEE Transactions on Vehicular Technology, 2007. 56(6): pp. 3631-3641.

[3] Xiang Cheng, Qi Yao, Miao-Wen Wen, Cheng-Xiang Wang, Ling-Yang Song, Bing-Li Jiao, "Wideband Channel Modeling and Intercarrier Interference Cancellation for Vehicle-to-Vehicle Communication Systems". IEEE Journal on Selected Areas in Communications, 2013. 31(9): pp. 434-448.

[4] Yi Yuan, Cheng-Xiang Wang, Xiang Cheng, Bo Ai, Laurenson D.I., "Novel 3D Geometry-Based Stochastic Models for Non-Isotropic MIMO Vehicle-to-Vehicle Channels". IEEE Transactions on Wireless Communications, 2014. 13(1): pp. 298-309.

[5] Xiang Cheng., Cheng-Xiang Wang, Laurenson D.I., "A Geometry-Based Stochastic Model for Wideband MIMO Mobile-to-Mobile Channels". Global Telecommunications Conference, 2009, IEEE , pp.1-6.

[6] Bakhshi G., Shahtalebi K., Rad H.S., "A novel Full-Three-Dimensional MIMO Mobile-to-Mobile channel reference model". 3rd International Conference on Signal Processing and Communication Systems, 2009, vol.1, no.6, pp. 28-30.

[7] Aslam M.I., Shaikh A.Z., "Joint and marginal probabilities for time of arrival and angle of arrival using ellipsoidal model", 3rd International Conference on Computer, 2013.9, vol.1, no.5: pp. 25-26.

[8] Mammasis K., Stewart R.W., "The Fisher–Bingham Spatial Correlation Model for Multielement Antenna Systems". IEEE Transactions on Vehicular Technology, 2009.7, vol.58, no.5, pp.2130-2136.

[9] Oestges C., Erceg V., Paulraj A.J., "A physical scattering model for MIMO macrocellular broadband wireless channels". IEEE Journal on Selected Areas in Communications, 2003.6, vol.21, no.5, pp.721-729.

[10] Newhall, W.G.; Reed, J.H., "A geometric air-to-ground radio channel model". MILCOM Proceedings, 2002.10, vol.1 pp.632-636.