A Non-Isotropic Simulation Model for Ship-to-Ship Fading Channels

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Abstract—**Accurate modeling of the ship-to-ship (S2S) fading channels is critical not only to the cognitive automatic identification system (CAIS, which includes shipborne AIS and satellite-based AIS by utlizing some promising technologies, such as spectrum sensing and OFDM, and is proposed by us in recent years) design but also to the verification and performance evaluation of other maritime wireless communication systems. The statistical properties of S2S fading channels are either quit different from the terrestrial-based mobile communication channels or typical fixed-to-mobile maritime radio channels, thereby requiring new methods for their simulation. This paper for the first time proposes a two-dimensional non-isotropic sctteing statistical model, which adopts sum-of-sinusoids and two-ring concepts, to simulate the S2S local environment and especially for Rayleigh fading. Moreover, the theoretical statistical properties for the non-isotropic sctteing are derived. The auto-correlation and cross-correlation functions, and the probability density function of the new model have been compared to the desired ones. In addtion, this model is also a generalized tool which can simulate the isotropic and non-isotropic maritime sctteing channels.**

Keywords-ship-to-ship fading channel; non-isotropic sctteing; Rayleigh fading; sum-of-sinusoids; statistical property

I. INTRODUCTION

Ship-to-ship (S2S) communications play an important role in the automatic identification system (AIS) that aims to minimize maritime traffic accidents, and improve maritime traffic efficiency. With the increments of shipborne AIS users and the emerging requirments for some new applications (such as the transmissions of the security video informations which are favourable to dealing with the emergency, the satellite-based AIS receivers which enlarge the using range of shipborne AIS informations), the next generation of the AIS employing some promising technologies, such as spectrum sensing and OFDM, has been developing by us in recent two years, and we will call it after cognitive automatic identification system (CAIS). As a new communication system, many research challenges and standardization work have to be addressed before CAIS is widely applied. This paper will concentrate on one of the most important and fundamental challenges: how to properly characterize S2S channels? To practically analyze and evaluate CAIS, it is necessary to have reliable knowledge of underlying propagation channel and the corresponding realistic easy-using channel model.

In contrast to conventional fixed-to-mobile (F2M) cellular radio channels, such S2S wireless channels consider that both the transmitter (Tx) and receiver (Rx) are moving. Moreover, in the literature, most channel models for wireless communications were mainly developed for the F2M systems [1]-[6]. Further, an in-depth comparative analysis of the most accepted and approved Rayleigh fading channel simulators is presented in [7] and it suggests that the recently published Wang's model [6] is very attractive. However, from the real maritime S2S communication scenarios and modeling perspective, the modeling approach of S2S fading channels is similar to that of mobile-to-mobile (M2M) communication channels. M2M systems also differ from the F2M ones, where the base station is fixed in location and only the mobile user is moving. In recent years, several methods for simulating M2M channels have been proposed in the literatures [8]-[11], [14]. Among them, Akki and Haber [8] were the first to propose the regular-shaped (e.g., one/two-ring, ellipse, etc.) geometry-based stochastic model for terrestrial-based isotropic single-input single-output (SISO) M2M Rayleigh fading channels. Vatalaro and Forcella [9] extended this two-dimensional (2-D) model to account for scattering in three-dimensional. Wang and Cox [10] described a model that approximates the continuous Doppler spectrum by a discrete line spectrum, but the correlation functions are periodic functions of the time delay and method requires numerical integration of the Doppler spectrum [11]. Patel et al. [11] proposed two sum-of-sinusoids (SoS) models for M2M channels. Generally, SoS models approximate the underlying random processes by the superposition of a finite number of properly selected sinusoids. They can be classified as either statistical or deterministic. Deterministic channel simulation model is ergodic, while the used model parameters may not reflect the physical nature. In order to adequately model the practically physical channel, stochastic method assumes that model parameters are random variables, but it always results in non-ergodic fading emulators. Due to the non-ergodic property, the stochastic model has to perform several simulation trials to represent its complete statistical properties. Therefore, its efficiency is degraded. [11] used the two-ring concept, proposed in [12], to derive their SoS models for M2M channels. They first modified the Method of Exact Doppler Spread (MEDS) proposed by Pätzold et al. for

F2M channels [13]. The statistical correlation functions of the faded envelope match those of the reference model only for a small range of normalized time delays. To improve the properties of their ergodic statistical model, [11] also modified a statistical SoS model proposed by Zheng et al. for F2M channels [1]. However, the model requires a large number of simulation trials (at least 50) to obtain adequate ensemble averaged statistical properties. Moreover, existing models have a notable difficulty in producing time averaged auto- and cross-correlation functions that match those of the reference model. To overcome these deficiencies, an improved simulator [14] based on the two-ring model has been suggested, but we found that the theoretical statistical properties of this model can be converged to the desired ones only when the number of propagation paths approaches infinity. In addition, to properly characterize the maritime S2S communication scenarios, a S2S Rayleigh fading channel simulator was firstly presented in [15]. However, it only considers the 2-D isotropic scttering environment.

In fact, non-isotropic scttering is usually experienced by the ship Tx and ship Rx in the maritime scenarios, especially in the dense maritime environments. Moreover, in the F2M and/or M2M terrestrial cellular radio channels, it has been shown that non-isotropic scttering around the mobile station is often the case [16]-[20]. Additionally, various scattering distributions, such as uniform, Gaussian, Laplacian, and von Mises, are used in prior work to characterize the angle of departure (AoD) and angle of arrival (AoA) of the mobile station. It can be seen that small variation in non-isotropic scttering environments can lead to large difference on the statistical properties. The design, verification and performance evaluation of the wireless communication systems will be greatly affected by these properties. To the best of the authors' knowledge, however, maritime S2S non-isotropic scttering modeling has not been investigated yet.

To fill the aforementioned gaps, this paper for the first time proposes a statistical SoS non-isotropic scttering model for S2S fading channels by adopting the two-ring concept. The von Mises probability density function (PDF) is used for the AoD and the AoA, which is suggested in many literatures because it approximates many of the aforementioned distributions, matches well measured results in [21], and in contrast to aforementioned distributions, and provides mathematical convenience for analysis. Akki and Haber's mathematical reference model, the von Mises PDF and theoretical statistical properties for the isotropic and non-isotropic scttering are stated and derived before the appearance of our S2S simulator, respectively. Besides, the correlation functions and PDF for our S2S non-isotropic scttering model are analyzed and verified by simulation. From the performance comparison, our S2S fading model has rapidly converging ensemble average statistics. Moreover, the new model is also a generalized tool which can simulate the isotropic and non-isotropic maritime scttering channels.

II. PROBLEM STATEMENT

From the above introduction, a computer simulation model has been reported in the literature for the isotropic scttering S2S channels. It achieves high efficiency and satisfactory match in statistical properties for the isotropic scttering channels. Unfortunately, it can not be used directly for the non-isotropic maritime scttering channels. From the point of view of the scattering distributions of the AoD and the AoA, however, Akki and Haber's Rayleigh fading model is also considered as a mathematical reference model. In addition, due to the merits of the von Mises distribution function that can approximate many other non-uniform PDF, the von Mises PDF can be adopted for the AoD and the AoA, which is a good choice for simulating non-isotropic scttering scenarios. Based on the above analysis, theoretical statistical properties for the isotropic and non-isotropic scttering are given when the uniform and the von Mises PDF are employed, respectively. All these are the foundation for modeling non-isotropic scttering S2S simulator.

A. Akki and Haber's Reference Model

For a frequency flat fading channel, Akki and Haber's Rayleigh fading model is usually considered as a mathematical reference model, and the baseband equivalent channel impulse response is given as

$$g(t)=\sqrt{\frac{2}{N}}\sum_{n=1}^{N}\exp\left\{j\left[\omega_1 t\cos(\alpha_n)+\omega_2 t\cos(\beta_n)+\phi_n\right]\right\}, \quad (1)$$

where N is the number of propagation paths, ω_1 and ω_2 are the maximum angular Doppler frequencies, α_n and β_n are the AoD and the AoA of the n th propagation path measured with respect to the Tx and Rx velocity vectors, respectively, and ϕ_n is the phase associated with the n th propagation path. It is assumed that α_n , β_n , and ϕ_n are mutually independent random variables and that ϕ_n is uniformly distributed on the interval $[-\pi,\pi)$.

According to the central limit theorem, the real part and the imaginary part of the frequency nonselective fading complex envelope $g(t)=g_i(t)+jg_q(t)$ are zero-mean Gaussian random processes. Thus, the envelope $|g(t)|$ is Rayleigh distributed.

B. The von Mises probability density function

In the view of statistical inference purposes, the von Mises distributions are most useful, because of their structure as exponential transformation models [22]. In addition, it can describe a normal distribution on a circle with period 2π , which is analogous to that of the normal distribution on a line. Moreover, it is close to the cardioid, wrapped normal, or wrapped Cauchy distributions very well. The von Mises PDF is defined as

$$f(\theta)=\frac{\exp\left[\kappa\cos(\theta-\mu)\right]}{2\pi I_0(\kappa)}, \quad (2)$$

where $\theta\in[-\pi,\pi)$, $I_0(\cdot)$ represents the zero-order modified Bessel function of the first kind, $\mu\in[-\pi,\pi)$ stands for the mean value of the angle θ at which the scatterers are distributed on the ring, and $\kappa \geq 0$ accounts for a real-valued concentration parameter which controls the spread of scatterers around the mean. Hereafter, we will denote the PDF as $\theta \sim M(\mu,\kappa)$. When $\kappa = 0$, $f(\theta) = \frac{1}{2\pi}$, i.e., $M(\mu,0)$ is a uniform distribution yielding 2-D isotropic scattering. As κ increases, the scatterers become more clustered around angle μ and the scattering becomes increasingly non-isotropic. Figure 1 shows the density for $\mu = 0$ and different values of κ. It can be seen that for $\kappa = 4$, over 99 % of the probability lies in the arc $(-90^{\circ}, 90^{\circ})$.

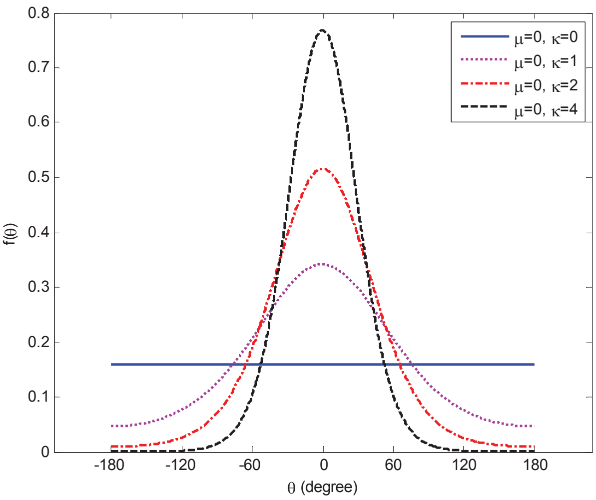

Figure 1. The von Mises PDF of the non-isotropic scatterers.

C. The Statistical Properties for the Isotropic and Non-isotropic Scttering

Under the 2-D isotropic scattering assumption, i.e., the AoD and the AoA are uniform on the interval $[-\pi,\pi)$, the statistical properties of the reference model have been discussed in detail in [8, 23]. Herein, the auto-correlation functions (ACFs) and cross-correlation functions (CCFs) are first listed

$$R_{g_i g_i}(\tau) = R_{g_q g_q}(\tau) = \frac{1}{2} J_0(\omega_1 \tau) J_0(\omega_2 \tau), \tag{3}$$

$$R_{g_i g_q}(\tau) = R_{g_q g_i}(\tau) = 0, \tag{4}$$

$$R_{gg}(\tau) = \frac{1}{2} E\left[g^*(t) g(t+\tau)\right] = J_0(\omega_1 \tau) J_0(\omega_2 \tau), \tag{5}$$

where $E[\cdot]$ denotes the statistical average operator, and $J_0(\cdot)$ represents the zero-order Bessel function of the first kind.

If the AoD and the AoA are non-uniform, the statistical properties (3)-(5) of the reference model are not valid because these results are based on isotropic scattering assumption. In what follows, the statistical properties of the reference model for the non-isotropic scattering will be given. Assume that the AoD is $\alpha_n \sim M(\mu_1,\kappa_1)$ and the AoA is $\beta_n \sim M(\mu_2,\kappa_2)$, some key statistics are presented here.

Theorem: The ACFs and the CCFs of the quadrature components, and the ACF of the complex envelop are given by

$$\begin{aligned}
R_{g_i g_i}(\tau) &= R_{g_q g_q}(\tau) \\
&= \frac{1}{4I_0(\kappa_1)} I_0\left(\sqrt{\kappa_1^2 - \omega_1^2\tau^2 + j2\kappa_1\omega_1\tau\cos(\mu_1)}\right) \\
&\cdot \frac{1}{I_0(\kappa_2)} I_0\left(\sqrt{\kappa_2^2 - \omega_2^2\tau^2 + j2\kappa_2\omega_2\tau\cos(\mu_2)}\right) \\
&+ \frac{1}{4I_0(\kappa_1)} I_0\left(\sqrt{\kappa_1^2 - \omega_1^2\tau^2 - j2\kappa_1\omega_1\tau\cos(\mu_1)}\right) \\
&\cdot \frac{1}{I_0(\kappa_2)} I_0\left(\sqrt{\kappa_2^2 - \omega_2^2\tau^2 - j2\kappa_2\omega_2\tau\cos(\mu_2)}\right),
\end{aligned} \tag{6}$$

$$\begin{aligned}
R_{g_i g_q}(\tau) &= -R_{g_q g_i}(\tau) \\
&= \frac{-1}{4jI_0(\kappa_1)} I_0\left(\sqrt{\kappa_1^2 - \omega_1^2\tau^2 + j2\kappa_1\omega_1\tau\cos(\mu_1)}\right) \\
&\cdot \frac{1}{I_0(\kappa_2)} I_0\left(\sqrt{\kappa_2^2 - \omega_2^2\tau^2 + j2\kappa_2\omega_2\tau\cos(\mu_2)}\right) \\
&+ \frac{1}{4jI_0(\kappa_1)} I_0\left(\sqrt{\kappa_1^2 - \omega_1^2\tau^2 - j2\kappa_1\omega_1\tau\cos(\mu_1)}\right) \\
&\cdot \frac{1}{I_0(\kappa_2)} I_0\left(\sqrt{\kappa_2^2 - \omega_2^2\tau^2 - j2\kappa_2\omega_2\tau\cos(\mu_2)}\right),
\end{aligned} \tag{7}$$

$$\begin{aligned}
R_{gg}(\tau) &= \frac{1}{2} E_{\alpha,\beta,\phi}\left[g(t) g^*(t-\tau)\right] \\
&= \frac{1}{I_0(\kappa_1)} I_0\left(\sqrt{\kappa_1^2 - \omega_1^2\tau^2 - j2\kappa_1\omega_1\tau\cos(\mu_1)}\right) \\
&\cdot \frac{1}{I_0(\kappa_2)} I_0\left(\sqrt{\kappa_2^2 - \omega_2^2\tau^2 - j2\kappa_2\omega_2\tau\cos(\mu_2)}\right).
\end{aligned} \tag{8}$$

Proof: Since the proof on ACFs and CCFs of the quadrature components of the fading $g(t)$ is complicated and lengthy, details are omitted here, and the interested readers can further refer our incoming paper.

Based on (6) and (7), for (8), one has

$$\begin{aligned}
R_{gg}(\tau) &= \frac{1}{2} E_{\alpha,\beta,\phi}\left[g(t) g^*(t-\tau)\right] \\
&= \frac{1}{2} E_{\alpha,\beta,\phi}\left\{\left[g_i(t) + jg_q(t)\right]\left[g_i(t-\tau) - jg_q(t-\tau)\right]\right\} \\
&= \frac{1}{I_0(\kappa_1)} I_0\left(\sqrt{\kappa_1^2 - \omega_1^2\tau^2 - j2\kappa_1\omega_1\tau\cos(\mu_1)}\right) \\
&\cdot \frac{1}{I_0(\kappa_2)} I_0\left(\sqrt{\kappa_2^2 - \omega_2^2\tau^2 - j2\kappa_2\omega_2\tau\cos(\mu_2)}\right).
\end{aligned} \tag{9}$$

This completes the proof of (6)-(8). Due to the difference of the statistics between the isotropic and non-isotropic scattering, the corresponding Doppler spectrum densities are also different.

III. S2S NON-ISOTROPIC SCTTERING FADING CHANNEL SIMULATOR

Based on the observation of the aforementioned statistical properties and the investigation of the two-ring models, a S2S non-isotropic scattering fading channel simulation model will be proposed in this paper. The description of the merits and functions for the two-ring models is lengthy, so the details are omitted for brevity. When using the two-ring model, the received complex faded envelope is

$$C(t) = A\sum_{m=1}^{M}\sum_{n=1}^{N}\exp\left\{j\left[\omega_1 t\cos(\alpha_n)+\omega_2 t\cos(\beta_m)+\phi_{mn}\right]\right\}, \qquad (10)$$

where the index n refers to the paths traveling from the Tx to the scatterers located on the Tx end ring, the index m refers to the paths traveling from the scatterers on the Rx end ring to the Rx, and the phases ϕ_{mn} are independent for all pairs.

When the von Mises random angles are directly used to the AoD and the AoA, this generally requires large value M and N which is the same as the reference model. To reduce the number of sinusoidal components needed for simulation, we use a method by choosing $\alpha_n = \mu_1 + \vartheta_{1n}$, $\alpha_{n+N_0} = \mu_1 - \vartheta_{1n}$, $\beta_m = \mu_2 + \vartheta_{2m}$, $N = 2N_0$, and $A = 2/\sqrt{MN_0}$, then the sum in (10) can be rewritten as

$$C(t) = \frac{2}{\sqrt{MN_0}}\sum_{m=1}^{M}\sum_{n=1}^{N_0}\cos\left[\omega_1 t\cos(\mu_1)\cos(\vartheta_{1n})\right] \cdot\exp\left\{j\left[\omega_2 t\cos(\mu_2+\vartheta_{2m})+\phi_{mn}\right]\right\}, \qquad (11)$$

where $\vartheta_{1n}\sim M(0,\kappa_1)$, $\vartheta_{2m}\sim M(0,\kappa_2)$, $\phi_{mn}\sim U[-\pi,\pi)$, and they are independent for all m and n.

IV. ANALYSIS AND PERFORMANCE COMPARISON

This section verifies the accuracy and efficiency of the proposed model. Throughout the following subsections, all simulators have been implemented by choosing a normalized sampling period $(\omega_1 T_s)/(2\pi)=0.01$ (T_s is the sampling period, $\omega_2 = \alpha\cdot\omega_1$, $\alpha\in[0,1]$) and $M = N = 16$.

A. Correlation Statistics Comparison

To validate the performance of the proposed model in terms of its ACFs and CCFs, we compare our model to the theoretical one firstly. Figures 2 and 3 show the ACFs and the CCFs of the quadrature components for $\alpha = 0.55, 1$, $\mu_1=\mu_2=0$, $\kappa_1 = 0.3$, $\kappa_2 = 1.3$ (the non-isotropic scattering) and $\alpha = 0.55, 1$, $\mu_1=\mu_2=0$, $\kappa_1=\kappa_2=0$ (the isotropic scattering) by averaging over 30 trials. As can be seen from these two figures, autocorrelation nearly overlies the theoretical one, and cross-correlation of the complex fading envelope for our model is also very close to the theoretical one.

B. Probability Density Function Analysis

In Figure 4, we compare the PDF of the fading envelope of the proposed model with the theoretical PDF for the different factors $\alpha = 0.1, 0.5, 1$, $\mu_1 = 0$, $\mu_2 = \pi/2$, $\kappa_1=\kappa_2=3$. The results indicate that the PDF of the fading envelope generated by 15 simulation trials is in excellent agreement with the theoretical one.

V. CONCLUSION

In this paper, a statistical simulation model is proposed for the S2S non-isotropic scattering channels. By introducing the SoS and two-ring concepts, and the von Mises random angles for the AoD and the AoA, the new model has more rapidly converging ensemble average statistics. In addition, the fading envelope's PDF almost approaches the desired one for any factors α. Furthermore, our research work can also be considered as partially theoretical guidance for establishing more purposeful S2S measurement campaigns in the future.

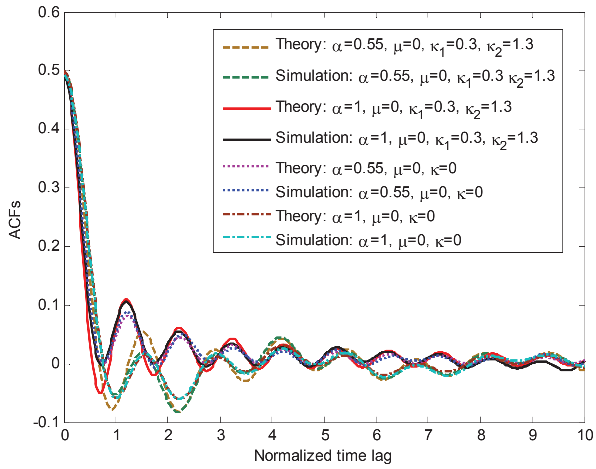

Figure 2. The ACFs of the quadrature components.

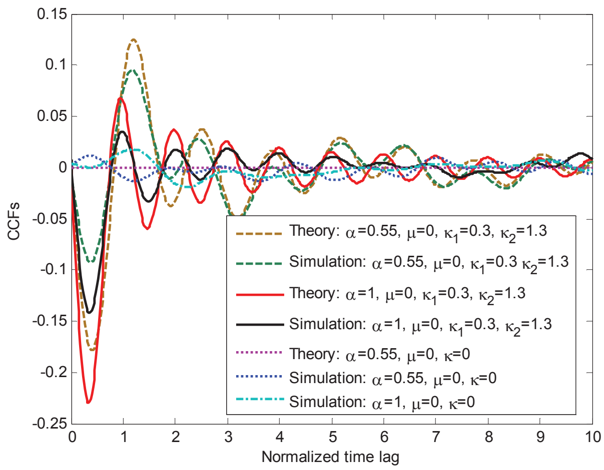

Figure 3. The CCFs of the quadrature components.

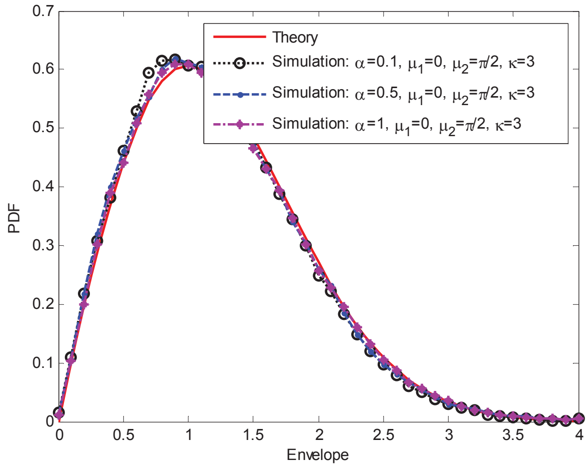

Figure 4. The PDF of the fading envelope.

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