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SIMULATION OF DOUBLY-SELECTIVE COMPOUND K FADING CHANNELS FOR MOBILE-TO-MOBILE COMMUNICATIONS

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ABSTRACT

A computer simulation model is proposed for discrete-time doubly-selective compound-K fading channel. It first generates multiple independent mobile-to-mobile Rayleigh fading Channel Impulse Response (CIR) using the non-isotropic scattering model, then generates the cross- and auto-correlated gamma shadowing matrix using the combination of the memoryless nonlinear transformation (MNLT) method and the decomposition methods. It then combines the complex Rayleigh CIR with the gamma shadowing matrix to yield the doubly-selective fading channel CIR whose envelop follows the compound K distribution. Simulation examples demonstrate that the proposed method can effectively produce compound K fading channel responses with satisfactory statistical properties.

Index Terms— Frequency-selective fading channel, compound K distribution, correlated gamma process, decomposition method, nonlinear transformation, non-isotropic scattering, mobile-to-mobile communications, underwater acoustic communications.

I. INTRODUCTION

The compound K fading channel is considered as a suitable model for medium and short range communication systems, where the Line-of-Sight (LOS) does not present, rich scatterers contribute to small-scale fading, and range-dependent shadowing effects are significant among multi-paths. Such channels are found in mobile-to-mobile ad hoc network communications [1], satellite communications [2], and shallow water acoustic communications [3], as well as radar and sonar clutters [4]–[6]. Assume Rayleigh fading and gamma shadowing distributions, the combination of Rayleigh and gamma yields the compound K distribution [1], [3], [4]. It is a good approximation of the composite Rayleigh-lognormal distribution, which, in comparison, has easy-to-use and closed-form formula.

Computer simulation of compound K distribution has been well studied for generating radar and sonar clutters [4], [5]. The challenge lays in the fact that the correlated gamma distribution is difficult to implement because of the infinite divisibility of the gamma distribution, in contrast to the stability of the Gaussian distribution. This means that the weighted sum of multiple independent gamma random variables and/or linearly filtered gamma random processes do not remain gamma distributed. To simulate a gamma process with prescribed correlation function, a memoryless nonlinear transformation method is proposed in [5] for generating compound K radar clutters. This method can be easily adopted to generate compound-K frequency-flat fading channels with a specified temporal correlation function or Doppler spectrum.

However, simulating frequency-selective compound K channels is less straightforward because both cross-correlation among different delay taps and auto-correlation of Doppler shifts have to be implemented. In [7], two methods have been adopted to implement cross-correlation among different receiver branches for gamma random vectors which in turn produce Nakagami fading channel responses. One is the decomposition method which is computationally efficient but has less accuracy in gamma probability density function (pdf); another is the Sim's method which produces more accurate gamma pdf with higher computational complexity. However, both methods do not consider the auto-correlation of the time-varying fading channel due to Doppler spread.

In this paper, we propose a new simulator for generating channel impulse response (CIR) of time-varying frequency-selective (so called doubly-selective [8], [9]) compound K channels. It models the discrete-time doubly-selective compound K fading channel by a time-varying channel matrix $\mathbf{H}(n,l)$, where $n = 1, \cdots, N$ is the time-domain samples, and $l = 1, \cdots, L$ is the delay taps. The proposed simulator implements the cross- and auto-correlation of the compound K channel matrix by the gamma shadowing matrix. It implements the auto-correlation by the MNLT method and the cross-correlation by the decomposition method. It generates multiple independent mobile-to-mobile Rayleigh fading CIR (complex Gaussian) using the non-isotropic scattering model [10]. It then combines the complex Gaussian CIR with the correlated gamma shadowing matrix to yield the doubly-selective fading channel CIR whose envelop follows the compound K distribution. Because of the high computational

complexity of the MNLT method, we introduce a down-sampling factor in the generation of the gamma shadowing matrix so that less number of time samples are needed for the correlated gamma matrix. Simulation examples demonstrate that the proposed method can effectively produce compound K fading channel responses with satisfactory statistical properties when a down-sampling factor is as large as several hundreds. This significantly reduces the computational complexity of the proposed simulator.

Notations: Boldface lower-case letters denote vectors. Boldface upper-case letters denote matrices. The superscripts $(\cdot)^h, (\cdot)^*, (\cdot)^t$ are the conjugate transpose, conjugate, and transpose, respectively. The expectation is denoted as $E(\cdot)$ and $j = \sqrt{-1}$.

II. THE MATHEMATICAL MODEL

II-A. The Compound K Distribution

The compound K distribution is a combination of Rayleigh and gamma distributions [1], [4]. Let R have a Rayleigh distribution with a random mode $\sqrt{G}$. The conditional probability density function of R is given as

$$f_{R}(r|G) = \frac{r}{G}\exp(-\frac{r^2}{2G}) \tag{1}$$

Assume that G is gamma distributed with shape parameter ν and scale parameter β

$$f_{G}(g) = \frac{2}{\beta\Gamma(\nu)}\left(\frac{2g}{\beta}\right)^{\nu-1}\exp\left(-\frac{2g}{\beta}\right), \quad g \geq 0 \tag{2}$$

where $\Gamma(\cdot)$ is the Euler gamma function. The compound K distribution is obtained by averaging $f_{R}(r|G)$ with respect to G

$$f_{R}(r) = \frac{4}{\sqrt{\beta}\Gamma(\nu)}\left(\frac{r}{\sqrt{\beta}}\right)^{\nu}K_{\nu-1}\left(\frac{2r}{\sqrt{\beta}}\right), \quad r \geq 0 \tag{3}$$

where K_ν is the modified Bessel function of the second kind and with order ν. Note that Rayleigh distribution is a special case of compound K distribution when $\nu \to \infty$ and $E(R^2) = \beta\nu$ remains constant. The smaller the ν, the worse the K-distributed channel.

II-B. Doubly-Selective Compound-K Fading Channels

Consider a wide-band doubly-selective wireless channel with a baseband equivalent impulse response $h(t,\tau)$ defined as the response at time t to an impulse applied to the channel at time instant $t-\tau$ [8]. Note that $h(t,\tau)$ includes the effects of the transmit pulse shaping filter and the receive matched filter [9]. Sampling the linear time-variant channel impulse response with the sampling period T_s and truncating the low-power coefficients yield the discrete-time channel impulse response $h(n,l) = h(nT_s, lT_s)$, where $n = 0, \cdots, N-1$ and $l = -L_1, \cdots, L_2$, with N, L_1, and L_2 being nonnegative integers. The channel is modeled as a time-varying FIR (Finite Impulse Response) filter with length $L = L_1+L_2+1$. Let $s(n)$ denote the transmitted base-band equivalent signal. Then the received base-band equivalent signal is

$$y(n) = \sum_{l=-L_1}^{L_2} s(n-l)h(n,l) + v(n), \tag{4}$$

where $v(n)$ is the additive white Gaussian noise. If the envelop of the channel coefficient $h(n,l)$ has a compound K distribution, then the channel random variable $H(n,l)$ may be represented as the mixture of a complex Gaussian random variable $X(n,l)$ and a gamma random variable $G(n,l)$ by

$$\begin{aligned} H(n,l) &= \sqrt{G(n,l)}\cdot X(n,l) \\ &= \sqrt{G(n,l)}\cdot\left[X_c(n,l) + jX_s(n,l)\right], \end{aligned} \tag{5}$$

where $X_c(n,l)$ and $X_s(n,l)$ are the real and imaginary parts of a Rayleigh fading channel, respectively. They are Gaussian random variables with zero mean and variance $\sigma^2 = 1$. For each delay tap l, the mobile-to-mobile Rayleigh fading channel is usually modeled by 2-dimensional isotropic or non-isotropic scattering without LOS

$$X(n) = \sqrt{\frac{2}{N_s}}\sum_{i=1}^{N_s}\exp\left[jn\left(\omega_{d_1}\cos\alpha_{1i} + \omega_{d_2}\cos\alpha_{2i}\right) + j\theta_i\right] \tag{6}$$

where N_s is the number of propagation paths, ω_{d_1} and ω_{d_2} are the maximum angular Doppler frequencies due to the motion of the transmitter (Tx) and the receiver (Rx), respectively. The angles α_{1i} and α_{2i} are the angle of departure (AoD) and the angle of arrival (AoA) of the ith path with reference to the velocity vectors of the Tx and Rx, respectively. And θ_i is a random phase uniformly distributed on $[-\pi, \pi)$. We adopt the von Mises PDF for AoD and AoA, defined as

$$f_\alpha(\alpha) = \frac{\exp[\kappa\cos(\alpha-\mu)]}{2\pi I_0(\kappa)}, \quad \kappa \geq 0, \tag{7}$$

where $I_0(\cdot)$ is the zero-order modified Bessel function of the first kind, μ is the mean direction of the AoD or AoA, and κ is the concentration parameter which controls the width of the scatterers. Denote the von Misses PDF as $\alpha \sim M(\mu,\kappa)$. If $\kappa = 0$, then the von Mises PDF reduces to the uniform distribution.

II-C. Channel Statistical Properties

Assuming independence between the gamma and complex Gaussian distributions, the correlation function of the channel coefficients is given by

$$\begin{aligned} &E\left[h(n_1,l_1)\cdot h^*(n_2,l_2)\right] \\ &\quad = E\left[\sqrt{g(n_1,l_1)g(n_2,l_2)}\right]\cdot E[x(n_1,l_1)x^*(n_2,l_2)] \\ &\quad = \Psi_{\sqrt{G}\sqrt{G}}(n_1,n_2;l_1,l_2)\cdot\Psi_{XX}(n_1,n_2), \end{aligned} \tag{8}$$

The complex Gaussian random variable X is independent at different delay taps which leads to (8). For AoD and AoA following the von Misses distribution with $\alpha_{1,i} \sim M(\mu_1,\kappa_1)$

and $\alpha_{2,i} \sim M(\mu_2, \kappa_2)$, the auto-correlation function of X is given by [10]

$$\Psi_{XX}(n_1, n_2) = \prod_{i=1}^{2} \frac{I_0\left(\sqrt{\kappa_i^2 - \omega_{d_i}^2 \Delta n^2 + j2\kappa_i \omega_{d_i} \Delta n \cos \mu_i}\right)}{I_0(\kappa_i)} \quad (9)$$

where $\Delta n = n_2 - n_1$ and $\prod$ is the multiplication operator.

The correlation function $\Psi_{\sqrt{G}\sqrt{G}}(n_1, n_2; l_1, l_2)$ is more complicated. To the best of our knowledge, a complete analysis of $\Psi_{\sqrt{G}\sqrt{G}}(n_1, n_2; l_1, l_2)$ or $\Psi_{GG}(n_1, n_2; l_1, l_2)$ has not been found in the literature. For many practical wireless channels, it is reasonable to assume that the correlation function can be decomposed into the product of the auto-correlation and cross-correlation functions. For $n_1 \neq n_2$ and $l_1 = l_2 = l$, the auto-correlation of G or $\sqrt{G}$ is commonly assumed to follow exponential decay [2], [9] as $\Psi_{GG}(n_1, n_2; l) = A \exp[-(n_2 - n_1)/\lambda]$. For $n_1 = n_2$ and $l_1 \neq l_2$, the cross-correlation between $g(n, l_1)$ and $g(n, l_2)$ is determined by the power delay profile of the channel and the transmit and receive filters, detailed in (17) of [9].

III. PROPOSED SIMULATION METHOD

Computer simulation of doubly-selective compound-K fading channel response $h(n, l)$ is implemented by three steps: first generate independent Rayleigh fading coefficient vectors $\mathbf{x}_l = [x(0, l), \cdots, x(N-1, l)]^t$ for $l = -L_1, \cdots, L_2$; second, generate correlated gamma random vectors $\mathbf{g}_l = [g(0, l), \cdots, g(J-1, l)]^t$, where $J = N/D$ and D is the down-sampling factor; finally, combine the Rayleigh and gamma vectors in an appropriate manner to yield compound K coefficients.

Computer simulation of independent Rayleigh fading coefficients has been thoroughly studied by the research community in recent years [2], [9]–[11]. In this paper, we adopt the mobile-to-mobile non-isotropic model [10] for the simulation of the Rayleigh fading channel coefficient vectors.

III-A. Generating Correlated Gamma Random Vectors

Generating correlated gamma random vectors is more challenging because both auto-correlation and cross-correlation are difficult to implement. Unlike Rayleigh random vectors, a filtered white gamma random vector does not remain gamma distributed. To generate multiple gamma random vectors with a prescribed auto-correlation function and cross-correlation function, we take a three-step approach. First, we map the cross-correlation matrix of the desired gamma random vectors into the shape and scale parameters of independent gamma random vectors; then we generate L independent gamma vectors with the corresponding parameters and the prescribed auto-correlation function using the MNLT method [5]; finally we combine the independent gamma vectors via the decomposition method [7] to generate the gamma random matrix with the cross- and auto-correlation properties. The detailed derivation of the decomposition and MNLT methods are available in [7] and [5]. Here we summarize the major steps involved.

Denote the l-th desired gamma random vector as $\mathbf{g}_l = [g(0, l), \cdots, g(J-1, l)]^t$ and the l-th independent gamma random vector as $\boldsymbol{\gamma}_l = [\gamma(0, l), \cdots, \gamma(J-1, l)]^t$. The gamma shadowing matrix $\mathbf{G} = [\mathbf{g}_1, \cdots, \mathbf{g}_L]$ is generated by the following six steps:

Step I. Compute the cross-correlation matrix $\mathbf{R}_{GG}$ whose elements are defined by $\rho_G(n; l_1, l_2) = E[g(n, l_1) g(n, l_2)]$. It is determined by the power delay profile and Tx/Rx filters and is computed by (17) of [9];

Step II. Compute the covariance matrix $\mathbf{C}_{GG}$ from the cross-correlation matrix $\mathbf{R}_{GG}$, whose (l_1, l_2)-th component is given by

$$c_G(l_1, l_2) = \rho_G(n, l_1, l_2) - E[g(n, l_1)] E[g(n, l_2)] \quad (10)$$

Step III. Decompose $\mathbf{C}_{GG}$ into the product of a lower triangular matrix $\boldsymbol{\Lambda}$ and its transpose, *i.e.*, $\mathbf{C}_{GG} = \boldsymbol{\Lambda}\Lambda^t$ and denote $\zeta_{l,k}$ the (l, k)-th entry of $\boldsymbol{\Lambda}$.

Step IV. Assuming the same shape parameter ν and different scale parameters β_l for all $\mathbf{g}_l$, compute the shape and scale parameters $(\nu_{\gamma_l}, \beta_{\gamma_l})$ for all $\boldsymbol{\gamma}_l$ by

$$\nu_{\gamma_1} = \nu, \quad (11)$$

$$\nu_{\gamma_l} = \left(\nu\beta_l/2 - \sum_{k=1}^{l-1} \zeta_{l,k} \sqrt{\nu_{\gamma_k}}\right)^2 / \zeta_{\gamma_{ll}}^2, \quad (12)$$

$$\beta_{\gamma_l} = 2/\sqrt{\nu_{\gamma_l}}. \quad (13)$$

Step V. Using the MNLT method, generate L independent gamma random vectors $\boldsymbol{\gamma}_l$ with the corresponding parameters and auto-correlation function. The steps for this method is summarized as Step V.1. – Step V.3.

Step VI. Group the independent auto-correlated gamma vectors into a gamma matrix $\boldsymbol{\gamma} = [\boldsymbol{\gamma}_1, \cdots, \boldsymbol{\gamma}_L]$, and generate the desired gamma matrix $\mathbf{G}$ by $\mathbf{G} = \boldsymbol{\Lambda}\gamma$.

The MNLT method used in **Step V** is summarized here. The basic idea of the MNLT method, originally proposed for computer simulation of Radar clutters, is to map the auto-correlation of a gamma distribution into the auto-correlation function of a Gaussian distribution, then generate the correlated Gaussian random vector, and finally convert the correlated Gaussian random vector into the correlated gamma random vector through memoryless nonlinear transformation. Denote a white Gaussian vector and the correlated Gaussian vector as $\mathbf{w} = [w(0), \cdots, w(J-1)]^t$ and $\mathbf{z} = [z(0), \cdots, z(J-1)]^t$, respectively. Note that we drop the subscript l for notation convenience. Denote the auto-correlation functions of the gamma and Gaussian random vectors as $\Psi_{\gamma\gamma}(\Delta n; l)$ and $\Psi_{ZZ}(\Delta n)$, respectively. The MNLT method generates the auto-correlated gamma random vector $\boldsymbol{\gamma}_l = [\gamma(0, l), \cdots, \gamma(J-1, l)]^t$ by three steps:

Step V.1. Map the auto-correlation function of the gamma distribution to the auto-correlation function of the Gaussian distribution

$$\Psi_{ZZ}(\Delta n) = \frac{\Psi_{\gamma\gamma}(\Delta n; l) - (E[\gamma(n,l)])^2}{\text{Var}[\gamma(n,l)]}. \quad (14)$$

Step V.2. Generate the auto-correlated Gaussian random vector $\mathbf{z}$ from the white Gaussian vector $\mathbf{w}$ by one of the two methods: the spectral representation method [12] and the IIR (infinite impulse response) filtering method [13].

Step V.3. Convert the auto-correlated Gaussian random values to gamma random values by the transformation

$$\gamma(n,l) = Q_\gamma[\text{erfc}(z(n)/\sqrt{2})/2], \quad n = 0, \cdots, J-1, \quad (15)$$

where $Q_\gamma(a)$ is the complementary quantifier function of the gamma distribution, defined by $\int_{Q_\gamma(a)}^{\infty} f_\Gamma(\gamma)d\gamma = a$.

III-B. Doubly-Selective Compound-K Fading Channel Matrix

The simulated cross- and auto-correlated gamma shadowing matrix has a size $L \times J$, while the simulated L Rayleigh fading vectors $\mathbf{x}_l$ are grouped into a $L \times N$ matrix $\mathbf{X} = [\mathbf{x}_1, \cdots, \mathbf{x}_L]$. Recall that $J = N/D$ with the down-sampling factor $D \geq 1$. We shall use one sample of gamma matrix to weigh D samples of Rayleigh matrix in n-domain when combining the two into a compound K fading channel matrix $\mathbf{H}$. Let $\mathbf{G}_D$ denote the up-sampled $L \times N$ gamma matrix (one sample repeated D times in n-domain), then the doubly-selective compound-K fading channel matrix is generated by $\mathbf{H} = \sqrt{\mathbf{G}_D} \odot \mathbf{X}$, where $\odot$ denotes the dot product. Choosing a down-sampling factor $D >> 1$ can reduce computational complexity by generating less number of gamma random variables, because the MNLT method (15) is computationally involved.

IV. SIMULATION RESULTS

We use two examples to demonstrate the proposed simulation method. One is a base-to-mobile RF fading channel with isotropic scattering ($\kappa = 0$ in von Mises pdf) and channel length $L = 20$. The maximum Doppler frequency $f_d = 3$ Hz. The auto-correlation of the gamma shadowing vector $\boldsymbol{\gamma}_l$ is $\Psi_{\gamma\gamma}(\Delta n; l) = \exp[-\Delta n/167]$. Another example is the underwater acoustic communication channel with a fixed Tx, a moving Rx, and a moving water medium. The propagation speed of sound underwater is $c = 1500$m/s and the carrier frequency is $f = 15$ kHz. The maximum Doppler shifts of the Rx and water medium are thus $f_{d_1} = 5$ Hz and $f_{d_2} = 10$ Hz, respectively. The AoD and AoA of the scatterers are non-uniform distributed with the von Mises concentration parameter $\kappa = [3, 2]$ and the mean directions $\mu = [0, \frac{\pi}{4}]$. The auto-correlation of the gamma shadowing vector is $\Psi_{\gamma\gamma}(\Delta n; l) = \exp[-\Delta n/500]$.

Simple power delay profiles were chosen for the two doubly-selective compound K fading channels, as shown in Fig. 1. The total average power of each channel was normalized to unity. The square-root raised-cosine filters were used for both Tx and Rx filters and the cross-correlation matrices were computed according to (17) of [9]. For both examples, the sampling period was $T_s = 2 \times 10^{-4}$ s and the down-sampling factor was $D = 500$. The number of elements in a correlated gamma vector $\mathbf{g}_l$ was $J = 2000$, the number of elements in a Rayleigh fading vector $\mathbf{x}_l$ was $N = 1 \times 10^6$, and the number of propagation paths was $N_s = 400$. The shape parameters ν of the compound K distribution were chosen to be 2.1 and 3.7.

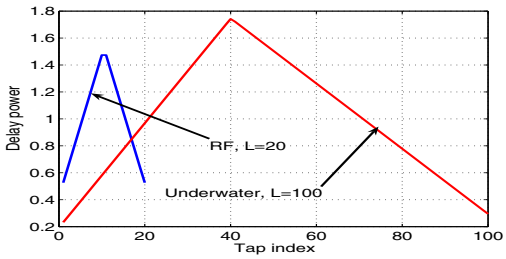


Fig. 1. Power delay profiles for RF and underwater simulation examples

Fig. 2 shows that the auto-correlated gamma vectors $\boldsymbol{\gamma}_l$ exhibit the prescribed exponentially decaying autocorrelation function, which indicates the effectiveness of the MNLT method.

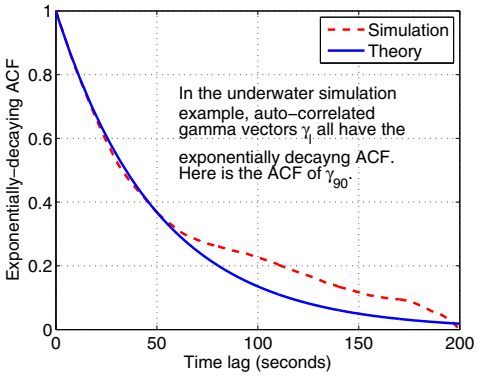
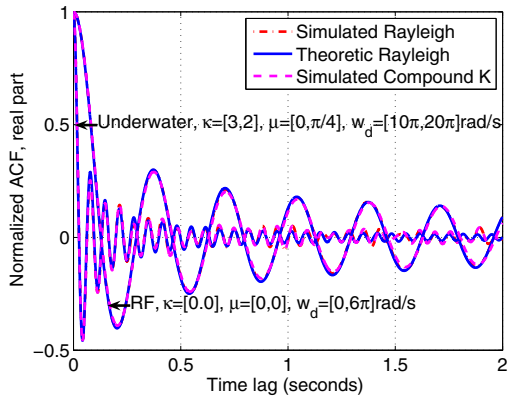
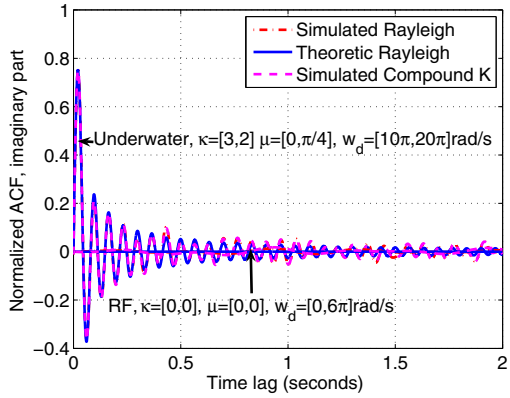


Fig. 2. Exponentially decaying ACF of auto-correlated gamma vector $\boldsymbol{\gamma}_l$ in the underwater simulation example

The small-scale autocorrelation properties of the Rayleigh fading channel matrix $\mathbf{X}$ and the compound K fading channel matrix $\mathbf{H}$ are shown in Fig. 3, where the auto-correlation $\Psi_{KK}(n_1, n_2; l)$ and $\Psi_{XX}(n_1, n_2)$ are almost the same after normalization. Note that, in the underwater example with non-isotropic scattering, the imaginary parts of both $\Psi_{KK}(n_1, n_2; l)$ and $\Psi_{XX}(n_1, n_2)$ are non-zero, which differs significantly from the commonly-used isotropic scattering model.



(a) Normalized real part of $\Psi_{KK}(n_1, n_2; l)$ and $\Psi_{XX}(n_1, n_2)$



(b) Normalized imaginary part of $\Psi_{KK}(n_1, n_2; l)$ and $\Psi_{XX}(n_1, n_2)$

Fig. 3. ACF properties of Rayleigh fading channel matrix $\mathbf{X}$ and compound K fading channel matrix $\mathbf{H}$

The samples of the normalized cross-correlation coefficients are shown in Table I for the RF example and in Table II for the underwater example, where $\rho_G(l_1, l_2) = c_G(l_1, l_2)/\sqrt{\text{Var}[g(n, l_1)]\text{Var}[g(n, l_2)]}$. The results show that the proposed method can produce fairly accurate cross-correlation coefficients yielding satisfactory statistical properties of the simulated CIR.

The pdf curves of the simulated fading CIR are compared with the theoretical ones in Fig. 4. In both examples, the simulated gamma matrices $\mathbf{G}$ exhibit small discrepancy of pdf from the theoretical ones, as shown in Fig. 4(a) and Fig. 4(c). The smaller the channel length L, the better match the gamma distributions. This is inherent to the decomposition method of implementing the cross-correlated gamma matrices. However, the overall compound K distributions match the theoretical ones very well in both examples, as shown in are Fig. 4(b) and Fig. 4(d). This is because the Rayleigh distribution plays the major role in the compound K distributions.

Table I. Comparison of normalized covariance matrix elements $\rho_G(l_1, l_2)$ in the RF example

$\rho_G(l_1, l_2)$	Specified	ν=2.1	ν=3.7
$\rho_G(1, 2)$	0.4634	0.4812	0.4591
$\rho_G(19, 20)$	0.4634	0.4421	0.4602
$\rho_G(18, 20)$	0.2147	0.1849	0.2033
$\rho_G(5, 7)$	0.2147	0.2234	0.2140
$\rho_G(10, 13)$	0.0995	0.0934	0.1020
$\rho_G(9, 12)$	0.0995	0.0910	0.0956
$\rho_G(7, 11)$	0.0461	0.0434	0.0512
$\rho_G(15, 19)$	0.0461	0.0444	0.0450

Table II. Comparison of normalized covariance matrix elements $\rho_G(l_1, l_2)$ in the underwater example

$\rho_G(l_1, l_2)$	Specified	ν=2.1	ν=3.7
$\rho_G(1, 2)$	0.4634	0.4745	0.4501
$\rho_G(90, 91)$	0.4634	0.4816	0.4704
$\rho_G(18, 20)$	0.2147	0.2048	0.2120
$\rho_G(46, 48)$	0.2147	0.2202	0.2184
$\rho_G(10, 13)$	0.0995	0.0973	0.0922
$\rho_G(97, 100)$	0.0995	0.1014	0.0964
$\rho_G(7, 11)$	0.0461	0.0494	0.0471
$\rho_G(66, 70)$	0.0461	0.0483	0.0428

V. CONCLUSIONS

A new discrete-time model for doubly-selective compound-K fading channel has been developed in this paper. The proposed computer simulator first generates multiple independent mobile-to-mobile Rayleigh fading CIR using the non-isotropic scattering model, then generates the cross- and auto-correlated gamma shadowing matrix using the combination of the MNLT and the decomposition methods. It then combines the complex Rayleigh CIR with the gamma shadowing matrix to yield the doubly-selective compound K fading channel CIR. Simulation examples demonstrate that the proposed method can effectively produce compound K fading channel responses with satisfactory statistical properties.

VI. ACKNOWLEDGEMENT

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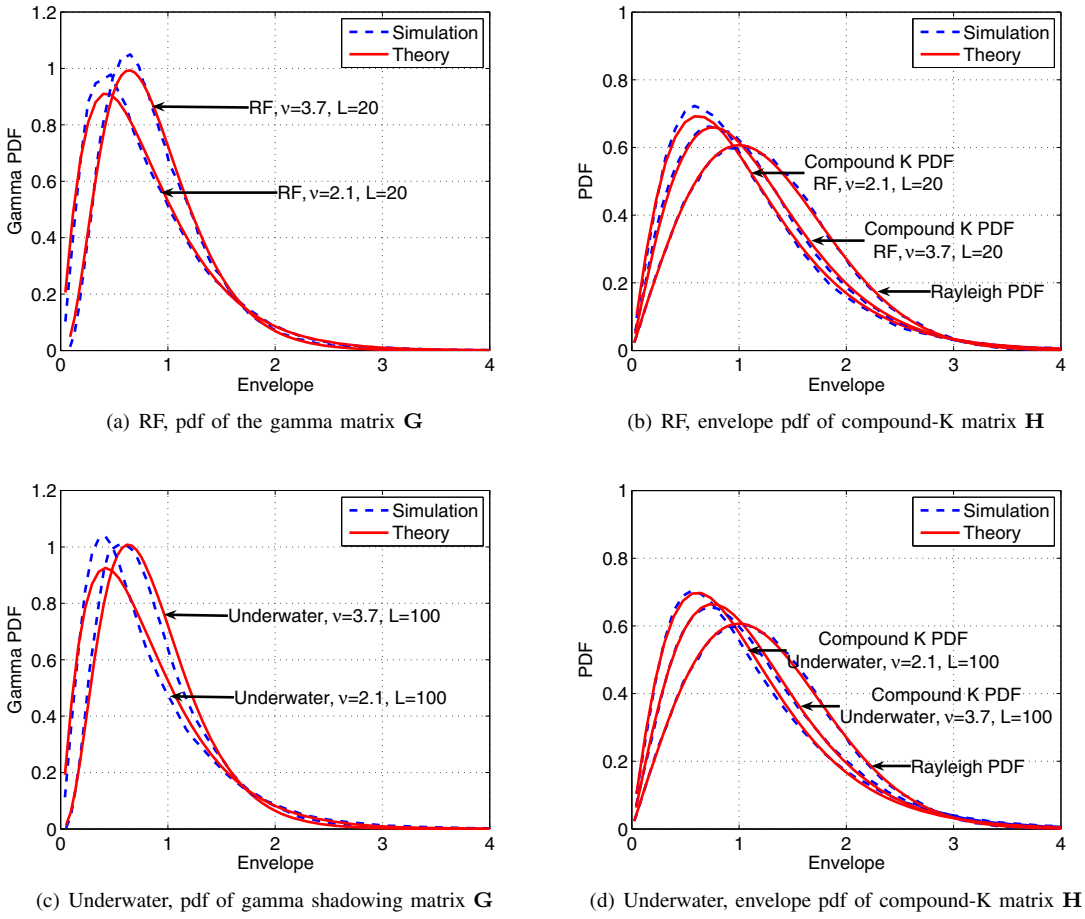

(a) RF, pdf of the gamma matrix $\mathbf{G}$

(b) RF, envelope pdf of compound-K matrix $\mathbf{H}$

(c) Underwater, pdf of gamma shadowing matrix $\mathbf{G}$

(d) Underwater, envelope pdf of compound-K matrix $\mathbf{H}$

Fig. 4. Envelope pdf of the RF and underwater fading channel examples. The pdf curves of the gamma shadowing matrix exhibit some discrepancy from the theoretical ones at the low magnitude values due to the long channel length. However, the envelope pdf curves of the overall compound K channel matrix match the theoretical ones very well.

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