On the Capacity of Vehicular Communications

Paschalis C. Sofotasios[*,‡], Seong Ki Yoo[†], Nidhi Simmons[§], Simon L. Cotton[§], Mikko Valkama[‡]

[*]Center for Cyber Physical Systems, Department of Electrical Engineering and Computer Science,
Khalifa University, 127788, Abu Dhabi, UAE, (e-mail: paschalis.sofotasios@ku.ac.ae)
[†]Centre for Future Transport and Cities, Faculty of Engineering, Environment and Computing,
Coventry University, CV1 2TE, UK, (e-mail: ad3869@coventry.ac.uk)
[§]Institute of Electronics, Communications and Information Technology, Queen's University Belfast,
BT3 9DT, Belfast, UK, (e-mail: {nidhi.simmons; simon.cotton}@qub.ac.uk)
[‡]Department of Electrical Engineering, Tampere University, FI-33101, Tampere, Finland
(e-mail: {mikko.valkama; paschalis.sofotasios}@tuni.fi)

***Abstract*—The κ-μ / inverse gamma and η-μ / inverse gamma distributions constitute two of the most distinct composite fading models. The present work offers novel results on the achievable ergodic capacity over these composite multipath/shadowing conditions. The derived expressions are corroborated with respective simulation results and are shown to be useful in practical wireless scenarios in the context of device to device communications, such as off-body, and vehicle-to-vehicle communications.**

I. Introduction

Realistic modeling of fading conditions is a major challenge in conventional and emerging wireless communications. Based on this, several fading distributions have been proposed that demonstrate a certain degree of mathematical tractability and/or acceptable modeling accuracy [1]–[12]. In the same context, it has been proven that generalized fading models are capable of providing accurate characterization of multipath fading [13]–[16]. Yet, it is also known that multipath fading and shadowing phenomena practically occur simultaneously and can be modeled with the aid of composite fading distributions [5], [8], [9], [17]–[19]. With this motivation, the authors in [9] proposed Fisher−Snedecor $\mathcal{F}$ and then the κ-μ / inverse gamma and the η-μ / inverse gamma composite distributions [10]–[12]. These models were shown extensively to achieve accurate fitting to results from various measurements in cellular, wearable and vehicle-to-vehicle communications [9], [12].

It is recalled that the algebraic representation of fading distributions determines how useful they can be in the derivation of useful analytic expressions for important information-theoretic measures. Consequently, this task is often challenging in practice, if not impossible, when it comes to digital communications over generalized and composite fading envornments. Based on this, the authors in [20] analyzed the capacity over generalized fading channels under different adaptation policies, whilst this topic was also addressed in [21] for the case of $K_{\rm G}$ fading channels, in [18] and [22] for the case of $\mathcal{G}$ fading channels and in [23] and [24] for the case of η-μ / gamma and κ-μ shadowed fading channels, respectively. Similarly, the channel capacity with optimum rate adaptation over inverse gamma based shadowing and generalized multipath fading composite channels was addressed in [25] and [26]. However, the offered analytic results were based on [10, eq. (10)] and [11, eq. (9)], which while they are valid for physical channel characterization, they exhibit some limitations in their admissible parameter range when used in analyses relating to digital communications. In the same context, the outage probability (OP) over different generalized interference-limited scenarios was investigated in [27].

This analysis quantifies the achievable capacity of digital communications over $\kappa - \mu$ / inverse gamma and $\eta - \mu$ / inverse gamma fading channels. To that end, we derive novel expressions for the corresponding ergodic capacity, which appear in agreement with corresponding results from respective computer simulations. Furthermore, they account for versatile multipath/shadowing conditions as these are encountered in realistic cellular, off-body and vehicular communications. To that end, the derived analytic expressions quantify the achievable ergodic capacity whereas useful insights are developed. Furthermore, their computation is straightforward using standard software packages such as MATLAB, MAPLE and MATHEMATICA. Thus, they are useful theoretically and practically since they can assist in the effective design of device-to-device communication systems, which are typically characterized by stringent quality of service requirements.

II. Inverse Gamma Based Composite Distributions

The η-μ / inverse gamma and the κ-μ / inverse gamma composite distributions are distinct multipath/shadowing fading models based on inverse gamma shadowing. The former is based on η-μ distribution assuming that the mean power of the scattered component experiences shadowing, weighted by an inverse gamma random variable (RV). It can provide remarkable accuracy in non-line of sight (NLOS) scenarios and its signal-to-noise (SNR) PDF is given by [12]

$$f_\gamma(\gamma) = \frac{2^{2\mu}\mu^{2\mu}h^{\mu}(m_s-1)^{m_s}\overline{\gamma}^{m_s}\gamma^{2\mu-1}}{B(m_s,2\mu)(2\mu h\gamma+(m_s-1)\overline{\gamma})^{m_s+\mu}}\times$$
$${}_2F_1\left(\frac{m_s}{2}+\mu, \frac{m_s+2\mu+1}{2}; \mu+\frac{1}{2}; \frac{(2\mu H\gamma)^2}{(2\mu h\gamma+(m_s-1)\overline{\gamma})^2}\right) \quad (1)$$

where ${}_2F_1(\cdot,\cdot;\cdot;\cdot)$ is the Gaussian hypergeometric function [28]. In addition, η is defined according to the two formats of the $\eta-\mu$ distribution [12], whereas μ is related to the number of multipath clusters and m_s is the shadowing parameter. Also, γ and $\overline{\gamma}=E[\gamma]$ represent the instantaneous and average SNRs, with $E[\cdot]$ denoting statistical expectation, whereas $B(\cdot,\cdot)$ denotes the beta function [28]. Likewise, the κ-μ / inverse gamma distribution assumes that the mean power of both the dominant and scattered signal components experiences shadowing, which is weighted by an inverse gamma RV. This model was proven remarkably accurate in line of sight (LOS) communications and its SNR (PDF) is given by [12]

$$f_\gamma(\gamma)=\frac{\mu^\mu(1+\kappa)^\mu(m_s-1)^{m_s}\overline{\gamma}^{m_s}e^{-\mu\kappa}\gamma^{\mu-1}}{B(m_s,\mu)[\mu(1+\kappa)\gamma+(m_s-1)\overline{\gamma}]^{m_s+\mu}} \times {}_1F_1\left(m_s+\mu;\mu;\frac{\mu^2\kappa(1+\kappa)\gamma}{\mu(1+\kappa)\gamma+(m_s-1)\overline{\gamma}}\right) \tag{2}$$

where κ is the ratio of the total power of the dominant components to the total power of the scattered waves and ${}_1F_1(\cdot;\cdot;\cdot)$ denotes the Kummer hypergeometric function [28].

III. Ergodic Capacity over Composite Channels

A. Ergodic Capacity over η-μ / Inverse Gamma Fading

By inserting the SNR PDF of the η-μ / inverse gamma distribution in [12, eq. (13)] into $C_e\triangleq B\int_0^\infty\log_2(1+\gamma)f_\gamma(\gamma)\mathrm{d}\gamma$ and setting $u=2\mu h\gamma+(m_s-1)\overline{\gamma}$ yields (3). By then setting $t=1-(m_s-1)\overline{\gamma}/u$, one obtains (4). Using [28, Eq. (1.111)] and expanding the logarithmic terms and the Gauss hypergeometric function using [28, Eq. (9.14.1)] yields

$$\begin{aligned}\frac{C_e}{B}=&\frac{1}{B(m_s,2\mu)\,h^\mu\ln(2)}\sum_{l=0}^{m_s-1}\sum_{i=0}^{\infty}(-1)^l\binom{m_s-1}{l}\\&\times\frac{\left(\frac{m_s+2\mu}{2}\right)_i\left(\frac{m_s+2\mu+1}{2}\right)_i}{i!\,\left(\mu+\frac{1}{2}\right)_i}\left(\frac{H}{h}\right)^{2i}\\&\times\left\{\int_0^1 t^{2\mu+2i+l-1}\ln\left(1-\left(1-\frac{(m_s-1)\,\overline{\gamma}}{2\mu h}\right)t\right)\mathrm{d}t\right.\\&\left.-\int_0^1 t^{2\mu+2i+l-1}\ln(1-t)\,\mathrm{d}t\right\}.\end{aligned} \tag{5}$$

The above integrals can be expressed in closed-form using [28, Eq. (2.729.1) / Eq. (4.293.8)]. Hence, by substituting in (5), the following analytic expression is deduced

$$\begin{aligned}\frac{C_e}{B}=&\frac{1}{B(m_s,2\mu)\,h^\mu\ln(2)}\sum_{l=0}^{m_s-1}\sum_{i=0}^{\infty}(-1)^l\binom{m_s-1}{l}\\&\times\frac{\left(\frac{m_s+2\mu}{2}\right)_i\left(\frac{m_s+2\mu+1}{2}\right)_i}{i!\left(\mu+\frac{1}{2}\right)_i}\left(\frac{H^2}{h^2}\right)^i\\&\times\left\{\frac{\ln\left(\frac{(m_s-1)\overline{\gamma}}{2\mu h}\right)+\mathbf{H}_{2\mu+2i+l}}{(2\mu+2i+l)}\right.\\&\left.+\frac{B_{t_2}(2\mu+2p+l+1,0)\,t_2^{-(2\mu+2i+l)}}{(2\mu+2i+l)}\right\}\end{aligned} \tag{6}$$

where $\mathbf{H}_n$ denotes the harmonic number and $t_2=1-(m_s-1)\overline{\gamma}(2\mu h)^{-1}$. Of note, (6) is valid for $\mu,\overline{\gamma}\in\mathbb{R}^+$, $m_s\in\mathbb{N}$, $m_s>1$, $\eta\in\mathbb{R}^+$ in *Format* 1 and $-1<\eta<1$ in *Format* 2. For the case of $\mu,\overline{\gamma},m_s\in\mathbb{R}^+$, $m_s>1$, $\eta\in\mathbb{R}^+$ in *Format* 1 and $-1<\eta<1$ in *Format* 2, and expanding the Gauss hypergeometric function in (5), it follows that

$$\begin{aligned}\frac{C_e}{B}=&\frac{1}{B(m_s,2\mu)\,h^\mu\ln(2)}\sum_{i=0}^{\infty}\frac{\left(\frac{m_s+2\mu}{2}\right)_i\left(\frac{m_s+2\mu+1}{2}\right)_i}{i!\,\left(\mu+\frac{1}{2}\right)_i}\left(\frac{H}{h}\right)^{2i}\\&\times\left\{\int_0^1\frac{t^{2\mu+2i-1}}{(1-t)^{1-m_s}}\ln\left(1-\left(1-\frac{(m_s-1)\,\overline{\gamma}}{2\mu h}\right)t\right)\mathrm{d}t\right.\\&\left.-\int_0^1\frac{t^{2\mu+2i-1}}{(1-t)^{1-m_s}}\ln(1-t)\,\mathrm{d}t\right\}.\end{aligned} \tag{7}$$

Using [28, Eq. (4.293.13)] and the series representations of the generalized hypergeometric function, it follows that

$$\begin{aligned}\frac{C_e}{B}=&\frac{1}{h^\mu\ln(2)}\sum_{i=0}^{\infty}\frac{(\mu)_i}{i!}\left(\frac{H}{h}\right)^{2i}\{\psi(m_s+2\mu+2i)-\psi(m_s)\\&-\frac{(\mu+i)[\,2\mu h-(m_s-1)\,\overline{\gamma}\,]}{\mu h(m_s+2\mu+2i)}\\&\times{}_3F_2\left(1,1,2\mu+2i+1;2,m_s+2\mu+2i+1;\frac{2\mu h-(m_s-1)\,\overline{\gamma}}{2\mu h}\right)\Bigg\}.\end{aligned} \tag{8}$$

B. Ergodic Capacity over κ-μ / Inverse Gamma Fading

By recalling that $C_e\triangleq B\int_0^\infty\log_2(1+\gamma)f_\gamma(\gamma)\mathrm{d}\gamma$ and substituting [12, eq. (4)], it follows that

$$\begin{aligned}\frac{C_e}{B}=&\frac{\mu^\mu(1+\kappa)^\mu(m_s-1)^{m_s}\overline{\gamma}^{m_s}}{B(m_s,\mu)\ln(2)\exp(\mu\kappa)}\\&\times\int_0^\infty\frac{\ln(1+\gamma)\,{}_1F_1\left(m_s+\mu;\mu;\frac{\mu^2\kappa(1+\kappa)\gamma}{\mu(1+\kappa)\gamma+(m_s-1)\overline{\gamma}}\right)}{\gamma^{1-\mu}[\,\mu(1+\kappa)\gamma+(m_s-1)\overline{\gamma}\,]^{m_s+\mu}}\mathrm{d}\gamma.\end{aligned} \tag{9}$$

Based on this, by setting $u=\mu(1+\kappa)\gamma+(m_s-1)\overline{\gamma}$ yields (10), which upon setting $t=1-(m_s-1)\overline{\gamma}/u$, one obtains (11). By applying [28, Eq. (1.111)] in (11) and expanding the involved hypergeometric functions leads to

$$\begin{aligned}\frac{C_e}{B}=&\sum_{l=0}^{m_s-1}\sum_{i=0}^{\infty}(-1)^l\binom{m_s-1}{l}\frac{(m_s+\mu)_i\mu^i\kappa^i\exp(-\mu\kappa)}{i!\,B(m_s,\mu)\ln(2)(\mu)_i}\\&\times\left\{\frac{\mathbf{H}_{\mu+l+i}+\ln((m_s-1)\overline{\gamma})-\ln(\mu(1+\kappa))}{\mu+l+i}\right.\\&+\frac{\mu(1+\kappa)-(m_s-1)\overline{\gamma}}{\mu(1+\kappa)(\mu+l+i)(\mu+l+i+1)}\\&\left.\times{}_2F_1\left(1,\mu+l+i+1;\mu+l+i+2;1-\frac{(m_s-1)\overline{\gamma}}{\mu(1+\kappa)}\right)\right\}\end{aligned} \tag{12}$$

$$\frac{C_e}{B} = \frac{(m_s-1)^{m_s}\overline{\gamma}^{m_s}}{B(m_s,2\mu)\,h^{\mu}\ln(2)}\int_{(m_s-1)\overline{\gamma}}^{\infty}\frac{[\,u-(m_s-1)\overline{\gamma}\,]^{2\mu-1}}{u^{m_s+2\mu}}\ln\left(1+\frac{u-(m_s-1)\overline{\gamma}}{2\mu h}\right) \times {}_2F_1\left(\frac{m_s+2\mu}{2},\frac{m_s+2\mu+1}{2};\mu+\frac{1}{2};\left(\frac{H\,[\,u-(m_s-1)\,\overline{\gamma}\,]}{uh}\right)^2\right)\mathrm{d}u. \tag{3}$$

$$\frac{C_e}{B} = \int_0^1 \frac{t^{2\mu-1}(1-t)^{m_s-1}}{B(m_s,2\mu)\,h^{\mu}\ln(2)}\,{}_2F_1\left(\frac{m_s+2\mu}{2},\frac{m_s+2\mu+1}{2};\mu+\frac{1}{2};\left(\frac{H\,t}{h}\right)^2\right)\left\{\ln\left(1-\left(1-\frac{(m_s-1)\,\overline{\gamma}}{2\mu h}\right)t\right)-\ln(1-t)\right\}\mathrm{d}t. \tag{4}$$

$$\frac{C_e}{B} = \frac{(m_s-1)^{m_s}\overline{\gamma}^{m_s}}{B(m_s,\mu)\ln(2)\exp(\mu\kappa)}\int_{(m_s-1)\overline{\gamma}}^{\infty}\frac{\ln\left(1+\frac{u-(m_s-1)\overline{\gamma}}{\mu(1+\kappa)}\right){}_1F_1\left(m_s+\mu;\mu;\mu\kappa-\frac{\mu\kappa(m_s-1)\overline{\gamma}}{u}\right)}{u^{m_s+\mu}\,[\,u-(m_s-1)\overline{\gamma}\,]^{\mu-1}}\mathrm{d}u \tag{10}$$

$$\frac{C_e}{B} = \frac{\exp(-\mu\kappa)}{B(m_s,\mu)\ln(2)}\int_0^1\frac{t^{\mu-1}}{(1-t)^{1-m_s}}\ln\left(1+\frac{[(m_s-1)\overline{\gamma}-\mu(1+\kappa)\,]t}{\mu(1+\kappa)}\right){}_1F_1(m_s+\mu;\mu;\mu\kappa t)\,\mathrm{d}t - \frac{\exp(-\mu\kappa)}{B(m_s,\mu)\ln(2)}\int_0^1\frac{t^{\mu-1}}{(1-t)^{1-m_s}}\ln(1-t)\,{}_1F_1\left(m_s+\mu;\mu;\mu\kappa t\right)\mathrm{d}t. \tag{11}$$

which is valid for $\kappa,\overline{\gamma},B\in\mathbb{R}^+$, $m_s\in\mathbb{N}$ and $m_s>1$. When, $\kappa,\mu,\overline{\gamma},m_s\in\mathbb{R}^+$ and $m_s>1$, we expand the involved Kummer hypergeometric functions in (11), yielding

$$\frac{C_e}{B} = \frac{\exp(-\mu\kappa)}{B(m_s,\mu)\ln(2)}\sum_{i=0}^{\infty}\frac{(m_s+\mu)_i(\mu\kappa)^i}{i!\,(\mu)_i} \times\int_0^1\frac{t^{\mu+i-1}}{(1-t)^{1-m_s}}\ln\left(1+\frac{[(m_s-1)\overline{\gamma}-\mu(1+\kappa)\,]t}{\mu(1+\kappa)}\right)\mathrm{d}t - \frac{\exp(-\mu\kappa)}{B(m_s,\mu)}\sum_{i=0}^{\infty}\frac{(m_s+\mu)_i(\mu\kappa)^i}{i!\,(\mu)_i\ln(2)}\int_0^1\frac{t^{\mu+i-1}\ln(1-t)}{(1-t)^{1-m_s}}\,\mathrm{d}t. \tag{13}$$

With the aid of [28, Eq. (4.293.13)] and the series representations of the generalized hypergeometric function yields

$$\frac{C_e}{B} = \sum_{i=0}^{\infty}\frac{\mu^i\kappa^i\exp(-\mu\kappa)}{i!\,\ln(2)}\left\{\psi(m_s+\mu+i)-\psi(m_s) - \frac{(\mu+i)[\,\mu(1+\kappa)-(m_s-1)\,\overline{\gamma}\,]}{\mu(1+\kappa)(m_s+\mu+i)}\times {}_3F_2\left(1,1,\mu+i+1;2,m_s+\mu+i+1;\frac{\mu(1+\kappa)-(m_s-1)\,\overline{\gamma}}{\mu(1+\kappa)}\right)\right\} \tag{14}$$

where $\psi(\cdot)$ and ${}_3F_2(\cdot,\cdot,\cdot;\cdot,\cdot;\cdot)$ are the digamma and generalized hypergeometric functions [28].

IV. Results and Closing Remarks

This section utilizes the derived expressions based on the well consolidated SNR PDFs in [12] to quantify the effects of composite multipath/shadowing conditions on the achievable ergodic capacity. Fig. 1 illustrates C_{e} over κ-μ / inverse gamma and η-μ / inverse gamma composite fading channels for different combinations of the fading parameters. For κ-μ / inverse gamma fading, these are: (a) heavy shadowing ($\kappa=5.0,\mu=3.0,m_s=1.1$); (b) severe multipath fading ($\kappa=0.1,\mu=0.1,m_s=30.0$); (c) intense composite fading ($\kappa=0.1,\mu=0.1,m_s=1.1$); (d) moderate composite fading ($\kappa=2.5,\mu=1.5,m_s=3.0$); and (e) light composite fading ($\kappa=5.0,\mu=3.0,m_s=30.0$). Likewise, for η-μ / inverse gamma fading these are: (a) heavy shadowing ($\eta=1.0,\mu=3.0,m_s=1.1$); (b) severe multipath fading ($\eta=0.1,\mu=0.1,m_s=30.0$); (c) intense composite fading ($\eta=0.1,\mu=0.1,m_s=1.1$); (d) moderate composite fading ($\eta=0.5,\mu=1.5,m_s=3.0$); and (e) light composite fading ($\eta=1.0,\mu=3.0,m_s=30.0$).

Evidently, the lowest spectral efficiency occurs in the intense composite fading conditions whilst the highest spectral efficiency appears in the light composite fading scenarios. Profoundly, when the channel conditions change from light fading to intense fading at $\overline{\gamma}=30$ dB, a 70% spectral efficiency decrease is observed for the κ-μ / inverse gamma fading channels, and a 60% reduction for the η-μ / inverse gamma fading channels. This verifies that different types of composite fading are crucial across all SNR regimes.

References

[1] P. C. Sofotasios, and S. Freear, “On the $\eta-\mu$/gamma and the $\lambda-\mu$/gamma multipath/shadowing distributions,” *IEEE ATNAC ‘11*, Melbourne, Australia, Nov. 2011, pp. 1−6.

[2] P. C. Sofotasios, S. Freear, “The $\kappa-\mu$ extreme/gamma distribution: A physical composite fading model,” *IEEE WCNC ’11,* Cancun, Mexico, Mar. 2011, pp. 1398-1401.

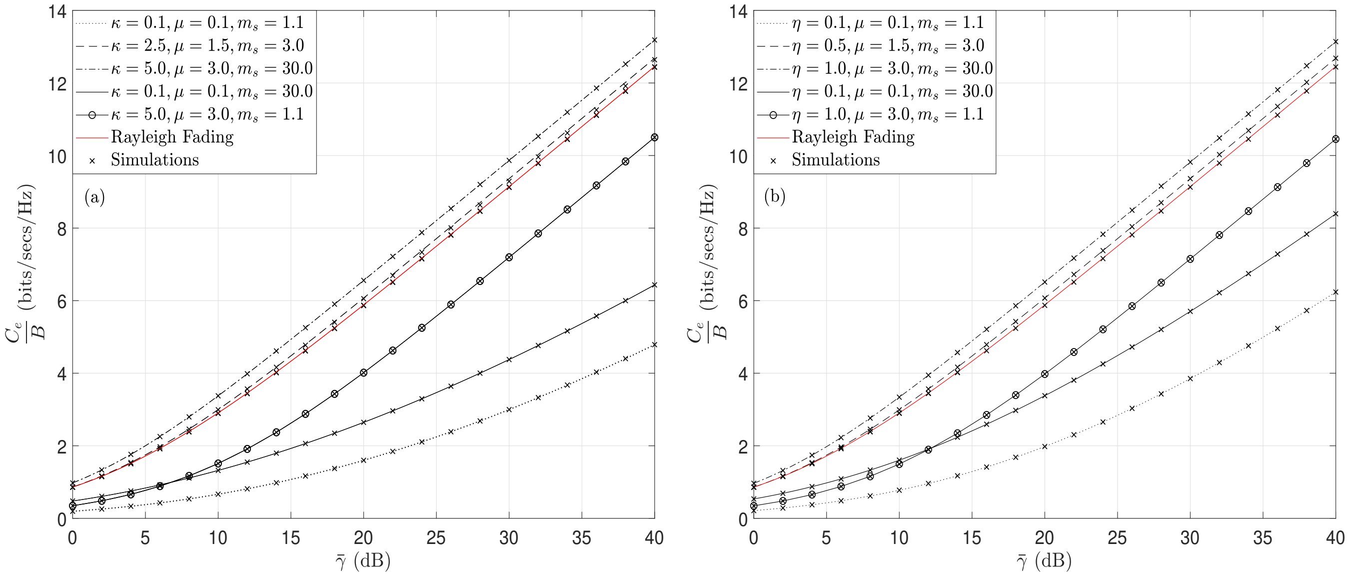

Fig. 1: $C_{\rm e}/B$ vs $\overline{\gamma}$ under κ-μ / inverse gamma & η-μ / inverse gamma fading channels for different κ, η, μ and m_s values.

[3] P. C. Sofotasios, S. Freear,"On the $\kappa-\mu$/gamma composite distribution: A generalized multipath/shadowing fading model," *SBMO/IEEE MTT-S '11*, Natal, Brazil, Oct. 2011, pp. 1−6.

[4] S. Ki Yoo, S. L. Cotton, P. C. Sofotasios, and S. Freear, "Shadowed fading in indoor off-body communications channels: A statistical characterization using the $\kappa-\mu$/gamma composite fading model," *IEEE Trans. Wireless Commun.*, vol. 15, no. 8, pp. 5231−5244, Aug. 2016.

[5] S. L. Cotton, "Human body shadowing in cellular device-to-device communications: Channel modeling using the shadowed κ-μ fading model," *IEEE J. Sel. Areas Commun.*, vol. 33, no. 1, pp. 111−119, Jan. 2015.

[6] P. C. Sofotasios, T. A. Tsiftsis, M. Ghogho, L. R. Wilhelmsson, and M. Valkama, "The $\eta-\mu$/inverse-Gaussian distribution: A novel physical multipath/shadowing fading model," *IEEE ICC '13*, Budapest, Hungary, Jun. 2013, pp. 5715−5719.

[7] P. C. Sofotasios, T. A. Tsiftsis, K. Ho-Van, S. Freear, L. R. Wilhelmsson, and M. Valkama, "The $\kappa-\mu$/inverse-Gaussian composite statistical distribution in RF and FSO wireless channels," *IEEE VTC '13 - Fall*, Las Vegas, NV, USA, Sep. 2013, pp. 1−5.

[8] J. F. Paris, "Statistical characterization of κ-μ shadowed fading," *IEEE Trans. Veh. Technol.*, vol. 63, no. 2, pp. 518−526, Feb. 2014.

[9] S. K. Yoo, P. C. Sofotasios, S. L. Cotton, M. Matthaiou, M. Valkama, and G. K. Karagiannidis, "The Fisher−Snedecor F distribution: A simple and accurate composite fading model," *IEEE Commun. Lett.*, vol. 21, no. 7, pp. 1661−1664, Jul. 2017.

[10] S. Ki Yoo, S. L. Cotton, P. C. Sofotasios, M. Matthaiou, M. Valkama, G. K. Karagiannidis, "The κ-μ / inverse gamma fading model," *IEEE PIMRC '15*, Hong Kong, Aug/Sep. 2015, pp. 949−953.

[11] S. Ki Yoo, P. C. Sofotasios, S. L. Cotton, M. Matthaiou, M. Valkama, and G. K. Karagiannidis, "The η-μ/ inverse gamma composite fading model," *IEEE PIMRC '15*, Hong Kong, Aug/Sep. 2015, pp. 978−982.

[12] S. K. Yoo, N. Bhargav, S. L. Cotton, P. C. Sofotasios, M. Matthaiou, M. Valkama, and G. K. Karagiannidis, "The κ-μ / inverse gamma and η-μ / inverse gamma composite fading models: Fundamental statistics and empirical validation," *IEEE Trans. Commun.*, vol. 69, no. 8, pp. 5515-5530, Aug. 2021.

[13] M. D. Yacoub, "The $\alpha-\mu$ distribution: A physical fading model for the Stacy distribution," *IEEE Trans. Veh. Technol.*, vol. 56, no. 1, pp. 27−34, Jan. 2007.

[14] M. D. Yacoub, "The $\kappa-\mu$ distribution and the $\eta-\mu$ distribution," *IEEE Antennas Propag. Mag.*, vol. 49, no. 1, pp. 68−81, Feb. 2007.

[15] F. J. Lopez-Martinez, E. Martos-Naya, D. Morales-Jimenez, and J. F. Paris, "On the bivariate Nakagami$-m$ cumulative distribution function: closed-form expressions and applications," *IEEE Trans. Commun.*, vol. 61, no. 4, pp. 1404−1414, Apr. 2013.

[16] M. A. G. Villavicencio, R. A. A. de Souza, G. C. de Souza, and M. D. Yacoub, "A bivariate $\kappa-\mu$ distribution," *IEEE Trans. Veh. Technol.*, vol. 65, no. 7, pp. 5737−5743, July 2016.

[17] P. S. Bithas, "Weibull-gamma composite distribution: Alternative multipath/shadowing fading model," *IET Electron. Lett.*, vol. 45, no. 14, July 2009.

[18] A. Laourine, M.-S. Alouini, S. Affes, and A. Stephenne, "On the performance analysis of composite multipath/shadowing channels using the $G-$distribution," *IEEE Trans. Commun.*, vol. 57, no. 4, pp. 1162−1170, Apr. 2009.

[19] L. Moreno-Pozas, F. J. Lopez-Martinez, J. F. Paris, and E. Martos-Naya, "The κ-μ shadowed fading model: Unifying the κ-μ and η-μ distributions, *IEEE Trans. Veh. Technol.*, vol. 65, no. 12, pp. 9630−9641, Dec. 2016.

[20] P. S. Bithas, G. P. Efthymoglou, and N. C. Sagias, "Spectral efficiency of adaptive transmission and selection diversity on generalized fading channels," *IET Commun.*, vol. 4, no. 17, pp. 2058−2064, 2010.

[21] P. S. Bithas, N. C. Sagias, P. T. Mathiopoulos, and G. K. Karagiannidis, "On the performance analysis of digital communications over generalized fading channels," *IEEE Commun. Lett.*, vol. 10, no. 5, pp. 353−355, May 2006.

[22] C. Zhong, M. Matthaiou, G. K. Karagiannidis, and T. Ratnarajah, "Generic ergodic capacity bounds for fixed-gain AF dual-hop relaying systems," *IEEE Trans. Wireless Commun.*, vol. 60, no. 8, pp. 3814−3824, Oct. 2011.

[23] J. Zhang, M. Matthaiou, Z. Tan, and H. Wang, "Performance analysis of digital communication systems over composite η-μ / gamma fading channels," *IEEE Trans. Veh. Technol.*, vol. 61, no. 7, pp. 3114−3124, Sep. 2012.

[24] C. García-Corrales, F. J. Canete, and J. F. Paris, "Capacity of κ-μ shadowed fading channels," *HINDAWI Int. J. Antennas and Propag.*, pp. 1−8, July 2014.

[25] P. C. Sofotasios, S. Ki Yoo, N. Bhargav, S. Muhaidat, S. L. Cotton, M. Matthaiou, M. Valkama, and G. K. Karagiannidis, "Capacity analysis under generalized composite fading conditions," *IEEE CommNet '18*, Marrakech, Morocco, Apr. 2018, pp. 1-10.

[26] P. C. Sofotasios, S. Ki Yoo, S. Muhaidat, S. L. Cotton, M. Matthaiou, M. Valkama, and G. K. Karagiannidis, "Ergodic capacity analysis of wireless transmission over generalized multipath/shadowing channels," *IEEE VTC Spring '18*, Porto, Portugal, June 2018, pp. 1-5.

[27] J. F. Paris, "Outage probability in η-μ / η-μ and κ-μ / η-μ interference-limited scenarios," *IEEE Trans. Commun.*, vol. 61, no. 1, pp. 335−343, Jan. 2013.

[28] I. S. Gradshteyn, and I. M. Ryzhik, *Tables of Integrals, Series, and Products*, in 7^{th} ed. Academic, New York, 2007.