International Journal of Engineering Inventions
e-ISSN: 2278-7461, p-ISSN: 2319-6491
Volume 12, Issue 2 [February. 2023] PP: 15-19

Evaluation of the performance of a wireless communication system in a general fading environment that is affected by both shadowing and interference

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ABSTRACT: *This paper will examine the performance of wireless communication over α-κ-μ fading channels. Specifically, the impact of co-channel interference (CCI) on communication will be analyzed. Mathematical expressions will be developed for the probability and cumulative distribution of the received signal-to-interference ratio (SIR). The probability of outage (OP) will be calculated for different system parameters and for the case where selection diversity (SC) is present at the receiver. Additionally, the effects of simultaneous multipath fading and shadowing will be studied by introducing a new composite α-κ-μ/Gamma fading distribution. Statistical parameters for this new distribution will be calculated and used to evaluate standard performance measures. These results will be presented and discussed in relation to system parameters.*

Keywords*:* $\alpha - k - \mu$ *distribution, CCI, SIR, SC, novel fading/shadowing composite model.*

Date of Submission: 24-01-2023 Date of acceptance: 07-02-2023

I. INTRODUCTION

When designing a wireless communication system, it is crucial to consider three key factors that can negatively impact the transmission: short-term fading caused by multipath propagation, long-term fading caused by shadowing, and the detrimental impact of interference from other channels [1].

Recently, there has been a growing interest in understanding the nonlinear properties of the medium through which signals propagate. Traditional short-time fading distributions such as Nakagami-m, Ricean and Rayleigh assume a homogenous diffuse scattering field from randomly distributed scatterers. However, surfaces in real-world environments are often spatially correlated, which leads to nonlinear effects. A novel α-κ-μ short-time fading model was recently proposed that takes into account the fact that the envelope of the signal is a nonlinear function of the sum of multipath components. This model is defined by a three-parameter probability density function (PDF) α,κ and μ that describes the nonlinearity of the environment, the number of multipath clusters, and the scattered wave power ratio between the in-phase and quadrature components of each cluster of multipath[2].

The $\alpha - k - \mu$ Distribution is a general fading distribution that includes the Rayleigh, Rice, Nakagami-m, $k - \mu$, Weibull, and One-Sided Gaussian distributions as special cases. The $k - \mu$ distribution can be obtained from the $\alpha - \eta - \mu$ Distribution in an exact manner by setting $\alpha = 2$. The Nakagami-m distribution can be obtained from the $k - \mu$ distribution by setting $k = 0$. The Rice distribution can obtained from the $k - \mu$ distribution by setting $\mu = 1$ and using the relation $\kappa = k$, where k is the Rice parameter. In the same way, from the Rice distribution the Rayleigh distribution is obtained in an exact manner for $k = 0$. Finally, the Weibull distribution can be obtained from the $\alpha - k - \mu$ distribution by setting $k = 0$ and $\mu = 1$. Table I shows how these distributions can be obtained from the $\alpha - k - \mu$ distribution.

Further, an analytical framework for performance analysis of wireless communication systems subjected to co-channel interference (CCI) over $\alpha - k - \mu$ fading channels will be presented in this paper. Signal-to-interference (SIR) based analysis will be provided, and closed-form expressions will be provided for received SIR PDF and CDF (cumulative distribution function). From these statistics, outage probability (OP) values will be obtained in the function of system parameters. Even OP improvement will be observed through a prism of space diversity reception techniques appliance, particularly selection combining (SC) reception appliance.

A number of composite channel models have been used in literature for wireless communication systems analysis, for the case when multipath fading and shadowing occur simultaneously. Such are the $k - \mu/gamma$ [3], the $k - \mu/gamma$ [4], the K [5], and the generalized-$K(KG)$ [6] distribution models. Starting from general the $\alpha - k - \mu$ distribution, closed-form PDF, CDF, and n-th order moments expressions, which have not been reported in the literature so far, will be introduced, for the newly presented composite distribution. That is another contribution of this work. An obtained mathematical form will allow simple performance analysis of wireless communication systems, operating in composite fading environments. This performance analysis is also accompanied by graphically presented numerical results, which show the influence of various communication system parameters (fading and shadowing parameters), on the standard performance criteria.

Table I – The $\alpha - k - \mu$ distribution and the odher fading distributions.

	Rayleigh	Rice			One-Sided Gaussian	Weibull	Nakagami-*m*
	2	2		2	2		2
	0		0		0	0	0
	1	1			1/2	1	*m*

II. TRANSMISSION SUBJECTED TO CO-CHANNEL INTERFERENCE

In modern wireless communication systems, there is a desire to make efficient use of the available spectrum. This can be achieved by reusing frequency channels in areas that are geographically close to each other. However, this is limited by the level of co-channel interference (CCI), which is defined as interfering signals that have the same carrier frequency as the desired information signal. When frequency channels are reused in different locations, it can lead to interference between the signals operating at the same carrier frequency. In this section, we will examine how CCI affects well-established performance criteria of wireless systems in terms of instantaneous and average signal-to-interference ratios (SIR). SIR-based performance analysis is particularly useful because SIR can be measured in real-time at both base and mobile stations. We will also focus on an interference-limited system, assuming that the effect of noise is negligible.

Desired information signal with a $\alpha - k - \mu$ distributed random amplitude process can be presented by [2]:

$$p_R(R) = \frac{\alpha k_d^{\frac{1-\mu_d}{2}}(1+k_d)^{\frac{1+\mu_d}{2}}\mu_d R^{\frac{\alpha(1+\mu_d)}{2}-1}}{\exp(\mu_d k_d)\Omega_d^{\frac{1+\mu_d}{2}}} \times \exp\left(-\frac{\mu_d(1+k_d)R^\alpha}{\Omega_d}\right) I_{\mu_d-1}\left(2\mu_d\sqrt{k_d(1+k_d)\frac{R^\alpha}{\Omega_d}}\right) \tag{1}$$

with$\Omega_d = E[R^2]$, denoting the desired signal average power, while $I_n(x)$ is the n-th order modified Bessel function of the first kind Gamma function [7, eq. (8.406)].

In a similar manner, resultant interfering signal can be presented as:

$$p_r(r) = \frac{\alpha k_c^{\frac{1-\mu_c}{2}}(1+k_c)^{\frac{1+\mu_c}{2}}\mu_c r^{\frac{\alpha(1+\mu_c)}{2}-1}}{\exp(\mu_c k_c)\Omega_c^{\frac{1+\mu_c}{2}}} \times \exp\left(-\frac{\mu_c(1+k_c)r^\alpha}{\Omega_c}\right) I_{\mu_c-1}\left(2\mu_c\sqrt{k_c(1+k_c)\frac{r^\alpha}{\Omega_c}}\right) \tag{2}$$

with$\Omega_c = E[r^2]$, denoting the CCI signal average power, and parametersα, $k$and μ_c explained in [2].

If the instantaneous SIR, λ, is defined as$\lambda = R^2/r^2$, while average SIR, S, defined as$S = \Omega_d/\Omega_c$, then by using the relation [8,9]:

$$p_\lambda(\lambda) = \frac{1}{2\sqrt{\lambda}}\int_0^\infty p_R\left(r\sqrt{\lambda}\right)p_r(r)dr \tag{3}$$

After performing similar mathematical transformations as ones already given in the literature, the PDF of instantaneous SIR can be presented in the form:

$$p_\lambda(\lambda) = \sum_{p=0}^{\infty}\sum_{j=0}^{\infty}\frac{\alpha\mu_d^{2p+\mu_d}\mu_c^{2j+\mu_c}k_d^p k_c^j(1+k_d)^{p+\mu_d}(1+k_c)^{j+\mu_c}}{\exp(\mu_d k_d+\mu_c k_c)\Gamma(p+\mu_d)\Gamma(j+\mu_c)p!j!} \times \frac{\Gamma(p+j+\mu_d+\mu_c)S^{j+\mu_c}\lambda^{\frac{\alpha(p+\mu_d)-1}{2}}}{\left(\lambda^{\frac{\alpha}{2}}\mu_d(1+k_d)+S\mu_c(1+k_c)\right)} \tag{4}$$

with $\Gamma(a)$ denoting the well-known Gamma function [7, eq. (8.310/1)]. The double infinity sum in (4) converges rapidly, since only about 20-30 terms should be summed in order to achieve accuracy at 5th significant digit for various values of corresponding system parameters.

III. TRANSMISSION SUBJECTED TO SHADOWING

In this section, we will present a novel composite fading distribution for the first time in literature, which combines the influence of multipath α-κ-μ fading modeled by a general distribution and shadowing modeled by a Gamma distribution. As both multipath fading and shadowing occur simultaneously in wireless transmission, it is necessary to develop a general model that can accurately describe this composite random process. In the case of composite fading, the average power of the multipath component, $\Omega = E[R^2]$ is also a randomly varying process, which will be modeled using the Gamma long-term fading model. The novel composite fading distribution can be obtained by averaging the short-time conditional random variable process,

$$f_{R|\Omega}(R|\Omega) = \frac{\alpha k^{\frac{1-\mu}{2}}(1+k)^{\frac{1+\mu}{2}}\mu R^{\frac{\alpha(1+\mu)}{2}-1}}{\exp(\mu k)\Omega^{\frac{1+\mu}{2}}} \times \exp\left(-\frac{\mu(1+k)R^{\alpha}}{\Omega}\right) I_{\mu-1}\left(2\mu\sqrt{k(1+k)\frac{R^{\alpha}}{\Omega}}\right) \quad (5)$$

over slowly varying Gamma process, which has been shown to accurately approximate shadowing phenomena, described with [10,11]:

$$f_{\Omega}(\Omega) = \frac{\Omega^{c-1}}{\Gamma(c)\Omega_0^c}\exp\left(-\frac{\Omega}{\Omega_0}\right) \quad (6)$$

with c denoting the shaping parameter and $\Omega_0 = E[\Omega]$. By using the total probability theorem, after some mathematical manipulations the PDF of the novel composite distribution can be expressed in closed form as:

$$f_R(R) = \int_0^{\infty} f_{R|\Omega}(R|\Omega) f_{\Omega}(\Omega) d\Omega$$

$$= \sum_{p=0}^{\infty} \frac{2\alpha\mu^{(3p+\mu+c)/2}k^p(1+k)^{(p+\mu+c)/2}R^{\frac{\alpha(p+\mu+c)-2}{2}}}{\exp(\mu k)\Gamma(p+\mu)p!\Gamma(c)\Omega_0^{(p+\mu+c)/2}} \times K_{(c-p-\mu)}\left(2\sqrt{\frac{\mu(1+k)R^{\alpha}}{\Omega_0}}\right) \quad (7)$$

with $K_{\upsilon}()$ denoting the modified Bessel function of second kind and order υ [7, eq. (8.407/1)]. The convergence of expression (7) is rapid since few terms should be summed for achieving 5th significant digit accuracy for various values of corresponding PDF parameters. A newly derived composite PDF is presented at Fig.1 for various values of corresponding parameters. Let us now derive other first-order statistical parameters for this composite fading distribution, namely CDF and n-th order moments. Capitalizing on (4), and by using the same mathematical transformations as in [12, eq. (03.04.26.0006.01)] and [13, eq. (26)], a closed-form expression for CDF of the composite process can be presented in the form of:

$$F_R(R) = \sum_{p=0}^{\infty} \frac{\mu^{(3p+\mu+c)/2}k^p(1+k)^{(p+\mu+c)/2}R^{(p+\mu+c)/2}}{\exp(\mu k)\Gamma(p+\mu)p!\Gamma(c)\Omega_0^{(p+\mu+c)/2}}$$

$$\times G_{1,3}^{2,1}\left[\begin{matrix} 1-(p+\mu+c)/2 \\ (c-p-\mu)/2, (p+\mu-c)/2, -(p+\mu+c)/2 \end{matrix} \middle| \frac{\mu(1+k)R}{\Omega}\right] \quad (8)$$

where $G_{m,n}^{p,q}\left[\begin{matrix}(a)_p \\ (b)_q\end{matrix}\middle| x\right]$ stands for the Meijer's G-function [7, eq. (9.301)].

IV. NUMERICAL RESULTS

From Fig.1,we can seethat the change inthe PDFandmuch more pronouncedat highervaluesof the parameterα,forconstant values μ and$k$, respectively, thePDFhas a highermaximum. When $c$parameter increases, the maximum PDFis reduced.

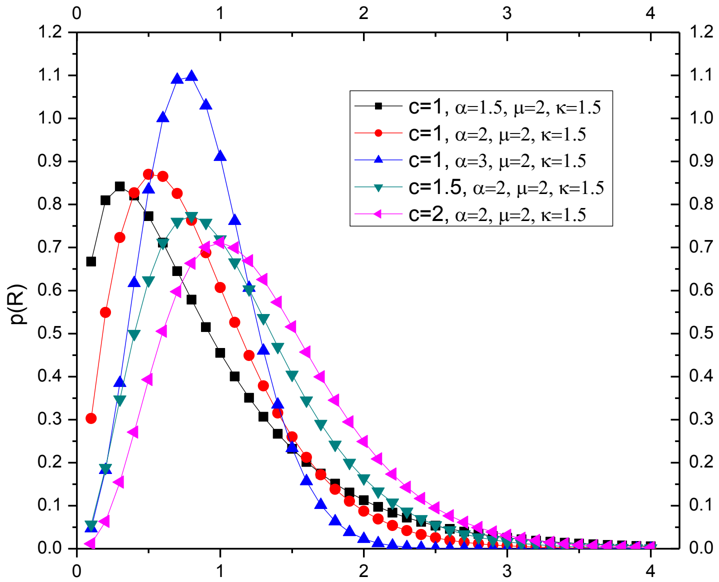

Fig 1. PDF of novel composite distribution for various values of corresponding parameters

In this section, we will discuss some standard wireless transmission performance measures for observed scenarios. Considering interference limited system, outage probability (OP) has been efficiently evaluated for various values of transmission parameters and graphically presented at Fig.2.

As one can see, in Fig.2, the influence of selection combining (SC) technique at the receiver, on the performance improvement, was also observed. Various techniques for reducing fading effect and influence of co-channel interference are used. Multi-branch diversity reception is an efficient remedy, based on providing the receiver with multiple faded replicas of the same desired signal [14-16]. In that way, transmission reliability is upgraded without transmission power and bandwidth increase. Simplest diversity reception, that process only one of the diversity branches is SC reception.

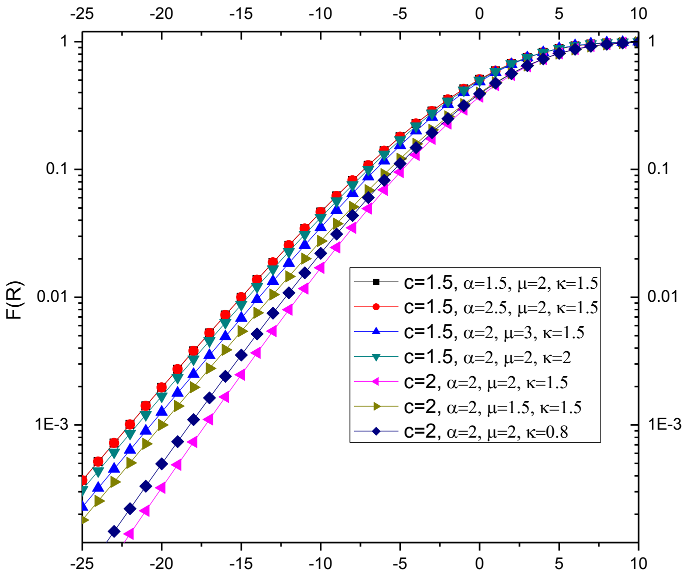

Fig. 2. CDF of the composite process for various values of corresponding parameters.

A general conclusion from Fig.2 is that lower OP values are achieved, in the areas where k, α and μ parameters obtain higher values. Similarly when shadowing c parameter increases lower OP values are obtained at Fig.2. This is because shadowing is less severe when c parameter has higher values. Performance improvement obtained with the usage of dual-branch SC diversity is visible, since for the same system parameter values, significantly lower OP values are reached.

V. CONCLUSION

This paper examines wireless communication in a general fading environment, which can be applied to other types of fading environments such as Rayleigh, κ-μ Nakagami-q (Hoyt), Nakagami-m, and Weibull. Closed-form expressions for the probability density function and cumulative distribution function of the signal-to-interference ratio are derived for the case of an interference-limited system. Additionally, closed-form expressions for the first-order statistics (probability density function, cumulative distribution function, and moments of various orders) of the newly introduced composite fading/shadowing model are presented, allowing for simple, unrestricted analysis, accurate wireless system planning, and performance evaluation. Some performance measures are also evaluated and discussed in the paper.

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