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Bhargav, N., da Silva, C. R. N., Chun, Y. J., Cotton, S. L., & Yacoub, M. (2017). Co-Channel Interference and Background Noise in kappa-mu Fading Channels. IEEE Communications Letters, 21(5), 1215-1218. DOI: 10.1109/LCOMM.2017.2664806

Published in:
IEEE Communications Letters

Document Version:
Publisher's PDF, also known as Version of record

Queen's University Belfast - Research Portal:
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Download date:23. Jul. 2018
Co-Channel Interference and Background Noise in $\kappa$-$\mu$ Fading Channels

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Abstract— In this letter, we derive novel analytical and closed form expressions for the outage probability, when the signal-of-interest (SoI) and the interferer experience $\kappa$-$\mu$ fading in the presence of Gaussian noise. Most importantly, these expressions hold true for independent and non-identically distributed $\kappa$-$\mu$ variates, without parameter constraints. We also find the asymptotic behaviour when the average signal to noise ratio of the SoI is significantly larger than that of the interferer. It is worth highlighting that our new solutions are very general owing to the flexibility of the $\kappa$-$\mu$ fading model.

Index Terms—Background noise, co-channel interference, generalized fading distribution, $\kappa$-$\mu$ fading, outage probability.

I. INTRODUCTION

UNDERSTANDING the performance of systems in the presence of co-channel interference (CCI) is critical for successful system design in many applications such as cellular networks, device-to-device (D2D) and body area networks (BANs). Several authors have dealt with the effects of CCI for different limiting factors [1], [2]. These include different types of fading for the signal-of-interest (SoI) and the interfering links [1], the presence or absence of background noise (BN), and number of independent or correlated interferers [2]. While all of these factors influence the impact of CCI, among the most prevalent are the fading characteristics of the SoI and the CCI links. As these are not always similar, it is important that a flexible model is used to represent the fading observed in both. Among the many fading models proposed, one of the most flexible and important is the $\kappa$-$\mu$ fading model [3]. It was developed to account for line-of-sight (LOS) channels which may promote the clustering of scattered multipath waves. Most importantly, it includes many of the popular fading models such as the Rice ($k=K$, $\mu=1$), Nakagami-$m$ ($k \rightarrow 0$, $\mu=m$), Rayleigh ($k \rightarrow 0$, $\mu=1$) and One-Sided Gaussian ($k \rightarrow 0$, $\mu=0.5$) as special cases.

The outage probability (OP) is an important performance metric that can be used to characterize the signal to interference ratio in systems with CCI. For generalized fading models, [2], [4], and [5] provide OP analyses when the SoI and the interfering links undergo $\eta$-$\mu/\eta$-$\mu$, $\eta$-$\mu/\kappa$-$\mu$ and $\kappa$-$\mu/\eta$-$\mu$ fading. These analyses either provide approximate expressions, or consider that $\mu$ takes positive integer values for the SoI or the interfering link. Furthermore, Bhargav et al. [6] provide an OP analysis over $\kappa$-$\mu/k$-$\mu$ fading channels which can be adapted to study interference-limited scenarios.

A plethora of research has been carried out to characterize the performance in the presence of CCI and BN. To the best of the authors’ knowledge, none of the prior works have considered the OP performance metric in the presence of BN, when both the SoI and CCI experience $\kappa$-$\mu$ fading with arbitrary parameters. Motivated by this, we derive novel expressions for the OP in the presence of CCI and BN for independent and non-identically distributed (i.i.d) $\kappa$-$\mu$ variates. Due to the flexibility of the $\kappa$-$\mu$ fading model, these novel formulations unify the OP expressions in the presence of BN, when the SoI and the CCI are subject to Rayleigh, Rice, Nakagami-$m$ and One-Sided Gaussian fading models.

II. THE SYSTEM MODEL

Consider the system model of a typical wireless communication scenario in the presence of multiple interferers as shown in Fig. 1. Let $P_S$, $P_I$, and $N_0$, represent the transmit power at the source of the SoI (Node $S$), the transmit power of the $j$th interfering node and the noise power at the intended receiver (Node $D$). Then, the instantaneous signal to noise ratio (SNR) at node $D$ is given by $\gamma_j = P_S|h_S|^2/N_0$, while the instantaneous interference-to-noise-ratio (INR) is given by $\gamma_{ij} = P_I|h_{ij}|^2/N_0$. Here, $h_S$ and $h_{ij}$ represent the complex fading channel gain for the SoI and the $j$th interfering channel, respectively. The OP of the signal-to-interference-plus-noise-ratio (SINR) in the presence of CCI and BN is defined as

$$P_{OP}(\gamma_{ih}) = \mathbb{P}(\gamma_S \leq (\gamma_{1h} + 1) \gamma_{ih}).$$

(1)

Let us assume that the SoI and the interferer are both subject to $\kappa$-$\mu$ fading. The probability density function (pdf) and the cumulative distribution function (cdf) of the instantaneous SNR, $\gamma$, for a $\kappa$-$\mu$ fading channel can be obtained from [3, eq. (10)] and [3, eq. (3)], where $\kappa > 0$ is the ratio of the total power of the dominant components to that of the scattered waves in each of the clusters, $\mu > 0$ is the number of multipath clusters, $\tilde{v} = \mathbb{E}(\gamma)$, is the average SNR where $\mathbb{E}(\cdot)$ denotes the expectation, $I_v(\cdot)$ is the modified Bessel function of the first kind with order $v$ [7, eq. (9.6.10)] and $Q(\cdot, \cdot)$ is the generalized Marcum $Q$-function. We consider the channel components of the SoI and the interfering links with parameters $\{k_S, \mu_S, \tilde{\gamma}_S\}$ and $\{k_I, \mu_I, \tilde{\gamma}_I\}$, respectively.

III. OUTAGE PROBABILITY ANALYSIS

Let us denote the set of interfering nodes as $\Phi$ and assume $M = |\Phi|$ nodes are randomly deployed in the network, where $|\Phi|$ represents the cardinality of set $\Phi$. Based on (1), the OP for multiple interferers is given as follows

$$\mathbb{E}_{G} \left[ \mathbb{P}(\gamma_S \leq (\gamma_{1h} + G + 1) \sum_{j \in \Phi} \gamma_{1j} = G) \right].$$

(2)
For the multiple interfering scenario depicted in Fig. 1, we consider that the interferers contribute CCI components which undergo independent and identically distributed (i.i.d) fading whereas the CCI components and the SoI are i.n.i.d RVs. Capitalizing on the fact that the sum of i.i.d $\kappa$-$\mu$ power RVs is another $\kappa$-$\mu$ power RV with appropriately chosen parameters, i.e., $G$ is a $\kappa$-$\mu$ power RV with parameters $\{\kappa_I, \mu_{I,1}, M_I\}$, an analytical expression for the OP can be obtained as

$$P_{OP}(\gamma) = \sum_{n=0}^{\infty} \sum_{i=0}^{\mu_{S}+n} C_S \left( \frac{\kappa_S \gamma}{\bar{\gamma}} \right)^{\mu_{S}+n} \mathbb{E} \left[ G^i \right]$$

(3)

where $C_S = (-1)^n L_{n}^{(\mu_{S}+1)}(\kappa_S \mu_{S}) e^{-\kappa_S \mu_{S}}$, $L_{n}^{(\mu_{S}+1)}(\kappa_S \mu_{S})$ is the generalized Laguerre polynomial [7, eq. (22.5.54)] of degree $p$ and order $\lambda$, and $\bar{\gamma}$ with $t$ being the appropriate index, $g_{in} = (i+1) \Gamma(\mu_S+n-i+1)$, $\Gamma(\cdot)$ is the Gamma function, $M$ denotes the number of interferers and $\mathbb{E}[G^i]$ is the $i$th moment of $G$. The proof of (3) is given in Appendix A.

Substituting for $\mathbb{E}[G^i]$ from (8) and performing the mathematical manipulations in Appendix A, we obtain (4), shown at the bottom of this page. Here, $C_{I,\mu} = (-1)^{i+n} L_{i+n}^{(\mu_{S}+1)}(\kappa_S \mu_{S}) e^{-\kappa_S \mu_{S}}$, $C_{I} = (\gamma)^{p} L_{-i}^{(\mu-1)}(\kappa_I \mu_I) e^{-\kappa_I \mu_I}$, $p_1 = n + \mu_S$, $p_2 = i + \mu_S$ and $U(\cdot, \cdot, \cdot)$ is the confluent Tricomi hypergeometric function [7, eq. (13.1.3)].

A closed form expression for the OP can be obtained by

$$P_{OP}(\gamma) = \frac{e^{-\kappa_S \mu_{S}}}{e^{\kappa_I \mu_I}} \mathcal{H}[\alpha_{M}, A; (\beta_{M}, B; \lambda)]$$

(5)

where $\mathcal{H}[\cdot; \cdot; \cdot]$ denotes the Fox H-function on several variables [9, eq. (1.1)], $\mathcal{L}$ is an infinite contour in the complex space, $\alpha_{M} = [\gamma_0^{\gamma_0} \gamma_0 \gamma_{\bar{\gamma}} \gamma_0 \gamma_{\bar{\gamma}} - M_{I,1} \mu_{I}]$, $\beta_{M} = [0, 0, 0, 0, 0, M_{I,1}, 0]$ and $\beta_{M} = [0, 0, 0, 0, 0, 0, 0]$; and $\mathcal{H}$ is the Fox H-function in (5) may be implemented as the sum of residues simplified as (4). See Appendix B for proof.

Furthermore, considering the special case when the interferers are subject to Nakagami-$m$ fading i.e., letting $\kappa_I \rightarrow 0$ and $\mu_I = m_{I}$ in the first expression of (4) we obtain

$$P_{OP}(\gamma) = \sum_{n=0}^{\infty} C_S \left( \frac{\kappa_S \gamma_0}{\gamma_{\bar{\gamma}}} \right)^{p_1} \times U \left( n - \mu_S, 1 - p_1 - M_{I,1}, \frac{\mu_I}{\gamma_{\bar{\gamma}}} \right)$$

(6)

where $m_{I}$ represents the well-known Nakagami parameter $m$ for the interfering channel; $C_S$, $\kappa_S$ and $p_1$ are as defined before. We now find the asymptotic behavior for the general case, (4), when the average SNR of the SoI is significantly larger than that of the interferer via Lemma 1.

**Lemma 1:** For $\frac{\gamma_0}{\gamma_{\bar{\gamma}}} \gg 1$, the OP of the SINR converges to the following asymptotic expression

$$\lim_{\gamma \rightarrow \infty} P_{OP}(\gamma) = \frac{e^{-\kappa_S \mu_S}}{\Gamma(1 + \mu_S)} \left( \frac{\gamma_{\bar{\gamma}} \kappa_S}{\kappa_I} \right)^{\mu_S} \times \left( \frac{m_{I}}{\gamma_{\bar{\gamma}}} \right)$$

(7)

which can be further simplified given that the interferers are subject to Nakagami-$m$ fading as follows

$$\lim_{\gamma \rightarrow \infty} P_{OP}(\gamma) = \frac{e^{-\kappa_S \mu_S}}{\Gamma(1 + \mu_S)} \left( \frac{\gamma_{\bar{\gamma}} \kappa_S}{\kappa_I} \right)^{\mu_S} \times \left( \frac{m_{I}}{\gamma_{\bar{\gamma}}} \right)$$

(8)

Proof: See Appendix C.

**IV. Numerical Results**

For the figures presented here, $\gamma = 0$ dB. Fig. 2 depicts the OP versus $\bar{\gamma}$ for a different number of interfering signals and for two sets of $\mu(\kappa, \kappa_I)$ and $\mu(\mu, \mu_I)$. We observe that as $\bar{\gamma}$ increases the OP decreases for each $M$. However, the rate at which the OP decreases is lower when $\kappa_0$ is small. In all cases, the analytical results agree with the simulations. It is worth highlighting that even with an efficient method of simulation [12] for non-integer values of $\kappa$ and $\mu$, the formulations compute as quickly and in the region of very low probability the formulas are much faster than simulation.

Fig. 3 shows the variation in OP versus $\bar{\gamma}$ when $M = 1$. We observe that in the low SNR region, the OP is barely affected.

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1It is noteworthy that (3) works for the i.n.i.d case but within some range of the parameters which, unfortunately, we have not had to specify yet. On the other hand, our main results, namely (4) and (5) are well consolidated.

2For example, in systems using interference suppression techniques which successfully constrain the interference power to be much less than the SoI.

3We note that due to the definition of the $\kappa$-$\mu$ fading model, for the particular case where $\mu$ takes an integer value, simulation is natural faster due to the straightforward combination of the underlying Gaussian variates.
applying the binomial series identity to the relevant bracketed term, we obtain (3). Substituting for \(E[G']\) from [8] we obtain

\[
\begin{align*}
P_{OP}(\gamma_{th}) &= \sum_{\mathbf{m}} \sum_{\mathbf{n}} C_{S}(M_{\mathbf{M}1})^{\mathbf{m}} \left( \frac{K_{S}^{\mathbf{m}+n}}{\mathbf{K}_{I}^{\mathbf{m}+n+n_{I}}} \right) \\
&\quad \times U(m + M_{\mathbf{M}1}, 1 + m + n + M_{\mathbf{M}1} + \mu_{S}, \mathbf{K}_{I}).
\end{align*}
\]

where \(C_{S}\) and \(g(n)\) are as defined before, \(x^{(p)} = \frac{\Gamma(x+p)}{\Gamma(x)}\) is the Pochhammer symbol and \(\mathbf{F}_{1}(...)\) is the confluent hypergeometric function. Replacing the confluent hypergeometric function with its series form [16, 07.20.02.0001.01], changing the order of summation and summing on index \(i\), we obtain

\[
P_{OP}(\gamma_{th}) = \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} C_{S}(M_{\mathbf{M}1})^{m} \left( \frac{K_{S}^{m+n}}{K_{I}^{m+n+n_{I}}} \right) \\
\quad \times U(m + M_{\mathbf{M}1}, 1 + m + n + M_{\mathbf{M}1} + \mu_{S}, \mathbf{K}_{I}).
\]

Now substituting \(U(a, b, z) = z^{1-b}U(a-b+1, 1-b, z)\) [16, 07.33.17.0007.01], and changing the order of summation using the third identity of the infinite double sum [17], we obtain the first expression in (4) that converges for \(\gamma_{th}K_{S}/K_{I} < 1\).

Replacing the confluent Tricomi hypergeometric function [16, 07.33.06.0002.01] and the generalized Laguerre polynomial [16, 05.02.02.0001.01] with their series representations in (10), we obtain (11), as shown at the top of the next page. Here, \(p_{3} = m + M_{\mathbf{M}1}\) and

\[
\begin{align*}
C_{mi} &= \left( \frac{K_{S}^{\mu_{S}}}{{\mathbf{K}_{I}^{\mu_{S}}}} \right)^{\mathbf{m}} ; \quad \mathbf{G}_{1} = \frac{\Gamma(p_{3})}{\Gamma(1+p_{3})} \left( 1 + i + n \right) ; \\
\mathbf{G}_{2} &= \frac{\Gamma(-p_{3}-p_{1}) (p_{3})^{(k)}}{\Gamma(-p_{1}) (1+p_{3}+p_{1})^{(k)}} ; \quad \mathbf{G}_{3} = \frac{\Gamma(p_{3}) (p_{3}+p_{1}) (p_{3}+p_{1})^{(k)}}{\Gamma(p_{3}) (1-p_{3}+p_{1})^{(k)}}.
\end{align*}
\]

Now, summing over index \(n\) using the fifth identity of the infinite double sum [17], substituting \(\mathbf{F}_{1}(b-a; a; b) = e^{i} \mathbf{F}_{1}(a; b; -z)\) [16, 07.20.17.0003.01], followed by transforming the Gauss hypergeometric function, \(\mathbf{F}_{2}(...)\), using [18, eq. (7.3.1.6)], and replacing \(z \mathbf{F}_{1}(...)\) with its series form [16, 07.23.02.0001.01] we obtain (12), as shown at the top of the next page, where

\[
\begin{align*}
\mathbf{G}_{4} &= \frac{\Gamma(-p_{3}-p_{2}) (p_{3})^{(k)}}{\Gamma(-p_{2}) (1+p_{3}) (1+p_{3}+p_{2})^{(k)}} ; \\
\mathbf{G}_{5} &= \frac{\Gamma(n+p_{3}) (n+p_{3}+p_{2}) (p_{3})^{(k)}}{\Gamma(1-p_{3}) (1+n+p_{3}) (p_{2}) (p_{3})^{2}}.
\end{align*}
\]

We then substitute \(k = n - m\) in the first summation [17] and sum over index \(m\). This is followed by using \(\mathbf{F}_{1}(b-a; a; b) = e^{i} \mathbf{F}_{1}(a; b; -z)\) in the second summation, substituting \(n = k - m\) [17] and summing the second summation over index \(m\). This simplifies (using the tricomi hypergeometric function [16, 07.33.02.0001.01]) to (13), as shown at the top of the next page. Finally, using \(U(a, b, z) = z^{1-b}U(a-b+1, 1-b, z)\) in (13) we obtain the second expression in (4) that converges for \(\gamma_{th}K_{S}/K_{I} > 1\).

**APPENDIX A**

**PROOF OF EQUATION (3) AND (4)**

An analytical solution for (2) can be derived by using the generalized Marcum \(Q\)-function in [15, eq. (2.6)] for non-negative real parameters \(a, b\) and \(v\). Substituting this in the \(\kappa-\mu\) cdf and using the resultant expression in (2), followed by
\[ P_{OP}(\gamma_{th}) = \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} \sum_{i=0}^{n} \frac{(-1)^{n-i} C_{m} G_{1}}{i! \Gamma(i)} \left( \gamma_{th} \mathcal{K}_{S} \right)^{p_{1}} \left( G_{2} \mathcal{K}_{S}^{k+p_{2}} + G_{3} \mathcal{K}_{S}^{k-p_{2}} \right) \] (11)

\[ P_{OP}(\gamma_{th}) = 1 + \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} \sum_{i=0}^{n} \frac{(-1)^{i} C_{m} G_{4}}{i! \Gamma(i)} (-\mathcal{K}_{S})^{n} \left( \gamma_{th} \mathcal{K}_{S} \right)^{p_{1}} \left( 1 + k + p_{2}; \gamma_{th} \mathcal{K}_{S} \right) \] (12)

\[ P_{OP}(\gamma_{th}) = 1 - \sum_{n=0}^{\infty} \sum_{i=0}^{n} \frac{C_{1} (\kappa_{S} \mu_{S})^{i} \mathcal{K}_{S}^{\mu_{S}+\mu_{1}}}{i! \Gamma(p_{2})} \left( \gamma_{th} \mathcal{K}_{S} \right)^{p_{2}} U \left( 1 + n + M \mu_{1}; 1 + p_{2} + n + M \mu_{1}; \gamma_{th} \mathcal{K}_{S} \right) \] (13)