Performance of Macrodiversity System with Selection Combining and Two Microdiversity MRC Receivers in the Presence of k-μ Fading

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Abstract – **In this paper, the outage probability (P_{out}) of the selection combining (SC) macrodiversity (MD) system with two maximal ratio combining (MRC) microdiversity (mD) receivers in Gamma shadowed k-μ fading environment is investigated. Each mD receiver has *L* input branches. For this system model, analytical expression for the probability density function (PDF) of the signal to noise ratio (SNR) at the output of the MD SC receiver, and the outage probability of the MD SC receiver are calculated. The obtained results are graphically presented to accentuate parameters influence to the system performance.**

Keywords – **Macrodiversity, Microdiversity, k-μ fading, Gamma shadowing, Outage probability.**

I. Introduction

This paper treats outage performances in selection combining (SC) macrodiversity (MD) system employed to reduce long-term fading (shadowing) effects with two maximal ratio combining (MRC) microdiversity (mD) receivers with *L*-branches aimed to mitigate the effects of short-term *k*-μ fading. The *k*-μ fading has been chosen because it is general fading distribution and includes, as special cases, Nakagami-*m* and Nakagami-*n* (Rician) fading, as well as their entire special cases: Rayleigh and one-sided Gaussian fading [1].

Because the sum of *k*-μ squares is *k*-μ square as well, but with different parameters, this distribution is an ideal choice for MRC analysis [2]. With that in mind, in this work, we will explore a model for a shadowed *k*-μ distribution and derive closed form expressions for outage probability at the MRC mD receivers' outputs and SC MD receiver output.

In available literature, the first and second-order statistics of SC MD systems with SC or MRC mD receivers, operating over Gamma-shadowed long-term fading channels are analyzed for independent [3] or correlated signals [4-10] for different fading distributions. The statistical characteristics have been somewhat less frequently determined in closed forms expressions due to complicated mathematical calculations. So in [3], infinite-series expressions for the second-order statistical measures of a MD structure operating over shadowed *k*-μ fading channels are provided. Here, shadowing is described with Gamma distribution, which is, as above mentioned, independent. Focus was on MRC combining at each base station (mD), and SC combining between base stations (MD).

Receiver in [4] uses MD SC technique in order to reduce the impact of long-term fading effects, and two mD SC receivers to mitigate Weibull short term fading effects on system performance: probability density function (PDF), and cumulative distribution function (CDF), as well as level crossing rate (LCR) and average fade duration (AFD). The outage probability (P_{out}) of MD SC receiver with two dual mD SC receivers working over Gamma shadowed Weibull multipath fading environment in the presence of co-channel interference subjected to Weibull short term fading has been examined in [5].

Macrodiversity system consisting of two mD SC receivers and one MD SC receiver is analyzed in [6]. Independent *k*-μ fading and correlated slow Gamma fading are present at the inputs of the receivers. The analytical expressions for the PDF of the MD SC receiver output signal and the output capacity are calculated.

The error performance of a mobile communication system with MRC mD and SC MD reception in Gamma-shadowed Rician fading channels for a binary differential phase-shift keying modulation scheme is found in [7]. The system model in [8] assumes implementation of *L*-branch MRC at the microlevel and SC at the macrolevel. The received signal envelope follows Rician distribution and suffers Gamma shadowing. The expressions for PDF, CDF, and moment-generating function (MGF) of the output signal-to-noise ratio (SNR) are obtained. Also, moments of the output SNR and P_{out} are analytically derived.

A case of a wireless communication system consisting of dual SC MD combiner and two MRC mD combiners with *L* branches is studied in [9]. In that scenario, received signal is disturbed by simultaneous impact of multipath Nakagami-*m* fading and Gamma shadow. Consequently, the envelope is described by generalized-*K* density function.

In [10], a wireless receiver model that employs the MD technique, consisting of a SC receiver fed by two dual mD SC, which is used to simultaneously reduce the effects of Nakagami-*m* short term fading, Gamma long term fading, and co-channel interference on the system performances, is considered. The interfering signal is also affected by Nakagami-*m* short term fading. There, closed form expressions for LCR of signal-to-interference ratio (SIR) at the outputs of the mD SC with *n* branches, as well as for the SIR at the output of the whole MD SC receiver are derived.

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This paper is organized as follows. In Section II, we first describe system model, examine the k-μ distribution and Gamma shadowing. Then, we describe the system performance by calculating the outage probability at the outputs of micro and macrodiversity receivers. In Section III, the corresponding graphs and tables are shown to point out the influence of specific parameters to P_{out}. In last section some conclusions have been drawn.

II. Outage Probability at the Outputs of Micro and Macrodiversity Receivers

A. System Model

This paper considers a macrodiversity combiner with a SC receiver consisting of two microdiversity MRC receivers, each with L branches. The mD combiner is more effective with more branches. MD SC combiner operates by choosing the highest signal from the inputs.

This system operates over Gamma-shadowed k-μ multipath fading channel. A model of considered MD system is shown in Fig. 1. The signals envelopes at the inputs and outputs of mD and MD receivers are denoted in the figure.

B. k-μ Distribution

Physical model of the k-μ fading and the derivation of this distribution are presented in [2]. The fading modeled with a k-μ distribution describes a signal consisting of clusters of multipath waves propagating in a nonhomogeneous environment. Within single cluster, the phases of the scattered waves are random with similar delay times, with delay-time spreads of different clusters being relatively large. It is assumed that the clusters of multipath waves have scattered waves with identical powers, and also that each cluster has a dominant component with arbitrary power. This distribution is well suited for line-of-sight (LoS) applications, since every cluster of multipath waves has a dominant component.

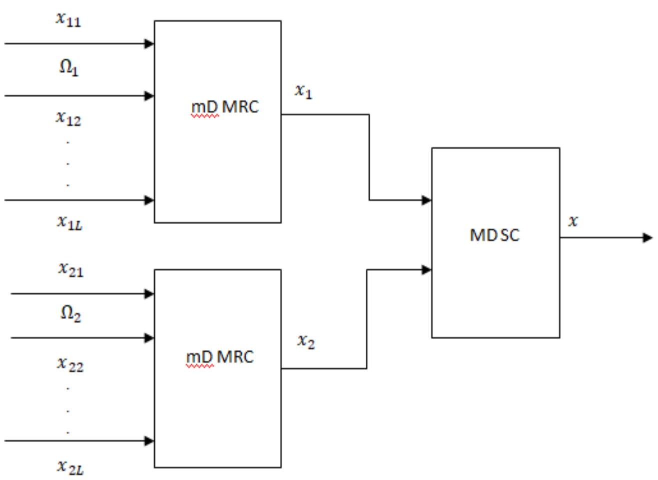

Fig. 1. Model of considered macrodiversity system

The probability density function of the envelope x_{ij}, modeled by k-μ distribution is given by [11, Eq. (1)]:

$$p_{x_i}(x_i)=\frac{2\mu x_i^{\mu}}{k^{(\mu-1)/2}e^{\mu k}}\left(\frac{1+k}{\Omega}\right)^{(\mu+1)/2}\cdot$$
$$\cdot e^{-\frac{\mu(1+k)}{\Omega}x_i^2}I_{\mu-1}(2\mu x_i)\sqrt{\frac{k(1+k)}{\Omega}} \quad (1)$$

where k>0 is the ratio of the total power of the dominant components and the total power of the scattered waves, μ>0 is the number of clusters, Ω is the mean value of the signal power. $I_v(\cdot)$ is the modified Bessel function of the first kind and order ν and can be expressed by the expression [12, Eq. 9.6.20] [13, eq. (17.7.1.1)]:

$$I_v(x)=\sum_{k=0}^{\infty}\frac{(x/2)^{v+2k}}{k!\Gamma(v+k+1)} \quad (2)$$

The MRC combiner's output SNRs x_i from i-th (i=1,2,.., L) base station are [14]:

$$x_i=x_{11}^2+x_{12}^2+....+x_{1L}^2=x_{21}^{\ 2}+x_{22}^{\ 2}+...+x_{2L}^{\ 2}=$$
$$=\sum_{j=1}^{L}x_{ij}^{\ 2}=,i=1,2.,\ j=1,2...L\ . \quad (3)$$

PDF of the SNR x_i is [15, Eq. (11)]:

$$p_{x_i}(x_i)=\frac{L\mu(1+k)^{\frac{L\mu+1}{2}}}{k^{\frac{L\mu-1}{2}}e^{L\mu k}(L\Omega)^{\frac{L\mu+1}{2}}}x_i^{\frac{L\mu-1}{2}}e^{-\frac{\mu(1+k)}{\Omega}x_i}\cdot$$
$$\cdot I_{L\mu-1}\left(2\mu\sqrt{\frac{LK(1+K)x_i}{\Omega}}\right),\quad x_i\geq 0\ . \quad (4)$$

Using expression (2) we obtain the PDF of SNR x_i as:

$$p_{x_i}(x_i)=\frac{e^{-\frac{\mu(1+k)}{\Omega}x_i}}{e^{L\mu k}}\sum_{i=0}^{\infty}\frac{\mu^{2i+L\mu}(LK)^i x_i^{i+L\mu-1}}{i!\Gamma(L\mu+i)}\left(\frac{1+K}{\Omega}\right)^{i+L\mu}. \quad (5)$$

CDF of x_i is [16]:

$$F_{x_i}(x_i)=\int_0^{x_i}p_{z_{ij}}(t)dt=p_{x_i}(x_i)=$$
$$=\frac{1}{e^{L\mu k}}\sum_{i=0}^{\infty}\frac{(\mu LK)^i}{i!\Gamma(L\mu+i)}\int_0^{x_i}n^{i+L\mu-1}e^{-n}dn\ . \quad (6)$$

Using the model [12; 6.5.2]:

$$\gamma(\alpha,x)=\int_0^x \mathrm{e}^{-t}t^{\alpha-1}\mathrm{d}t \quad (7)$$

for integral inside (6), where γ(b,c) is a lower Gamma function, CDF of SNR at the output of mD MRC receiver is:

$$F_{x_i}(x_i)=\frac{1}{e^{L\mu k}}\sum_{i=0}^{\infty}\frac{(\mu LK)^i}{i!\Gamma(L\mu+i)}\gamma\left(i+L\mu,\frac{\mu(1+k)}{\Omega}x_i\right). \quad (8)$$

Lower incomplete Gamma function can be represented by a complementary incomplete Gamma function Γ(α, x), and Gamma function Γ (·) [17, eq. (8.356.3)] as:

$$\gamma(n,x)=\Gamma(n)-\Gamma(n,x)=\Gamma(n)\left(1-e^{-x}\sum_{k=0}^{n-1}\frac{x^k}{k!}\right). \qquad (9)$$

Applying expression (9) to expression (8), the expression for CDF of SNR at the output of the mD MRC combiners is obtained as:

$$F_{x_i}(x_i)=\frac{1}{e^{L\mu k}}\sum_{i_1=0}^{\infty}\frac{(\mu LK)^{i_1}}{i_1!}\cdot$$

$$\cdot\left(1-e^{-\frac{\mu(1+k)}{\Omega_i}x_i}\sum_{i_2=0}^{i_1+L\mu-1}\frac{1}{i_2!}\left(\frac{\mu(1+k)}{\Omega_i}x_i\right)^{i_2}\right). \qquad (10)$$

C. Gamma Shadowing

The joint probability density function (JPDF) of the signal envelope average powers $\boldsymbol{\Omega_1}$ and $\boldsymbol{\Omega_2}$ at the inputs of MD SC receiver is [18]:

$$p_{\Omega_1\Omega_2}(\Omega_1,\Omega_2,....\Omega_n)=\frac{(\Omega_1\Omega_n)^{\frac{c-1}{2}}\rho^{-\frac{(n-1)(c-1)}{2}}}{\Gamma(c)(1-\rho)^{n-1}\Omega_0^{n+c-1}}\cdot$$

$$\cdot e^{-\frac{1}{\Omega_0(1-\rho)}\left[\Omega_1+\Omega_n+(1+\rho)\sum_{i=2}^{n-1}\Omega_i\right]}\prod_{i=1}^{n-1}I_{c-1}\left(\frac{2\sqrt{\rho\Omega_i\Omega_{i+1}}}{\Omega_0(1-\rho)}\right), \qquad (11)$$

where c is order of Gamma distribution, $\boldsymbol{\Omega_0}$ denotes average value of $\boldsymbol{\Omega_1}$ and $\boldsymbol{\Omega_2}$, and ρ is correlation coefficient. Using form (2), when the number of input branches in MD is two, we get that the PDF of $\boldsymbol{\Omega_1}$ and $\boldsymbol{\Omega_2}$:

$$p_{\Omega_1\Omega_2}(\Omega_1\Omega_2)=\frac{1}{\Gamma(c)}e^{-\frac{\Omega_1+\Omega_2}{\Omega_0(1-\rho)}}\cdot$$

$$\cdot\sum_{i=0}^{\infty}\frac{\rho^i(\Omega_1\Omega_2)^{i+c-1}}{i!\Gamma(i+c)\Omega_0^{2i+2c}(1-\rho)^{2i+c}} \qquad (12)$$

D. Cumulative Distribution Function

MD SC receiver selects mD MRC with higher signal level in order to improve the received signal quality and enable better system performance. Therefore, CDF of SNR at output of MD SC receiver is expressed as [16]:

$$F_x(x)=\int_0^{+\infty}d\Omega_1\int_0^{\Omega_1}d\,\Omega_2F_{x_1|\Omega_1}(x_1)\,p_{\Omega_1\Omega_2}(\Omega_1\Omega_2)+$$

$$+\int_0^{+\infty}d\Omega_2\int_0^{\Omega_2}d\Omega_1F_{x_2|\Omega_2}(x_2)\,p_{\Omega_1\Omega_2}(\Omega_1\Omega_2)=$$

$$=2\int_0^{+\infty}d\Omega_1\int_0^{\Omega_1}d\,\Omega_2F_{x_1|\Omega_1}(x_1)\,p_{\Omega_1\Omega_2}(\Omega_1\Omega_2). \qquad (13)$$

Using expressions (11) and (13), CDF we get:

$$F_x(x)=\frac{2}{\Gamma(c)e^{L\mu k}}\sum_{i_1=0}^{\infty}\sum_{i_2=0}^{\infty}\frac{(\mu LK)^{i_2}}{i_1!i_2!\Gamma(i_1+c)\Omega_0^{2i_1+2c}}\cdot$$

$$\cdot\frac{\rho^{i_1}}{(1-\rho)^{2i_1+c}}\left[\int_0^{+\infty}d\Omega_1\Omega_1^{i_1+c-1}e^{-\frac{\Omega_1}{\Omega_0(1-\rho)}}\int_0^{\Omega_1}d\,\Omega_2\Omega_2^{i_1+c-1}\cdot\right.$$

$$\cdot e^{-\frac{\Omega_2}{\Omega_0(1-\rho)}}-\sum_{i_3=0}^{i_2+L\mu-1}\frac{(\mu(1+k)x_i)^{i_3}}{i_3!}\int_0^{+\infty}d\Omega_1\Omega_1^{i_1-i_3+c-1}e^{-\frac{\Omega_1}{\Omega_0(1-\rho)}}\cdot$$

$$\cdot e^{-\frac{\mu(1+k)}{\Omega_i}x_i}\int_0^{\Omega_1}d\,\Omega_2\Omega_2^{i_1+c-1}e^{-\frac{\Omega_2}{\Omega_0(1-\rho)}}. \qquad (14)$$

By substituting the expression (A1) in (14), the CDF of the SNR is obtained as:

$$F_x(x)=\frac{2}{\Gamma(c)e^{L\mu k}}\sum_{i_1=0}^{\infty}\sum_{i_2=0}^{\infty}\frac{(\mu LK)^{i_2}\rho^{i_1}}{i_1!i_2!\Omega_0^{i_1+c}(1-\rho)^{i_1}}\cdot$$

$$\left[\left\{\int_0^{+\infty}d\Omega_1\Omega_1^{i_1+c-1}e^{-\frac{\Omega_1}{\Omega_0(1-\rho)}}-\sum_{i_4=0}^{i_1+c-1}\frac{1}{i_4!}\left(\frac{1}{\Omega_0(1-\rho)}\right)^{i_4}\cdot\right.\right.$$

$$\left.\cdot\int_0^{+\infty}d\Omega_1\Omega_1^{i_1+i_4+c-1}e^{-\frac{2\Omega_1}{\Omega_0(1-\rho)}}\right\}-\sum_{i_3=0}^{i_2+L\mu-1}\frac{(\mu(1+k)x_i)^{i_3}}{i_3!}\cdot$$

$$\left\{\int_0^{+\infty}d\Omega_1\Omega_1^{i_1-i_3+c-1}e^{-\frac{\Omega_1}{\Omega_0(1-\rho)}}e^{-\frac{\mu(1+k)}{\Omega_i}x_i}-\sum_{i_4=0}^{i_1+c-1}\frac{1}{i_4!}\cdot\right.$$

$$\left.\left.\cdot\left(\frac{1}{\Omega_0(1-\rho)}\right)^{i_4}\int_0^{+\infty}d\Omega_1\Omega_1^{i_1-i_3+i_4+c-1}e^{-\frac{2\Omega_1}{\Omega_0(1-\rho)}}e^{-\frac{\mu(1+k)}{\Omega_i}x_i}\right\}\right]. \qquad (15)$$

Substituting expressions (A2) - (A6) into expression (15) yields CDF of SNR at output of SC MD receiver:

$$F_x(x)=\frac{2}{\Gamma(c)e^{L\mu k}}\sum_{i_1=0}^{\infty}\sum_{i_2=0}^{\infty}\frac{\rho^{i_1}(\mu LK)^{i_2}(1-\rho)^c}{i_1!i_2!}\cdot$$

$$\cdot\left[\left\{\Gamma(i_1+c)-\sum_{i_4=0}^{i_1+c-1}\frac{\Gamma(i_1+i_4+c)}{i_4!}\right\}-2\sum_{i_3=0}^{i_2+L\mu-1}\frac{1}{i_3!}\cdot\right.$$

$$\cdot\left(\frac{\mu x(1+k)}{\Omega_0(1-\rho)}\right)^{\frac{i_1+i_3+c}{2}}\left\{K_{i_1-i_3+c}\left(2\sqrt{\frac{\mu x(1+k)}{\Omega_0(1-\rho)}}\right)-\sum_{i_4=0}^{i_1+c-1}\frac{1}{2^{\frac{i_1-i_3+i_4+c}{2}}i_4!}\cdot\right.$$

$$\left.\left.\cdot\left(\frac{\mu x(1+k)}{\Omega_0(1-\rho)}\right)^{\frac{i_4}{2}}K_{i_1-i_3+i_4+c}\left(2\sqrt{\frac{2\mu x(1+k)}{\Omega_0(1-\rho)}}\right)\right\}\right]. \qquad (16)$$

E. Outage Probability

The outage probability is actually defined as the probability that the receiver output signal envelope is falling below a given threshold value. Mathematically, the P_{out} is the CDF of the signal and is given by [19, eq. (2.23)]:

$$P_{out}\left(\gamma_{th}\right)=P\left(z<\gamma_{th}\right), \tag{17}$$

with γ_{th} as this threshold value. Here, the P_{out} of the SC MD system with two MRC mD receivers in Gamma shadowed k-μ fading environment is given by expression (16).

III. Obtained Results

In this section, some numerical results of the system's outage probability are presented, in order to examine the influence of various parameters such as: shadowing and fading severity, number of the diversity branches at the mD receiver, number of clusters and correlation coefficient on the concerned quantities.

Figs. 2 to 4 show the P_{out} depending on the SNR (dB) obtained from (17), when $\Omega=\Omega_0$, some parameters are changing, and other set has constant values.

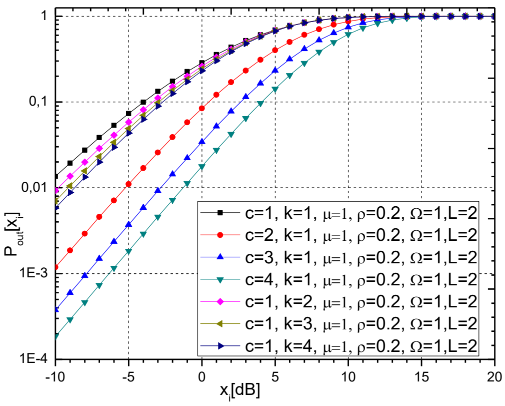

Fig. 2. P_{out} at the output of the MD SC combiner, for variable parameters *c* and *k*

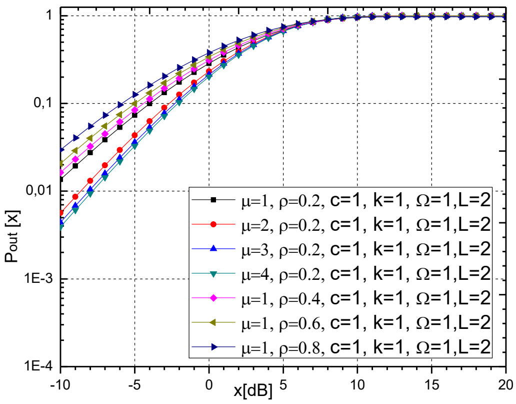

Fig. 3. The P_{out} at the output of the MD SC combiner, for different values of parameters μ and ρ

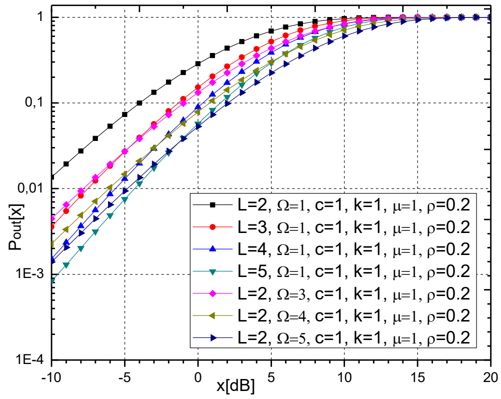

Fig. 4. The P_{out} at the output of the MD SC combiner when the parameters *L* and Ω change

Number of terms that should be added in expression (16) for calculating P_{out} in order to reach accuracy at 5th significant digit, are given in Tables I to III for different combinations of parameters.

TABLE I
NUMBER OF TERMS THAT SHOULD BE ADDED TO CALCULATE P_{OUT} WHEN PARAMETERS *C* AND *K* CHANGE, WHILE THE OTHER PARAMETERS ARE: $\mu=\Omega_0=1$, $L=2$, $\rho=0.2$ (FIG. 2)

	x=-10 dB	*x*=0 dB	*x*=10 dB
$c=1,\ k=1$	6	10	9
$c=2,\ k=1$	5	10	7
$c=3,\ k=1$	5	9	5
$c=4,\ k=1$	5	9	6
$c=1,\ k=2$	10	15	14
$c=1,\ k=3$	12	19	16
$c=1,\ k=4$	15	22	20

TABLE II
NUMBER OF TERMS WHEN PARAMETERS μ AND ρ CHANGE, AND THE OTHER PARAMETERS ARE: $c=\Omega_0=k=1$, $L=2$ (FIG.3)

	x=-10 dB	*x*=0 dB	*x*=10 dB
$\mu=1,\ \rho=0.2$	6	10	9
$\mu=2,\ \rho=0.2$	10	15	14
$\mu=3,\ \rho=0.2$	13	19	17
$\mu=4,\ \rho=0.2$	15	23	21
$\mu=1,\ \rho=0.4$	6	11	10
$\mu=1,\ \rho=0.6$	7	18	11
$\mu=1,\ \rho=0.8$	10	39	25

TABLE III
NUMBER OF TERMS IN A SUM WHEN PARAMETERS $\Omega_0=\Omega$ AND *L* CHANGE; OTHER PARAMETERS ARE: $c=k=\mu=1$, $\rho=0.2$ (FIG.4)

	x=-10 dB	*x*=0 dB	*x*=10 dB
$\Omega=1,\ L=2$	6	10	9
$\Omega=2,\ L=2$	6	8	10
$\Omega=3,\ L=2$	5	8	10
$\Omega=4,\ L=2$	5	8	10
$\Omega=1,\ L=3$	8	12	10
$\Omega=1,\ L=4$	8	14	12
$\Omega=1,\ L=5$	9	16	14

It can be seen from Table I that as the parameter c increases, the number of terms in the series does not change significantly and the system converges rapidly. As the parameter k increases, the number of terms that need to be added to achieve the accuracy of the expression increases and the system converges slowly.

Table II shows that when both of the parameters μ and ρ increase, the number of terms in the series grows and the sum converges slowly.

Finally, Table III displays that the number of terms in the series decreases with increasing of Ω, and the system converges faster for x = -10 dB and x = 0 dB, while for x = 10 dB, the number of terms increases and the system converges slowly. As the parameter L increases, for all x the number of terms that need to be added to achieve the accuracy of the expression increases and the system convergence is slow.

IV. Conclusion

In this paper macrodiversity system that consists of SC macrodiversity receiver with two microdiversity MRC receivers with L branches is analyzed. Independent k-μ fading and correlated slow Gamma fading are present at the mD MRC receivers' inputs. For this system model, analytical expression for the probability density of the signal to noise ratio at the output of the macrodiversity SC receiver, and the outage probability of the macrodiversity SC receiver are calculated. The obtained results are graphically presented to show the impact of fading severity parameter k, shadowing severity of the channel c, the number of clusters μ and correlation coefficient ρ, on the outage probability at the output of the macrodiversity system. Based on the given analytical and numerical results it is possible to estimate the behavior of the real wireless macrodiversity system in the presence of shadowed k-μ fading.

Appendix

Integral I_1 from (14) is defined and solved as:

$$I_1 = \int_0^{\Omega_1} d\,\Omega_2 \Omega_2^{\,i_1+c-1} e^{-\frac{\Omega_2}{\Omega_0(1-\rho)}} = \left(\Omega_0\left(1-\rho\right)\right)^{i_1+c} \cdot$$

$$\cdot \int_0^{\frac{\Omega_1}{\Omega_0(1-\rho)}} t^{i_1+c-1} e^{-t} dt = \left(\Omega_0\left(1-\rho\right)\right)^{i_1+c} \Gamma\left(i_1+c\right) \cdot$$

$$\cdot \left(1 - e^{-\frac{\Omega_1}{\Omega_0(1-\rho)}} \sum_{i_4=0}^{i_1+c-1} \frac{1}{i_4!} \left(\frac{\Omega_1}{\Omega_0\left(1-\rho\right)}\right)^{i_4}\right). \tag{A1}$$

Integral I_2 from (15) is:

$$I_2 = \int_0^{+\infty} d\Omega_1 \Omega_1^{\,i_1+c-1} e^{-\frac{\Omega_1}{\Omega_0(1-\rho)}} = \left(\Omega_0\left(1-\rho\right)\right)^{i_1+c} \cdot$$

$$\cdot \int_0^{+\infty} dt t^{i_1+c-1} e^{-t} = \left(\Omega_0\left(1-\rho\right)\right)^{i_1+c} \Gamma\left(i_1+c\right), \tag{A2}$$

where $\Gamma(\cdot)$ is well-known form of Gamma function.

The next integral I_3 appearing in (15) is:

$$I_3 = \int_0^{+\infty} d\Omega_1 \Omega_1^{\,i_1+i_4+c-1} e^{-\frac{2\Omega_1}{\Omega_0(1-\rho)}} =$$

$$= \left(\Omega_0\left(1-\rho\right)\right)^{i_1+i_4+c} \Gamma\left(i_1+i_4+c\right). \tag{A3}$$

Using the form [17; 3.471]:

$$\int_0^{\infty} x^{\nu-1} \mathrm{e}^{-\frac{\beta}{x}-\gamma x} \mathrm{d}x = 2\left(\frac{\beta}{\gamma}\right)^{\frac{\nu}{2}} K_\nu\left(2\sqrt{\beta\gamma}\right), \tag{A4}$$

the integral I_4 from (15) becomes:

$$I_4 = \int_0^{+\infty} d\Omega_1 \Omega_1^{\,i_1-i_3+c-1} e^{-\frac{\Omega_1}{\Omega_0(1-\rho)}} e^{-\frac{\mu(1+k)}{\Omega_1}x} =$$

$$= 2\left(\mu x(1+k)\Omega_0\left(1-\rho\right)\right)^{\frac{i_1-i_3+c}{2}} K_{i_1-i_3+c}\left(2\sqrt{\frac{\mu x(1+k)}{\Omega_0\left(1-\rho\right)}}\right). \tag{A5}$$

Integral I_5 from (15) is:

$$I_5 = \int_0^{+\infty} d\Omega_1 \Omega_1^{\,i_1-i_3+i_4+c-1} e^{-\frac{2\Omega_1}{\Omega_0(1-\rho)}} e^{-\frac{\mu(1+k)}{\Omega_1}x} =$$

$$= 2\left(\frac{\mu x(1+k)\Omega_0\left(1-\rho\right)}{2}\right)^{\frac{i_1-i_3+i_4+c}{2}} K_{i_1-i_3+i_4+c}\left(2\sqrt{\frac{2\mu x(1+k)}{\Omega_0\left(1-\rho\right)}}\right). \tag{A6}$$

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