Outage probability of correlated SIR-based SSC diversity systems over composite $K_G$ fading/shadowing channels

In this paper, the effects of multipath fading and shadowing over the propagation channel are observed through the performance analysis of switch and stay selection combining (SSC) technique. The short term fading (multipath fading) in conjunction with the long term fading (shadowing) are both modeled by Generalized-$K$ ($K_G$) distribution. The proposed system is considered as interference-limited system in correlated fading environment. The probability density function (PDF) of signal-to-interference ratio (SIR) at the output of SSC receiver is derived in form of Meijer $G$ functions. According to this new expression, the outage probability is considered and the effects of fading and shadowing parameters and correlation coefficients on the performance gain are analyzed.

Key words: Composite fading channels, Generalized-$K$ distribution, SSC combining method, Wireless communications

In performance evaluation of wireless communication systems, the statistical characterization of signal propagation is frequently based on analysis of composite fading: large-scale fading due to multipath propagation and small-scale fading resulting from shadowing [1]. This destructive combination of obstacles often occurs simultaneously. The multipath fading can be modeled by Rice, Rayleigh and Nakagami-$m$ distributions and shadowing by lognormal distribution. These lognormal based fading models are analyzed in few papers [1]-[3].

However, the analytical analysis of these models is very complicated, so in some other papers the Gamma distribution is employed as an useful solution for describing shadow fading phenomena [4]. Furthermore, based on Gamma distribution, several generalized distributions have been proposed as composite fading channel models, the generalized Gamma, the $G$ [5], the $K$ [6] and the Generalized-$K$ ($K_G$) [7]-[11] channel models.

In an interference-limited system (the thermal noise is ignored), the effect of interference needs to be taken into consideration of performance analysis. The most effective performance criterion, in that case, is to select the signal-to-interference ratio [12]. Independently of the channel condition, the transmitted signals as well as the interfered ones could be correlated due to small distance between the diversity antennas.

In [8], the brief performance evaluations of the output signal-to-noise ratio (SNR) for the maximal-ratio combining (MRC), equal-gain combining (EGC), selection combining (SC) and switch and stay combining (SSC) operating over $K_G$ fading channels are presented. The performance analysis of various diversity combining techniques, this time over the correlated $K_G$ fading channels is considered in [9]. The infinite series expressions for the probability density function (PDF), cumulative distribution function (CDF) and joint moments of two correlated $K_G$ vari-
ables are also derived in [9].

In [10], the uncorrelated composite fading channels in the presence of co-located interferers are considered. In this paper, the performance of SSC diversity receiver in interference-limited environment is analyzed. Considering the composite correlated fading channel condition, infinite series expressions for the performance evaluation are derived. The detailed analysis of outage probability is presented. Based on analytical results, required numerical results are also presented.

The paper is organized as follows. In the Section 2, we give the brief description of channel model and mathematical formulation of proposed problem. The switch and stay combining scheme is presented in Section 3. In Section 4 the derived expression for evaluating the outage probability is presented and in Section 5 numerical results are given.

1 CHANNEL MODEL

Assuming the composite fading channel model, the $K_G$ distribution is convenient and mathematically tractable distribution for evaluating adequate performance criteria. The $K_G$ distribution accurately approximates a great variety of fading and/or shadowing models. The received resultant of desired and interfering signal, considering $K_G$ fading environment, can be presented as [13]:

$$y(t) = x(t) \exp[j(2\pi f_c t + \psi(t) + \theta(t))],$$

where $f_c$ is a carrier frequency, $\psi(t)$ is the information signal, $\theta(t)$ is the random phase and $x(t)$ is $K_G$ distributed random envelope process, given by [8, eq. (1)]:

$$p(x) = \frac{4m^{(m+k)/2}}{\Gamma(m)\Gamma(k)\Omega^{(m+k)/2}}x^{m-k-1}K_{k-m}(2x\sqrt{m/\Omega}),$$

where $K_{k-m}(.)$ is the $(k-m)^{th}$ order modified Bessel function of the second kind [14, eq. (8.407)], $\Omega(.)$ is the Gamma function [14, eq. (8.310)].$\Omega = \mathbb{E}(x^2)/k$ with $\mathbb{E}(.)$ being expectation operator. The parameter $m$ is a fading severity parameter and $k$ is a shadowing severity parameter. The two shaping parameters, $m$ and $k$, can take different values ($m \geq \frac{1}{2}$ and $k \in (0, \infty)$). Therewith a great variety of short-term and long-term fading (shadowing) conditions can be described. For example Rayleigh-Gamma fading model can be obtained by setting parameter $m$ value $m = 1$. In addition, more severe scenarios than Rayleigh-Gamma fading can be obtained by setting parameter $m$ value $m < 1$. Finally, for less severe scenarios by introducing $m > 1$, very good approximation of the Rician-Gamma fading model can be obtained. The shadowing level described by parameter $k$ and the shadowing spread $\sigma$(dB) of Log-normal model, are related through the relation given in [19].

The proposed model refers to the case of a single co-channel interferer. We assume that the remaining interferers are combined and considered as uncorrelated interference between antennas. The fading amplitude of the desired signal $R(t)$ as well as of the interfering one $r(t)$ is $K_G$ distributed. So, the PDF for instantaneous SIR, denoted by $z = R^2/r^2$, can be evaluated as (Appendix A):

$$p_z(z) = \frac{z((m+d)/2)}{\Gamma(m)\Gamma(k)\Gamma(m_c)\Gamma(k_c)} \left(\frac{md}{mc}\right)^{(m+d)/2} \times G_{2,2}^{2,2} \left[ \frac{mdz}{mcS} \right]  \left| \begin{array}{c} 1 - \frac{md+kd+2k_c}{2}, 1 - \frac{md+kd+2m_c}{2} \\ \frac{(k_c-m)_c}{2}, \frac{(k_c-m)_c}{2} \end{array} \right],$$

where $G_{p,q}^{m,n}[.]$ is the Meijer’s $G$-function [14, eq. (9.301)], $S$ is the average SIR at the two input branches defined as $S = \Omega_d/\Omega_c$, $\Omega_d = \mathbb{E}(R^2)/k_d$, $\Omega_c = \mathbb{E}(r^2)/k_c$; $m_d$ and $k_d$ are the two shaping parameters for $R(t)$ and $m_c$ and $k_c$ are the two shaping parameters for $r(t)$. Also, the CDF of instantaneous SIR can be evaluated as (Appendix A):

$$F_z(z) = z((m+d)/2) \times G_{3,3}^{2,3} \left[ \frac{mdz}{mcS} \right]  \left| \begin{array}{c} 1 - \frac{md+kd+2k_c}{2}, 1 - \frac{md+kd+2m_c}{2} \\ \frac{(k_c-m)_c}{2}, \frac{(k_c-m)_c}{2} \end{array} \right].$$

Furthermore, due to a scenario with closely placed diversity antennas, both desired and interfering signal envelopes experience correlated $K_G$ fading. In this paper, we analyze dual diversity system with balanced SIRs ($S_1 = S_2 = S$) at the input branches. The joint PDF for input balanced SIRs, denoted by $z_1 = R_1^2/r_1^2$ and $z_2 = R_2^2/r_2^2$, regarding $\Omega_{d_1} = \mathbb{E}(R_1^2)/k_{d_1}$, $\Omega_{c_1} = \mathbb{E}(r_1^2)/k_c$, $\Omega_{d_2} = \mathbb{E}(R_2^2)/k_{d_2}$, $\Omega_{c_2} = \mathbb{E}(r_2^2)/k_c$ and $S = \Omega_{d_1}/\Omega_{c_1} = \Omega_{d_2}/\Omega_{c_2}$, can be evaluated as (Appendix B):

$$p_{z_1 z_2}(z_1, z_2) = \sum_{a,b,c,d=0}^{\infty} A \times \frac{z_1^{a/2-1} z_2^{b/2-1}}{\Gamma(a/2) \Gamma(b/2) \Gamma(c/2) \Gamma(d/2)}$$

$$\times G_{2,2}^{2,2} \left[ \frac{mdz_1 \sigma}{mcS} \right]  \left| \begin{array}{c} 1 - \frac{z_1 + z_2 + \psi_c}{2}, 1 - \frac{z_1 + z_2 - \psi_c}{2} \\ \frac{\psi_c}{2}, \frac{\psi_c}{2} \end{array} \right]$$

$$\times G_{2,2}^{2,2} \left[ \frac{mdz_2 \sigma}{mcS} \right]  \left| \begin{array}{c} 1 - \frac{z_1 + z_2 + \psi_c}{2}, 1 - \frac{z_1 + z_2 - \psi_c}{2} \\ \frac{\psi_c}{2}, \frac{\psi_c}{2} \end{array} \right].$$
with

\[ A = \frac{m_d^2 \rho_{nac}^b \rho_{nd}^c}{\Gamma(m_d)\Gamma(k_d)\Gamma(m_c)\Gamma(k_c)\Gamma(m_d+a)\Gamma(k_d+a+b)} \]

\[ \times \left[ \Gamma(m_c+c)\Gamma(k_c+d)S^c \psi_d \psi_c \right] \]

where \( \rho_{nd} \) and \( \rho_{nc} \) are the power correlation coefficients between the envelopes of the desired and interfering signals, and \( \rho_{gd} \) and \( \rho_{gc} \) are correlation coefficients between the average fading power of the desired and interfering signal, respectively.

2 SWITCH AND STAY COMBINING

The switched combining diversity technique is the less complex combining technique compared to the other space diversity combining methods. Because of its low complexity implementation requirements, SSC diversity systems are frequently used. The SSC combiner processes one branch unless the instantaneous SIR of that branch falls below the threshold when the combiner switches the treated branch with the other one:

\[ P_{SSC}(z) = Pr(zT \leq z_1 \leq z) + Pr(z_2 < zT \land z_1 \leq z), \]

(6)

The PDF of instantaneous SIR at the output of SSC, by differentiating equation (6), is given by [15, eq. (9)]:

\[ p_{SSC}(z) = \begin{cases} f_{SSC}(z), & z \leq zT \\ f_{SSC}(z) + p(z), & z > zT \end{cases}, \]

(7)

where \( p_z(z) \) is defined as (3) and \( f_{SSC}(z) \) is solved using [16, eq. (26)]:

\[ f_{SSC}(z) = \int_0^z p_{z1z2}(z_1, z_2)dz_2 = \sum_{a,b,c,d=0}^{\infty} A \times z^a \psi_d \psi_c \]

\[ \times G_{a,b}^{3,3} \left[ \frac{m_d z \sigma}{m_c S} \right] \left[ 1 - \frac{\epsilon_d + \psi_c + \psi_d}{2}, -\frac{\psi_c}{2}, -\frac{\psi_d}{2} \right] \]

\[ \times G_{a,b}^{3,3} \left[ \frac{m_d z \sigma}{m_c S} \right] \left[ 1 - \frac{\epsilon_d + \psi_c + \psi_d}{2}, -\frac{\psi_c}{2}, -\frac{\psi_d}{2} \right] \]

(8)

Moreover, after some manipulations of (6), the CDF of instantaneous output SIR can be expressed as [15, eq. 10]:

\[ F_{SSC}(z) = \begin{cases} F_{z1z2}(z, zT), & z \leq zT \\ F_{z}(z) - F_{z1z2}(z, zT) + F_{z1z2}(z, zT), & z > zT \end{cases}, \]

(9)

where \( F_{z}(z) \) is given by (4) and \( F_{z1z2}(z, zT) \) is evaluated as:

\[ F_{z1z2}(z, zT) = \int_0^z \int_0^z p_{z1z2}(z_1, z_2)dz_1dz_2 = \]

\[ \sum_{a,b,c,d=0}^{\infty} A \times z^a \psi_d \psi_c \]

\[ \times G_{a,b}^{3,3} \left[ \frac{m_d z \sigma}{m_c S} \right] \left[ 1 - \frac{\epsilon_d + \psi_c + \psi_d}{2}, -\frac{\psi_c}{2}, -\frac{\psi_d}{2} \right] \]

\[ \times G_{a,b}^{3,3} \left[ \frac{m_d z \sigma}{m_c S} \right] \left[ 1 - \frac{\epsilon_d + \psi_c + \psi_d}{2}, -\frac{\psi_c}{2}, -\frac{\psi_d}{2} \right] \]

(10)

3 OUTAGE PROBABILITY

The outage probability \( P_{out} \) is a standard measure of the communication system performance and is commonly used to control the noise or co-channel interference level in wireless communication systems. In the interference-limited environment, outage probability \( P_{out} \) is defined as the probability that combined-SIR falls below a given outage threshold \( \lambda \) also known as a protection ratio:

\[ P_{out} = \int_0^\lambda p_{SSC}(z)dz = F_{SSC}(\lambda). \]

(11)

Protection ratio depends on modulation technique and expected quality-of-service (QoS).

4 NUMERICAL RESULTS

Figure 1 shows, \( P_{out} \), versus the normalized switching threshold \( zT/S \) for various correlation coefficient values. It is obvious that there is an optimal threshold that minimizes outage probability. For this threshold value, SSC combining can be observed as SC.

The outage probability, as a function of normalized average SIR for different values of shaping parameters is shown in Fig. 2. The influence of correlation between branches of desired, as well as interfering signal, is much more significant in the case of lower fading and shadowing severity. It is interesting to note here that, for pre-Rayleigh fading conditions \( (m_d = 0.5, m_c = 0.5) \),
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5 CONCLUSION

New expressions for PDF and CDF of SIR at the output of SSC receiver were derived. Major contribution of this paper is that analysis has been carried out for Generalized-$K$ ($K_G$) fading model, which as general model includes in itself other important composite fading/shadowing models. Capitalizing on obtained expressions, important wireless transmission performance measure, OP was efficiently evaluated. The effects of various parameters, such as the fading and shadowing severity parameters and level of correlation of desired signal and interference to the system’s performance were also examined. By taking into account these results, optimal values of link parameters could be chosen in the designing process of wireless communication systems, for wide range of propagation environments.

APPENDIX A

The desired signal envelope and interfering one are both $K_G$ random variables with the PDFs, respectively [8, eq. (1)]:

$$p_R(R) = \frac{4}{\Gamma(m_d)\Gamma(k_d)} \left( \frac{m_d}{\Omega_d} \right)^{m_d+k_d/2} R^{m_d+k_d-1}$$

$$p_r(r) = \frac{4}{\Gamma(m_c)\Gamma(k_c)} \left( \frac{m_c}{\Omega_c} \right)^{m_c+k_c/2} R^{m_c+k_c-1}$$

The PDF of input instantaneous SIR is given by [17]:

$$p_z(z) = \frac{1}{2\sqrt{\pi}} \int_0^\infty r p_R(r\sqrt{z}) p_r(r) dr.$$

Substituting (12) and (13) in (14); representing $K_v(.)$ by Meijer $G$ function as:

$$K_v(x) = \frac{1}{2} \sqrt{\frac{\Omega_v}{\Omega_r}} \left( \frac{-\Omega_v}{2}, -\frac{x^2}{4} \right),$$

where $\Omega_v$ is the shaping parameter of the interferer, $\Omega_r$ is the shaping parameter of the desired user instead of $\Omega_r$ and $\Omega_v$.

It is interesting to note here that shadowing the outage probability as a function of normalized average parameters of the interferers (Fig. 3). Figure 3 also shows parameters of the desired user, rather than by the fading ability of outage is predominantly affected by the fading parameters of the desired user, rather than by the fading parameters of the interferers (Fig. 3). Figure 3 also shows the outage probability as a function of normalized average SIR for different fading and shadowing severity. In this figure the case of uncorrelated diversity system is observed. It is interesting to note here that shadowing parameter of the interfering signal acts inversely. When parameter increases the outage probability also increases, which means degradation in performance gain.

Fig. 1. Outage probability for various correlation coefficient values

Fig. 2. Outage probability for different values of shaping parameters

Fig. 3. Outage probability of uncorrelated system for different values of shaping parameters
[18, eq. (03.04.26.0006.01)], and making change of variables $t = r^2/m_c/\Omega_c$ and $dt = 2rm_c dr/\Omega_c$ in integral, we get:

$$p_z(z) = \left(\frac{m_d}{m_c}\right)^{(m_d+k_d)/2} \frac{z^{(m_d+k_d)/2-1}}{\Gamma(m_d)\Gamma(k_d)\Gamma(m_c)\Gamma(k_c)} \times G_{0,2}^2\left[\begin{array}{c}
\frac{m_d}{2} k_c-m_c \\
\frac{m_c}{2}, k_c-m_c
\end{array}\right] \times G_{0,2}^2\left[\begin{array}{c}
m_d t \\
\frac{m_c}{2}, k_d-m_c
\end{array}\right] dt.$$  (15)

Integral in (15) can be solved in closed form (3), using [18, eq. (07.34.21.0011.01)]. The CDF of input instantaneous SIR is given by [17]:

$$F_z(z) = \int_0^z p_z(u) du.$$  (16)

This integral can be solved, formula (4), using [16, eq. (26)].

**APPENDIX B**

Assuming [9, eq. (4)], the joint PDFs for both desired and interfering signal envelopes can be respectively expressed as:

$$p_{R_1,R_2}(R_1,R_2) = \frac{16}{\Gamma(m_d)\Gamma(k_d)} \sum_{a,b=0}^{\infty} \frac{m_d^a \rho_{ad}^a \rho_{bd}^b}{\Gamma(m_d+\alpha)\Gamma(k_d+\beta)} \times K_\alpha\left(2R_1 \sqrt{\frac{m_d}{1-\rho_{ad}^a} (1-\rho_{bd}^b)} R_2\right)$$

$$\times a^{a\beta}(1-\rho_{ad}^a)k_d+a+b \times (1-\rho_{bd}^b)m_d+a+b R_1 R_2.$$  (17)

and

$$p_{R_1R_2}(r_1,r_2) = \frac{16}{\Gamma(m_c)\Gamma(k_c)} \sum_{c,d=0}^{\infty} \frac{m_c^c \rho_{ac}^c \rho_{dc}^d}{\Gamma(m_c+\gamma)\Gamma(k_c+d)} \times K_\gamma\left(2r_1 \sqrt{\frac{m_c}{1-\rho_{ac}^c} (1-\rho_{dc}^d)} R_2\right)$$

$$\times e^{d\gamma}(1-\rho_{ac}^c)c+d \times (1-\rho_{dc}^d)m_c+c+d R_1 R_2.$$  (18)

The joint PDF of the instantaneous SIRs at the two input branches of SSC, is given by [17]:

$$p_{z_1,z_2}(z_1,z_2) = \int_0^\infty \int_0^\infty p_{R_1,R_2}(r_1, \sqrt{z_1}, r_2, \sqrt{z_2}) \times p_{R_1R_2}(r_1, r_2) r_1 r_2 dr_1 dr_2.$$  (19)

Substituting (17) and (18) in (19), this double-fold integral is solved in the form of infinite series (5), using the same change of variables and the same equations as in solving integral in (14).

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