Closed-Form Expressions for Selection Combining System Statistics over Correlated Generalized-K Fading Channels in the Presence of Interference

Bojana Z. Nikolic, Mihajlo C. Stefanovic, Stefan R. Panic, Jelena A. Anastasov, and Borivoje Milosevic

This paper considers the effects of simultaneous correlated multipath fading and shadowing on the performances of a signal-to-interference ratio (SIR)-based dual-branch selection combining (SC) diversity receiver. This analysis includes the presence of cochannel interference. A generalized fading/shadowing channel model in an interference-limited correlated fading environment is modeled by generalized-*K* distribution. Closed-form expressions are obtained for probability density function and cumulative distribution function of the SC output SIR, as well as for the outage probability. Based on this, the influence of various fading and shadowing parameter values and the correlation level on the outage probability is examined.

Keywords: Composite fading channels, generalized-*K* distribution, selection combining, signal-to-interference ratio (SIR), outage probability.

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I. Introduction

In the evaluation of wireless system performance, the presence of channel propagation impairments must be considered. Large-scale fading and the small-scale fading are certainly among the most deleterious. The former arises from shadowing (it affects the link quality by slow variation of the mean level), and the latter occurs because of multipath propagation (introduced due to the constructive and destructive combination of randomly delayed, reflected, scattered, and diffracted signal components) [1]. This composite propagation environment of multipath fading that is superimposed by lognormal or gamma shadowing results in lognormal or gamma-based fading models, such as Rayleigh-lognormal fading, Rayleigh-gamma fading, Rician-lognormal fading, and Rician-gamma fading channels. However, thus based fading models are very difficult to handle analytically. Therefore, rather complicated mathematical expressions have been derived for the performance measures of digital communication systems operating in such environments. The recently proposed generalized-*K* (K_G) distribution is a generic and versatile distribution for the accurate modeling of a great variety of short-term fading that is in conjunction with long-term fading (shadowing) channel conditions. This composite distribution is convenient for modeling multipath/shadowing correlated fading environments when the correlations between the instantaneous signal powers and the average powers are different.

K_G distribution was first introduced as a generalized fading/shadowing channel model in [2], and some basic system performances were evaluated in such a fading environment. In [3]-[7], outage probabilities and various performance analyses of several families of modulation schemes and receiver structures operating over a K_G fading channel have been presented. The performance analysis of maximal-ratio combining (MRC), equal-gain combining (EGC), selection combining (SC), and switched-and-stay combining diversity receivers, operating over independent but non-identically distributed K_G fading channels, has been presented in [8]. Novel expressions for the statistics of these diversity receivers, including the probability density function (PDF), cumulative distribution function (CDF), moment-generating function, and the moments of output SNR, have been derived. However, the bivariate (correlated) K_G distribution is very scarce in the literature. In [9], the PDF at the output of a hybrid diversity scheme operating over identical distributed K_G fading channels was presented. At the microdiversity level, an MRC receiver was considered, while a selection diversity receiver was applied at the macrodiversity level. Finally, [10] introduces and studies arbitrarily correlated K_G distribution with non-identical parameters and presents the most important statistical metrics of this composite fading/shadowing channel model; namely, the PDF, CDF, joint moments, and outage probability. Based on this, the authors analyzed the performance of dual-branch selection MRC and EGC diversity receivers operating over bivariate K_G fading channels.

Cochannel interference, another corruptive effect, is also present due to the aggressive frequency reuse in neighboring cells. Each interfering signal is also subject to large-scale fading and small-scale fading. A very efficient technique that reduces influence of fading and channel interference is SC diversity based on the signal-to-interference ratio (SIR). Combining techniques, such as EGC and MRC, requires all or some amount of the channel state information of the received signal. In fading environments, such as cellular systems, where the level of the cochannel interference is sufficiently high compared to the thermal noise, SC selects the branch with the highest SIR.

In this paper, we analyzed the system performance of a dual branch SIR-based SC receiver operating over composite fading channels. The fading is correlated and follows K_G distribution for both direct diversity branches and interfering branches. Very useful closed-form expressions, obtained for PDF and CDF of the SC output SIR, are the main contribution of this paper. Outage probability is efficiently evaluated and discussed for various values of system parameters.

II. System Model

Let us assume that, because of the insufficient antenna spacing, both desired and interfering signal envelopes experience correlative K_G fading with joint distributions [10]:

$$p_{R_1,R_2}(R_1,R_2)=\frac{16}{\Gamma(m_d)\Gamma(k_d)}\sum_{i,j=0}^{+\infty}\frac{m_d^{\xi_d}\rho_{Nd}^{i}\rho_{Gd}^{j}}{\Gamma(m_d+i)\Gamma(k_d+j)}\times\frac{\left(\frac{R_1}{\sqrt{\Omega_{d1}}}\right)^{\xi_d}K_{\psi_d}\left(2\sqrt{\frac{m_d}{\sigma_{d1}}}R_1\right)\left(\frac{R_2}{\sqrt{\Omega_{d2}}}\right)^{\xi_d}K_{\psi_d}\left(2\sqrt{\frac{m_d}{\sigma_{d2}}}R_2\right)}{i!\,j!(1-\rho_{Nd})^{k_d+i+j}(1-\rho_{Gd})^{m_d+i+j}R_1R_2},\tag{1}$$

$$p_{r_1,r_2}(r_1,r_2)=\frac{16}{\Gamma(m_c)\Gamma(k_c)}\sum_{i_c,j_c=0}^{+\infty}\frac{m_c^{\xi_c}\rho_{Nc}^{i_c}\rho_{Gc}^{j_c}}{\Gamma(m_c+i_c)\Gamma(k_c+j_c)}\times\frac{\left(\frac{r_1}{\sqrt{\Omega_{c1}}}\right)^{\xi_c}K_{\psi_c}\left(2\sqrt{\frac{m_c}{\sigma_{c1}}}r_1\right)\left(\frac{r_2}{\sqrt{\Omega_{c2}}}\right)^{\xi_c}K_{\psi_c}\left(2\sqrt{\frac{m_c}{\sigma_{c2}}}r_2\right)}{i_c!\,j_c!(1-\rho_{Nc})^{k_c+i_c+j_c}(1-\rho_{Gc})^{m_c+i_c+j_c}r_1r_2}\tag{2}$$

with

$$\begin{aligned}&\xi_d=k_d+j+m_d+i,\ \ \xi_c=k_c+j_c+m_c+i_c,\\&\psi_d=k_d+j-m_d-i,\ \ \psi_c=k_c+j_c-m_c-i_c,\\&\sigma_{dl}=(1-\rho_{Nd})(1-\rho_{Gd})\Omega_{dl},\\&\sigma_{cl}=(1-\rho_{Nc})(1-\rho_{Gc})\Omega_{cl},\quad l=1,2,\end{aligned}\tag{3}$$

where $m_d\geq 1/2$ and $m_c\geq 1/2$ represent the Nakagami-m shaping parameters for the desired and interference signals, respectively; $k_d>0$ and $k_c>0$ denote the shadowing shaping parameters of desired and interference signal, respectively, which approximate several shadowing conditions, from severe shadowing (k_d, $k_c\to 0$) to no shadowing (k_d, $k_c\to\infty$); ρ_{Nd} is the power correlation coefficient between instantaneous powers of Nakagami-m fading processes and corresponds to desired signals, while ρ_{Gd} is the correlation coefficient between the average fading powers of desired signals. Similarly, ρ_{Nc} and ρ_{Gc} represent correlation levels related to the interfering signal. Finally, Ω_{dl} and Ω_{cl} denote the average powers of the desired and interfering signals affected by the previously mentioned composite fading/shadowing channel models. The second kind of modified Bessel function of order v, (8.407/1) of [11], is denoted by $K_v(\cdot)$, and $\Gamma(\cdot)$ denotes the Gamma function, (8.310/1) of [11].

Let us define the instantaneous value of SIR at the k-th diversity branch input as $\lambda_k=R_k/r_k$. The selection combiner chooses and outputs the branch with the largest SIR, and in the case of dual branch SC, it is

$$\lambda=\lambda_{\text{out}}=\max(\lambda_1,\lambda_2).\tag{4}$$

Joint PDF of instantaneous values of SIR at the two input branches λ_k, k=1, 2, is obtained as [12]:

$$p_{\lambda_1,\lambda_2}\left(t_1,t_2\right)=\frac{1}{4\sqrt{t_1t_2}}\int_0^\infty\int_0^\infty p_{R_1,R_2}\left(r_1\sqrt{t_1},r_2\sqrt{t_2}\right)\times p_{r_1,r_2}\left(r_1,r_2\right)r_1r_2dr_1dr_2. \tag{5}$$

Substituting (1) and (2) in (5) and using (9.34/3) of [11] and (07.34.21.0011.01) of [13], we get

$$\begin{aligned}p_{\lambda_1,\lambda_2}\left(t_1,t_2\right)=&\frac{\left(\sigma_{c1}\sigma_{c2}\right)^{\frac{\xi_d+\xi_c}{2}}}{\Gamma\left(m_d\right)\Gamma\left(k_d\right)\Gamma\left(m_c\right)\Gamma\left(k_c\right)}\\&\times\sum_{i,j,i_c,j_c=0}^{+\infty}\frac{m_d^{\xi_d}\rho_{Nd}^{i}\rho_{Gd}^{j}m_c^{-\xi_d}\rho_{Nc}^{i_c}\rho_{Gc}^{j_c}}{\Gamma\left(m_d+i\right)\Gamma\left(k_d+j\right)\Gamma\left(m_c+i_c\right)\Gamma\left(k_c+j_c\right)}\\&\times\frac{t_1^{\xi_d/2-1}t_2^{\xi_d/2-1}\Omega_{d1}^{-\xi_d/2}\Omega_{d2}^{-\xi_d/2}}{i!j!\left(1-\rho_{Nd}\right)^{k_d+i+j}\left(1-\rho_{Gd}\right)^{m_d+i+j}}\\&\times\frac{\Omega_{c1}^{-\xi_c/2}\Omega_{c2}^{-\xi_c/2}}{i_c!j_c!\left(1-\rho_{Nc}\right)^{k_c+i_c+j_c}\left(1-\rho_{Gc}\right)^{m_c+i_c+j_c}}\\&\times G_{2,2}^{2,2}\left(\frac{m_dt_1\sigma_{c1}}{\sigma_{d1}m_c}\left|\begin{matrix}1-\frac{\xi_d+\xi_c+\psi_c}{2},1-\frac{\xi_d+\xi_c-\psi_c}{2}\\ \psi_d/2,-\psi_d/2\end{matrix}\right.\right)\\&\times G_{2,2}^{2,2}\left(\frac{m_dt_2\sigma_{c2}}{\sigma_{d2}m_c}\left|\begin{matrix}1-\frac{\xi_d+\xi_c+\psi_c}{2},1-\frac{\xi_d+\xi_c-\psi_c}{2}\\ \psi_d/2,-\psi_d/2\end{matrix}\right.\right),\end{aligned} \tag{6}$$

where $G_{p,q}^{m,n}\left[\cdot\middle|\cdot\right]$ is the Meijer's G-function [11]. For this case, one can obtain joint CDF as [12]

$$F_{\lambda_1,\lambda_2}\left(t_1,t_2\right)=\int_0^{t_1}\int_0^{t_2}p_{\lambda_1,\lambda_2}\left(x_1,x_2\right)dx_1dx_2\ . \tag{7}$$

Let $S_k=\Omega_{dk}/\Omega_{ck}$ be the average SIR at the k-th input branch of the selection combiner. A cumulative distribution function of the output SIR can be derived from (7) by using (6) and equating the arguments $t_1=t_2=t$:

$$\begin{aligned}F_\lambda(t)=&\frac{1}{\Gamma\left(m_d\right)\Gamma\left(k_d\right)\Gamma\left(m_c\right)\Gamma\left(k_c\right)}\\&\times\sum_{i,j,i_c,j_c=0}^{+\infty}\frac{m_d^{\xi_d}\rho_{Nd}^{i}\rho_{Gd}^{j}m_c^{-\xi_d}\rho_{Nc}^{i_c}\rho_{Gc}^{j_c}}{\Gamma\left(m_d+i\right)\Gamma\left(k_d+j\right)\Gamma\left(m_c+i_c\right)\Gamma\left(k_c+j_c\right)}\\&\times\frac{t^{\xi_d}}{i!j!\left(1-\rho_{Nd}\right)^{k_d+i+j}\left(1-\rho_{Gd}\right)^{m_d+i+j}}\\&\times\frac{\left(S_1S_2\right)^{-\xi_d/2}}{i_c!j_c!\left(1-\rho_{Nc}\right)^{k_c+i_c+j_c-\xi_d-\xi_c}\left(1-\rho_{Gc}\right)^{m_c+i_c+j_c-\xi_d-\xi_c}}\\&\times G_{3,3}^{2,3}\left(\frac{m_d\left(1-\rho_{Nc}\right)\left(1-\rho_{Gc}\right)t}{m_c\left(1-\rho_{Nd}\right)\left(1-\rho_{Gd}\right)S_1}\left|\begin{matrix}1-\frac{\xi_d+\xi_c+\psi_c}{2},1-\frac{\xi_d+\xi_c-\psi_c}{2},1-\frac{\xi_d}{2}\\ \psi_d/2,-\psi_d/2,-\xi_d/2\end{matrix}\right.\right)\\&\times G_{3,3}^{2,3}\left(\frac{m_d\left(1-\rho_{Nc}\right)\left(1-\rho_{Gc}\right)t}{m_c\left(1-\rho_{Nd}\right)\left(1-\rho_{Gd}\right)S_2}\left|\begin{matrix}1-\frac{\xi_d+\xi_c+\psi_c}{2},1-\frac{\xi_d+\xi_c-\psi_c}{2},1-\frac{\xi_d}{2}\\ \psi_d/2,-\psi_d/2,-\xi_d/2\end{matrix}\right.\right).\end{aligned} \tag{8}$$

Using (8), one can easily obtain a PDF of the output SIR as

$$\begin{aligned}p_\lambda(t)=&\frac{d}{dt}F_\lambda(t)=\frac{1}{\Gamma\left(m_d\right)\Gamma\left(k_d\right)\Gamma\left(m_c\right)\Gamma\left(k_c\right)}\\&\times\sum_{i,j,i_c,j_c=0}^{+\infty}\frac{m_d^{\xi_d}\rho_{Nd}^{i}\rho_{Gd}^{j}m_c^{-\xi_d}\rho_{Nc}^{i_c}\rho_{Gc}^{j_c}}{\Gamma\left(m_d+i\right)\Gamma\left(k_d+j\right)\Gamma\left(m_c+i_c\right)\Gamma\left(k_c+j_c\right)}\\&\times\frac{t^{\xi_d-1}}{i!j!\left(1-\rho_{Nd}\right)^{k_d+i+j}\left(1-\rho_{Gd}\right)^{m_d+i+j}}\\&\times\frac{\left(S_1S_2\right)^{-\xi_d/2}}{i_c!j_c!\left(1-\rho_{Nc}\right)^{k_c+i_c+j_c-\xi_d-\xi_c}\left(1-\rho_{Gc}\right)^{m_c+i_c+j_c-\xi_d-\xi_c}}\\&\times\left(\xi_dG_{3,3}^{2,3}\left(\frac{m_d\left(1-\rho_{Nc}\right)\left(1-\rho_{Gc}\right)t}{m_c\left(1-\rho_{Nd}\right)\left(1-\rho_{Gd}\right)S_1}\left|\begin{matrix}1-\frac{\xi_d+\xi_c+\psi_c}{2},1-\frac{\xi_d+\xi_c-\psi_c}{2},1-\frac{\xi_d}{2}\\ \psi_d/2,-\psi_d/2,-\xi_d/2\end{matrix}\right.\right)\right.\\&\times G_{3,3}^{2,3}\left(\frac{m_d\left(1-\rho_{Nc}\right)\left(1-\rho_{Gc}\right)t}{m_c\left(1-\rho_{Nd}\right)\left(1-\rho_{Gd}\right)S_2}\left|\begin{matrix}1-\frac{\xi_d+\xi_c+\psi_c}{2},1-\frac{\xi_d+\xi_c-\psi_c}{2},1-\frac{\xi_d}{2}\\ \psi_d/2,-\psi_d/2,-\xi_d/2\end{matrix}\right.\right)\\&+G_{4,4}^{2,4}\left(\frac{m_d\left(1-\rho_{Nc}\right)\left(1-\rho_{Gc}\right)t}{m_c\left(1-\rho_{Nd}\right)\left(1-\rho_{Gd}\right)S_1}\left|\begin{matrix}0,1-\frac{\xi_d+\xi_c+\psi_c}{2},1-\frac{\xi_d+\xi_c-\psi_c}{2},1-\frac{\xi_d}{2}\\ \psi_d/2,-\psi_d/2,1,-\xi_d/2\end{matrix}\right.\right)\\&\times G_{3,3}^{2,3}\left(\frac{m_d\left(1-\rho_{Nc}\right)\left(1-\rho_{Gc}\right)t}{m_c\left(1-\rho_{Nd}\right)\left(1-\rho_{Gd}\right)S_2}\left|\begin{matrix}1-\frac{\xi_d+\xi_c+\psi_c}{2},1-\frac{\xi_d+\xi_c-\psi_c}{2},1-\frac{\xi_d}{2}\\ \psi_d/2,-\psi_d/2,-\xi_d/2\end{matrix}\right.\right)\\&+G_{3,3}^{2,3}\left(\frac{m_d\left(1-\rho_{Nc}\right)\left(1-\rho_{Gc}\right)t}{m_c\left(1-\rho_{Nd}\right)\left(1-\rho_{Gd}\right)S_1}\left|\begin{matrix}1-\frac{\xi_d+\xi_c+\psi_c}{2},1-\frac{\xi_d+\xi_c-\psi_c}{2},1-\frac{\xi_d}{2}\\ \psi_d/2,-\psi_d/2,-\xi_d/2\end{matrix}\right.\right)\\&\left.\times G_{4,4}^{2,4}\left(\frac{m_d\left(1-\rho_{Nc}\right)\left(1-\rho_{Gc}\right)t}{m_c\left(1-\rho_{Nd}\right)\left(1-\rho_{Gd}\right)S_2}\left|\begin{matrix}0,1-\frac{\xi_d+\xi_c+\psi_c}{2},1-\frac{\xi_d+\xi_c-\psi_c}{2},1-\frac{\xi_d}{2}\\ \psi_d/2,-\psi_d/2,1,-\xi_d/2\end{matrix}\right.\right)\right).\end{aligned} \tag{9}$$

III. Outage Probability

Outage probability P_{out} is one of the accepted performance measures for the control of the cochannel interference level. It also helps designers of wireless communication systems to meet the quality of service and grade of service demands in diversity systems operating in fading environments. In the interference limited environment, P_{out} is defined as the probability that the output SIR of the SC falls below the given outage threshold γ_{th}, also known as a protection ratio:

$$P_{\text{out}}=P_R\left(\lambda<\gamma\right)=\int_0^\gamma p_\lambda\left(t\right)dt=F_\lambda\left(\gamma\right). \tag{10}$$

In Fig. 1, the dependence of outage probability on normalized instantaneous SIR λ/S is presented for two values of the Nakagami-m shaping parameter for desired signal m_d. The increase of m_d value causes P_{out} to decrease, and this effect is more emphasized for small values of λ/S. The influence of the interference signal Nakagami-m fading parameter m_c on P_{out} is negligible when other parameters are chosen as in Fig. 1. The shadowing parameter of interfering signal k_c dramatically affects the outage probability, so the increase of this value

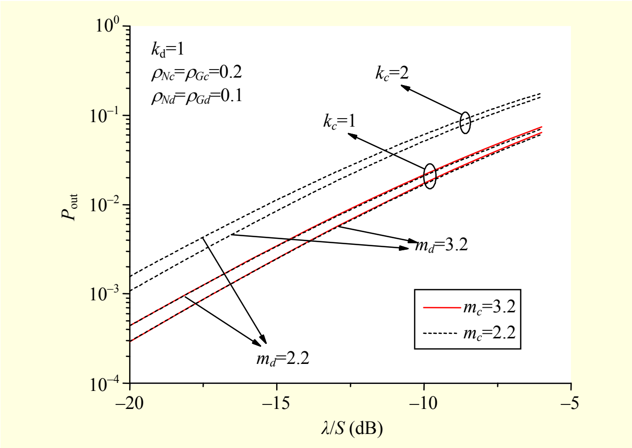

Fig. 1. Outage probability for two values of parameter m_d.

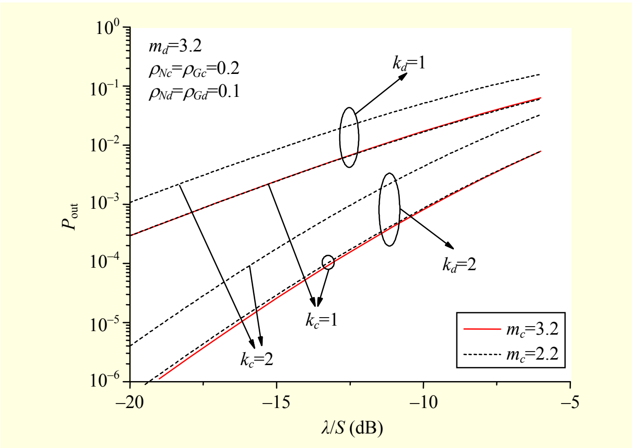

Fig. 2. Outage probability for two values of parameter k_d.

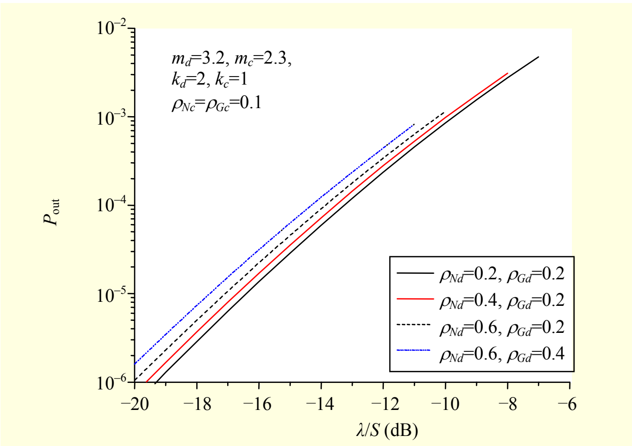

Fig. 3. Influence of correlation coefficients between desired signals on outage probability.

significantly impairs system performance. However, the shadowing parameter of the desired signal k_d, among all the other parameters of composite fading, shows the largest impact on the system performance, as illustrated in Fig. 2. (Lower P_{out} corresponds to larger k_d values.)

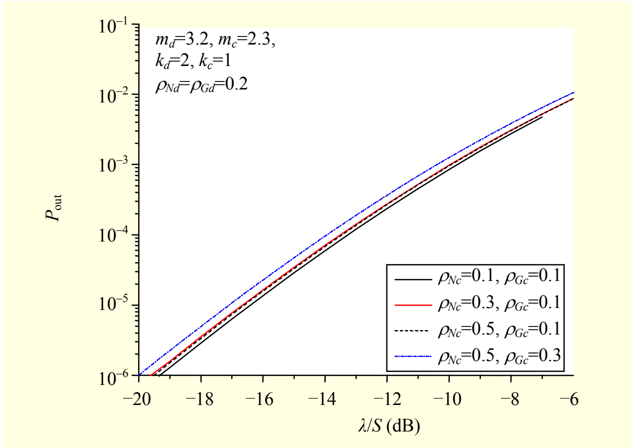

Fig. 4. Influence of correlation coefficients between interfering signals on outage probability.

In Fig. 3, the influence of correlation coefficients between desired signals ρ_{Nd} and ρ_{Gd} on P_{out} is analyzed. For small λ/S values, one can notice that lower values of ρ_{Gd} improve system characteristics, while this effect is much less significant for larger λ/S values. The influence of the ρ_{Nd} coefficient stays equally emphasized for a wide range of λ/S values.

In Fig. 4, the influence of correlation coefficients between interfering signals ρ_{Nc} and ρ_{Gc} on P_{out} is presented. The influence of the ρ_{Nc} coefficient is almost negligible, while larger ρ_{Gc} values lead to the increase of P_{out}.

The numerical results presented in this paper are obtained in the domain of λ/S values which satisfy the conditions of definiteness [11], [13] for the employed Meijer G functions.

IV. Conclusion

This paper studies the effects of simultaneous multipath fading and shadowing over the correlated propagation channels in the presence of cochannel interference on the performances of the SIR-based dual-branch SC diversity receiver. A generalized fading/shadowing channel model in interference-limited correlated fading environment was modeled by K_G distribution. The new closed-form expressions for PDF and CDF of SIR at the output of the SC receiver were derived. Using these new formulae, the outage probability was efficiently evaluated. As an illustration of the mathematical formalism, numerical results of this performance criterion are graphically presented, describing the dependence on the correlation level fading and shadowing severity parameters.

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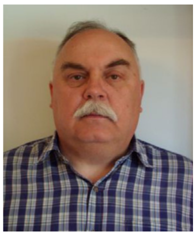

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