Effect of Microdiversity and Macrodiversity on Average Bit Error Probability in Shadowed Fading Channels in the Presence of Interference

Aleksandra S. Panajotović, Mihajlo Č. Stefanović, and Dragan Lj. Drača

The detrimental effect of short-term fading and shadowing can be mitigated using microdiversity and macrodiversity systems, respectively. In this paper, implementation of selection combining at both micro and macro levels to improve system performance is analyzed. An assessment of the performance of such a system is carried out by considering the desired signal as Rician fading with lognormal shadowing and cochannel interference signal as Rayleigh fading superimposed over lognormal shadowing. The proposed analysis is complemented by various performance evaluation results, including the effects on overall system performance of fading severity, shadowing spreads and branch correlation existing at the base station, and correlation between base stations.

Keywords: Shadowed fading channels, cochannel interference, microdiversity, macrodiversity, correlated channels, average bit error probability (ABEP).

Manuscript received Jan. 9, 2009; revised Apr. 16, 2009; accepted Apr. 21, 2009.

Aleksandra S. Panajotović (phone: +381 18 529 309, email: aleksandra.panajotovic@elfak.ni.ac.rs), Mihajlo Č. Stefanović (email: mihajlo.stefanovic@elfak.ni.ac.rs), and Dragan Lj. Drača (email: dragan.draca@elfak.ni.ac.rs) are with the Faculty of Electrical Engineering, University of Niš, Niš, Serbia.

doi:10.4210/etrij.09.0109.0011

I. Introduction

In wireless communication systems, the received signal may suffer from both fading and shadowing. Fading is the result of multipath propagation, and shadowing is the result of large obstacles in the propagation path that block the signal. To describe the effect of shadowing, a lognormal distribution is generally used to characterize the mean-square value of the received signal [1]. Various fading models can be used to describe the fading envelope of the received signal. The most frequently used models are Nakagami, Rayleigh, Rician, and Weibull [2].

The channel in a wireless communication system is simultaneously subjected to fading and shadowing, which makes it more vulnerable to performance degradation. Diversity is a powerful processing technique used to mitigate shadowed fading channel impairments. It exploits the random nature of wireless propagation by combining or selecting from two or more fading signal paths, which results in improved system performance. Microdiversity reduces the effect of short-term fading at the base station [3], [4]. The most popular microdiversity techniques are selection combining (SC), equal gain combining, and maximal ratio combining. Among these types of diversity combining, SC, the diversity technique considered in this paper, has the least implementation complexity because SC-type systems process only one of the microdiversity branches [2]. To mitigate the effects of shadowing in wireless systems, the macrodiversity technique can be used [1], [5]. In macrodiversity, a group of base stations is available to serve each cell. The base station having received the signal with the largest local mean-square value is selected to set up the communication link with the user. It is the most commonly used macrodiversity combining method [6], although other macrodiversity combining methods have been proposed to improve the diversity gain and the system capacity [7]. While each base station applies a microdiversity technique to alleviate fading, the simultaneous use of multiple base stations and the processing signals from these base stations provides an opportunity to improve the system performance in shadowed fading channels [8].

In this paper, we consider the effectiveness of microdiversity and macrodiversity techniques to combat the degradation problems in shadowed fading channels in the presence of cochannel interference (CCI) using dual SC at the micro (two diversity branches at the base station) and macro (two base stations) levels. In a microcell environment, an undesired signal from a distant cochannel cell may well be modeled by Rayleigh statistics; however, Rayleigh fading may not be a good assumption for the desired signal because a line-of-sight (LoS) path may exist within a microcell [9]-[11]. Then, the Rician distribution is often used to model a propagation path consisting of one strong direct LoS signal and many randomly reflected and usually weaker signals [12]. Therefore, in this situation, different fading statistics are needed to characterize the desired and undesired signals in a microcellular radio system. The performance analysis of macrodiversity, microdiversity, and their composition are reported in numerous research papers. For example, there have been many technical studies concerning dual SC microdiversity systems in either correlated or uncorrelated fading channels [13]-[17]. Previous studies on macrodiversity systems have evaluated the cochannel interference performance with shadowing only [6], [18], [19] and shadowed fading channels [20], [21]. Moreover, in the presence of both shadowing and fading, the error rate performance of macrodiversity systems has been analyzed [4], [22], [23]. The use of composite microdiversity and macrodiversity has been investigated to simultaneously combat both fading and shadowing. Error performance of such systems has been the subject of many studies [8], [24]-[26]. However, these papers did not consider the effects of CCI. This is the reason for investigating the effect of both correlated lognormal shadowing and correlated Rician fading on the average bit error probability (ABEP) of digital cellular systems with microdiversity and macrodiversity reception in the presence of CCI. Numerical results for ABEP of differential binary phase-shift keying (DBPSK) systems are graphically presented to show the effect on system performance of various system parameters, such as fading severity, shadowing spreads and branch correlation existing at the base station, and correlation between base stations.

To the best of the authors' knowledge, the performance of the system considered in this paper has not been previously addressed.

II. System Model

A cellular mobile radio system in which two base stations are used to serve each cell is considered in the paper. In this system model, each base station has a dual-branch SC microdiversity combiner operating in a correlated Rician fading channel with correlated lognormal shadowing. Wireless systems are subject to the unwelcome effects of CCI arising from other channels, operating at the same frequency located away from the desired channel [27]-[29]. This CCI is also subject to both fading and shadowing, and it is necessary to consider all these effects in assessing the performance of wireless systems [20], [21], [30]. Therefore, in this paper, we consider the case of a single CCI (the strongest CCI), as in [15]-[17] and [31]-[33].

The starting point of analyzing this system is the implementation of diversity at the base station, that is, the implementation of microdiversity. Instead of the simple case of the channels being independent, channels are correlated, with constant correlation. The conditional probability density function (PDF) of the output signal-to-interference ratio (SIR) at the dual SC microdiversity combiner in the shadowed fading channel can be expressed as in [34] as

$$
\begin{aligned}
& p\left(\mu_j / \beta_j, \Omega_{1j}\right) \\
& = \exp\left(-\frac{2K}{1+r}\right) \sum_{k,p,n,l,m=0}^{\infty} \frac{\varepsilon_k K^{p+l+k}}{\beta_j^{2n+2k+p+l+2}} \\
& \times \frac{(1-r)^{p+l+k+2}(1+K)^{2n+2k+p+l+2}\mu_j^{2n+2k+p+l+1}\Omega_{1j}^{2n+2k+p+l+2}}{n!\,p!\,m!\,l!\,\Gamma(m+1)} \\
& \times \frac{\Gamma(n+p+k+m+2)\Gamma(n+l+k+m+2)\, r^{2m+2n+k}}{\Gamma(l+k+1)\Gamma(n+k+1)\Gamma(p+k+1)(1+r)^{p+l+k-2}} \\
& \times \left(\frac{{}_2F_1\left[n+l+k+m+2, n+l+k+1, n+l+k+2, -\alpha_j\mu_j\right]}{(n+l+k+1)(1+\alpha_j\mu_j)^{n+p+k+m+2}} \right. \\
& \left. + \frac{{}_2F_1\left[n+p+k+m+2,\ n+p+k+1,\ n+p+k+2,\ -\alpha_j\mu_j\right]}{(n+p+k+1)(1+\alpha_j\mu_j)^{n+l+k+m+2}} \right),
\end{aligned}
$$

$$
\varepsilon_k = \begin{cases} 1, & k=0, \\ 2, & k\neq 0, \end{cases} \qquad (1)
$$

where r is the correlation between branches existing at the base station, K is the Rice factor defined as the ratio of the signal power in the dominant component over the scattered power, and β_j and Ω_{1j} are the local mean power of the desired and interference signals, respectively. Here, $\Gamma(\cdot)$ is the Gamma function, ${}_2F_1$ [a, b, c, d] is the Gaussian hypergeometric function, and $\alpha_j = \Omega_{1j}(1+K)/\beta_j$. The conditioning in (1) reflects the existence of shadowing, with β_j and Ω_{Ij} being random variables with lognormal PDF. That is,

$$p_{\Omega}(x) = \frac{1}{\sqrt{2\pi}\sigma x}\exp\left(-\frac{(\ln x - \ln\mu)^2}{2\sigma^2}\right), \quad (2)$$

where σ is the shadow standard deviation (often refered to as shadowing spread). The area mean power, μ, may be estimated as in [21] using

$$\mu = \frac{P_t C}{d^a (1+d/g)^b}, \quad (3)$$

where P_t is the transmitted power, C is constant that incorporates the effects of antenna gain, d is distance between the transmitter and receiver, g is the break point, a is the basic path-loss exponent, and b is the additional path-loss exponent.

The case of two base stations will be considered in this paper for implementation of macrodiversity as indicated by j ($j = 1, 2$) in (1). It is assumed that the local mean power of the desired signal β_j is available for each base station. In practice, the base station with the largest β_j is selected to provide service to a user

$$\beta = \max\{\beta_1, \beta_2\}. \quad (4)$$

Very often, correlation exists between base stations due to insufficient spacing between them, especially in microcell systems. In such a case, the PDF of the output local mean power of the desired signal at the dual selection combining macrodiversity system is expressed as in [21] as

$$p_{\beta}(y) = \frac{\sqrt{2}}{\sqrt{\pi}\sigma_d y}\left[1 - Q\left(\left(\frac{1-\rho}{\sqrt{1-\rho^2}}\right)\left(\frac{\ln y - \ln\mu_d}{\sigma_d}\right)\right)\right] \times \exp\left(-\frac{(\ln y - \ln\mu_d)^2}{2\sigma_d^2}\right), \quad (5)$$

where $Q(z) = \int_z^{\infty}\left(1/\sqrt{2\pi}\right)\exp\left(-x^2/2\right)dx$, and ρ is the correlation between base stations, σ_d is shadow standard deviation of the desired signal, and μ_d is area mean power of the desired signal.

The ABEP is the one of the most important performance criterion. In the system with microdiversity and macrodiversity reception, ABEP is given for DBPSK as in [4], [17], and [22] by

$$\overline{P_e} = \int_0^{\infty}\int_0^{\infty}\int_0^{\infty}\frac{1}{2}\exp(-\mu)\,p(\mu/\beta,\Omega_I)\,p_{\beta}(\beta) \times p_{\Omega_I}(\Omega_I)\,d\beta\, d\Omega_I\, d\mu, \quad (6)$$

where

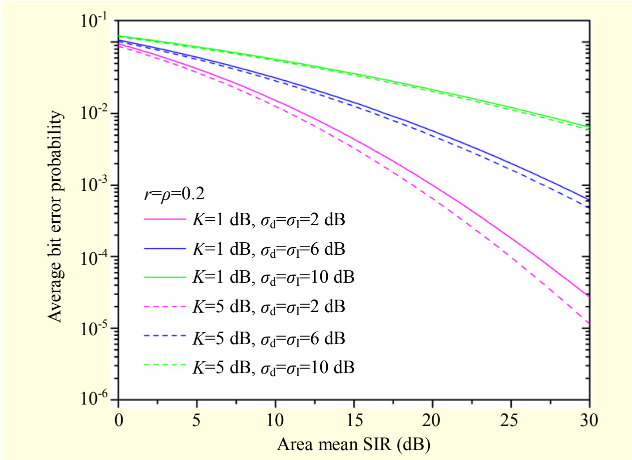

Fig. 1. Average bit error probability of a DBPSK system versus area mean signal-to-interference power ratio for several Rice factor and shadowing spread values.

$$p_{\Omega_I}(x) = \frac{1}{\sqrt{2\pi}\sigma_I x}\exp\left(-\frac{(\ln x - \ln\mu_I)^2}{2\sigma_I^2}\right), \quad (7)$$

where σ_I is the shadow standard deviation and μ_I is area mean power of the interference signal.

III. Numerical Results

In this section, the ABEP for the system employing microdiversity and macrodiversity is obtained numerically. To illustrate the influence of various system parameters on the ABEP in a correlated lognormal shadowing environment, the numerical results are presented for a DBPSK system in a correlated Rician fading channel in the presence Rayleigh distributed CCI.

Figure 1 shows the effect of fading severity and shadowing spreads on system performance. We observe that system performance deteriorates as fading severity and/or shadowing spread increases. Also, the influence of the Rice factor on the ABEP value is reduced as the shadow standard deviation increases. For values of practical interest of lognormal shadowing, σ is in the range of 2 dB to 10 dB [8]. Figure 1 shows the negligible effect of fading severity on the error performance of the system for the upper limit of shadow standard deviation.

Figure 2 shows the influence of correlation between base stations, and Fig. 3 shows the influence of correlation at a base station. From these figures, it is evident that, as the correlation coefficients increase, the error performance of the system is degraded. For example, at an ABEP of 10^{-3}, a 2.2 dB margin is required for the system with correlated shadowing with $\rho = 0.6$ to provide the same performance as that for the system with $\rho = 0.2$ when $\sigma_d = \sigma_I = 4$ dB (Fig. 2). The required margin is

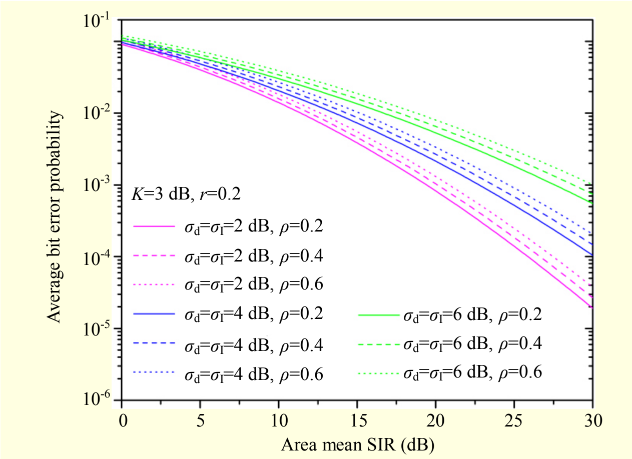

Fig. 2. Average bit error probability of a DBPSK system versus area mean signal-to-interference power ratio for several values of correlation between base stations.

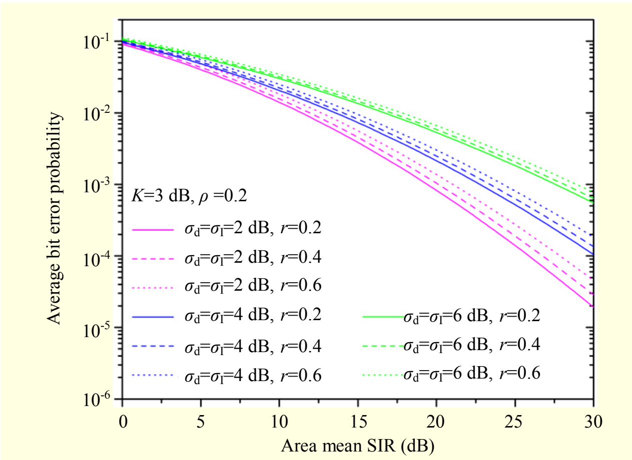

Fig. 3. Average bit error probability of a DBPSK system versus area mean signal-to-interference power ratio for several values of correlation at the base station.

reduced to 1.5 dB when correlation at the base station decreases from r = 0.6 to r = 0.2 (Fig. 3). Also, Figs. 2 and 3 demonstrate that the influence of correlation coefficient variation on system performance depends on shadow standard deviation of both desired and interference signals. This effect is more noticeable for correlation between base stations than for correlation at the base station.

The main problem in the infinite-series expression of (1) is its convergence. Obtained numerical results have shown that the number of terms required in every five sums that need to be summed to attain the desired ABEP accuracy strongly depends on the fading severity, correlation coefficients, and shadowing spread, as shown in Tables 1 and 2. The results in Tables 1 and 2 demonstrate that the number of terms required to obtain three-significant-figure accuracy of the ABEP increases as the previously mentioned parameters increase. Also, it is evident

Table 1. Number of terms of (6) required for three-significant-figure accuracy (area mean SIR = 10 dB, ρ = 0.2).

	$\sigma_d = \sigma_I = 2$ dB		$\sigma_d = \sigma_I = 6$ dB		$\sigma_d = \sigma_I = 10$ dB	
	K=3 dB	K=5 dB	K=3 dB	K=5 dB	K=3 dB	K=5 dB
r=0.2	5	7	6	8	7	9
r=0.4	5	7	6	8	7	9
r=0.6	7	11	9	12	12	13

Table 2. Number of terms of (6) required for three-significant-figure accuracy (area mean SIR = 10 dB, r = 0.2).

	$\sigma_d = \sigma_I = 2$ dB		$\sigma_d = \sigma_I = 6$ dB		$\sigma_d = \sigma_I = 10$ dB	
	K=3 dB	K=5 dB	K=3 dB	K=5 dB	K=3 dB	K=5 dB
ρ=0.2	5	7	6	8	7	9
ρ=0.4	5	7	7	9	8	9
ρ=0.6	6	8	7	9	8	9

that variation of the correlation coefficient between base stations provokes faster convergence of the ABEP than variation of the correlation coefficient at the base station.

IV. Conclusion

It is well known that the combination of microdiversity and macrodiversity is more efficacious in achieving improvement of system performance in shadowed fading channels than either microdiversity or macrodiversity. In this paper, ABEP, as the important performance criterion, was evaluated numerically for a system with microdiversity and macrodiversity reception over a correlated Rician fading channel in the presence of Rayleigh distributed CCI. The analysis considered the effect of correlated lognormal shadowing on the error performance of the system. The simple constant correlation model, in which the correlation coefficient between both microdiversity branches and base stations is a constant, was considered. Based on the proposed system model, the effect of fading severity, shadowing spread, and correlation at the base station and between base stations was analyzed. Obtained numerical results demonstrated that deterioration of system error performance is caused by decrease in the Rice factor and/or increase of shadowing spread. The computational results also indicate that when base stations in a cellular system are closely located, the system shows poor error performance which is more noticeable when the effect of shadowing is stronger. Moreover, an increase in the correlation between diversity branches at the base station leads to an increase in the ABEP. Semianalytical expression of the ABEP necessitates convergence of the infinity-series expression of the PDF of the output SIR at the diversity combiner. The verification of that convergence is the number of terms required for three-significant-figure accuracy of the ABEP presented in Tables 1 and 2. These results demonstrate the great dependence of the number of terms on fading severity, shadowing spread, and correlations.

References

[1] W.C. Jakes, *Microwave Mobile Communications*, New York: John Wiley & Sons, 1974.

[2] M.K. Simon and M.S. Alouini, *Digital Communication over Fading Channels*, New York: John Wiley & Sons, 2005.

[3] T.S. Rappaport, *Wireless Communications Principle and Practice*, New Jersey: Prentice-Hall, 1996.

[4] J. Zhang and V. Aalo, "Effect of Macrodiversity on Average-Error Probabilities in a Rician Fading Channel with Correlated Lognormal Shadowing," *IEEE Trans. Commun.*, vol. 49, no. 1, Jan. 2001, pp. 14-18.

[5] W.C.Y. Lee, *Mobile Communications Engineering*, New York: McGraw-Hill, 1982.

[6] R.C. Bernhardt, "Macroscopic Diversity in Frequency Reuse Radio Systems," *IEEE J. Select. Areas Commun.*, vol. 5, no. 5, June 1987, pp. 862-870.

[7] A.L. Brandao, L.B. Lopes, and D.C. McLernon, "Base Station Macrodiversity Combining Merge Cells in Mobile Systems," *Electron. Lett.*, vol. 31, no. 1, Jan. 1995, pp. 12-13.

[8] P.M. Shankar, "Analysis of Microdiversity and Dual Channel Macrodiversity in Shadowed Fading Channels Using a Compound Fading Model," *Int. J. Electron. Commun. (AEÜ)*, vol. 62, no. 6, June 2008, pp. 445-449.

[9] R.J. Bultitude and G.K. Bedal, "Propagation Characteristics on Microcellular Urban Mobile Radio Channels at 910 MHz," *IEEE J. Select. Areas Commun.*, vol. 7, no. 1, Jan. 1989, pp. 31-39.

[10] F. Adachi and K. Ottno, "Block Error Probability for Noncoherent FSK with Diversity Reception in Mobile Radio," *Electron. Lett.*, vol. 24, no. 24, Nov. 1988, pp. 1523-1525.

[11] Y.-D. Yao and A.U.H. Sheikh, "Investigations into Cochannel Interference in Microcellular Mobile Radio Systems," *IEEE Trans. Veh. Technol.*, vol. 41, no. 2, May 1992, pp. 114-123.

[12] R. Steel, "The Cellular Environment of Lightweight Handheld Portables," *IEEE Commun. Mag.*, vol. 27, no. 7, July 1989, pp. 20-29.

[13] N.C. Sagias, D.A. Zogas, and G.K. Karagiannidis, "Selection Diversity Receivers over Nonidentical Weibull Fading Channels," *IEEE Trans. Veh. Techol.*, vol. 54, no. 6, Nov. 2005, pp. 2146-2151.

[14] D.A. Zogas and G.K. Karagiannidis, "Infinite-Series Representations Associated with the Bivariate Rician Distribution and Their Applications," *IEEE Trans. Commun.*, vol. 53, no. 11, Nov. 2005, pp. 1790-1794.

[15] S. Okui, "Effects of CIR Selection Diversity with Two Correlated Branches in the m-Fading Channels," *IEEE Trans. Commun.*, vol. 48, no. 10, Oct. 2000, pp. 1631-1633.

[16] M.Č. Stefanović et al., "Performance Analysis of System with Selection Combining over Correlated Weibull Fading Channels in the Presence of Cochannel Interference," *Int. J. Electron. Commun. (AEÜ)*, vol. 62, no. 9, Sept. 2008, pp. 695-700.

[17] G.K. Karagianidis, "Performance Analysis of SIR-Based Dual Selection Diversity over Correlated Nakagami-m Fading Channels," *IEEE Trans. Veh. Technol.*, vol. 52, no. 5, Sept. 2003, pp. 1207-1216.

[18] Y.-S. Yeh, J.C. Wilson, and S.C. Schwartz, "Outage Probability in Mobile Telephony with Directive Antennas and Macrodiversity," *IEEE Trans. Veh. Techn.*, vol. 33, no. 3, Aug. 1984, pp. 123-127.

[19] L.-C. Wang and C.-T. Lea, "Macrodiversity Cochannel Interference Analysis," *Electron Lett*, vol. 31, no. 8, Apr. 1995, pp. 614-616.

[20] L.-C. Wang and C.-T. Lea, "Performance Gain of a S-Macrodiversity in a Lognormal Shadowed Rayleigh Fading Channel," *Electron. Lett.*, vol. 31, no. 20, Sept. 1995, pp. 1785-1787.

[21] L.-C. Wang, G.L. Stüber, and C.-T. Lea, "Effects of Rician Fading and Branch Correlation on a Local-Mean-Based Macrodiversity Cellular System," *IEEE Trans. Veh. Technol.*, vol. 48, no. 2, Mar. 1999, pp. 429-436.

[22] W.-P. Yung, "Probability of Bit Error for MPSK Modulation with Diversity Reception in Rayleigh Fading and Lognormal Shadowing Channel," *IEEE Trans. Commun.*, vol. 38, no. 7, July 1990, pp. 933-937.

[23] A.M.D. Turkmani, "Probability of Error for M-Branch Macroscopic Selection Diversity," *IEE Proc.-I: Commun. Speech and Vision*, vol. 139, no. 1, 1992, p. 71-78.

[24] A.M.D. Turkmani, "Performance Evaluation of a Composite Microscopic Plus Macroscopic Diversity System," *IEE Proc.-I: Commun. Speech and Vision*, vol. 138, no. 1, 1991, p. 15-20.

[25] A.A. Abu-Dayya and N.C. Beaulieu, "Micro- and Macrodiversity NCFSK (DPSK) on Shadowed Nakagami-Fading Channels," *IEEE Trans. Commun.*, vol. 42, no. 9, Sept. 1994, pp. 2693-2702.

[26] A.A. Abu-Dayya and N.C. Beaulieu, "Micro- and Macrodiversity MDPSK on Shadowed Frequency Selective Channels," *IEEE Trans. Commun.*, vol. 43, no. 8, Aug. 1995, pp. 2334-2343.

[27] A.A. Abu-Dayya and N.C. Beaulieu, "Outage Probabilities of Cellular Mobile Radio Systems with Multiple Nakagami Interferers," *IEEE Trans. Veh. Tech.*, vol. 40, no. 4, Nov. 1991, pp. 757-768.

[28] J. Reig and N. Cardona, "Approximation of Outage Probability on Nakagami Fading Channels with Multiple Interferers," *Elect. Lett.*, vol. 36, no. 19, Sept. 2000, pp. 1649-1650.

[29] P.M. Shankar, "Outage Analysis in Wireless Channels with

Multiple Interferers Subject to Shadowing and Fading Using Compound pdf Model," *Int. J. Electron. Commun. (AEÜ)*, vol. 61, no. 4, Apr. 2007, pp. 255-261.

[30] R. Prasad and A. Kegel, "Effects of Rician Faded and Log-Normal Shadowed Signals on Spectrum Efficiency in Microcellular Radio," *IEEE Trans. Veh. Tech.*, vol. 42, no. 3, Aug. 1993, pp. 274-280.

[31] A.S. Panajotović, M.Č. Stefanović, and D.Lj. Drača, "Performance Analysis of System with Selection Combining over Correlated Rician Fading Channels in the Presence of Cochannel Interference," *Int. J. Electron. Commun. (AEÜ)* (in press doi:10.1016/j.aeue.2008.08.001)

[32] J.H. Winters, "Optimum Combining in Digital Mobile Radio with Co-channel Interference," *IEEE J. Select. Areas Commun.*, vol. 2, no. 4, July 1984, pp. 528-539.

[33] D.V. Bandjur, M.Č. Stefanović, and M.V. Bandjur, "Performance Analysis of SSC Diversity Receiver over Correlated Ricean Fading Channels in Presence of Co-channel Interference," *Elec. Lett.*, vol. 44, no. 9, Apr. 2008, pp. 587-588.

[34] A. Panajotović et al., "Channel Capacity of SC Receiver over Rician Fading in the Presence of Cochannel Interference," *Proc. ETRAN'08*, 2008, p. TE 1.3.

Aleksandra S. Panajotović received the BSc, MSc, and PhD degrees in electrical engineering from the University of Niš, Serbia, in 1999, 2003, and 2007, respectively. Her previous research interests have included telecommunications theory and optical communication systems. Her current work mainly focuses on different aspects of wireless communications, with special emphasis on diversity combining techniques, statistical characterization and modeling of fading channels, and performance evaluation of systems subject to interference. She works as a teaching assistant with the Faculty of Electronic Engineering, University of Niš.

Mihajlo Č. Stefanović received the BSc, MSc, and PhD degrees in electrical engineering from the University of Niš, Serbia, in 1971, 1976, and 1979, respectively. His primary research interests are statistical communication theory and optical and wireless communications. His areas of interest also include applied probability theory, optimal receiver design, and synchronization. He has written or co-authored a great number of journal publications. He has also written five monographs. Dr. Stefanović is a professor with the Faculty of Electronic Engineering in University of Niš.

Dragan Lj. Drača received the BSc, MSc, and PhD degrees in electrical engineering from the University of Niš, Serbia, in 1975, 1981, and 1995, respectively. His field of research is optical and wireless communication systems and packet-based transport networking. He is author or co-author of great number of publications and two monographs. Dr. Drača is a professor with the Faculty of Electronic Engineering in University of Niš.