Outage Statistics of V2I Macro Diversity Communications over Interference Limited Composite Fading Channels

Caslav Stefanovic
Faculty of Natural Sciences and Mathematics, Kosovska Mitrovica, Serbia
caslav.stefanovic@pr.ac.rs

Stefan Panic
National Research Tomsk Polytechnic University, Tomsk, Russia
stefanpnc@tpu.ru

Georgy Osokin
National Research Tomsk Polytechnic University, Tomsk, Russia
geosokin@tpu.ru

Hranislav Milosevic
Faculty of Natural Sciences and Mathematics, Kosovska Mitrovica, Serbia
hranislav.milosevic@pr.ac.rs

Mihajlo Stefanovic
Faculty of Electronic Engineering
University of Nis
Nis, Serbia
mihajlo.stefanovic@elfak.ni.ac.rs

***Abstract*— This paper addresses outage statistics of vehicle-to-infrastructure (V2I) macro (MAC) diversity communications over interference limited (IL) fading channels. The MAC diversity selection combining (SC) reception is used to decrease the effect of the composite fading (the fading when multipath and shadowing are presented at the same time). Analytical framework for obtaining fast converging, infinite series expression for outage probability at the output of MAC SC diversity V2I communications model is developed and used to numerically present obtained results for various sets of V2I channel parameters.**

Keywords— MAC-diversity, outage statistics, V2X.

I. Introduction

The vehicular networks over fading channels are one of the main research fields with the tendency to increase overall traffic safety [1]-[2]. The knowledge of the propagation environment which can support low-latency (LL) vehicle-to-everything (V2X) communications under all traffic scenarios is the main issue due to the fact that vehicular networks are characterized by fast mobility of the cars with the antennas approximately at the same level [3]-[5]. Therefore, composite fading (multipath and shadowing) can cause severe degradation of the system performances in this type of communications. Moreover, co-channel interference (CCI) can cause additional impairments especially in urban V2X communication environments.

The outage statistics of SC (selection combining) macro (MAC) diversity for radio-frequency (RF) cellular wireless communications have already been addressed in references [6]-[9]. This type is practical reception technique for improving system performances in composite fading environments. Additionally, the impact of CCI can be decreased by MAC diversity [10]. Moreover, MAC diversity has already found its application for mm-wave communications [11]. The MAC SC diversity with micro (MIC) SC diversity due to its relatively simpler implementation design could play more dominant role in vehicular communications, since low-latency (LL) communications are expected in V2X networks.

Motivated by this, this paper addresses V2I MAC diversity communications with four RSUs each with m inputs in interference limited (IL) composite fading environment. We observe the scenario when desired signal as well as CCI signals are under the influence of the composite fading. The fast converging, infinite series expressions for the cumulative distribution functions at the output of the SC MIC diversity as well as the outage probability at the output of the SC MAC diversity are provided. Then, we provide the numerical examples at the output of the MAC V2I model with four RSUs each with *m* inputs for various sets of V2I parameters.

II. System Model

The SC MAC V2I communication is maintained simultaneously between the car and four SC MIC RSUs each with *m* inputs.

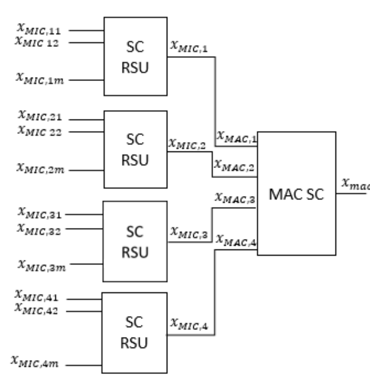

Fig. 1. V2I SC MAC diversity block scheme with four RSUs (each with *m* inputs).

The work was funded by the framework of Competitiveness Enhancement Program of the National Research Tomsk Polytechnic University, Russia.

TABLE I. CDF AT THE OUTPUT OF SC MAC SYS.

$$F_{X_{MAC}} = \int_0^{\infty} d\theta_{I,1} \int_0^{\infty} \mathrm{d}\theta_{S,1} \int_0^{\theta_{S,1}} \mathrm{d}\theta_{S,2} \int_0^{\theta_{S,1}} d\theta_{S,3} \int_0^{\theta_{S,1}} F_{X_{MAC,1}}(x_{MAC}) p_{\Theta_{S,1}\Theta_{S,2}\Theta_{S,3}\Theta_{S,4}}(\theta_{S,1}\theta_{S,2},\theta_{S,3},\theta_{S,4})\, p_{\Theta_{I,1}}(\theta_{I,1}) \mathrm{d}\theta_{S,4}$$
$$+\int_0^{\infty} d\theta_{I,2} \int_0^{\infty} \mathrm{d}\theta_{S,2} \int_0^{\theta_{S,2}} \mathrm{d}\theta_{S,1} \int_0^{\theta_{S,2}} \mathrm{d}\theta_{S,3} \int_0^{\theta_{S,2}} F_{X_{MAC,2}}(x_{MAC}) p_{\Theta_{S,1}\Theta_{S,2}\Theta_{S,3}\Theta_{S,4}}(\theta_{S,1}\theta_{S,2},\theta_{S,3},\theta_{S,4})\, p_{\Theta_{I,2}}(\theta_{I,2}) \mathrm{d}\theta_{S,4}$$
$$+\int_0^{\infty} d\theta_{I,3} \int_0^{\infty} \mathrm{d}\theta_{S,3} \int_0^{\theta_{S,3}} \mathrm{d}\theta_{S,1} \int_0^{\theta_{S,3}} \mathrm{d}\theta_{S,2} \int_0^{\theta_{S,3}} F_{X_{MAC,3}}(x_{MAC}) p_{\Theta_{S,1}\Theta_{S,2}\Theta_{S,3}\Theta_{S,4}}(\theta_{S,1}\theta_{S,2},\theta_{S,3},\theta_{S,4})\, p_{\Theta_{I,3}}(\theta_{I,3}) \mathrm{d}\theta_{S,4}$$
$$+\int_0^{\infty} d\theta_{I,4} \int_0^{\infty} \mathrm{d}\theta_{S,4} \int_0^{\theta_{S,4}} \mathrm{d}\theta_{S,1} \int_0^{\theta_{S,4}} \mathrm{d}\theta_{S,2} \int_0^{\theta_{S,4}} F_{X_{MAC,4}}(x_{MAC}) p_{\Theta_{S,1}\Theta_{S,2}\Theta_{S,3}\Theta_{S,4}}(\theta_{S,1}\theta_{S,2},\theta_{S,3},\theta_{S,4})\, p_{\Theta_{I,4}}(\theta_{I,4}) \mathrm{d}\theta_{S,3} \quad (9)$$

The RSUs outputs are then connected to the input of MAC SC receiver. The Fig. 1 shows SC MAC V2I block scheme.

The signals at the inputs of four SC MIC RSUs in IL environment are defined as [4]-[5]:

$$x_{MIC,ij} = \frac{x_{S,MIC,ij}}{x_{I,MIC,ij}}, \ i = 1,4;\ j = 1,m; \quad (1)$$

The desired signals, $x_{S,MIC,ij}$ follow well-known Rayleigh pdfs [12]:

$$p_{X_{S,MIC,ij}}(x_{S,MIC,ij}) = \frac{2x_{S,MIC,ij}}{\theta_{S,i}} e^{-\frac{x_{S,MIC,ij}^2}{\theta_{S,i}}}, i = 1,4;\ j = 1,m; \quad (2)$$

where $\theta_{S,i}$ are average powers of $x_{S,MIC,ij}$. Accordingly, CCI signals $x_{I,MIC,ij}$ follow also Rayleigh pdfs [12]:

$$p_{X_{I,MIC,ij}}(x_{I,MIC,ij}) = \frac{2x_{I,MIC,ij}}{\theta_{I,i}} e^{-\frac{x_{I,MIC,ij}^2}{\theta_{I,i}}}, i = 1,4;\ j = 1,m; \quad (3)$$

where $\theta_{I,i}$ are average powers of $x_{I,MIC,ij}$.

The conditional probability density functions (pdfs) at the inputs of SC MIC RSUs can be derived by [13, (3.478.1)] and after simple algebraic transformations:

$$p_{X_{MIC,ij/\theta_{S,i}\theta_{I,i}}} = \int_0^{\infty} x_{I,MIC,ij} p_{X_{S,MIC,ij}}(x_{MIC,ij} x_{I,MIC,ij}) p_{X_{I,MIC,ij}}(x_{I,MIC,ij}) dx_{I,MIC,ij}$$

$$= 2\theta_{S,i}\theta_{I,i} \frac{x_{MIC,ij}}{(\theta_{S,i}+\theta_{I,i} x_{MIC,ij}^2)^2}, \ i = 1,4;\ j = 1,m \quad (4)$$

The cumulative density functions (cdfs) at the inputs of SC MIC RSUs are [12]:

$$F_{X_{MIC,ij}}(x_{MIC,ij}) = \int_0^{x_{MIC,ij}} p_{X_{MIC,ij}}(t) dt$$

$$\frac{\theta_{I,j} x_{MIC,ij}^2}{\theta_{S,i}+\theta_{I,i} x_{MIC,ij}^2}, i = 1,4;\ j = 1,m; \quad (5)$$

The cdfs at the outputs of SC MIC RSUs for independent and identically distributed (i.i.d) random processes are:

$$F_{X_{MIC,i}} = F_{X_{MIC,ij}}(x_{MIC,i})^m = \frac{\theta_{I,i}^{\ m} x_{MIC,i}^{\ 2m}}{(\theta_{S,i}+\theta_{I,i} x_{MIC,i}^2)^m}, i = 1,4; \quad (6)$$

In order to take the correlation of the desired signals between RSUs, the pdfs of average powers $\theta_{S,i}$ at the inputs of four MIC SC RSUs are distributed according to correlated joint Gamma pdf [6. Eq. 12]:

$$p_{\Theta_{S,1}\Theta_{S,2}\Theta_{S,3}\Theta_{S,4}}(\theta_{S,1}\theta_{S,2},\theta_{S,3},\theta_{S,4})$$
$$= \frac{(\theta_{S,1}\theta_{S,4})^{\frac{c_S-1}{2}} \prod_{i=1}^{3} I_{c_S-1}\left(\frac{2}{\theta_0(1-\rho)}\sqrt{\rho\theta_{S,i}\theta_{S,i+1}}\right)}{\Gamma(c_S)(1-\rho)^3 \rho^{\frac{3(c_S-1)}{2}} \theta_{S,0}^{\ 3+c_S}}$$
$$\times e^{-\frac{\theta_{S,1}+(1+\rho)(\theta_{S,2}+\theta_{S,3})+\theta_{S,4}}{\theta_{S,0}(1-\rho)}} \quad (7)$$

where $I_y(\cdot)$ is the first kind modified Bessel function of the order y (which can easily be transformed by [13, (8.445)], $\Gamma(\cdot)$ is the (complete) Gamma function, ρ is parameter which describes correlation, c_S is severity parameter for shadowing and $\theta_{S,0}$ is mean value of $\theta_{S,1}, \theta_{S,2}, \theta_{S,3}$ and $\theta_{S,4}$. The CCI signals with mean powers $\theta_{I,i}$ follow i.i.d Gamma random processes [13]:

$$p_{\theta_{I,i}}(\theta_{I,i}) = \frac{1}{\Gamma(c_I)\theta_{I,0}^{\ c_I-1}} \theta_{I,i}^{\ c_I-1} e^{-\frac{\theta_{I,i}}{\theta_{I,0}}}, i = 1,4; \quad (8)$$

where c_I is severity parameter for CCI shadowing and $\theta_{I,0}$ is average power of $\theta_{I,1}$, $\theta_{I,2}$, $\theta_{I,3}$ and $\theta_{I,4}$. The MAC SC chooses the MIC RSUs with the maximum $\theta_{S,i}$ at their inputs. Thus, the expression for cdf at the output of MAC SC can be derived from (9), which has been shown at the top of the page, where MIC outputs present MAC inputs ($x_{MIC,i} = x_{MAC,i}$).

TABLE II. P_{out} AT THE OUTPUT OF SC MAC SYS.

$$
\begin{aligned}
P_{out}\left(x_{th,MAC}\right) = & \frac{2{x_{th,MAC}}^{2m}}{\Gamma(c_I){\theta_{I,0}}^{c_I}\Gamma(c_S)(1-\rho)^3\rho^{\frac{3}{2}(c_S-1)}{\theta_{S,0}}^{c_S+3}} \sum_{i_1=0}^{\infty}\left(\frac{\sqrt{\rho}}{\theta_{S,0}(1-\rho)}\right)^{2i+c_S-1} \frac{1}{i_1!\,\Gamma(i_1+c_S)} \sum_{i_2=0}^{\infty}\left(\frac{\sqrt{\rho}}{\theta_{S,0}(1-\rho)}\right)^{2i_2+c_S-1} \frac{1}{i_2!\,\Gamma(i_2+c_S)} \\
& \times \sum_{i_3=0}^{\infty}\left(\frac{\sqrt{\rho}}{\theta_{S,0}(1-\rho)}\right)^{2i_3+c_S-1} \frac{1}{i_3!\,\Gamma(i_3+c_S)} \frac{1}{i_2+i_3+c_S} \sum_{i_4=0}^{\infty}\left(\frac{1}{\theta_{S,0}(1-\rho)}\right)^{i_4} \sum_{i_5=0}^{\infty}\frac{1}{(i_2+i_3+c_S+1)_{(i_5)}} \frac{(1+\rho)^{i_5}}{\left(\theta_{S,0}(1-\rho)\right)^{i_5}} \frac{1}{i_3+c_S} \\
& \times \sum_{i_6=0}^{\infty}\frac{1}{(i_3+c_S+1)_{(i_6)}} \frac{1}{\left(\theta_{S,0}(1-\rho)\right)^{i_6}} \frac{\Gamma(2i_1+2i_2+2i_3+i_4+i_5+i_6+4c_S)\Gamma(2i_1+2i_2+2i_3+i_4+i_5+i_6+4c_S+c_I)\Gamma(c_I+m)}{\Gamma(2i_1+2i_2+2i_3+i_4+i_5+i_6+4c_S+c_I+m)} \\
& \times {}_2F_1\left(2i_1+2i_2+2i_3+i_4+i_5+i_6+4c_S+c_I, c_I+m, 2i_1+2i_2+2i_3+i_4+i_5+i_6+4c_S+c_I+m, 1-\frac{\theta_{S,0}(1-\rho)}{2\theta_{I,0}(2+\rho){x_{th,MAC}}^2}\right) \\
& \times \frac{1}{{x_{th,MAC}}^{2(c_I+m)}}\left(\frac{\theta_{S,0}(1-\rho)}{2(2+\rho)}\right)^{2i_1+2i_2+2i_3+i_4+i_5+i_6+4c_S+c_I}\left(\frac{1}{i_1+i_2+c_S}\frac{(1+\rho)^{i_4}}{(i_1+i_2+c_S+1)_{(i_4)}}+\frac{1}{i_1+c_S}\frac{1}{(i_1+c_S+1)_{(i_4)}}\right)
\end{aligned}
\quad (11)
$$

III. NUMERICAL RESULTS

The outage probability of MAC SC V2I communication with four RSUs is defined as the probability that the output signal of MAC SC goes below the outage threshold $x_{th,MAC}$ [12]:

$$P_{out}\left(x_{th,MAC}\right) = \int_0^{x_{th,MAC}} p_{X_{MAC}}(t)\,dt = F_{X_{MAC}}\left(x_{th,MAC}\right) \quad (10)$$

The $P_{out}\left(x_{th,MAC}\right)$ in the form of infinite series expression can be obtained from (9) by using [13, (8.350.1)], [13, 8.351.2], [13, 9.210.1], [13, (9.211.4)] and [13, (7.621.6)] respectively, which is presented as expression (11) at the top of the page. The ${}_2F_1(a,p;h;x)$ is Gauss hypergeometric function and $(b)_{(v)}$ is Pochammer symbol [13].

The $P_{out}\left(x_{th,MAC}\right)$ of MAC SC V2I for various numbers of RSUs inputs (m) and the normalized values of signal and CCI severity parameters ($c_S = 1$, $c_I = 1$) as well as the normalized values of signal and CCI mean values ($\theta_{S,0} = 1$, $\theta_{I,0} = 1$), respectively are presented in Fig 2.. It can be seen that by increasing the m, the system performance improvement of the MAC SC V2I is provided, since the decreasing trend of $P_{out}\left(x_{th,MAC}\right)$ is evident.

Further, the $P_{out}\left(x_{th,MAC}\right)$ of MAC SC V2I for various values of fading severity parameters c_S and c_I and constant values of ($m = 2$, $\theta_{S,0} = 1$, $\theta_{I,0} = 1$) is shown in Fig 3.. As expected, by increasing the c_S, the $P_{out}\left(x_{th,MAC}\right)$ decreases, whereas by increasing the c_I, the $P_{out}\left(x_{th,MAC}\right)$ increases.

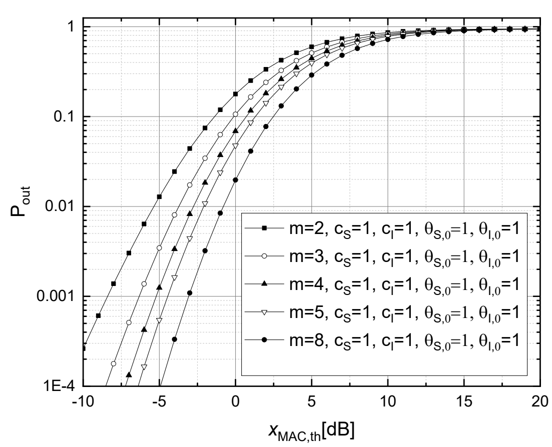

Fig. 2. $P_{out}\left(x_{th,MAC}\right)$ of V2I MAC SC for various numbers of RSUs inputs.

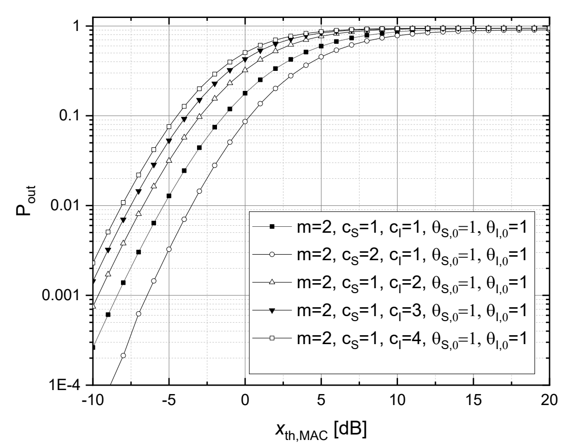

Fig. 3. $P_{out}\left(x_{th,MAC}\right)$ of V2I MAC SC for various values of V2I channel parameters.

IV. CONCLUSION

The MAC SC V2I communications with four RSUs in IL composite fading channel is considered. The infinite series expressions for cdf at the output of SC MIC diversity RSUs are derived and used for deriving $P_{out}(x_{th,MAC})$ of MAC SC V2I system. The results are numerically evaluated for four SC RSUs and analyzed for different number of RSUs inputs and different values of composite fading severity parameters. The increasement of the number of V2I RSUs inputs, could help improving the performance outcome of V2I MAC SC communications at reception. Further improvements of the observed model are achievable by increasing V2I channel severity parameters c_S while decreasing c_I. Our future works are directed toward the second order statistics and general model of V2I MAC SC communications.

ACKNOWLEDGMENT

The authors would like to acknowledge the support by the Ministry of Education, Science and Technical Development of Republic of Serbia, grant no. III44006 and IRACON COST Action 15104.

REFERENCES

[1] H. Peng, L. Liang, X. Shen, G. Y. Li, "Vehicular communications: A network layer perspective", *IEEE Trans. Veh. Technol.,* May 2018. DOI: 10.1109/TVT.2018.2833427.

[2] W. Viriyasitavat, M. Boban, H. M. Tsai, and A. Vasilakos, "Vehicular communications: Survey and challenges of channel and propagation models," *IEEE Veh. Technol. Mag*., vol. 10, no. 2, pp. 55–66, Jun. 2015.

[3] P. S. Bithas, G. P. Efthymoglou, A. G. Kanatas, "A cooperative relay selection scheme in V2V communications under interference and outdated CSI" *IEEE 27th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications 2016,* pp. 1-6, Sep. 2016.

[4] N. Milosevic, M. Stefanovic, Z. Nikolic, P. Spalevic, C. Stefanovic, "Performance Analysis of Interference-Limited Mobile-to-Mobile κ–μ Fading Channel." *Wireless Personal Communications,* vol. 101, no. 3, pp. 1685-1701, 2018.

[5] N. Milosevic, C. Stefanovic, Z. Nikolic, M. Bandjur, M. Stefanovic, "First-and Second-Order Statistics of Interference-Limited Mobile-to-Mobile Weibull Fading Channel", *Journal of Circuits, Systems and Computers*, vol. *27, no.* 11, p.1850168, 2018.

[6] P. M. Shankar,"Macrodiversity and microdiversity in correlated shadowed fading channels", *IEEE Trans. on Vehicular Technol.,* vol. 2, no. 58, pp. 727-732, 2009.

[7] D. A. Basnayaka, P. J. Smith, P. A.Martin, "Performance analysis of macrodiversity MIMO systems with MMSE and ZF receivers in flat Rayleigh fading", *IEEE Transactions on Wireless Communications*, vol. *12*, no. 5, pp. 2240-2251, 2013.

[8] C. Stefanovic, D. Djosic, "The LCR of wireless macrodiversity SSC receiver in presence of Gamma shadowed Kappa-Mu Fading", University Thought, Publication in Natural Sciences, vol. 6, pp. 32-37, 2016.

[9] C. Stefanovic, S. Jovkovic, V. Milenkovic, M. Stefanovic, "Outage Probability of Macro-Diversity with Switch-and-Stay Receiver over Gamma-Shadowed Kappa-Mu Multipath Fading Channel", *Journal of Advances in Computer Networks*, vol. *4, no.* 3, pp. 174-178, 2016.

[10] D. Stefanović, Č. Stefanović, D. Rančić, M. Stefanović, "Outage probability of macrodiversity system in the presence of Gamma long term fading Rayleigh short term fading and Nakagami-m CCI", *IEEE Eight International Conference ICUFN 2016, Proceedings of papers*, Vienna, Austria, July, 5-8, 2016, pp. 259-263.

[11] A. K. Gupta, J. G. Andrews, and R. W. Heath ,"Macro diversity in Cellular Networks with Random Blockages." *arXiv preprint arXiv:1701.02044*, 2017.

[12] S. Panic, M. Stefanovic, J. Anastasov, P. Spalevic, Fading and Interference Mitigation in Wireless Communications. CRC Press: New York, 2013.

[13] I. S. Gradshteyn, I. M. Ryzhik, *Table of Integrals, Series, and Products*, 6th ed., New York: Academic, 2000.