On the Effect of Channel Impairments on VANETs Performance

Konstantinos B. BALTZIS

RadioCommunications Laboratory, Dept. of Physics, Aristotle University of Thessaloniki, Thessaloniki 541 24, Greece

kmpal@physics.auth.gr

Abstract. *The primary means of studying the performance of vehicular ad hoc networks (VANETs) are computer simulations. Nowadays, the development of analytical models and the use of hybrid simulations that combine analytical modeling with discrete-event simulation are of great interest due to the significant reduction in computational cost. In this paper, we extend previous work in the area by suggesting an analytical model that includes distance-dependent losses, shadowing and small-scale fading. Closed-form expressions for the packet reception probability and the packet forwarding distance in the absence of simultaneous transmissions are presented. Numerical simulations validate the proposed formulation. The impact of path loss and fading on network throughput is explored. Interesting results that show the efficacy of the approach are provided. The derived formulation is a useful tool for the modeling and analysis of vehicular communication systems.*

Keywords

VANET, packet reception, hop count, packet forwarding distance, composite fading channel, path loss.

1. Introduction

An innovative and rapidly emerging class of ad hoc communication systems is vehicular ad hoc networks (VANETs). A VANET is a distributed and self-organizing wireless network built up from travelling vehicles that aims to provide communications among adjacent vehicles and between vehicles and nearby equipment, [1]. In VANETs, the nodes move around without any boundaries on their direction or speed. The arbitrary motion of vehicles and the unpredictability and wide variety of the propagation environment pose several challenges to engineers. Tests are usually being carried out through simulated environments before they are used in practice [2]. However, the computational cost of the simulations restricts their use in large-scale systems. A solution to this problem is the combination of discrete-event simulation with analytical modeling, [3].

Early proposals assumed a deterministic attenuation of the radio signal power over the transmission distance, [4]. However, a deterministic reception behavior is inaccurate because successful packet reception is determined by the comparison of the received signal power to the total (additive and multiplicative) noise level. Several studies, e.g. [3], [5-6], indicate that the Nakagami-*m* distribution, [7], enables an efficient characterization of the radio wave propagation in vehicular networks in the absence of simultaneous transmissions. Measured data, [8], have further shown that the Nakagami-*m* small-scale fading model combined with the Friis or the two-ray ground path loss model, [9], gives adequate results; however, these approaches neglect shadowing. On the other hand, many studies, e.g. [10-13], report on the impact of shadowing on the performance of vehicular ad hoc networks but underestimate or even ignore the small-scale fading effect.

In this paper, we extend the model proposed in [3] and [6] by further considering shadowing and the variability in the path loss exponent. In order to simplify the analysis, we neglect simultaneous transmissions; therefore, packet reception is determined only by the characteristics of the propagation medium. Simple closed-form expressions for the packet reception probability (PRP) and the packet forwarding distance are derived. Estimation of these performance metrics is useful in the analysis and performance evaluation of a VANET. In particular, packet reception probability reflects the loss rate caused by reception variation and it is commonly used in routing and broadcasting decisions, [14-15]; packet forwarding distance is related to parameters such as energy consumption, end-to-end packet delay and number of collisions, [16-17]. The proposed model is validated through simulations. We further investigate the impact of channel impairments on VANET throughput in terms of packet reception probability and packet forwarding distance. Use of the derived formulas simplify the analysis of vehicular ad hoc networks and reduces significantly the computational complexity of their simulations.

The rest of the paper is organized as follows: Section 2 discusses the theoretical background and presents the PRP model. Results and discussions are provided in Section 3. Finally, Section 4 concludes the paper.

2. The Proposed Model: Background and Mathematical Formulation

In the wireless environment, the mean path loss is usually expressed in the log domain as, [18], [19],

$$L = L_0 + 10n\log\left(d/d_0\right) + X_S + Y, \quad d \ge d_0 \tag{1}$$

where L_0 is the path loss at a reference distance d_0 which is chosen large enough to be in the far-field region of the transmitting antenna, n is the path loss exponent, d is the distance between the transmitting and receiving antennas, X_S is the shadowing term and Y describes the small-scale fading variation.

2.1 Distance-Dependent Path Loss Modeling

Signal propagation is strongly affected by the dissipation of the power radiated by the transmitter. Usually, we assume that distance-dependent losses are proportional to the nth-power of the distance between the communicating nodes. In particular, use of a strict power law instead of a piecewise one is common for extended ad hoc networks or when interferers are neglected; in this case, the use of piecewise laws have only second order effects on network performance, [20]. Therefore, in the absence of interferers, the average reception power at a distance d, Ω, and the reception threshold R_x are

$$\Omega \propto d^{-n} \tag{2}$$

and

$$R_x \propto d_{CR}^{-n} \tag{3}$$

where d_{CR} is the intended communication range, i.e. the deterministic maximum communication distance without fading.

2.2 Small-Scale Modeling

As it has already been mentioned, the Nakagami-m small-scale fading model combined with the previous model is, under certain assumptions, a suitable representation of signal propagation in the vehicular environment.

Let us assume a single transmitter (single sender scenario). In this case, according to the Nakagami-m distribution the cumulative distribution function (cdf) for a signal to be successfully received with power x for a given Ω at distance d, is [21],

$$F_n\left(x;m,\Omega\right) = \frac{m^m}{\Gamma(m)\Omega^m}\int_0^x z^{m-1}\exp\left(-\frac{mz}{\Omega}\right)dz \tag{4}$$

where m is the shape factor and $\Gamma(\cdot)$ denotes the complete gamma function. It can easily be shown that this expression can be written in a more compact form as

$$F_n\left(x;m,\Omega\right) = \frac{1}{\Gamma(m)}\gamma\left(m,\frac{m}{\Omega}x\right) \tag{5}$$

with $\gamma(\cdot,\cdot)$ the incomplete gamma function.

Obviously, the probability for a message to be successfully received in the absence of interferes is derived from the probability that its power is greater than the reception threshold. In this case, it has been found, [3], [6], that

$$\begin{aligned} P_R\left(x > R_x\right) &= 1 - F_n\left(R_x;m,\Omega\right) \\ &= 1 - \frac{1}{\Gamma(m)}\gamma\left(m,\frac{m}{\Omega}R_x\right). \end{aligned} \tag{6}$$

2.3 The Combined Effect of Small-Scale Fading and Shadowing

Shadowing is usually modeled as a lognormal random process, [18], [19], [21]. As a result, the pdf of the slowly varying signal power can be written as

$$f_S\left(r;\mu,s\right) = \frac{\xi}{\sqrt{2\pi}sr}\exp\left(-\frac{\left(10\log r - \mu\right)^2}{2s^2}\right), \quad r > 0 \tag{7}$$

where μ and s are the logarithmic mean and standard deviation, respectively, and $\xi = 10/\ln 10 \approx 4.343$.

In the proposed model, we consider the effect of both small-scale fading and shadowing on signal propagation. However, instead of treating them separately, we model their combined effect by the composite Nakagami-lognormal distribution as in [22]. In this case, the received signal power follows a gamma-lognormal distribution and the composite pdf for a signal to be received with power x is

$$f_c\left(x;m,s,\Omega\right) = \int_0^{+\infty}\left[\begin{array}{l}\dfrac{\xi m^m x^{m-1}}{\sqrt{2\pi}s\Gamma(m)z^{m+1}} \\ \times\exp\left(-\dfrac{mx}{z} - \dfrac{\left(10\log z - 10\log\Omega\right)^2}{2s^2}\right)\end{array}\right]dz \tag{8}$$

To the best of the author's knowledge, solution of (8) can not be given in closed form. However, $f_c(x; m, s, \Omega)$ can be accurately approximated by a lognormal pdf with logarithmic mean μ_C and deviation s_C given, [22], by

$$\mu_C = 10\log\Omega + \xi\left[\psi(m) - \ln m\right] \tag{9}$$

and

$$s_C = \sqrt{s^2 + \xi^2\zeta\left(2,m\right)}. \tag{10}$$

In the above expressions, notations $\Psi(\cdot)$ and $\zeta(\cdot,\cdot)$ denote the digamma and the Hurwitz zeta functions, [23]:

$$\begin{aligned} \psi(z) &\overset{\text{def}}{=} \frac{d}{dz}\ln\Gamma(z) \\ &= \frac{\Gamma'(z)}{\Gamma(z)} \end{aligned} \tag{11}$$

$$\zeta\left(z,n\right) \overset{\text{def}}{=} \sum_{k=0}^{+\infty}\left(n+k\right)^{-z}. \tag{12}$$

After some algebraic manipulation, we find that the approximate cdf for a signal to be received with power x for a given average power strength Ω is

$$F_c(x;m,s,\Omega) \approx \frac{1}{2}\left(1+\text{erf}\left(\frac{10\log x-\mu_C}{\sqrt{2}s_C}\right)\right). \quad (13)$$

In this case, (6) becomes

$$\begin{aligned} P_R(x>R_x) &= 1-F_c(R_x;m,s,\Omega) \\ &\approx \frac{1}{2}\text{erfc}\left(\frac{10\log R_x-\mu_C}{\sqrt{2}s_C}\right). \end{aligned} \quad (14)$$

2.4 Packet Reception Probability Formulas

The model in [3] and [6] neglects shadowing. Using (6) and setting $m = 3$ and $n = 2$ (Friis transmission formula, [9]), the model calculates the expected probability of successfully receiving a message at distance d given d_{CR} in the absence of simultaneous transmissions from the expression

$$P_R(d,d_{CR}) = \left(1+3\left(\frac{d}{d_{CR}}\right)^2+\frac{9}{2}\left(\frac{d}{d_{CR}}\right)^4\right)\exp\left(-3\left(\frac{d}{d_{CR}}\right)^2\right). \quad (15)$$

In our proposal, we substitute (2), (3), (9) and (10) into (14) and find that the probability of successful message reception at a distance d given d_{CR} for given channel parameters n, s and m is

$$P_R(d,d_{CR}) \approx \frac{1}{2}\text{erfc}\left(\frac{10n\log(d/d_{CR})+\xi(\ln m-\psi(m))}{\sqrt{2(s^2+\xi^2\zeta(2,m))}}\right). \quad (16)$$

3. Results and Discussion

In this Section, we first investigate the impact of channel impairments (small-scale fading, shadowing and distance-dependent losses) on packet reception probability in a vehicular ad hoc network by using the derived formulation. Next, we compare the theoretical results with simulation data and verify the accuracy of the proposed model. We finally discuss and evaluate an application of the new model in the calculation of the maximum packet forwarding distance in a hop-by-hop retransmission scheme. In our analysis, we ignore the interference from other nodes due to simultaneous transmissions.

3.1 The Impact of Channel Impairments on Packet Reception Probability

A simplified approach of signal propagation assumes a deterministic attenuation of the signal power over the transmission distance. This means that the packets are received with certainty within d_{CR} but at greater distances message reception is impossible. However, the signal variation due to fading decreases the probability of successful packet reception at distances smaller than the intented communication range but also allows successful signal reception at greater ones.

Fig. 1 illustrates the probability of packet reception with respect to the normalized to d_{CR} distance between two communicating nodes. The curves refer to the scenarios described by the deterministic, [4], the Nakagami/Friis with $m = 3$, [3], [6], and the proposed model. In order to assure a fair comparison between our proposal and the rest of the models, we neglect shadowing and set $m = 3$ and $n = 2$.

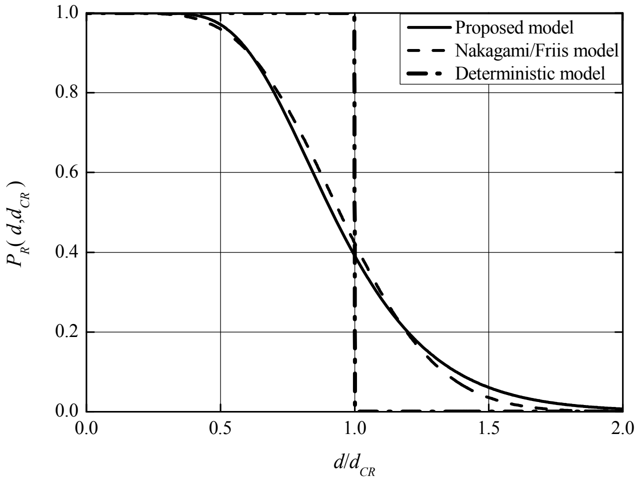

Fig. 1. Packet reception probability: Comparison between deterministic and probabilistic propagation models.

Notice the similarities between our proposal and the Nakagami/Friis model for the specific channel parameters; small differences are due to the approximation error introduced by the approximation of the composite gamma/lognormal pdf with a lognormal one. A striking discrepancy between the deterministic and the two stochastic models is obvious.

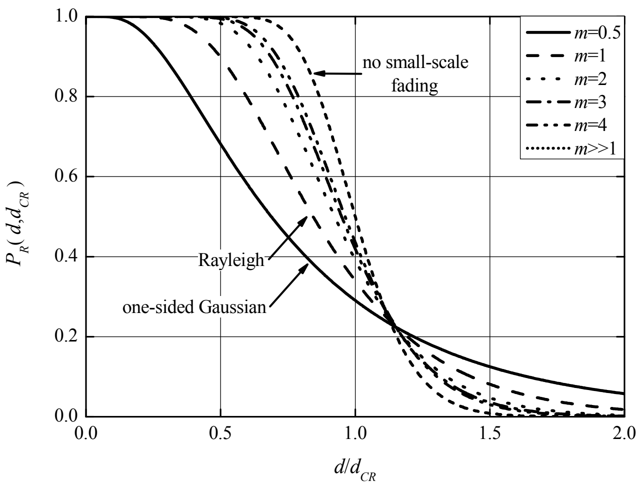

Fig. 2. Impact of small-scale fading on packet reception probability.

The curves in Fig. 2 show the impact of small-scale fading on packet reception probability. The severity of fading decreases with m; in urban environments, the shape factor usually ranges from 0.5 to 3.5, [7], (the Nakagami-m

distribution includes the one-sided Gaussian and the Rayleigh distribution for $m = 0.5$ and $m = 1$, respectively). Without loss of generality, we set $n = 3.4$ and $s = 4$ dB. The proposed model resembles the deterministic one as m increases. In this case, only shadowing and distance-dependent loss affect system performance. Notice also that packet reception probability does not practically depends on m for $d \approx 1.15d_{CR}$.

Fig. 3 shows the packet reception probability versus d/d_{CR} in different shadowing environments. Typically, s varies between 4 and 10 dB, [11]. Without loss of generality, we set $m = 3$ and $n = 3.4$. Similar to before, when s decreases, the curves approach the deterministic performance because only small-scale fading and distance dependent losses affect significantly the propagating signal. We further notice that packet reception probability does not depend on shadowing at distance $d \approx 0.95d_{CR}$. In this case, we see that half of the packets are successfully received.

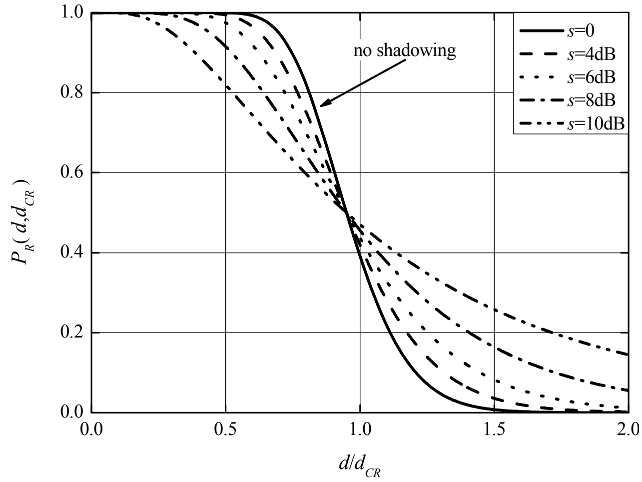

Fig. 3. Impact of shadowing on packet reception probability.

Finally, the impact of path loss exponent on VANET performance in terms of packet reception probability is shown in Fig. 4.

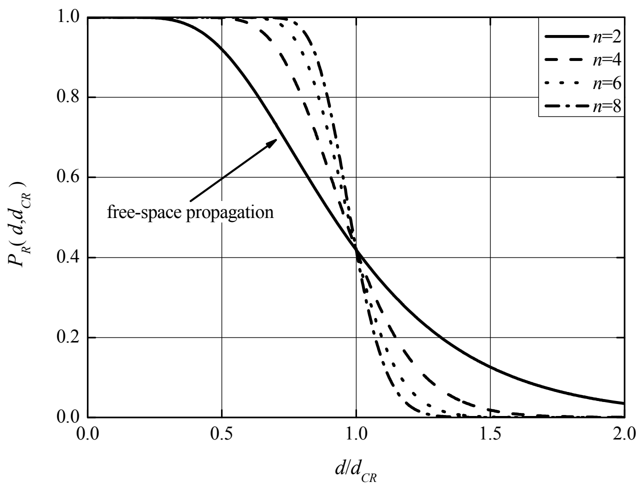

Fig. 4. Impact of distance-dependent path loss on packet reception probability.

In a vehicular environment, a typical value of n is close to three but values between two and eight can also be found, [11], [24]. Without loss of generality, we set $m = 3$ and $s = 4$ dB. The resulting curves approach the deterministic behavior as path losses increase; obviously, the impact of path loss on system performance increases with n. The curves intersect at $d = d_{CR}$ as it was expected from (16).

3.2 Model Validation

We now present some simulation results that verify the accuracy of the proposed model. In the simulations, the distance between sender and receiver is uniformly distributed within a range twice the intended communication range. Channel parameters are $m = 3$, $s = 4$ dB and $n = 3.4$. We employ the DX-120-4 pseudorandom number generator, [25], and apply the rejection sampling method, [26], to generate the random samples. A total of 10^5 independent simulation runs are performed. In each snapshot, a distance value between the communicating nodes is randomly found. The shadowing and the small-scale fading contributions are computed as random variables that follow the lognormal and the Nakagami-m distribution, respectively. We then calculate path loss using (1) and compare it to the deterministic value of loss. The simulation values in the diagram are averaged over a d/d_{CR} step-size of 0.01. Fig. 5 shows the match between the simulated PRP and (16). A good agreement between the theoretical curve and the simulation results is observed.

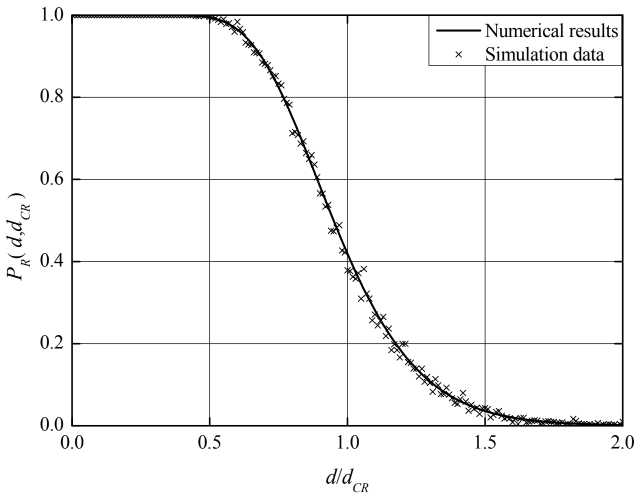

Fig. 5. Packet reception probability: Theoretical curve (16) and simulation results.

3.3 The Impact of Channel Impairments on Packet Forwarding Distance

In the last part of this section, we explore the relation between environmental parameters and packet forwarding distance. We consider a hop-by-hop retransmission scheme, [27]. The interference due to simultaneous transmissions is neglected. For simplicity, we further assume that the receiving node sends separate acknowledgement and forwarding packets to the previous and next nodes on the route. After a packet reception, the receiver sends u acknowledgements. The sender retransmits the packet when it does not receive any acknowledgement. In this case, the total expected hop count between two nodes separated by distance x is, [28],

$$K(x,u) = \frac{1+up(x)}{p(x)\left(1-(1-p(x))^u\right)} \quad (17)$$

where $p(x)$ is the probability of successful packet reception. Obviously, if we require single packet transmission, it is

$$\operatorname{sgn}\left(K(d,1)-K(d,2)\right) = -1 . \quad (18)$$

After some algebraic manipulation, (17) and (18) give that the maximum distance between the transmitting and the receiving node that minimizes hop count is the positive root of the quadratic equation

$$p^2(x)+p(x)-1=0 . \quad (19)$$

Then, replacement of $p(x)$ with $P_R(d,d_{CR})$ in the acceptable solution of (19) gives that the maximum packet forwarding distance is

$$d_{\max} \approx d_{CR} \exp\left(\frac{\psi(m)-\ln m - 0.069\sqrt{s^2+\xi^2\zeta(2,m)}}{n}\right). \quad (20)$$

Tab. 1 presents the maximum packet forwarding distance for the examples discussed in the previous subsections. We observe that $d_{\max}$ reduces with the severity of fading but increases with path loss exponent. The results show that the packet forwarding distance value which minimizes hop count is lower than the intended communications range (a similar conclusion was drawn in [28]). Notice also the significance of small-scale fading compared to the rest of the channel impairments in the values of maximum packet forwarding distance.

(n,s) = (3.4,4dB)		(n,m) = (3.4,3)		(m,s) = (3,4dB)	
m	$d_{\max}/d_{CR}$	s	$d_{\max}/d_{CR}$	n	$d_{\max}/d_{CR}$
0.5	0.562	0	0.898	2	0.806
1	0.745	4dB	0.881	4	0.898
2	0.846	6dB	0.861	6	0.930
3	0.881	8dB	0.826	8	0.947
4	0.898	10dB	0.769	–	–
inf.	0.950	–	–	–	–

Tab. 1. Maximum sender-receiver packet forwarding distances.

4. Conclusions

In this paper, we provided a set of analytical expressions for the description of the packet reception probability and the packet forwarding distance in a vehicular ad hoc network. The proposed formulation extends previous model by comprising the small-scale fading effect and the impact of distance-dependent losses on signal variation. The dependence of specific VANET performance metrics on environmental parameters was investigated and interesting conclusions were derived. Simulation results validated the formulation. The proposed model may be a useful tool in the analysis and modeling of vehicular ad hoc networks and it can find application in hybrid simulations of large-scale vehicular systems.

References

[1] OLARIU, S., WEIGLE, M. C. *Vehicular Networks: From Theory to Practice*. Boca Raton: CRC Press, 2009.

[2] WIESER, V., PŠENÁK, V. Performance of advanced hybrid link adaptation algorithms in mobile radio channel. *Radioengineering*, 2008, vol. 17, no. 3, p. 81-86.

[3] KILLAT, M., SCHMIDT-EISENLOHR, F., HARTENSTEIN, H., RÖSSEL, C., VORTISCH, P., ASSENMACHER, S., BUSCH, F. Enabling efficient and accurate large-scale simulations of VANETs for vehicular traffic management. In *Proceedings of the 4th ACM International Workshop on Vehicular Ad Hoc Networks*. Montreal (Canada), 2007, p. 29-38.

[4] CUOMO, F., MARTELLO, C., BAIOCCHI, A., CAPRIOTTI, F. Radio resource sharing for ad hoc networking with UWB. *IEEE Journal on Selected Areas in Communications*, 2002, vol. 20, no. 9, p. 1722-1732.

[5] KITANI, T., SHINKAWA, T., SHIBATA, N., YASUMOTO, K., ITO, M., HIGASHINO, T. Efficient VANET-based traffic information sharing system using buses on regular routes. In *Proceedings of the 67th IEEE Vehicular Technology Conference*. Singapore (Singapore), 2008, p. 3031-3036.

[6] KILLAT, M., HARTENSTEIN, H. An empirical model for probability of packet reception in vehicular ad hoc networks. *EURASIP Journal on Wireless Communications and Networking*, 2009, vol. 2009, article ID 721301, 12 pages. DOI:10.1155/2009/721301.

[7] RUBIO, L., REIG, J., CARDONA, N. Evaluation of Nakagami fading behaviour based on measurements in urban scenarios. *AEU International Journal of Electronics and Communications*, 2007, vol. 61, no. 2, p. 135–138.

[8] TALIWAL, V., JIANG, D., MANGOLD, H., CHEN, C., SENGUPTA, R. Empirical determination of channel characteristics for DSRC vehicle-to-vehicle communication. In *Proceedings of the 1st ACM International Workshop on Vehicular Ad Hoc Networks*. Philadelphia (USA), 2004, p. 88.

[9] SEYBOLD, J. S. *Introduction to RF Propagation*. Hoboken: Wiley, 2005.

[10] NEKOVEE, M. Modelling the spread of computer worms in vehicular ad hoc networks. In *Proceedings of the 1st European Conference on Computer Network Defence*. Glamorgan (UK), 2005, p. 115–124.

[11] SETIWAN, G., ISKANDER, S., CHEN, Q. J., KANHERE, S. S., LAN, K. C. The effect of radio models on vehicle network simulators. In *Proceedings of the 14th World Congress on Intelligent Transport Systems*. Beijing (China), 2007, p. 1-10.

[12] WOLNY, G. Modified DMAC clustering algorithm for VANETs. In *Proceedings of the 3rd International Conference on Systems and Networks Communications*. Sliema (Malta), 2008, p. 268-273.

[13] OKADA, H., TAKANO, A., MASE, K. A proposal of link metric for next-hop forwarding methods in vehicular ad hoc networks. In *Proceedings of the 6th IEEE Consumer Communications and Networking Conference*. Fredericton (Canada), 2009, p. 1-5.

[14] STOJMENOVIC, I., NAYAK, A., KURUVILA, J., OVALLE-MARTINEZ, F., VILLANUEVA-PENA, E. Physical layer impact on the design and performance of routing and broadcasting protocols in ad hoc and sensor networks. *Computer Communications*, 2005, vol. 28, no. 10, p. 1138–1151.

[15] XU, H., GARCIA-LUNA-ACEVES, J. J. Efficient broadcast for wireless ad hoc networks with a realistic physical layer. *Ad Hoc Networks*, 2010, vol. 8, no 2, p. 165-180.

[16] KUMAR, D., VENKATESH, R., KUMAR, A., ALTMAN E. Capacity optimizing hop distance in a mobile ad hoc network with power control. In *Proceedings of the 4th International Symposium on Modeling and Optimization in Mobile, Ad Hoc and Wireless Networks*. Boston (USA), 2006, p. 207-212.

[17] TORRENT-MORENO, M., SCHMIDT-EISENLOHR, F., FUBLER, H., HARTENSTEIN, H. Effects of realistic channel model on packet forwarding in vehicular ad hoc networks. In *Proceedings of the 2006 IEEE Wireless Communications and Networking Conference*. Las Vegas (USA), 2006, p. 385-391.

[18] BALTZIS, K. B. Closed-form description of microwave signal attenuation in cellular systems. *Radioengineering*, 2010, vol 19, no. 1, p. 11-16.

[19] BALTZIS, K. B. Analytical and closed-form expressions for the distribution of path loss in hexagonal cellular networks. *Wireless Personal Communications*, 2010, 12 pages. DOI: 10.1007/s11277-010-9962-2.

[20] DOUSE, O., THIRAN, P. Connectivity vs capacity in dense ad hoc networks. In *Proceedings of the 23rd Annual Joint Conference of the IEEE Computer and Communication Societies*. Hong Kong (China), 2004, p. 476-486.

[21] SIMON, M. K., ALOUINI, M.-S. *Digital Communication over Fading Channels*. 2nd ed. Hoboken: John Wiley & Sons, Inc., 2005.

[22] ALOUINI, M.-S., GOLDSMITH, A. J. Area spectral efficiency of cellular mobile radio systems. *IEEE Transactions on Vehicular Technology*, 1999, vol. 48, no. 4, p. 1047–1066.

[23] GRADSHTEYN, I. S., RYZHIK, I. M. *Table of Integrals, Series, and Products*. 5th ed. London: Academic Press, 1994.

[24] JIANG, T., CHEN, H.-H., WU, H.-C., YI, Y. Channel modeling and inter-carrier interference analysis for V2V communication systems in frequency-dispersive channels. *Mobile Networks and Applications*, 2010, vol. 15, no. 1, p. 4-12.

[25] DENG, L.-Y., XU, H. A system of high-dimensional, efficient, long-cycle and portable uniform random generators. *ACM Transactions on Modeling and Computer Simulation*, 2003, vol. 13, no. 4, p. 299-309.

[26] RAESIDE, D. E. Monte Carlo principles and applications. *Physics in Medicine and Biology*, 1976, vol 21, no. 2, p. 181-197.

[27] ZHU, J., HUNG, K.-L., BENSAOU, B., NAIT-ABDESSELAM, F. Real-time tradeoff for reliable communication in wireless sensor networks. *Computer Networks*, 2008, vol. 52, no. 1, p. 25-43.

[28] KURUVILA, J., NAYAK, A., STOJMENOVIC, I. Hop count optimal position-based packet routing algorithms for ad hoc wireless networks with a realistic physical layer. *IEEE Journal on Selected Areas in Communications*, 2005, vol. 23, no. 6, p. 1267-1275.

About Author...

Konstantinos B. BALTZIS was born in Thessaloniki, Greece. He received his B.Sc. degree in Physics in 1996, his M.Sc. degree in Communications and Electronics in 1999 and his PhD degree in Communications Engineering in 2005, all from the Aristotle University of Thessaloniki (AUTh), Greece. He is a member of the permanent research staff of the RadioCommunications Laboratory of AUTh. He is also a teaching staff member in the Program of Postgraduate Studies in Electronic Physics of AUTh. He has authored or co-authored more than forty papers in peer-reviewed international journals and conferences. His current research interests include mobile communications, radio propagation, antennas, microwave systems and evolutionary optimization methods.